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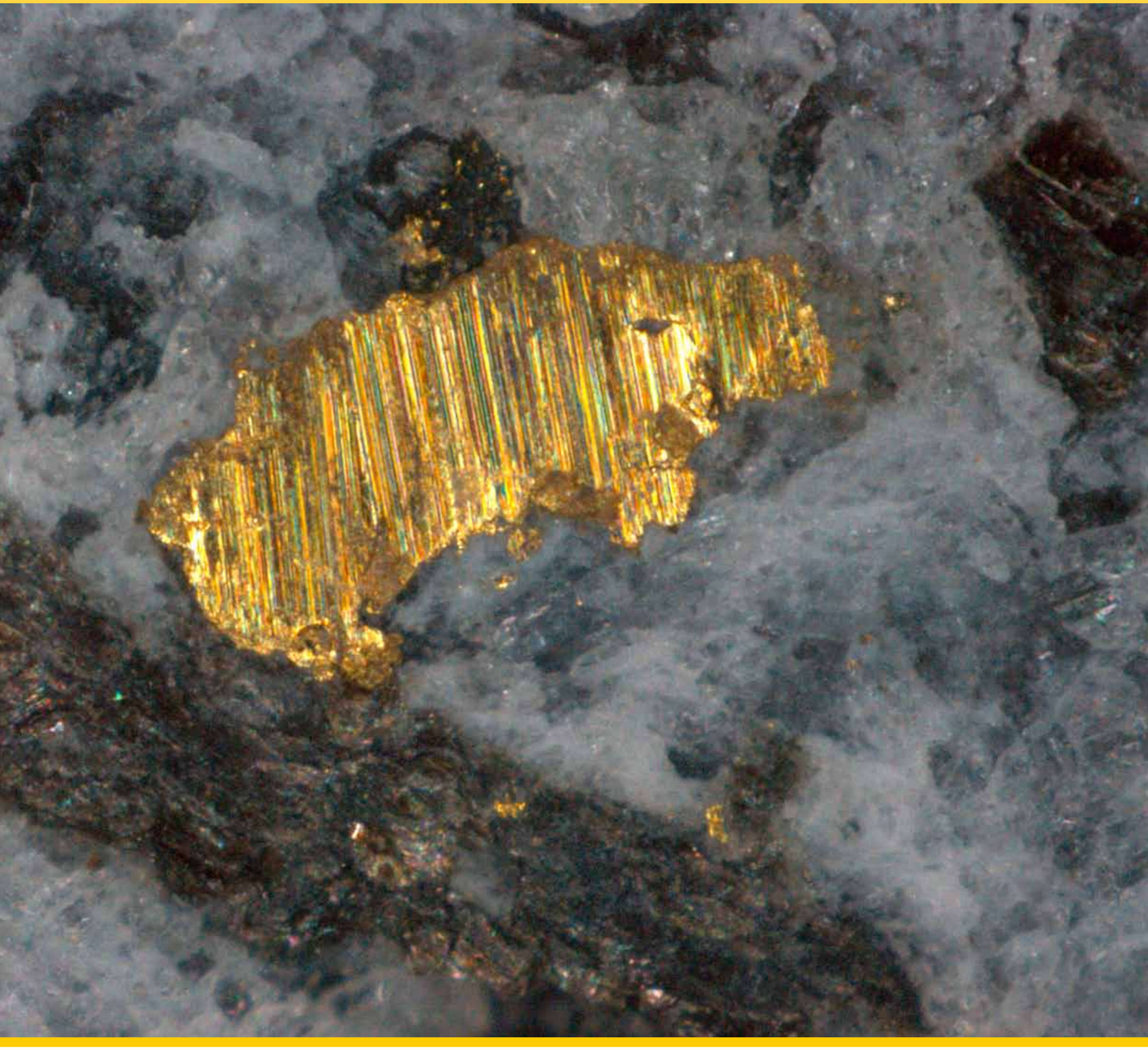

Gold in Southern Finland: Results of GTK studies 1998 – 2011

Edited by Sari Grönholm and Niilo Kärkkäinen

GTK

Geological Survey of Finland, Special Paper 52

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Geological Survey of Finland
Espoo 2012

Front cover: Gold grain in the drill core of the Velkua Au occurrence, Naantali.
Diameter of the grain is about 1 mm. Photo: Kari Kojonen, GTK.

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Grönholm, S. & Kärkkäinen, N. (eds.) 2012. Gold in Southern Finland: Results of GTK studies 1998–2011. *Geological Survey of Finland, Special Paper 52,* 276 pages, 185 figures, 23 tables and 6 appendices.

This publication introduces the results of studies by the Geological Survey of Finland (GTK) concerning the gold potential of southern Finland. The volume contains 16 articles under three themes: regional surveys, case studies and applied research methods.

The first article summarizes updated data on the known Au occurrences of southern Finland, while the two following papers describe the exploration of the region by GTK. Geochemical mapping based on the till has proven to be a powerful method in regional exploration, as demonstrated in a paper on regional geochemical mapping in the Tampere, Pirkkala and Forssa-Huittinen areas. The use and results of boulder prospecting and heavy mineral studies are described in one article, and a review of detailed airborne geophysical surveys for gold exploration in Kullaa, Vampula, Nuutajärvi and Humppila is presented in another.

The second theme of the volume comprises selected case studies. These are the porphyry-type Kedonojankulma Cu-Au deposit, the shear zone-hosted Palokallio Au occurrence, and four Au occurrences in the high-grade metamorphic terrain of SW Finland. The application of geochemical gold exploration is described from the Seinäjoki Sb-Au zone of western Finland. The most suitable grain size in the till geochemical exploration of gold has been investigated in the Kalliojärvi area of the Pirkanmaa belt.

The third theme is recent research on geophysics, ore genesis and geochemistry. An article on palaeomagnetic and AMS studies demonstrates the connections in the Au mineralized shear and fault zones relative to the host bedrock, and the use of absolute timing of the processes. One article estimates the Au potential in the geophysical structures of southern Finland. Two articles review the classic Haveri Au-Cu deposit, one of these focusing on geophysical studies and the other discussing the genetic considerations of the Haveri ore. The final study of the volume tests the application of weak-leaching geochemistry in exploration.

Keywords (GeoRef Thesaurus, AGI): gold ores, potential deposits, mineral exploration, geochemical methods, till, geophysical methods, airborne methods, paleomagnetism, Southern Finland

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Geological Survey of Finland, Special Paper 52, 7–10, 2012

PREFACE

This Special Paper (volume 52) introduces the results of gold exploration and research in southern Finland by the Geological Survey of Finland (GTK) in two projects that were active during 1998–2002 and 2003–2007. In general, gold exploration in Finland has been most intensive in the Archaean and Palaeoproterozoic greenstone belts in the eastern and northern parts of the country, published in Special Papers 17 and 44, which concern gold in the Archaean Hattu schist belt in the Ilomantsi area and the Palaeoproterozoic Central Lapland greenstone belt. Three mines, Suurikuusikko (Kittilä), Pahtavaara (Sodankylä) and Pampalo (Ilomantsi), are the results of discoveries by GTK.

Gold exploration in southern Finland has been more or less active for over 70 years, since GTK started gold exploration in the early 1940s in the Tampere schist belt, which was in those days regarded as one of the few Au potential areas in the country. Soon after that, the Haveri Cu-Au deposit became the first mine in Finland with gold as the main commodity. Two papers in this volume present new interpretations of the Haveri ore, one by Pasi Eilu concerning its genesis and another by Tapio Ruotoistenmäki presenting its geophysical characteristics.

Nowadays, gold is mined in southern Finland from two deposits: Kutemajärvi at Orivesi (1994–2003, 2007–) and Jokisivu (2009–) at Huittinen (http://www.dragon-mining.com.au/-Overview-.html). According to the gold database maintained by GTK, there are about 30 recorded gold deposits south of the Tampere belt. However, only a few of them have been sufficiently drilled to make estimations of the mineral resources.

During the 1960s and 1970s, GTK carried out tentative studies on gold in the Seinäjoki Au-Sb-Sn zone during exploration for antimony. However, gold began to be more intensively researched by GTK from the late 1980s onwards, based on the preliminary results of a nationwide geochemical survey. Geochemistry indicated that gold was anomalous in many localities in the western part of the Svecofennian domain of southern Finland. Elevated gold concentrations were first mapped in the Pirkanmaa migmatite belt, to the south of the Tampere schist belt. Several gold occurrences were found, but so far the most promising GTK discovery has been the Kaapelinkulma Au occurrence at Valkeakoski.

The papers in this volume roughly fall under three themes, the first articles concerning regional surveys, the second theme describing case studies on some recently reported discoveries, and the third theme presenting applied research methods.

In the first paper, Pasi Eilu summarizes updated data on the known Au occurrences of southern Finland. The two following papers by the project geologists describe the regional exploration carried out in the project. One major effort was a regional mineral resource assessment in an area of 250 km^2 between Huittinen and

Forssa, which was based on a till geochemical survey. Other geochemical surveys were performed in the Pirkanmaa and Tampere belts. These studies resulted in the discoveries of the Ritakallio Au occurrence (Huittinen) and Kedonojankulma Au-Cu occurrence (Jokioinen). At Ritakallio, gold is hosted by a shear zone within mafic intrusive rock, and the mineralization is analogous to the Jokisivu and Kaapelinkulma Au deposits. Subsequently, similar occurrences have been found at Palokallio (described by Sari Grönholm in this volume) and Uunimäki (drilling target during 2011) in Huittinen. However, Kedonojankulma, described by Markku Tiainen et al. in this volume, has similarities with the porphyric ore type, and this demonstrates some other fascinating multi-element geochemical anomalies of the region. Prospecting for heavy minerals and mineralized boulders in till (glacial drift) is summarized in a paper by Pekka Huhta et al. In many localities, elevated numbers of gold grains or boulders in till have been the first indications of a mineral deposit. These methods are mainly used in supporting geochemistry, and are good tools for testing geochemical anomalies. A current problem is that only a few experts are left who actively use a stone hammer.

Detailed airborne geophysical measurements have been conducted in three areas in southern Finland, with the aim of supporting this project (Jaana Lohva, this volume). These areas are linked to each other between Forssa and Huittinen, partially overlapping the regional geochemical survey.

The second theme of this volume includes some selected case studies. Two papers describe the Kedonojankulma and Palokallio occurrences, repectively, and next three papers concern diverse Au occurrences in the highly metamorphic area of SW Finland. Target-scale geochemical exploration is described by Aimo Hartikainen from the South-Pohjanmaa area. The problem of determining the most suitable till material for geochemical exploration is examined by Thair Al-Ani in the area of the Kalliojärvi Au occurrence.

The third theme comprises articles presenting recent research on geophysics and geochemistry. Two geophysical studies have been carried out in close collaboration with the project. Palaeomagnetic and AMS studies by Satu Mertanen and Fredrik Karell were undertaken to demonstrate the connections between the Au-mineralized shear and fault zones relative to the host bedrock, and the use of absolute timing of the processes. Geophysical surveys are a key method for recognizing and categorizing gold potential structures, faults and shear zones, in addition to providing information on the compositional variation of the bedrock. Meri-Liisa Airo and Hanna Leveinen have investigated geophysical structures in southern Finland and estimated their gold potential. Tapio Ruotoistenmäki presents results from Haveri in a paper that is based on a study executed by the exploration company holding the property. A method based on weak-leaching geochemistry was tested by Aimo Hartikainen and is presented here, although the most interesting element in the study was not gold.

In addition to the papers and references therein, the project has produced an extensive constellation of unpublished reports, field observations, samples (including drill cores), chemical analyses and geophysical data. Unpublished reports are available in the final archive of GTK and are accessible in digital form via the following address: http://www.gtk.fi/tietopalvelut/tietokannat/rapgeo.html.

In addition, several theses in different universities have been prepared with the co-operation of the project. The primary data are maintained in digital form in GTK's geodabase, and the samples are preserved at the Loppi drill core depot.

The editors of the present volume are grateful to all collegues who shared their time to review the manuscripts included in it: M.-L. Airo, P. Eilu, P. Huhta, E. Hyvönen, P. Hölttä, O. Kontoniemi, E. Korkiakoski, H. Makkonen, T. Niiranen, J. Nenonen, L. Pesonen, and T. Tarvainen. R. Siddall revised the English. Technical editors of the present volume were P. Kuikka-Niemi and S. Seppänen.

Espoo, 23 December 2011

Sari Grönholm and Niilo Kärkkäinen

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GOLD MINERALISATION IN SOUTHWESTERN FINLAND

by
Pasi Eilu

Eilu, P. 2012. Gold mineralisation in southwestern Finland. *Geological Survey of Finland, Special Paper 52*, 11–22, 1 figure and 1 appendix.

The bedrock of southwestern Finland was chiefly formed during the composite Svecofennian orogeny at 1.9–1.8 Ga. The orogeny evolved through accretion and attempted collapse to collisional stages. This complex evolution produced several genetic types of gold mineralisation: 1) The most common type is orogenic gold, which probably occurs in all major supracrustal belts of the region. 2) Metamorphosed epithermal gold is present in the Tampere and, apparently, Uusimaa belts, whereas indications of epithermal mineralisation are less clear or not present in all the other belts. 3) One deposit, Haveri, probably belongs to the Au-rich VMS type; the gold-rich base-metal deposits of the Uusimaa belt may also be of the VMS type, if they are not epithermal. 4) Indications of porphyry and/or other types of granitoid-related Au-Cu mineralisation have been detected in the Häme belt. The presence of high-sulphidation epithermal gold mineralisation in the Tampere belt points towards the possibility of porphyry Cu(-Au) mineralisation also occurring in that area.

Keywords (GeoRef Thesaurus, AGI): gold ores, metallogeny, tectonics, Svecofennian Orogeny, orogenic belts, Paleoproterozoic, Southwestern Finland

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INTRODUCTION

Two active and one closed mine, and a large number of prospects in various stages of exploration indicate the potential for economic gold mineralisation in SW Finland (Fig. 1; Appendix 1). The style of gold mineralisation indicates rather large variation in the area, as at least orogenic, porphyry and other intrusion-related, epithermal and VMS styles of mineralisation have been suggested (Eilu 2007). Such extensive genetic variation suggests a complex geological evolution of the area. Hence, I first briefly review the geological evolution of SW Finland and then discuss the various genetic types of mineralisation suggested to exist in the area.

GEOLOGICAL SETTING AND EVOLUTION OF THE CRUST IN SW FINLAND

The bedrock of southwestern Finland essentially comprises, from south to north, the Uusimaa, Häme, Pirkanmaa and Tampere, and the southern part of the Pohjanmaa supracrustal belts with syn- to late-orogenic intrusion (Vaasjoki et al. 2005). In addition, the SW part of the Central Finland Granitoid Complex occupies a large area between the Tampere and Pohjanmaa belts (Fig. 1). Rocks in the region mostly show ages between 1.9 and 1.8 Ga, indicating deposition, intrusion and evolution during the composite Svecofennian orogeny (Lahtinen et al. 2005, 2008, Kähkönen 2005, Nironen 2005).

The oldest unambiguously dated stages of plate-tectonic evolution in the area relate to microcontinent accretion with an Archaean craton to the northeast, beyond the area under consideration in this report, and the simultaneous northward subduction of an igneous arc (Tampere belt) and an accretionary complex (Pirkanmaa belt) under a microcontinent (Central Finland Granitoid Complex) during 1.91–1.89 Ga. Almost contemporaneously, during 1.90–1.87 Ga, the Tampere–Pirkanmaa igneous arc–accretionary complex also subducted to the south under the Bergslagen microcontinent, that is, under the Häme and Uusimaa belts. Subduction of the Tampere and Pirkanmaa belts towards the north ended at 1.89 Ga. This was followed, during 1.89–1.87 Ga, by the first major stage of deformation, regional metamorphism and N-S shortening in southern Finland. After an interlude of attempted orogenic collapse, the second major orogenic stage, with extensive magmatism, high-T metamorphism and transpressional deformation followed during 1.84–1.79 Ga. The latter stage was related to continent–continent collision in the southeast during 1.84–1.82 Ga and in the west during 1.82–1.80 Ga, beyond the area discussed in this report. Instead of merely continent–continent collision-related processes, the orogenic evolution of southern Finland (and Central Sweden) during 1.84–1.79 Ga could, at least partly, also be explained by a southward retreating Andean-type active margin system. In any case, most of the active orogenic evolution of the area, including all ductile deformation, ended by 1.79 Ga. (Kilpeläinen 1998, Kähkönen 2005, Lahtinen et al. 2005, 2008)

GOLD DEPOSIT TYPES DETECTED AND THEIR RELATIONSHIP TO CRUSTAL EVOLUTION

The types of gold mineralisation detected or suspected to occur in SW Finland include: 1) Au-rich VMS, 2) epithermal gold, 3) porphyry and/or other types of granitoid-related Au-Cu, and 4) orogenic gold (Appendix 1). In this paper, their geological context is briefly discussed, whereas more detailed descriptions of investigated occurrences are provided in other papers of this publication.

All hosts to gold in the region are within the age range of 1.9–1.8 Ga. Some mineralisation appear to be syngenetic, many postdate the intrusion or extrusion of the igneous hosts and at least the earliest deformation, and all predate the post-1.79 Ga brittle structures (e.g., Väisänen et al. 2002, Lahtinen et al. 2005, 2008, Kärkkäinen 2007, Saalmann et al. 2008, Eilu & Pankka 2009). This indicates that gold mineralisation in southwestern Finland is related to various stages of orogenic development in the area. It also means that the metallogeny of gold of the region is closely related to one of the globally main stages (Goldfarb et al. 2001) of formation of the continental crust.

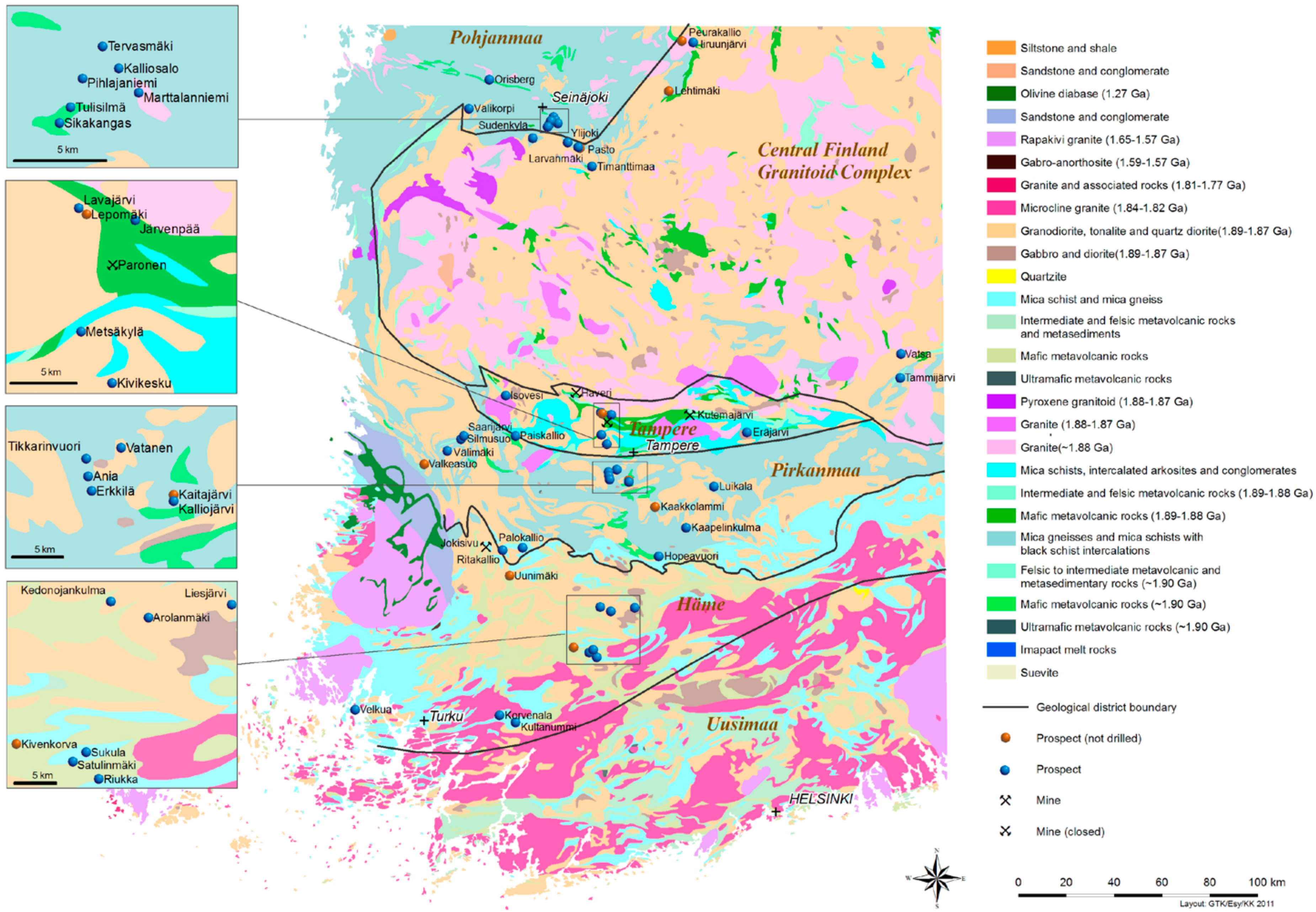

Figure 1. Geology of southwestern Finland and gold deposits and occurrences detected in the area. Geology from Vaasjoki et al. (2005) and GTK (Bedrock of Finland – DigiKP), gold occurrences after Eilu & Pankka (2009) and recent exploration by GTK (Kärkkäinen et al. 2003, Kärkkäinen 2007, and unpublished GTK data). Boundary between Häme and Pirkanmaa belts is according to Sipilä et al. (2011).

There is very little radiometric age data for gold mineralisation in the region, and the timing must chiefly be constrained from indirect indications essentially resulting from structural investigations. The VMS and epithermal mineralisation probably took place during ca. 1.905–1.889 Ga in the Tampere belt and at ca. 1.89 Ga in the Uusimaa belt (Väisänen et al. 2002, Skyttä et al. 2005, Kähkönen 2005, Väisänen & Kirkland 2008). Hence, all such deposits have metamorphosed after mineralisation. Mineralisation was probably related to mafic submarine volcanism in a back-arc setting in the western Tampere belt and of bimodal, submarine to subaerial, volcanism and synvolcanic intrusion in igneous arcs above subduction zones in both belts. Such tectonic settings are favourable for both VMS and epithermal styles of mineralisation. If there was epithermal mineralisation in the Häme belt, it took place during the synvolcanic evolution of the belt, perhaps at ca. 1.89–1.88 Ga. Granitoid-related Au-Cu mineralisation, if there is any in the region, took place in the same tectonic setting and in roughly the same time interval as epithermal mineralisation. Orogenic gold mineralisation, by definition, is formed by orogenic fluids and takes place close to the peak of regional metamorphism under a compressive to transpressive tectonic regime typical for accretionary and continent–continent collisional settings (Goldfarb et al. 2001, Groves et al. 2003). This gives two possible periods for orogenic gold mineralisation in SW Finland: the main deformation and metamorphic stages of 1.89–1.87 Ga and 1.84–1.80 Ga.

VMS and epithermal gold

VMS-style base metal mineralisation occurs in the western parts of the Uusimaa, Häme and Tampere belts. In nearly all cases, as is typical for most VMS mineralisation anywhere, there is minor gold (0.1–1 ppm) in the deposits (Latvalahti 1979, Eilu et al. 2003). This typically means a possibility of by-product gold, which is not discussed any further here. However, two major exceptions to the low gold–base metal ratio in VMS settings of SW Finland have been detected: at Haveri in the Tampere belt and at Iilijärvi in the Uusimaa belt (Fig. 1, Appendix 1). Haveri probably represents the roots of a submarine Cu-Au VMS system partially remobilised by deformation (e.g., Mäkelä 1980, Eilu & Pankka 2009), and is discussed in more detail in a separate paper in this publication.

Iilijärvi is either a gold-rich VMS deposit or an epithermal deposit at least spatially related to VMS mineralisation (Mäkelä 1989, Eilu 2007). The metal association at Iilijärvi is Ag-Au-Cu-Pb-Zn, and there is some metal zoning with the gold-rich parts being somewhat separate from the Ag-Pb-Zn-rich parts (Mäkelä 1989). The parts rich in gold are characterised by quartz-andalusite-muscovite gangue (Isomäki 1988), suggesting acid fluids typical for epithermal processes (Hedenquist et al. 1996). Like Iilijärvi, a few other gold occurrences in the western Uusimaa belt are in apparently sericitised rocks (Eilu 2007). However, not enough work has been done to be sure of the genetic type of these occurrences. This also holds for the possible epithermal occurrences of the Häme belt, including the Kultanummi, Velkua, Satulinmäki and Riukka occurrences (Appendix 1). The latter two are characterised by abundant K mica in gangue, whereas their structures and preliminary age dating suggest a syn-peak orogenic timing (Saalmann et al. 2008), which would mean that they belong to the category of orogenic gold mineralisation *sensu* Goldfarb et al. (2001), as suggested in the section on the Somero–Tammela area below. The argument for Kultanummi being a metamorphosed epithermal occurrence essentially lies in gold being closely related to a deformed sillimanite-rich zone (Grönholm et al. 2005); this suggests an early timing and an intense argillic alteration during mineralisation – possibly analogous to Enåsen, central Sweden (Hallberg 1994).

The most obvious and most extensively studied case for an epithermal mineralisation in SW Finland is the Kutemajärvi (Orivesi) mine in the Tampere belt (Fig. 1, Appendix 1). There, practically all reported features (Luukkonen 1994, Poutiainen & Grönholm 1996, Kojonen et al. 1999, Talikka & Mänttäri 2005) indicate metamorphosed epithermal gold mineralisation without any later introduction of gold. The deposit is characterised by strong leaching out of major elements, intense silicification, and the formation of pyrophyllite. Locally, phosphates and F-rich minerals (e.g., topaz, lazulite) occur in the alteration assemblage. No carbonatisation, potassic or sodic alteration, nor auriferous quartz veining has been detected. These features suggest high-sulphidation epithermal mineralisation in the sense defined by Hedenquist et al. (1996). The relative timing of alteration and, most probably, also for mineralisation predate all deformation. The Järvenpää Au-Ag-

Cu-Zn occurrence, 30 km west of Kutemajärvi, occurs in roughly the same stratigraphic position and has most features similar to the latter (Luukkonen 1994, Dragon Mining 2005).

Granitoid-related gold

Lavajärvi and Tammijärvi in the Tampere belt, and Liesjärvi and Kedonojankulma in the Häme belt have features that would locate them in the broad category of granitoid-related gold mineralisation, indicating that they were immediate products of fluids produced by the hosting granitoids or by granitoids whose immediate country rocks host the mineralisation. Typical features for these occurrences include (Kokkola 1986, Luukkonen 1994, Kärkkäinen et al. 2003, Kärkkäinen 2007, Tiainen et al. 2012): an elevated copper content, a disseminated style of sulphide–gold mineralisation, abundant tourmaline, only a minor volume of quartz veins, and the main host being a granodiorite (or a synorogenic granodiorite occurs near the mineralisation). However, none of these occurrences have been investigated in significant detail. Hence, it is possible that they occur in or near a granitoid just because the structural setting in those locations during deformation was suitable for orogenic gold mineralisation, and that the mineralisation significantly postdates its hosts.

Orogenic gold

Orogenic gold mineralisation seems to occur in all belts of SW Finland (Appendix 1; Eilu & Pankka 2009). In the Pirkanmaa and Pohjanmaa belts, all occurrences probably belong to this category. This may also be the case for the Häme belt, although the available information is not as unequivocal as for the former belts. In the Uusimaa and Tampere belts, the orogenic type seems to have a minor proportion of the total number of gold occurrences so far detected.

Orogenic gold occurrences in SW Finland are all hosted by rocks metamorphosed under amphibolite-facies conditions. Their location is structurally controlled: they are in secondary to tertiary shear zones hosted by the locally most competent lithological units (e.g., Rosenberg 1997, Ojala 2003, Vuori et al. 2005). They are gold-only deposits and the main ore minerals typically include, in decreasing order, pyrrhotite, arsenopyrite, pyrite, and löllingite. Gold occurs in native grains associated with gangue and the sulphides, in quartz veins and in the host rock. Structural studies indicate that the timing of mineralisation is syn-peak deformation, significantly postdating the formation of the host rocks (Rosenberg 1997, Ojala 2003). The few radiometric ages on host rocks and mineralisation also support this age relationship (Saalmann et al. 2008). It remains unclear, however, whether all mineralisation took place during the 1.89–1.87 Ga accretionary stage of the Svecofennian evolution, whether there was also significant mineralisation during the 1.84–1.80 Ga collisional stage, or whether it all took place during 1.84–1.80 Ga. Many of the occurrences in the Seinäjoki area of the Pohjanmaa belt differ from the common style in having such a high antimony content that Sb can be regarded as a major commodity in them (Appelqvist 1993). More details on the orogenic gold occurrences of SW Finland can be found in the following sections of this publication.

CONCLUSIONS

Southwestern Finland chiefly comprises orogenic rocks of 1.9 to 1.8 Ga in age. These were produced by the complex, accretionary to collisional orogenic evolution of Fennoscandia. Much work is still to be done before the genetic types of all the known gold occurrences in SW Finland are firmly established. Nevertheless, we can rather safely say that the multi-stage evolution of the crust has resulted into several genetic types of gold mineralisation in the region:

1. The most common type is orogenic gold, which appears to occur in all major domains of SW Finland.
2. Evidence for the presence of metamorphosed epithermal gold is most convincing in the Tampere and Uusimaa belts, whereas indications of epithermal mineralisation are less obvious or non-existent in other areas.

3. The Haveri gold-copper deposit probably belongs to the VMS type. It has a synorogenic deformational overprint, however, and the possibility of orogenic gold overprinting VMS-style Cu or Cu-Au mineralisation cannot be completely rejected. The gold-rich base-metal deposits of the Uusimaa belt, such as Iilijärvi, are, if not epithermal, also of the VMS type.
4. The Häme belt contains indications of porphyry and/or other types of granitoid-related Au-Cu mineralisation. However, the amount of investigation still is too limited to state anything with certainty about the genetic types of those occurrences within and near synorogenic granitoids of the Häme belt. The presence of high-sulphidation epithermal gold mineralisation in the Tampere belt suggests that porphyry Cu(-Au) deposits could occur also there.

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Appendix 1. Gold deposits and drilling-indicated occurrences in southwestern Finland. Location of the occurrences is indicated in Figure 1.

Deposit / Prospect (parallel name)	Size / Best sections	Geological district	Main host rocks	Main ore minerals[1]	Siting of gold[1]	Commodity association	Genetic type[2]	References
Mine								
Haveri	26.26 Mt @ 1 ppm Au, 0.5 % Cu	Tampere	Basalt	Po, Apy, Cpy	Native with gangue, Apy, Cob, Cpy	Au-Cu	VMS	Mäkelä (1980), Lappland Goldminers (2008)
Kutemajärvi (Orivesi)	2.8 Mt @ 9 ppm Au	Tampere	Intermediate volcanic rock	Alt, Py, Apy	Free native with Qz, Py, Apy, Te	Au	Epithermal	Poutiainen & Grönholm (1996), Dragon Mining (2009)
Paronen (Ylöjärvi)	4.013 Mt @ 14 ppm Ag, 0.04 ppm Au, 0.75 % Cu, 0.11 % W[3]	Tampere	Granodiorite	Apy, Cpy, Sch, Po	Not reported	Cu-W(-Ag, Au)	Intrusion-related	Himmi et al. (1979)
Jokisivu	1.567 Mt @ 6.5 ppm Au	Pirkanmaa	Gabbro	Po, Apy	Free native in Qz veins, related to Apy, with Te	Au	Orogenic	Luukkonen (1994), Dragon Mining (2009)
Prospect, drilled								
Arolanmäki	2 m @ 0.8-1.6 ppm Au	Häme	Granitoid	Cpy, Py, Po	Not reported	Au-Cu	Intrusion-related	GTK unpublished data
Kedonojankulma	1 m @ 8 ppm, 3 m @ 1.1-3.7 ppm Au	Häme	Granitoid	Cpy, Cc, Py, Apy	Not reported	Au-Cu	Intrusion-related	GTK unpublished data
Korvenala	5.5 m @ 1 ppm Au	Häme	Plagioclase porphyry	Apy	Not reported	Au	Orogenic	Rosenberg (2000c)
Kultanummi	1-6 m sections @ 0.5-10 ppm Au	Häme	Intermediate volcanic rock	Py, Po, Apy	Free native in host rock and Qz vein, with Apy	Au	Epithermal?	Grönholm et al. (2005)
Liesjärvi	6 m @ 2 ppm Au	Häme	Granodiorite	Apy, Löl, Po, Cpy	Not reported	Au-Cu	Orogenic	Kokkola (1986)
Riukka	9 m @ 4.3 ppm Au; 6.5 m @ 6.7 ppm Au, 0.4 % Zn, 0.04 % Cu, 0.29 % Pb	Häme	Mafic-Intermediate volcanic rock	Apy, Po, Löl, SP, Ga	Native and Ele as inclusions in silicates, Apy, Löl	Au (-Cu, Pb, Zn)	Orogenic or epithermal	Etelämäki (2007)
Satulinmäki	0.36 Mt @ 2.23 ppm Au	Häme	Intermediate volcanic rock	Apy, Po	Native in Qz-Tou veins and in host rock; assoc with Apy, Bi and Sb minerals	Au	Orogenic	Kärkkäinen et al. (2006b)
Sukula	1 m @ 1.7 ppm Au	Häme	Intermediate volcanic rock	Apy, Po, Py	Not reported	Au	Orogenic	GTK unpublished data
Uunimäki	1 m @ 12.2 ppm	Häme	Gabbro	Po	Not reported	Au, W	Orogenic	GTK unpublished data
Velkua	6 m @ 5.5 ppm Au	Häme	Amphibolite	Po, Apy	Free native in gangue > inclusions in Apy,	Au	Epithermal?	GTK unpublished data
Ania	0.5-0.8 m sections @ 3.3-4.2 ppm Au	Pirkanmaa	Greywacke	Apy, Po, Löl	Native free in gangue, inclusions in Apy	Au	Orogenic	Kärkkäinen et al. (2006a)
Erkkilä	3-6 m sections @ 1-8 ppm Au	Pirkanmaa	Greywacke, black schist	Po, Apy	Native free in gangue	Au	Orogenic	Kärkkäinen et al. (2003)
Eräjärvi	1 m @ 1 ppm Au	Pirkanmaa	gabbro	Apy, Po	Native inclusions in Apy	Au	Orogenic	GTK unpublished data
Hopeavuori	17.5 m @ 13.1 ppm Au	Pirkanmaa	Intermediate volcanic rock	Apy	Not reported	Au	Orogenic	Lindmark & Koistinen (1996)
Isovesi	3.7 m @ 5.3 ppm Au	Pirkanmaa	Intermediate tuffite	Apy	Native free with gangue, Apy, Bi	Au	Orogenic	Luukkonen (1994)

Appendix 1. cont.

Deposit / Prospect (parallel name)	Size / Best sections	Geological district	Main host rocks	Main ore minerals[1]	Siting of gold[1]	Commodity association	Genetic type[2]	References
Kaapelinkulma	0.127 Mt @ 8.15 ppm Au	Pirkanmaa	Quartz diorite	Apy, Po	Free native with Qz, Bi; inclusions in Apy	Au	Orogenic	Rosenberg (1997), Dragon Mining (2009)
Kaitajärvi	1 m @ 0.6 ppm Au	Pirkanmaa	Greywacke	Po, Py	Not reported	Au	Orogenic	Lehto (2004a)
Kalliojärvi	4.3 m @ 7.2 ppm Au	Pirkanmaa	Greywacke	Apy	Not reported	Au	Orogenic	Lehto (2000), Rosenberg (2000a)
Kivikesku	5 m @ 3.4 m Au	Pirkanmaa	Greywacke	Apy, Po	Free native and inclusions in Apy	Au	Orogenic	Lindmark (1995)
Palokallio	1 m @ 1-41.8 ppm	Pirkanmaa	Gabbro	Po, Apy, Löl	Inclusions in Apy-Löl and silicates	Au	Orogenic	GTK unpublished data
Ritakallio	4.7 m @ 1.7 ppm Au	Pirkanmaa	Gabbro	Apy, Löl, Po	Free native in gangue and inclusions in Apy, with Bi, Sb and Te minerals	Au	Orogenic	Vuori et al. (2005)
Saarijärvi	1 @ 2.3 ppm Au	Pirkanmaa	Mafic metavolcanic rock	Po, Apy	Free native in gangue and inclusions in Apy	Au	Orogenic	GTK unpublished data
Silmussuo	1.2 m @ 3.2 ppm Au	Pirkanmaa	Mica gneiss	Apy, Mgt			Orogenic?	Kokkola (1991)
Tikkarinvuori	1 m @ 8.1 ppm (76 ppm in hand specimen)	Pirkanmaa	Greywacke	Apy, Löl, Po	Native, free, visible in Qz vein margins	Au	Orogenic	Rosenberg (1998)
Vatanen	10 m @ 0.5 ppm Au	Pirkanmaa	Granodiorite	Apy	Free native with Qz, inclusions in Apy	Au	Orogenic	Rosenberg (1990)
Välimäki	1 m sections @ 2-18 ppm Au	Pirkanmaa	Mica gneiss	Py, Po, Apy	Free native and Au-Bi-Te grains in gangue, inclusions in Apy-Löll	Au	Orogenic	Lehto & Kärkkäinen (2006)
Kalliosalo	0.3 Mt @ 0.85% Sb, 1.0 ppm Au	Pohjanmaa	Plagioclase porphyrite	Apy, Löl, Sb	Aust; native inclusions Löl and Apy	Au-Sb	Orogenic	Tyni (1983), Kärkkäinen (1992a), Appelqvist (1993)
Larvanmäki	1 m @ 4.85 ppm Au	Pohjanmaa	Plagioclase porphyry	Apy	Native	Au	Orogenic	GTK unpublished data
Marttalanniemi	1 m @ 14.8 ppm Au	Pohjanmaa	Plagioclase porphyry	Py, Po, Apy	Native in Tou-Qz veins, and in host rock	Au	Orogenic	Kärkkäinen (1990)
Pihlajaniemi	1 m @ 1 ppm Au	Pohjanmaa	Plagioclase porphyrite	Native Sb, Apy	Not reported	Au-Sb	orogenic	Oivanen (1982)
Sikakangas (Tulisilmä)	3 m @ 27.24 ppm Au	Pohjanmaa	Plagioclase porphyry	Apy	Native in host rock, Qz-veins	Au	Orogenic	Kärkkäinen (1993a), Isomaa at al. (2010)
Sudenkylä (Haudankylä)	1 m @ 3.5 ppm Au	Pohjanmaa	Mafic volcanic rock	Apy, Po, Py	Not reported	Au-Sb	Orogenic	Lestinen et al. (1991)
Tervasmäki	5 m @ 1.3 ppm Au, 0.55% Sb	Pohjanmaa	Plagioclase porphyry	Sb, Apy	Not reported	Au-Sb	Orogenic	Oivanen (1982)
Timanttimaa	1 Mt @ 1 ppm Au	Pohjanmaa	Plagioclase porphyry	Po, Apy	Free native in Qz veins	Au	Orogenic	Kärkkäinen (1993b)
Välikorpi	1 m @ 10.3 ppm Au	Pohjanmaa	Interm. volcanic rock	Apy, Po	Native	Au	Orogenic	GTK unpublished data

Appendix 1. cont.

Deposit / Prospect (parallel name)	Size / Best sections	Geological district	Main host rocks	Main ore minerals[1]	Siting of gold[1]	Commodity association	Genetic type[2]	References
Ylijoki	7 m @ 1 ppm Au	Pohjanmaa	Greywacke	Apy, Po	Native	Au	Orogenic	Kärkkäinen (1992b)
Järvenpää	2.3 m @ 2.6 ppm Au, 0.8 % Cu, 0.8 % Zn; 1.6-3.4 m @ 1.0-2.2 ppm Au, 10.4-22.4 ppm Ag	Tampere	Intermediate volcanic rock	Py, Po	Ele with sulphides and Pb-Sb minerals, some as native and in Aust	Au-Ag-Cu-Zn	Epithermal?	Luukkonen (1994)
Lavajärvi (Pässärinvuori)	4 m @ 1 ppm Au	Tampere	Granodiorite, felsic volc rock	Py, Apy	Native with Apy in veins and host rocks	Au	Orogenic or intrusion-related	Lehto & Vuori (2006)
Lepomäki	13.8 ppm Au in outcrop grab sample	Tampere	Qz-Tour vein in volcanic rock	Apy, Po	Not reported	Au	Intrusian related	Lehto & Vuori (2006)
Metsäkylä	1 m @ 27.6 ppm Au	Tampere	Plagioclase porphyry	Apy, Cpy, Po	Free native	Au(-Cu)	Orogenic?	Lehto (2004b)
Paiskallio	0.5-2 m sections @ 0.16-62.9 ppm Au	Tampere	Amphibolite	Apy	Free native in Qz veins	Au	Orogenic	Rosenberg (2000b)
Pääjärvi	1 m @ 2.9 ppm Au with up to 3% Cu	Tampere	Mica schist		Not reported	Au-Cu	Orogenic?	Mäkelä (1981)
Tammijärvi	4.5 m @ 0.4 ppm Au and 0.84% Cu; 6 m at 0.92% W	Tampere	Greywacke		Mainly Ele with Bi, some native with Te	Au-Cu, W	Orogenic + skarn?	Luukkonen (1994)
Vatsa	7 m @ 6.5 ppm Au	Tampere	Gabbro	Apy, Py	Not reported	Au	Orogenic	William Resources (1997)
Stenmo (Bjensböle)	1 m @ 4 ppm Au	Uusimaa	Felsic(?) volcanic rock		Not reported	Au	Epithermal or orogenic	Lindroos & Ehlers (2005)
Iilinjärvi (Iililammi)	45,000 t @ 30 ppm Ag, 4 ppm Au, 0.6 % Cu, 0.6 % Pb, 1.3 % Zn	Uusimaa	Felsic to intermed. volcanic rocks	Apy, Po, Py, Sp, Gn, Cpy, Tet	Not reported	Au-Zn-Cu-Ag-Pb	VMS or epithermal	Mäkelä (1989)
Pyhälammi	1.5 m @ 6.7 ppm Au, 0.01-0.12% Cu	Uusimaa	Quartz rock (chert?)		Not reported	Au-Cu	VMS or epithermal	Isomäki (1987)
Prospect, not drilled								
Kivenkorva	16.6 ppm Au in outcrop grab sample	Häme	Intermediate volcanic rock	Py, Apy	Not reported	Au	Orogenic?	GTK unpublished data
Kaakkolammi (Lastusenkulma)	4-7 ppm in outcrop grab samples	Pirkanmaa	Gabbro	Apy	Not reported	Au	Orogenic	GTK unpublished data
Valkeasuo	31-70 ppm in outcrop grab samples	Pirkanmaa	Granitoid	Cpy	Native in host rock and in Cpy	Au-Cu	Intrusian related	GTK unpublished data
Luikala	0.3 ppm Au in outcrop grab sample	Pirkanmaa	Mica gneiss	Ele	Visible gold in prehnite veins	Ag-Au	Post-orogenic?	Oivanen (1977)
Iiruunjärvi	Up to 55.5 ppm Au in boulders	Pohjanmaa	Intermediate volcanic rock		Not reported	Au	Orogenic	Laxström (2010)
Lehtimäki	3.7-3.9 ppm Au in outcrop grab sample	Pohjanmaa	Granitoid		Not reported	Au±Mo	Orogenic	Kärkkäinen (1991)
Orisberg	1.1-3.3 ppm Au in local boulders	Pohjanmaa	Amphibolite	Po, Apy	Not reported	Au	Orogenic	Kärkkäinen & Huuskonen (1992)

Appendix 1. cont.

Deposit / Prospect (parallel name)	Size / Best sections	Geological district	Main host rocks	Main ore minerals[1]	Siting of gold[1]	Commodity association	Genetic type[2]	References
Peurakallio	9.5 ppm in outcrop grab sample	Pohjanmaa	Tonalite	Apy	Not reported	Au	Orogenic	GTK unpublished data
Mickelsängs-bergen	1 m @ 1-2 ppm Au in channel samples	Uusimaa	Felsic or intermed volc rock			Au	VMS or epithermal	Isomäki (1987)

1) Alt = altaite, Apy = arsenopyrite, Aust = aurostibite, Bi = native bismuth, Cc = chalcocite, Cob = cobaltite, Cpy = chalcopyrite, Ele = electrum, Gn = galena, Grs = gersdorffite, Möl = löllingite, Mgt = magnetite, Qz = quartz, Po = pyrrhotite, Py = pyrite, Sb = native antimony, Sch = scheelite, Sp = sphalerite, Te = tellurides, Tet = tetrahedrite, Tou = tourmaline. Minerals are mentioned in the order of descending abundance
2) Orogenic: as defined by Goldfarb et al. (2001)
3) Only the mined amount is available.

Gold in Southern Finland: Results of GTK studies 1998–2011
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NEW GEOCHEMICAL DATA FOR GOLD EXPLORATION IN SOUTHERN FINLAND

by
Niilo Kärkkäinen, Pekka Huhta, Tapio Lehto, Markku Tiainen, Saku Vuori and Mikko Pelkkala*

Kärkkäinen, N., Huhta, P., Lehto, T., Tiainen, M., Vuori, S. & Pelkkala, M. 2012. New geochemical data for gold exploration in southern Finland. *Geological Survey of Finland, Special Paper 52*, 23–46, 22 figures and 4 tables.

Geochemical mapping based on basal till has proven to be a powerful method in regional studies on the mineral potential in Svecofennian areas of southern Finland. During the last decade, the Geological Survey of Finland has carried out regional geochemical mapping in three separate areas in southern Finland: Tampere, Pirkkala and Forssa-Huittinen. This paper introduces these studies and the results.

A total of 4247 till samples were analysed, mainly by ICP (base metals) and GFAAS (Au, Bi, Te), from an aqua regia leach of the fine fraction (<0.06 mm). Sampling was mainly performed on a 500 m grid (4 samples per km^2). A number of anomalies possibly related to undiscovered gold and base metal mineralisations were identified for use in future exploration.

The Ritakallio gold prospect and Kedonojankulma Cu-Au prospect were discovered during the geochemical mapping.

Keywords (GeoRef Thesaurus, AGI): mineral exploration, gold ores, geochemical methods, till, base metals, gold, arsenic, tellurium, antimony, geochemical maps, Tampere, Pirkkala, Forssa, Huittinen, Finland

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INTRODUCTION

One role of the Geological Survey of Finland (GTK) is to explore and model the main geological units of the bedrock of Finland and their potential for mineral resources. In this work, till geochemical mapping has been used as a method to recognize the gold potential of the poorly explored and exposed terrains in southern Finland.

This paper describes three regional geochemical studies carried out in the project "Mapping of the gold potential of southern and western Finland" during 1998–2007. The areas investigated were within the Tampere belt, the Pirkanmaa belt and the western part of the Häme belt (Fig. 1).

Previous studies

The Geological Survey of Finland carried out nationwide geochemical mapping from the fine fraction (<0.06 mm) of basal till during the 1980s (Salminen 1995). The sampling depth was 1.5–2 m, the density 1 sample per 4 km^2 (2 km grid), and the aqua regia soluble concentration was analysed for approximately 24 elements. In this data set, the regional variation in many elements clearly correlated with the composition of the bedrock. However, interesting features for exploration were also identified, such as a large arsenic anomaly in the Tampere area and high concentrations of gold at many individual sampling sites in the same area. Some of the most striking Au anomalies were checked by GTK soon after the national data were collected by using detailed profile sampling. The follow-up work in 1990–1997 occurred contemporaneously with GTK's first systematic gold studies in southern Finland, which began in the Tampere area during the late 1980s. Additional geochemical studies with a grid of 0.2 to 0.5 km gave indications of Au-favourable localities and

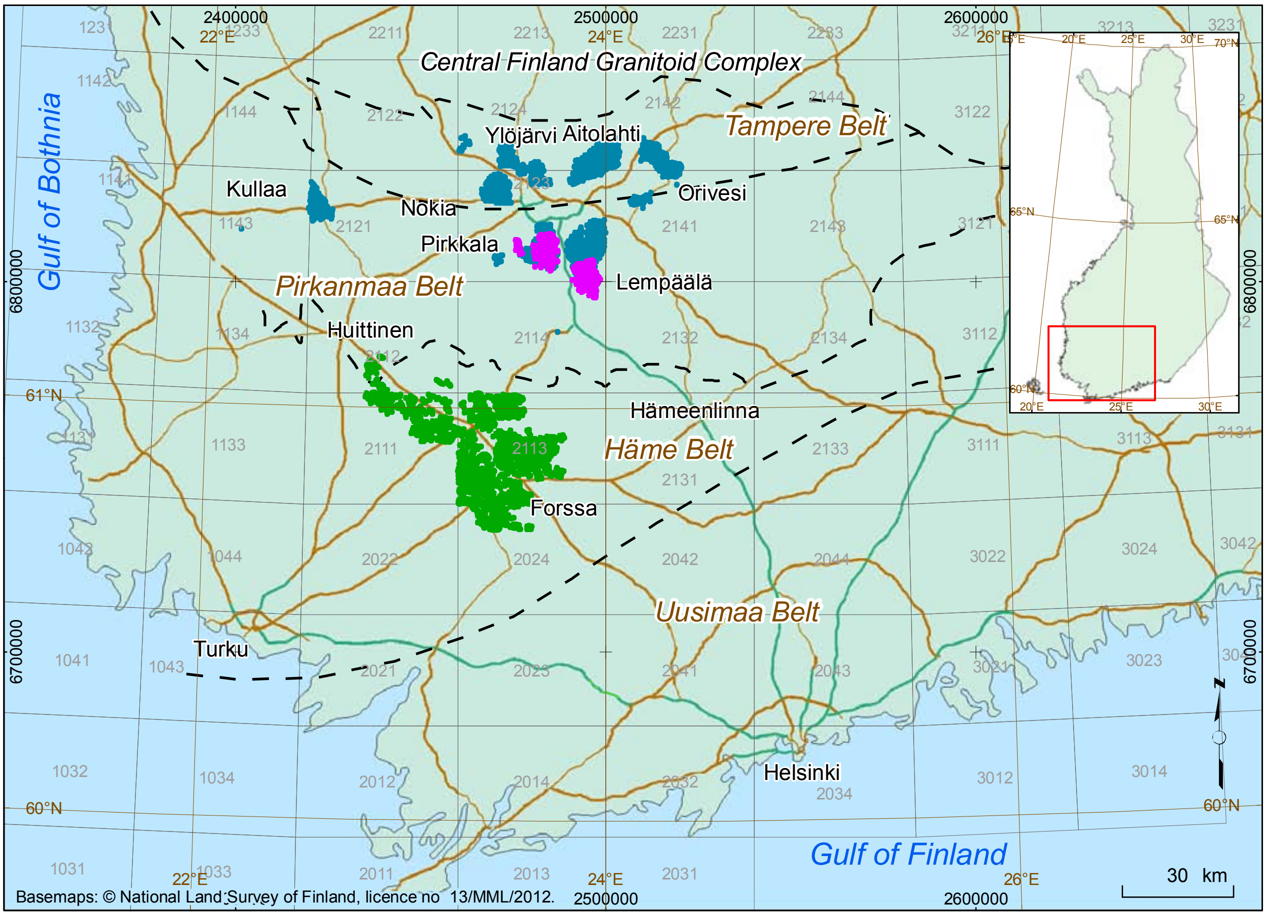


Figure 1. Areas of regional geochemical mapping in the GTK Au-Potential Project in southern Finland during 2001–2008. Blue = Tampere area (2001–2002); red = Pirkkala–Lempäälä area (2007); green = Forssa–Huittinen area (2003–2007). The sampling grid varies between 100 m and 500 m. Black lines indicate main roads.

structures (Lestinen 1987, Rosenberg 1990) and proved that till-based geochemistry is a suitable method for gold exploration in this area.

Recent investigations

Since 2001, GTK has continued regional geochemical mapping as a tool to estimate the gold potential in southern Finland. The work has been targeted at basal till and the sampling grid has been 4 samples per 1 km^2 (500 m grid) or 100 m in profile sampling. The sampling depth and analysed grain size have varied depending on the regional circumstances, as described below. The aim has been to find new gold-potential regions and localities from southern and western Finland (Kärkkäinen et al. 2003, Kärkkäinen et al. 2008b).

Regions studied

The geochemical survey in the GTK Gold Potential Project (Fig. 1) was carried out in three regions:

1: The Tampere area, comprising selected areas from the Tampere and Pirkanmaa belts during 2001 and 2002;
2: The Forssa–Huittinen area during 2003–2007;
3: The Pirkkala area during 2007–2008.

Geochemical anomalies in these studies have been completed by other indications from heavy mineral studies on till (Huhta et al. 2012), boulder prospecting and bedrock mapping. Results from the Forssa–Huittinen area (Kärkkäinen et al. 2007) and Pirkkala area (Kärkkäinen et al. 2008a) have been provided in GTK's final archive reports. However, only tentative results have previously been presented from the Tampere area, in a technical report of the first project period (Kärkkäinen et al. 2003).

TAMPERE AREA

The Tampere area has been under active gold exploration for more than 20 years. The closed Haveri gold-copper mine and the active Orivesi gold mine demonstrate the local Au potential. GTK has mainly carried out highly localized studies, and regional geochemical sampling had previously only been performed in the Pirkkala area (Rosenberg 1990, 1997a, Lestinen 1987). The area has been covered in nationwide till geochemical mapping (Salminen 1995) and lithogeochemical mapping (Lahtinen & Lestinen 1996, Rasilainen et al. 2008). The nationwide geochemical arsenic map depicts a prominent NW-oriented anomaly southwest of Tampere extending through the Pirkkala area to the southeast of Hämeenlinna (Fig. 2). The reason for this anomaly is unknown, as it does not seem to correlate with the mapped bedrock. Nevertheless, it is very interesting because arsenic commonly has a close relationship with gold, and arsenopyrite is practically always present in the Svecofennian orogenic Au deposits.

Gold occurrences

The ore potential of the surroundings of the Hämeenkyrö batholith has ranked highly since the 1940s discoveries of the Haveri Au-Cu ore, Paronen Cu-W ore and Järvenpää Au-Sb-Cu occurrences (Fig. 3). GTK has found gold occurrences in Kivikesku (Lindmark 1995), Metsäkylä (Rosenberg 2000b, Lehto 2004a) and Lavajärvi regions (Lehto & Vuori 2006). Till geochemistry and heavy mineral studies have indicated all of these occurrences. Respectively, Au occurrences at Tikkarinvuori (Rosenberg 1997a), Vatanen (Rosenberg 1990), Ania (Kärkkäinen et al. 2006b), Kalliojärvi (Rosenberg 2000a, Lehto 2004b) and Kaapelinkulma (Rosenberg 1997b) indicate the high gold potential of Pirkkala-Lempäälä area, which is also characterized by a prominent As anomaly in nationwide geochemical maps. Regional studies at Kullaa, on the western end of the Pirkanmaa migmatite belt, were based on the discovery of the Välimäki Au occur-

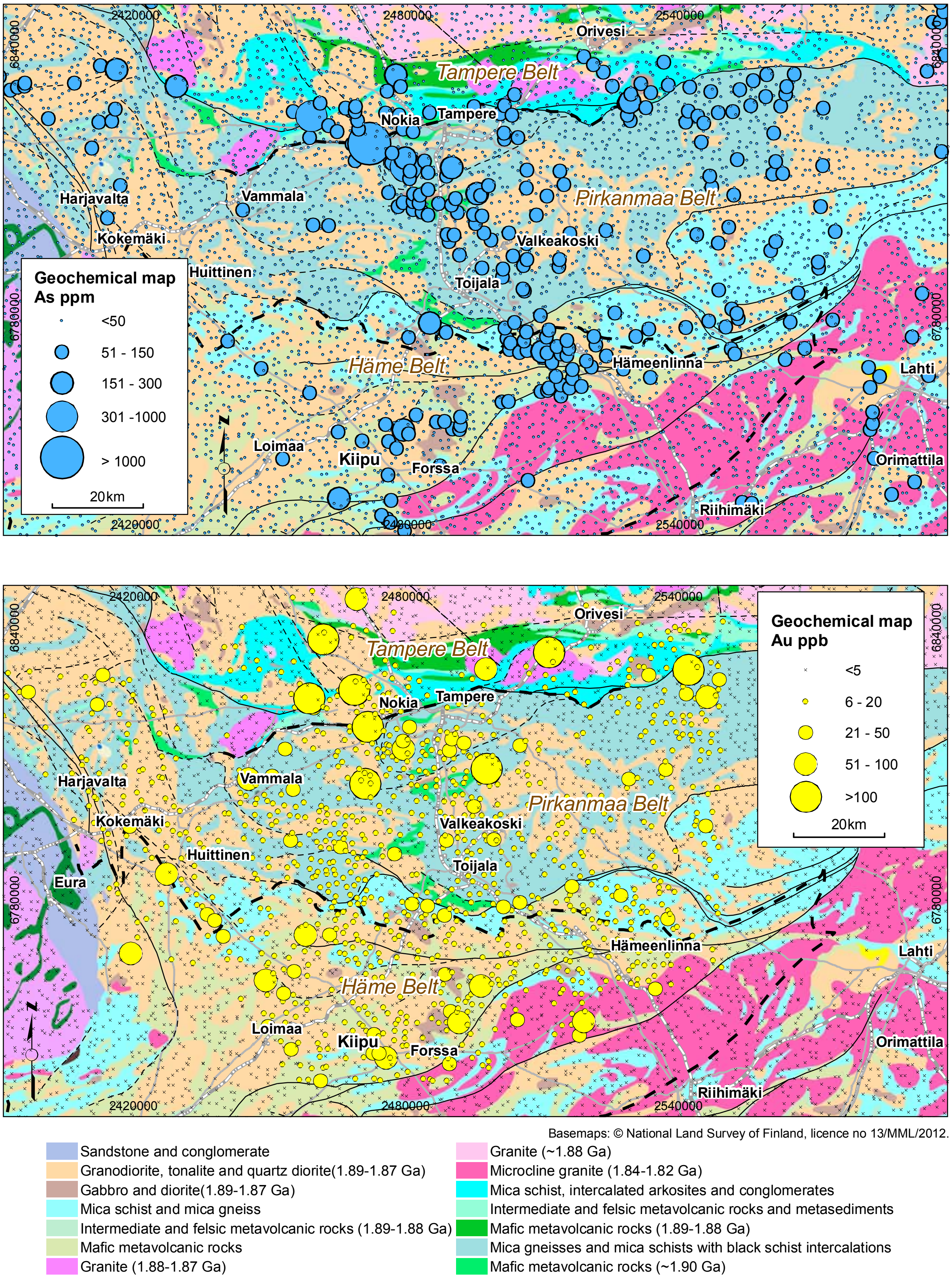


Figure 2. Arsenic and gold in the fine fraction of basal till in the area described. As and Au data from Salminen et al. (1995).

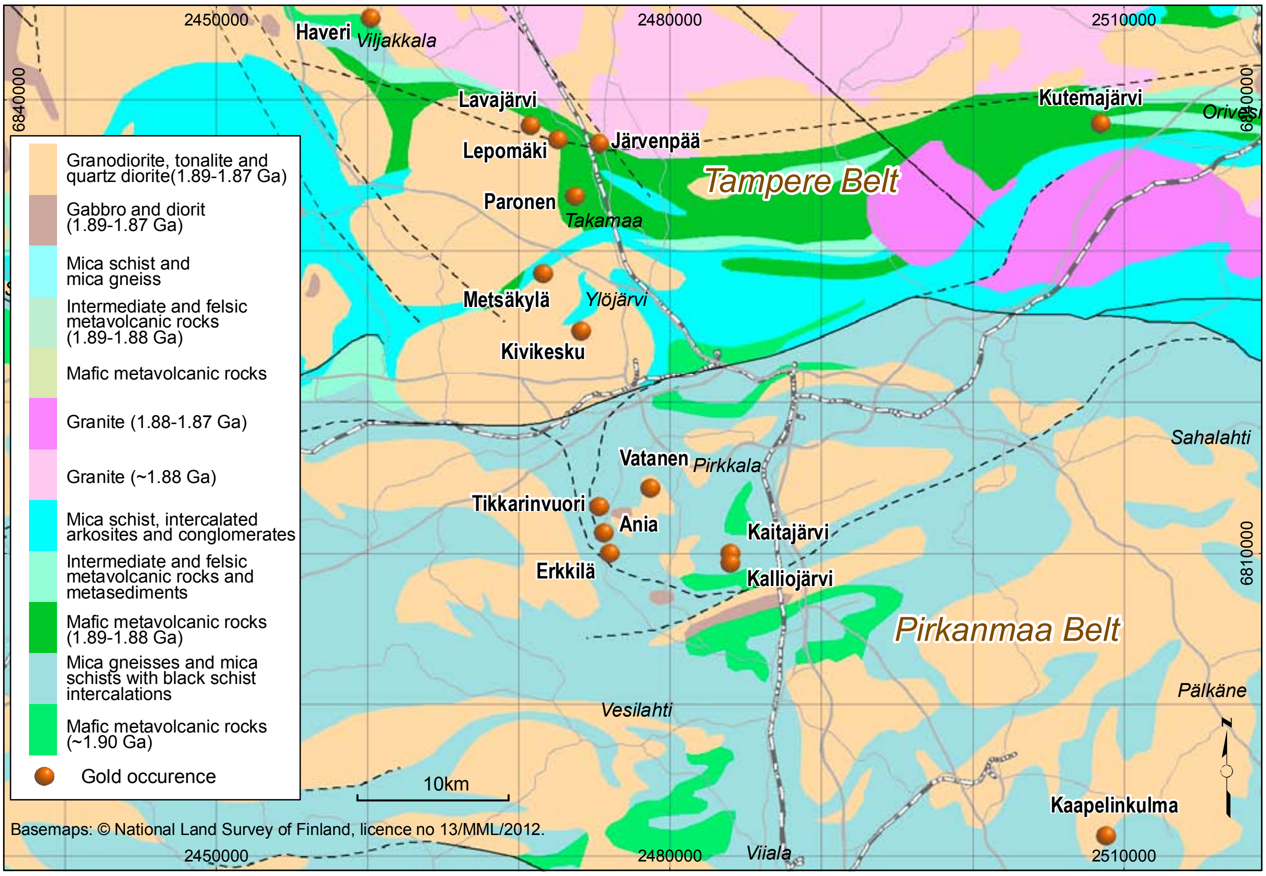


Figure 3. Gold deposits and occurrences in the Tampere Belt and Pirkkala–Lempäälä area on the bedrock map of Finland (Korsman et al. 1997).

rence (Lehto & Kärkkäinen 2006a) and numerous gold-bearing boulder trains along the east-west oriented schist zone. Aitolahti and Orivesi areas were considered interesting because of the poor geochemical visibility of the Orivesi gold deposit in the nationwide geochemical map.

Geology

The bedrock of the Tampere area is variable. The Ylöjärvi and Aitolahti sampling sites (Figs. 4–7) were partly within volcanic rocks and schists of the Tampere belt and partly within the surrounding granitoid batholiths, while the Orivesi sampling site was mainly in a granitoid area and the Pirkkala, Kangasala and Kullaa sampling sites were within the migmatites of the Pirkanmaa belt. The most prominent feature in Quaternary geology of the region is the Pispala interlobate esker, which runs east-west through the city of Tampere and its surroundings. In nationwide geochemical maps, the esker is a local divide so that, for instance, the Haveri Au-Cu mining district and the Orivesi gold mine area north of this esker do not have any significant gold geochemical anomalies in the nationwide geochemical data.

Sampling and analyses

Geochemical mapping in this project was carried out in the Tampere schist belt and Pirkanmaa migmatite belt during 2001 and 2002. Samples were taken by spade from basal till close to the surface, so that the average sampling depth was 0.5 m. Clay basins, marshes and some larger regions are not suitable for this type of mapping, such as part of Nokia due to the ablation moraine cover. This ablation moraine covers basal till and represents material that is usually more mixed or washed and originates from a source area that is much larger than in basal till.

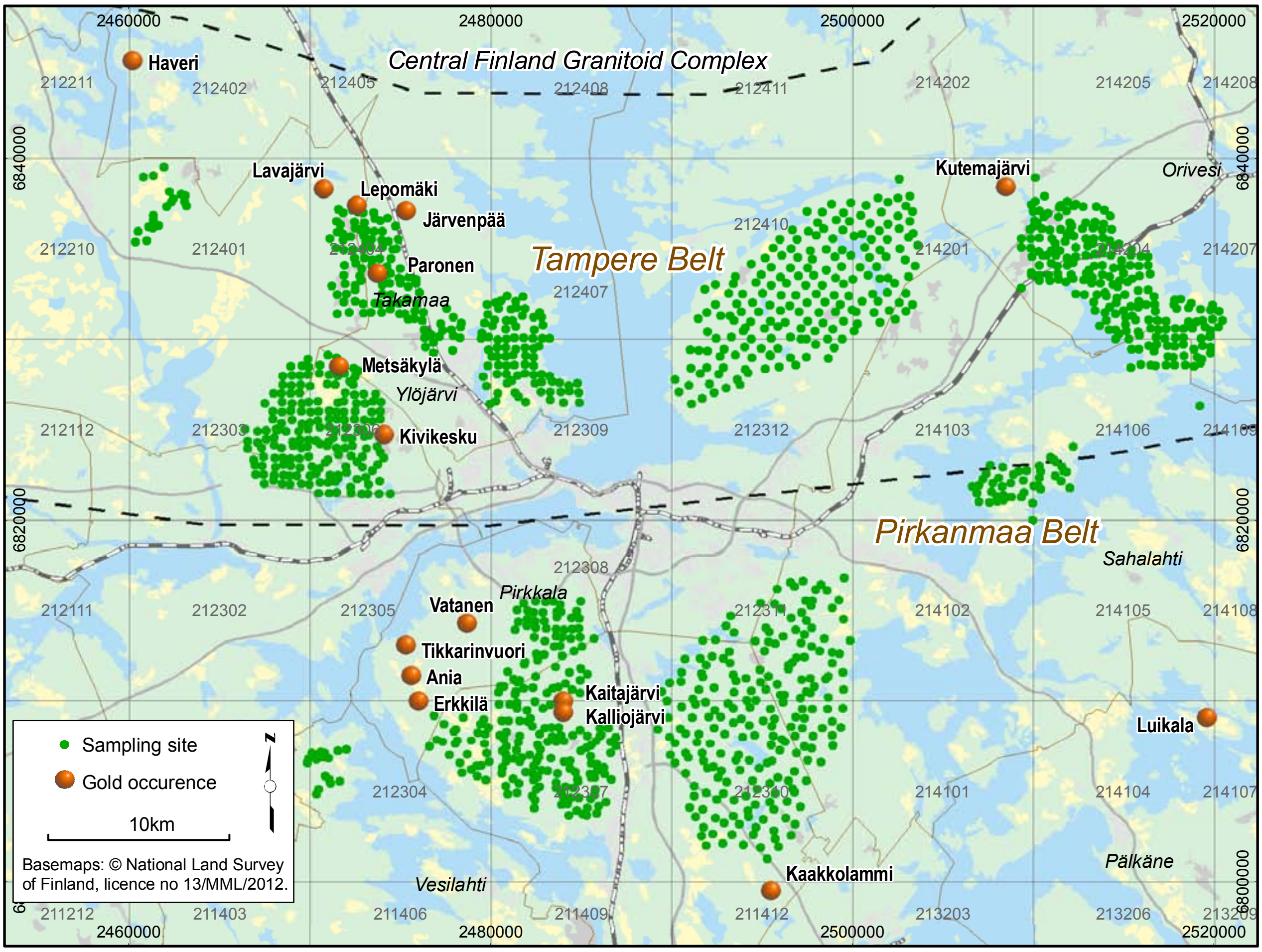


Figure 4. Geochemical mapping of the Tampere area during 2001–2002; sampling (green dots) from the surface of the basal till (depth 0.5 m); analyses from fine fraction (<0.06 mm).

Altogether, 1715 samples were taken and analysed from six subareas: 1) Ylöjärvi, NW of Tampere, 2) Aitolahti and 3) Orivesi east of Tampere, 4) Pirkkala-Lempäälä and 5) Kangasala south of Tampere and 6) Kullaa, further west of Tampere (Fig. 4).

Gold was analysed by graphite furnace AAS (GFAAS) after an aqua regia leach from a 5 g subsample at a temperature of 20 °C and Hg co-precipitation (method code 520U of GTK and Labtium Oy). Other metals were determined by ICP-AES from aqua regia leaches at 90 °C (method code 511P). The detection limits were 1 or 2 ppb for Au and 15 or 20 ppm for As, depending on the batch analysed.

Results

For all samples from the Tampere area, the average content of gold was 4.2 ppb (Table 1). This is two times higher than the average of 2.1 ppb Au reported for till in Finland (Salminen 1995).

Differences between the subareas in the data were small (Table 2). The highest mean Au concentration was recorded at Kullaa and the lowest in the granite dominated areas of Aitolahti and Orivesi. Where the Au content was less than the detection limit (< 1 or <2 ppb), the detection limit was used for that sample in calculating the average. Thus, the real averages are lower than those given in Tables 1 and 2. Because of the high detection limit of arsenic (15 or 20 ppm As), the averages for arsenic are also estimates. However, the anomalies distinguished in the geochemical map are real (Figs. 5–8).

The geochemical maps (Fig. 5) indicate increased gold in 3 to 4 restricted regions. South of Tampere, these are Lastusenkulma, Säijä and Vatanen. North of Tampere there are less uniform anomalies located east and south-east of

Table 1. Average and maximum concentrations of selected elements in the Tampere sampling area.

	Number of samples	Mean	Detection Limit	Maximum
Au ppb	1714	4.2	1.0 - 2.0	222
As ppm	1715	20.5*	15 - 20	1050
Cu ppm	1715	2944	1	202
S ppm	1715	322	50	21600
Te ppb	1714	18.9	5	742

* The mean of As is high when compared to the map in Fig. 6, because the detection limit of As (15 or 20 ppm) was used for the lowest concentrations in the calculation of the average.

Table 2. Averaged concentrations of selected elements in the subareas of the Tampere sampling area

Average	1 Ylöjärvi	2 Aitolahti	3 Orivesi	4 Pirkkala	5 Kangasala	6 Kullaa
Number of samples	415	189	214	446	43	408
Au ppb	4.1	2.0	1.6	4.9	2.4	6.1
As ppm	24*	22*	16*	15*	16*	24*
Cu ppm	36.9	19.6	22.5	36.2	32.8	22.1
S ppm	283	273	215	302	336	459
Te ppb	33	8	9	16	18	18

* The mean of As is high when compared to the map in Fig. 6, because the detection limit of As (10 or 20 ppm) was used for the lowest concentrations in the calculation of the average.

the Hämeenkyrö batholith (e.g. in Metsäkylä). Only spiky gold anomalies are recognizable elsewhere in the map.

Arsenic (Fig. 6) is clearly only anomalous in the Paronen and Metsäkylä areas east of the Hämeenkyrö batholith. Arsenic is surprisingly low south of Tampere, especially when compared to geochemical maps based on samples taken from deeper in the basal till (Fig. 2). Weathering is the probable reason for this, resulting in the leaching of arsenopyrite and transportation of arsenic by surface waters (Loukola-Ruskeniemi et al. 2007).

Tellurium (Fig. 7) is an important trace metal in the Orivesi Au ore (Luukkonen 1994). Regional variation in the Te data set can be interpreted to be related to normal variation within the bedrock. Only the Metsäkylä area at Ylöjärvi is anomalous and overlaps with an arsenic anomaly.

Mafic intrusive rocks are common in the southern part and also explain higher Ni concentrations in till (Fig. 8).

PIRKKALA AREA

Geochemical mapping continued during 2007 in the area to the south of Tampere to clarify the gold anomalies recognized during previous geochemical mapping in the Tampere area.

Gold occurrences

There are orogenic type shear and quartz vein related gold occurrences in this area (Fig. 3): Tikkarinvuori, Ania, Erkkilä, Vatanen at Pirkkala, Kalliojärvi at Lempäälä and Kaapelinkulma and Hopeavuori at Valkeakoski (e.g. Lindmark & Koistinen 1996, Rosenberg 1997b, 2000a).

Geology

The bedrock is mainly composed of migmatitized mica gneisses and metagraywackes intruded by granites and mafic intrusive rocks (Fig. 9). Other rock types are amphibolites and mafic metavolcanic rocks and black schists.

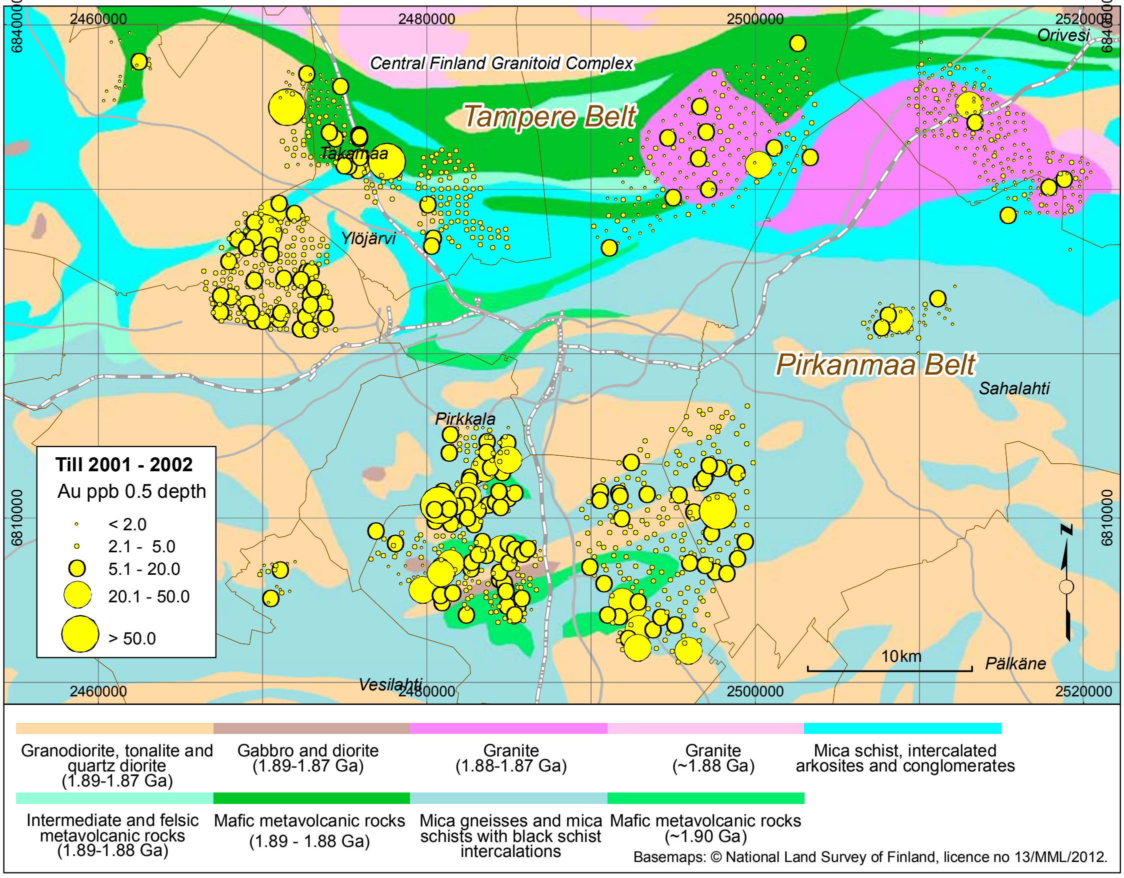


Figure 5. Distribution of gold in the Tampere area.

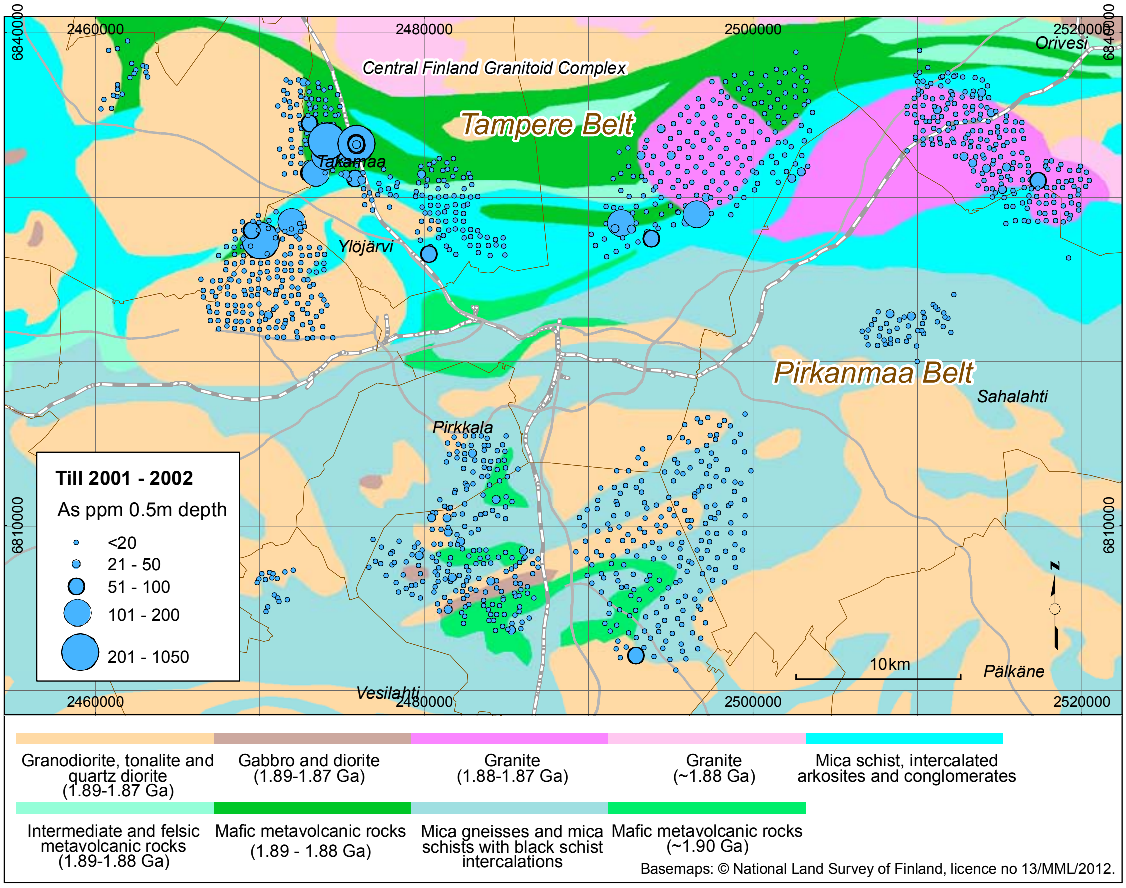


Figure 6. Distribution of arsenic in the Tampere area.

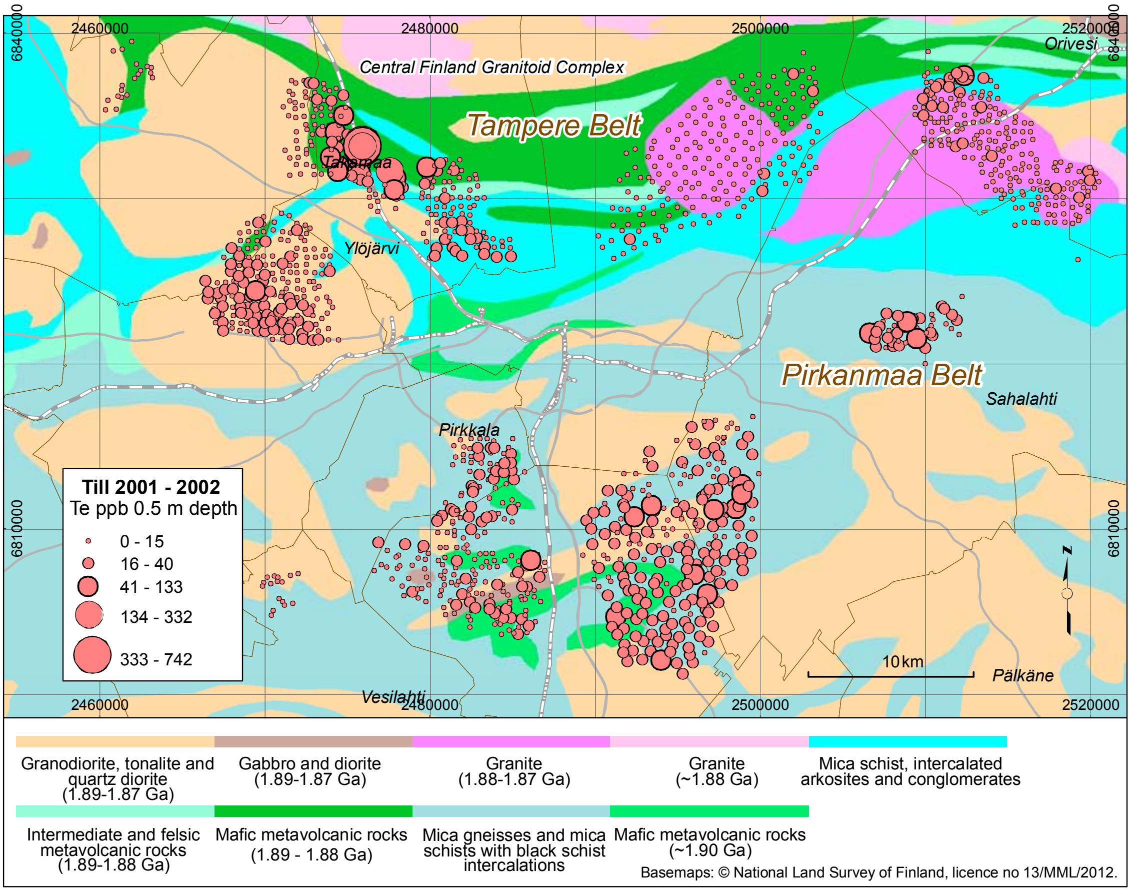


Figure 7. Distribution of tellurium in the Tampere area.

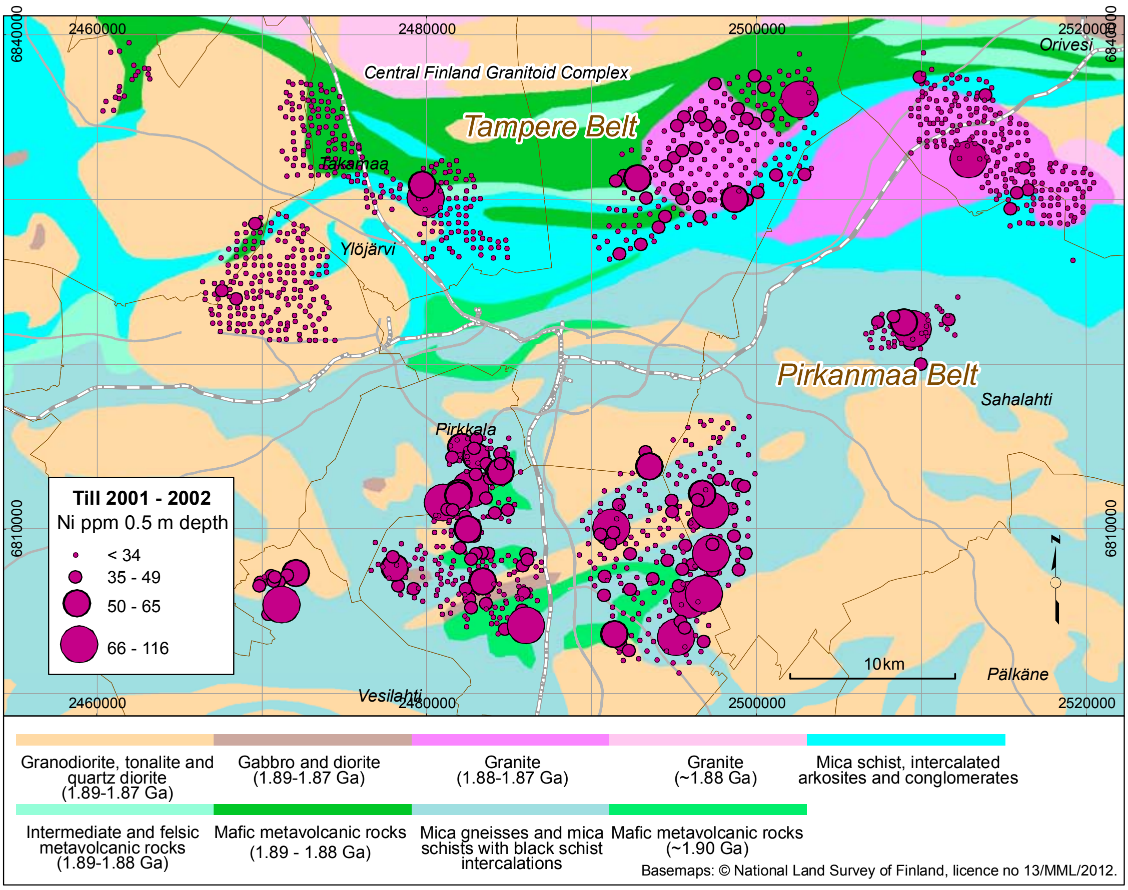


Figure 8. Distribution of nickel in the Tampere area; note the differences between Au and its pathfinder metals in Figs. 5–8.

Sampling and chemical analyses

Sampling was carried out close to the surface of the basal till. A good reference for geochemical exploration is the Kalliojärvi gold occurrence, because it is clearly visible in any fraction of till from the surface of the basal moraine (Al-Ani & Kärkkäinen 2012). At Kalliojärvi, the thickness of the basal till is from 3 to 5 m. Respectively at Ania, the distance from a large boulder containing visible gold to the unexposed source bedrock occurrence under a 2- to 4-m-thick till bed is only 20 m.

Sampling was carried out along forest roads and trails in an area of 10 x 40 km^2 by maintaining a 100 m distance between the sampling sites (Fig. 9). Altogether, 1329 till samples were taken from a depth of 10–25 cm below the organic layer. Gold was determined by GFAAS from a 5-g subsample sieved to under 0.06 mm and by using aqua regia leaching and Hg co-precipitation. An additional 32 elements were analysed by ICP-MS and ICP-OES from aqua regia leaches. The detection limits were 2 ppm for As and 1 ppb for Au.

Results

The average Au content in Pirkkala samples was 4.7 ppb, and the maximum 149 ppb Au (Table 3). The most common element enriched with gold in the area was arsenic. The median As content was 24.2 ppm, which is higher than the average of 6.8 ppm As in the larger Pirkanmaa area reported by Tarvainen (2007). The statistical correlation of Au with As, Sb, Te and Bi in this data was weak (Kärkkäinen et al. 2008a). However, the spatial correlation between Au and As was rather good. Close to places of high Au, As was also commonly high (Figs. 10 and 11). The most abundant ore minerals in the local Au prospects were found to be arsenopyrite-loellingite and pyrrhotite, and typical accessory minerals were chalcopyrite, pyrite, scheelite native Au and native Bi, whereas Au-Bi, Au-Te and Au-Sb minerals and Te and Bi minerals were rare.

The geochemical map of gold (Fig. 10) indicates scattered anomaly fields. The regional variation in

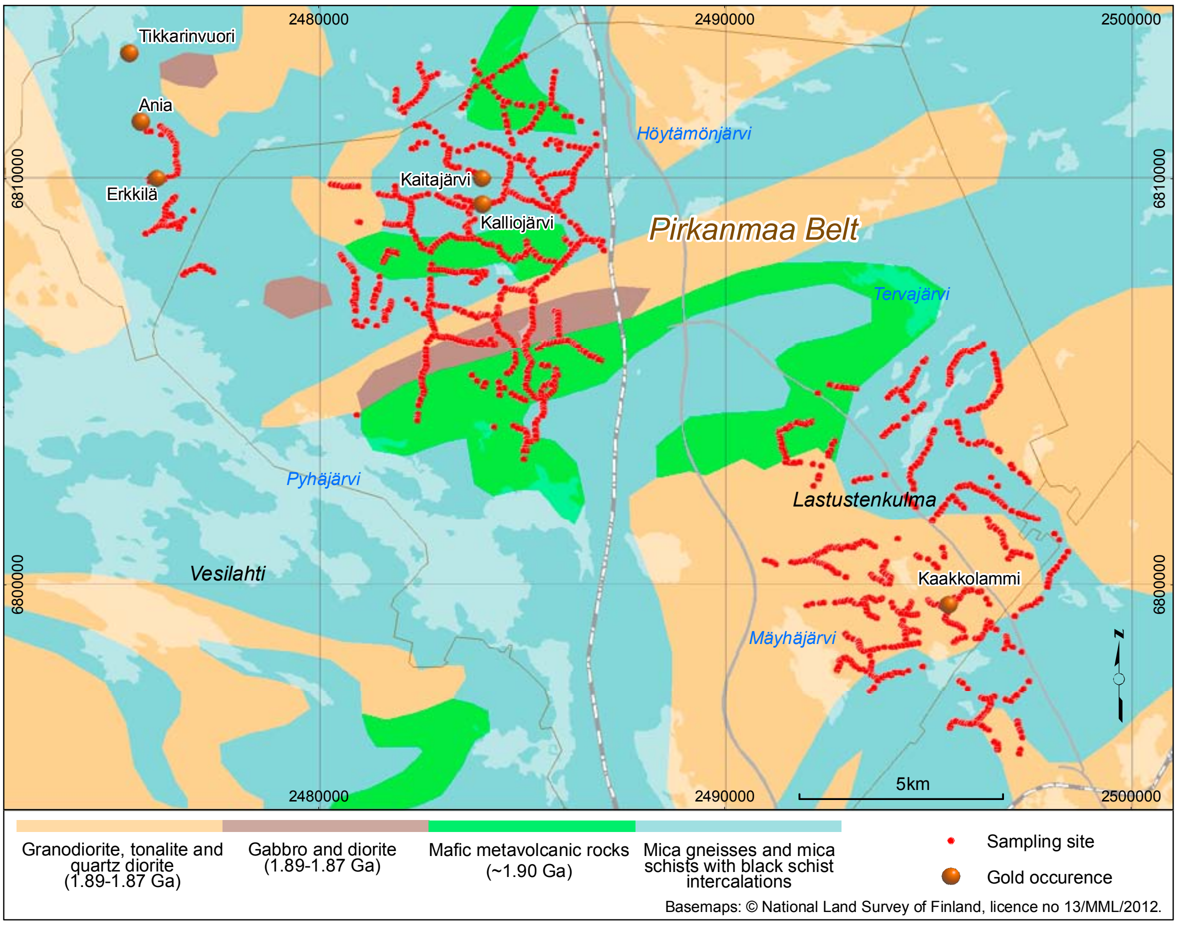


Figure 9. Sampling profiles of the Pirkkala area on the bedrock map of Finland (Korsman et al. 1997).

Table 3. Statistics for gold and potential pathfinder elements in Pirkkala till samples. The detection limit of gold was 1 ppb.

	Au ppb	As ppm	Bi ppb	Sb ppb	Te ppb
Method	520U	511M	520U	520U	520U
Number of samples	1318	1318	1318	1318	1318
Mean	4.7	32.2	348	91	32
Median	3.4	24.2	314	82	29
Mode	1.0	10	236	103	31
Maximum	149	1658	4810	2360	257
90% percentile	8.0	58	503	137	49

Au is clearly not dependant on the composition of the bedrock (Fig. 10). The As map is generally similar to that of Au. However, high values of Au and As occur in many places side by side instead of in the same samples. Increased Au occurs as peaks. Arsenic anomalies cover larger areas than gold, and the concentration varies gradually. It is likely that the gold mineralization is a result of the same hydrothermal process that enriched arsenic in the bedrock

Two coherent anomalies are distinguished in the Au map (Fig. 10), one in the northern part and another in the southern part of the area. The northern anomaly is fragmented but covers a larger area. The Kalliojärvi occurrence is easily recognized within the northern anomaly field and there are other analogous places that were not related to any known Au mineralization in the bedrock. Some of these anomalies have subsequently been tested by excavation and additional sampling by percussion drilling, and one tested anomaly is awaiting diamond drilling.

The southern anomaly at Lastusenkulma is smaller and homogeneous. Gold and arsenic ocur in parallel. The bedrock below the anomaly field is composed of a mafic intrusion that is broken by a NE-oriented gravity low. Close to the anomaly, an outcrop sample from sulphide-mineralized shear zones has given gold grades of 7.8–10.7 ppm Au, and anomalies in a detailed till geochemical survey (Rosenberg 1996). Additional geochemical sampling is ongoing in this area.

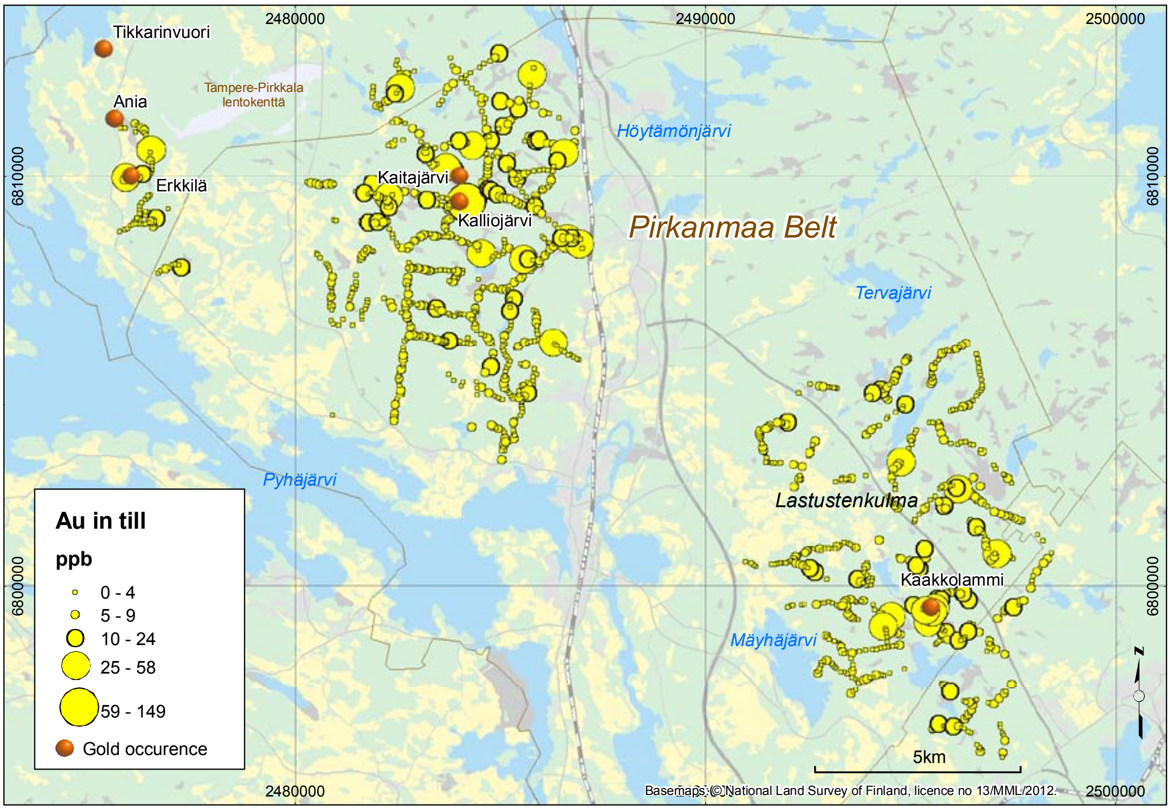


Figure 10. Distribution of Au in the Pirkkala area; till samples, sampling depth 0.5 m, analysis by GFAAS from an aqua regia leach of the fine fraction (<0.06 mm).

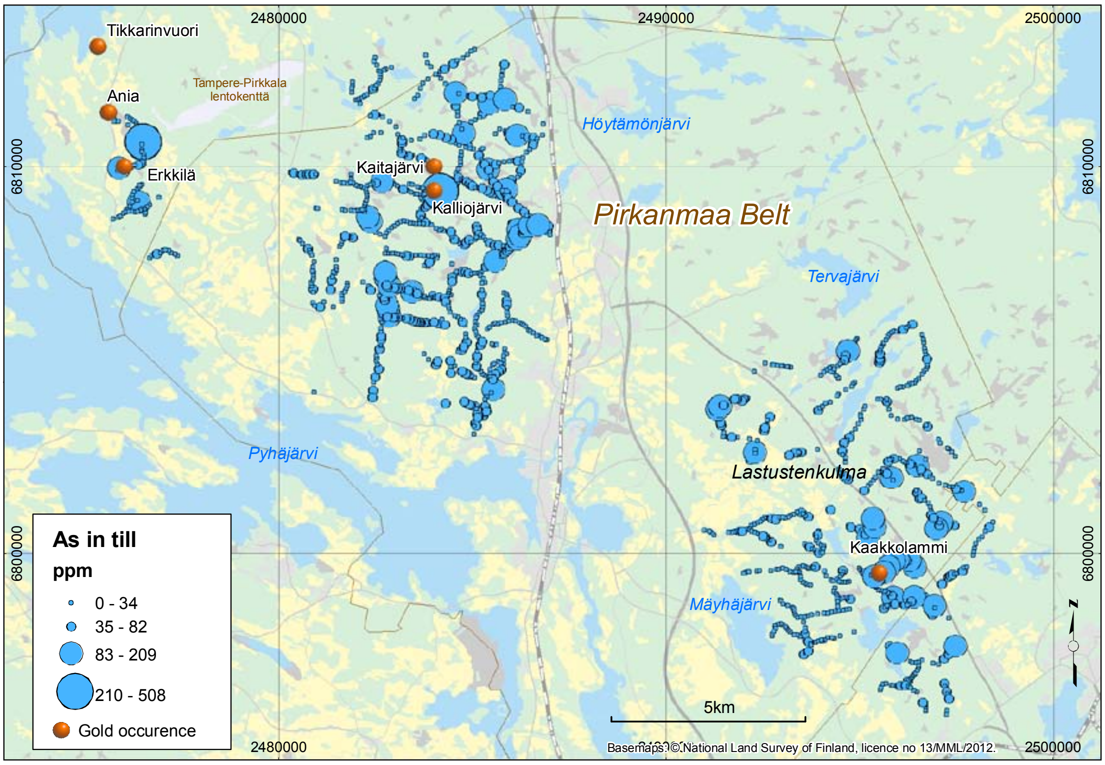


Figure 11. Distribution of As in the Pirkkala area; till samples, sampling depth 0.5 m, analysis by ICP-MS/ICP-OES from an aqua regia leach of the fine fraction (<0.06 mm).

All data from the Tampere area

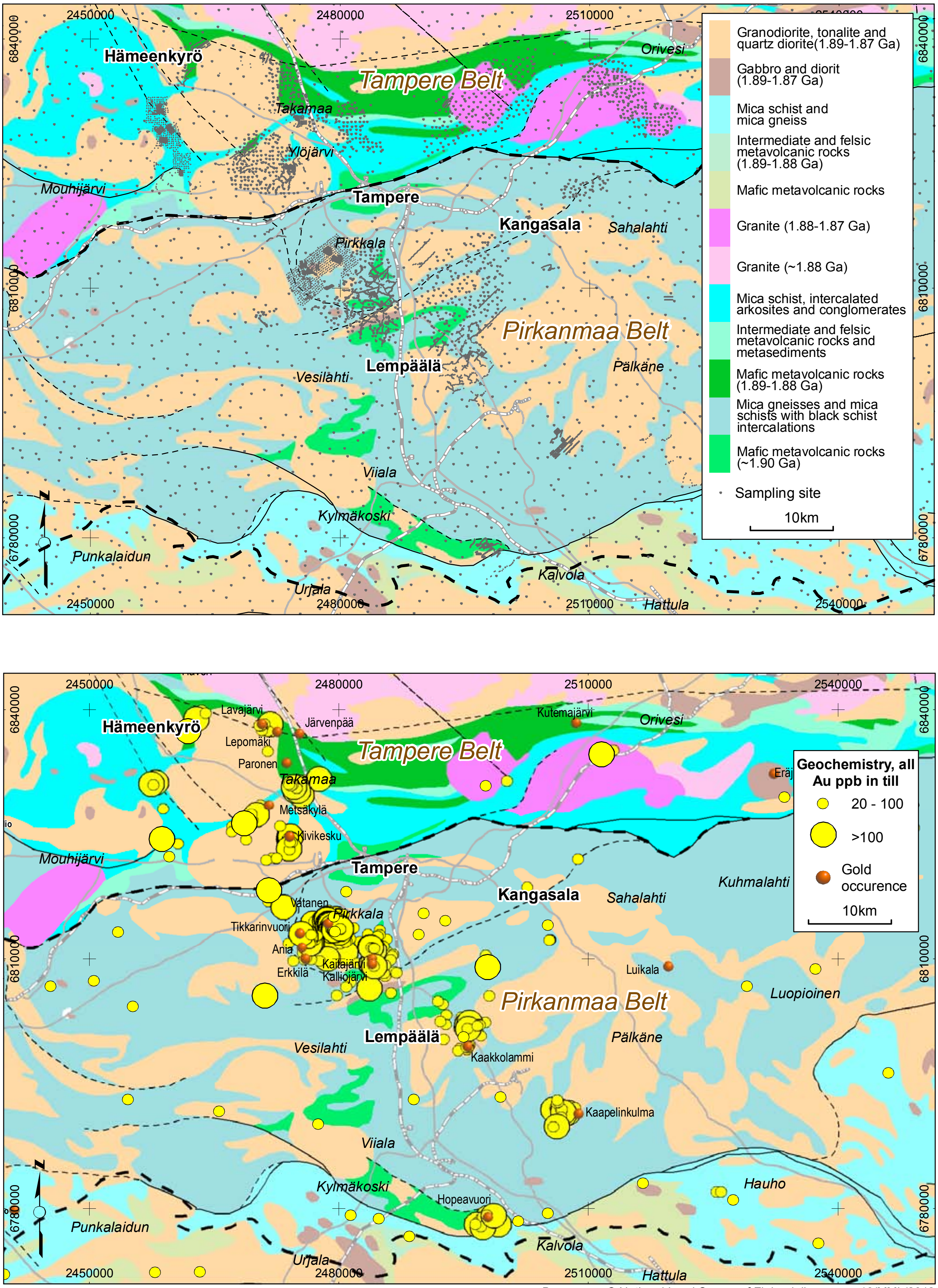
Till geochemical data available from separate GTK projects were combined to examine the distribution of Au in a larger data set (Fig. 12). The NW-trending Au-anomalous belt is emphasized in the Au geochemical map (Fig. 12). In the southern part of the area, the exploration targets of Kaapelinkulma and Hopeavuori Au prospects stand out, partly because the sampling grid further away from these locations was far too sparse to be useful in defining any anomalies.

The type of expression derived from Figure 12 is realistic in generalized geochemical maps, when the short length of glacial and postglacial transportation has no practical meaning in the scale. The transportation distance of basal till material during ice drift was mostly short in the Tampere area. Our detailed work at Ania and Kalliojärvi has indicated that the transportation distances were between 20 to 500 m.

The geochemical data include nationwide geochemical mapping, test profiles and detailed geochemical data from GTK's exploration targets, as well as the material presented in this paper. Earlier samples have mainly be taken from close to the bottom of the basal till, partly including rock chips or powder or weathered bedrock. However, according to our observations, the sampling depth is not critical in geochemistry. Consequently, all geochemical data from till fine fraction have been combined here.

FORSSA–HUITTINEN AREA

GTK started regional mapping in the Forssa–Huittinen area during 2003, after screening for gold-potential areas in southern Finland that had never previously been systematically explored. During the 1990s, GTK's mineral resource mapping in southern Finland was directed to the Tampere area in gold studies and to SW Finland in industrial mineral studies. Recent investigations in the Somero-Tammela belt, south of Forssa, have indicated a high gold ore potential for this area. Nationwide geochemical mapping (Salminen 1995) also revealed high concentrations of Au, Te and Cu in the Forssa region.



Basemaps: © National Land Survey of Finland, licence no 13/MML/2012.

Figure 12. Distribution of elevated Au (> 20 ppb) in all till samples in the Tampere area (down) and sampling sites for all till geochemical data from GTK's exploration projects in this area (up). Note the NW-oriented trend in anomalous gold contents.

Gold occurrences

During 2000–2007, GTK performed gold-related work in the Somero-Tammela belt, where the major Au occurrences are at Satulinmäki and Riukka (Kärkkäinen et al. 2006a, 2007, Saalmann 2007). This work was directed by observations of the strong alteration of volcanic rocks in a zone more than 10 km long. This alteration is characterized by the occurrence of arsenopyrite, tourmaline, quartz veins, shearing, sericite, biotite, and by local mineralization of gold, scheelite, sphalerite and chalcopyrite.

In addition, a couple of other gold occurrences, RE pegmatites and Zn occurrences are known from Forssa area (Eilu & Pankka 2010, Vesasalo 1959, Mäkelä 1980, Mäkelä 1989). Earlier exploration was restricted to areas close to these findings. The known gold targets form good references for recognizing gold-critical geochemical anomalies elsewhere. Arsenopyrite and loellingite are common and locally abundant in shear and alteration zones, which are gold-potential areas in the Svecofennian domain. In addition, Sb and Bi minerals are common at Satulinmäki and Riukka.

The Jokisivu Au mine, owned by Dracon Mining Limited/Polar Mining Oy, at Huittinen is situated at the northwestern end of the area. It has been active since September 2009, and the resources are estimated to total 356 300 ounces (10.1 tons) (http://www.dragon-mining.com.au/-Jokisivu-Finland-.html). The discovery of the Ritakallio prospect close to the Jokisivu ore was a result of a pilot study during this mapping program. Because of the positive results in the first stage of the mapping in 2003, indicating a new multimetal anomaly near Forssa, the geochemical mapping program was planned to extend from Forssa to the Huittinen area.

Geology

The NW-trending sampling area covered the western part of the Häme Belt (Fig. 13), which is mainly composed of volcanic and igneous intermediate to felsic rocks. Volcanic rocks in the area are mainly intermediate in composition, although mafic and felsic rocks are also common. Mica schists and gneisses are much less common than in the Pirkanmaa migmatite belt to the north.

An aeromagnetic survey has suggested that the area is located on a transitional zone between three or four geophysically different regions (Fig. 14). In the northeast, the level of magnetism is low and characterized by thin folded ribbons (related to pyrrhotite-bearing interlayers in mica gneisses). In the western part, the magnetic level is high. The centre of the area has a low magnetic level with few anomalies (mainly granitoids and intermediate volcanic rocks), whereas the southern part has rather wide anomaly zones (magnetic volcanic/subvolcanic units).

The landscape between Forssa and Huittinen is characterized by farms on clay basins. On the map of Quaternary deposits, one-third of the topmost overburden in the Forssa–Huittinen area is composed of basal till. About 4% of the area is hummocky moraine and drumlins and outcrops cover an area of 5%. The proportions of clay and peat areas covering the basal moraine are large in this area (Fig. 15). Till sampling was mainly directed to basal moraine areas and close to them, because clay basins are usually too thick for the light sampling device used. Over large areas the thickness of the basal moraine is only 1–3 m, but it may reach 20 m in moraine ridges. The basal till here is usually sandy and contains a clay fraction (< 0.002 mm) of only 2%. The ice flow has been from the direction 280–310° (Fig. 16) with some local variation. Only one moraine bed of the latest glacial period was found in this area.

Sampling and analyses

Work at Forssa-Huittinen was preceded by a pilot heavy mineral and geochemical study on till covering the whole area. Fifty large till samples (50 kg) were taken by a tractor excavator. A weak geochemical anomaly at Huittinen, comprising 25 ppb Au in the fine fraction of till, was the first showing of gold at the Ritakallio gold prospect (Vuori et al. 2002). Successful heavy mineral studies at Ritakallio prompted test sampling with an auger drill to obtain enough material (10 l) to determine the concentration of gold grains. However, auger sampling was too slow due to large boulders in the till and locally deep clay beds. Hence, sampling was mainly performed by light percussion drill, using roads and trails and the permission of 2200 landowners.

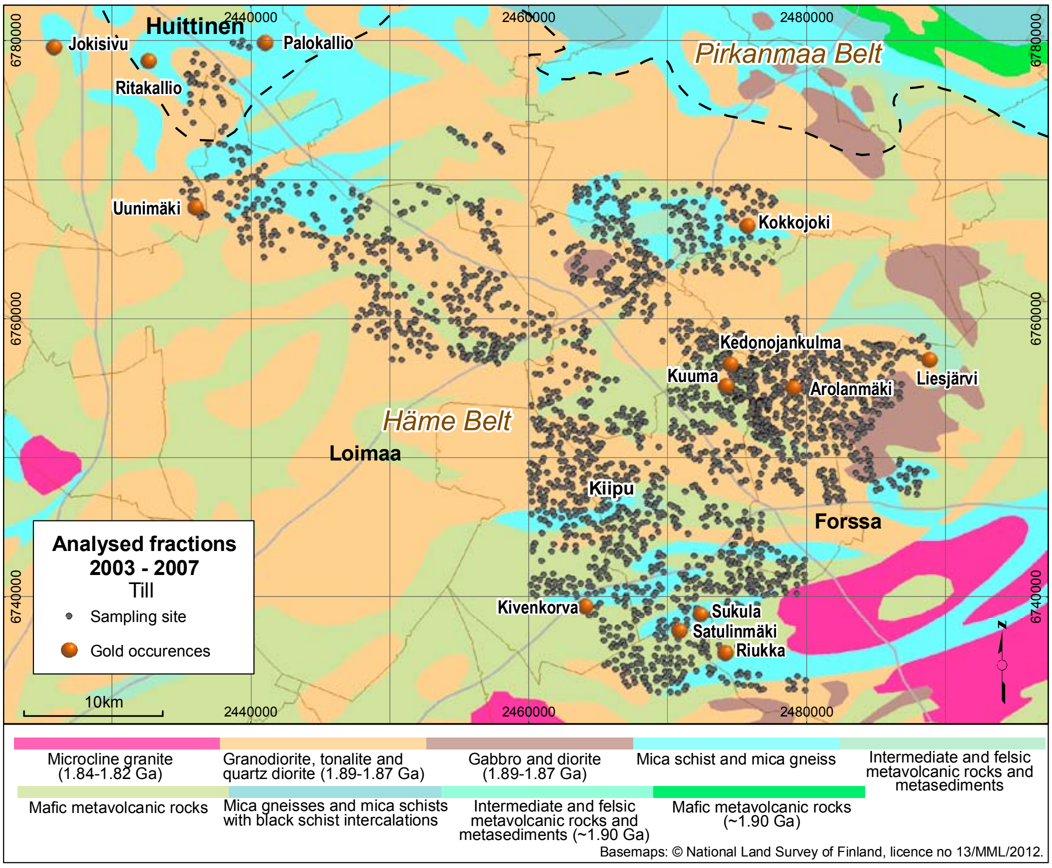


Figure 13. Forssa–Huittinen sampling sites on the bedrock (Korsman et al. 1997) and the known mineral occurrences (named in labels). Shown are a grid of base map sheets (10 km), and borders of municipalities (thin black).

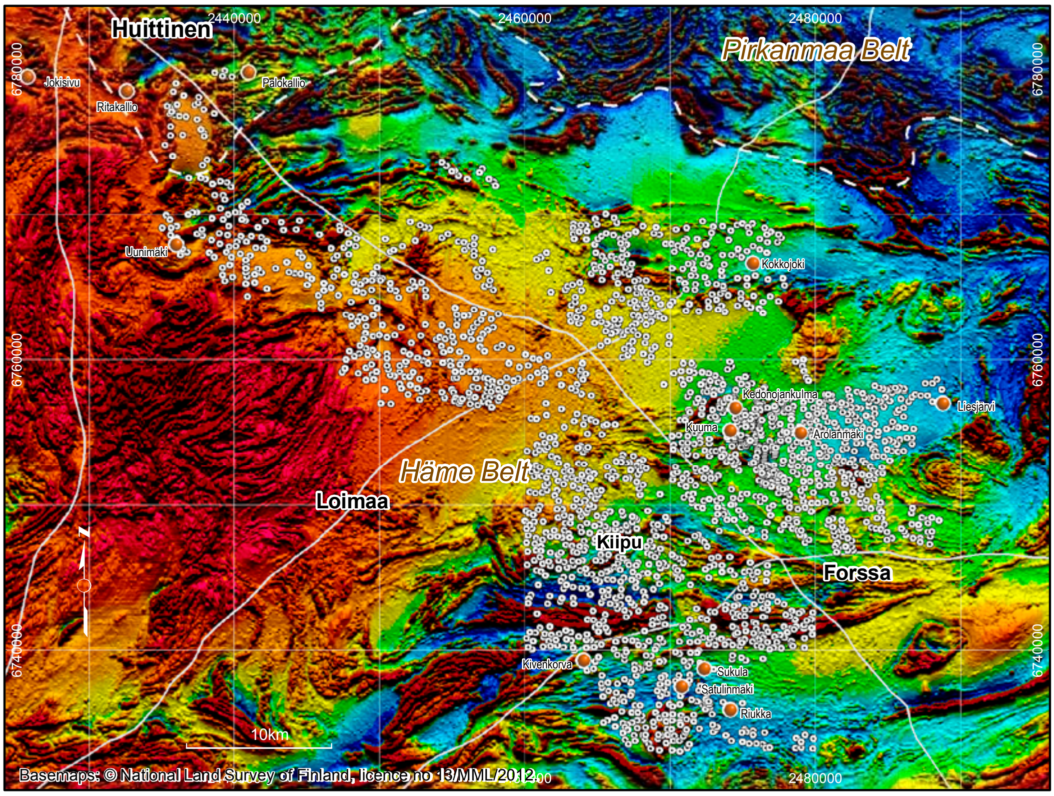


Figure 14. A low-altitude airborne magnetic map of the Forssa–Huittinen area; names refer to Au, Cu and Zn occurrences. Dots indicate the geochemical sampling sites.

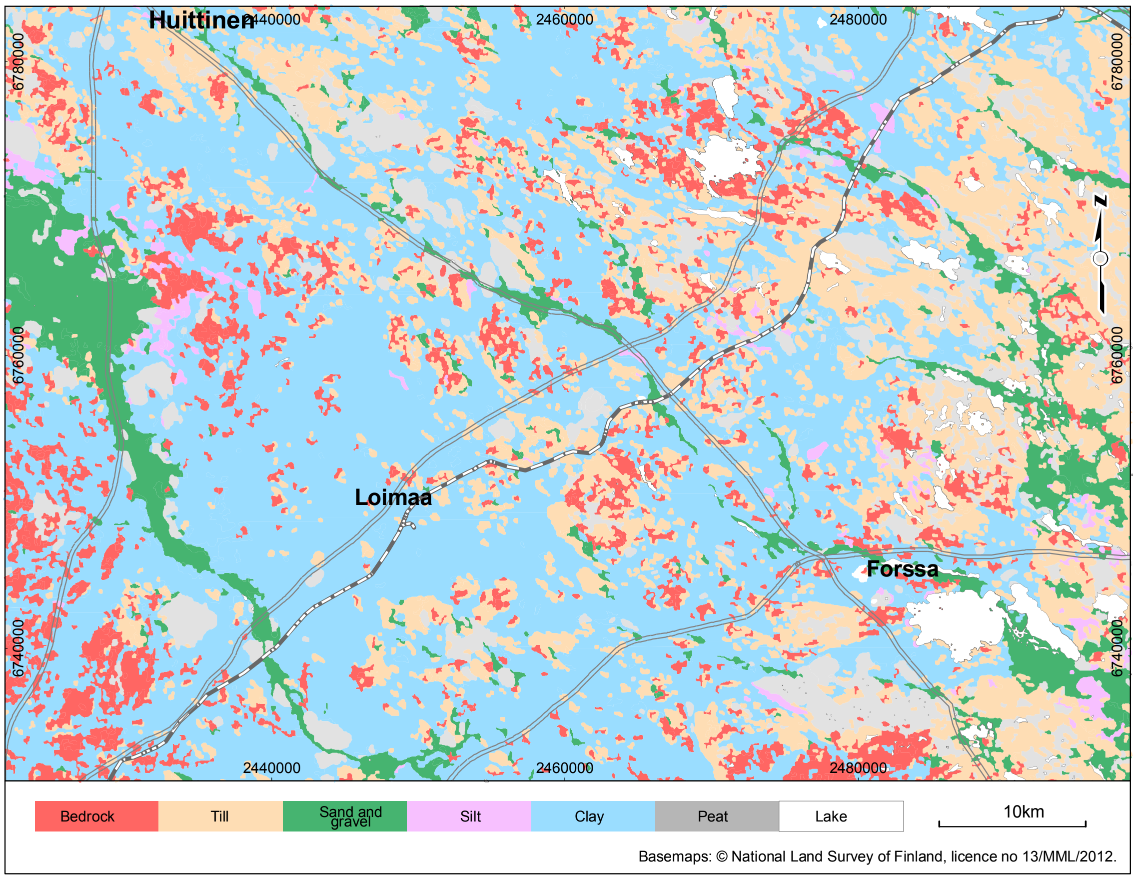


Figure 15. An extract of the map of Quaternary deposits in Finland; example from Huittinen Kanteenmaa. Colour codes: blue = clay, brown = moraine, red = outcrop, grey = peat, green = sand (esker). Source: DigiMP200 soil map, GTK.

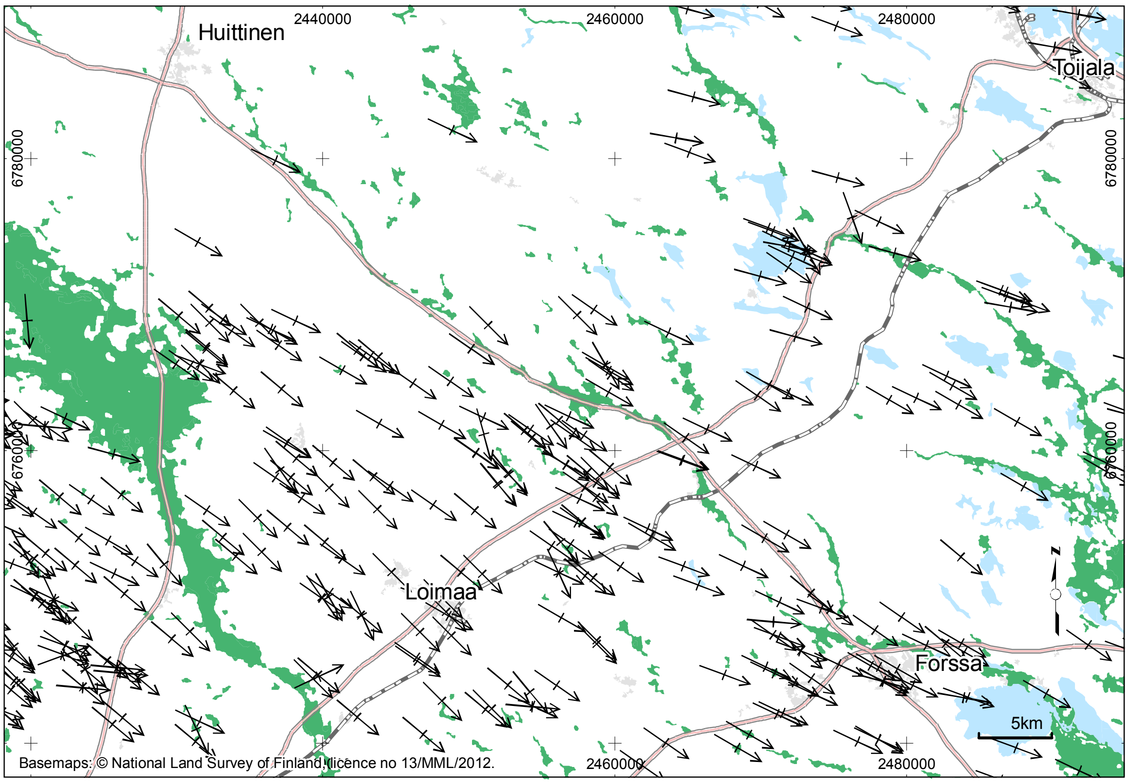


Figure 16. Direction of glacial ice drift based on the observations of striations on outcrops. Green = eskers, blue = lakes.

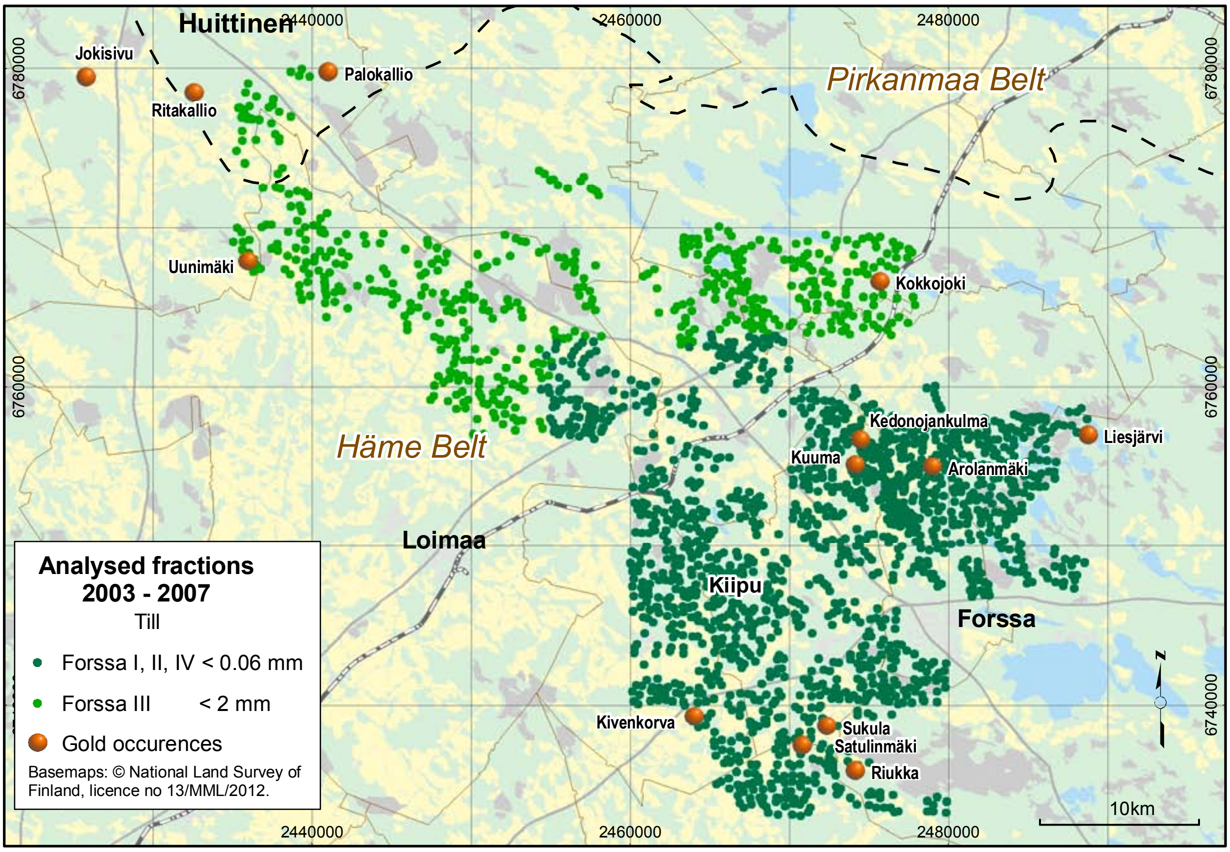


Figure17. Analyzed fractions (<0.06 dark green; < 2 mm light green) of till in the Forssa–Huittinen geochemical mapping campaign. Also shown are a grid of base map sheets (10 km), and gold occurrences.

Sampling was carried out during 2003 and 2005–2007 from basal moraine in a 500 m grid (4 samples per 1 km^2). The average sampling depth was 3.2 m, varying from less than 1 m up to 5–10 m where the overburden was clay or sand. Sampling was divided into 4 subareas: Forssa I, II, III and IV. The total number of analysed samples was 1984.

Chemical analyses were performed on the fine fraction (<0.06 mm) of till, except for the subarea Forssa III that covered the northern part of the area. Chemical analyses from this subarea were carried out on a coarser fraction (< 2 mm) (Fig. 17). This division of analysis fractions originated from earlier studies from Ritakallio in subarea Forssa III. In heavy mineral studies at Ritakallio, abundant gold grains (0.1–0.5 mm) were recovered from till. During detailed geochemical studies at Ritakallio, chemical analyses were thus carried out on the till fraction < 2 mm. If the fine fraction (<0.06 mm) had been used, some Au might have been lost before the chemical analysis.

Samples were analysed in GTK's chemical laboratory (now Labtium Oy) at Kuopio. In the laboratory, the sample preparation began with drying in forced air ovens at 70 ^{o}C and sieving to a fraction <0.064 mm, which was directly analysed, or sieving to fraction < 2 mm (Forssa III), which was then pulverized in a ring mill before analysis. Au, Bi, Te and Sb were determined by GFAAS (method code 520U) from a 5-g subsample and As, Cu, Fe, S and some other elements by ICP-AES (code 511P). Both analyses were performed on an aqua regia leach and in 520U with a Hg co-precipitation.

Results

The first period of this study (Forssa I, during 2003) indicated a complex gold and trace element anomaly field north of Forssa, an area known as Latovainio. These promising results prompted the continuation of sampling during 2005–2007 to cover the region between Latovainio and Ritakallio. Studies at Latovainio began from the Arolanmäki Au-Sb-Te and Au-Te-As anomaly areas and were later targeted at the Kedonojankulma Au-Cu-prospect (Tiainen et al. 2008, 2011).

Chemical analyses of the northern part (Forssa III) and the southern part (Forssa I, II, IV) are statistically not comparable, because coarse fraction (<2 mm) was used in the northern area and the fine fraction (<0.06 mm) elsewhere. The statistics are different and an unknown part of this difference originates from the differences between the sampling areas.

The high proportion of felsic silicates reduced the metal contents in sieved samples. In general, the coarser fraction contained relatively less clay material than quartz and feldspar. Thus the average concentrations of As, Sb, Cu and Te were greater in the fine fraction (<0.06 mm) than in the coarse fraction (<2 mm), but the Au concentration was also greater (Table 4). The grades of Ni and Zn were practically same in both data sets (16.9 vs. 17.7 ppm Ni, 59.4 vs. 53.1 ppm Zn). The concentrations of Bi (275 ppb vs. 432 ppb) and Mo (0.2 vs. 0.4 ppm) were greater in fine fraction.

The regional distribution of the elements of interest is shown in geochemical maps (Figs. 18-21), where each metal is presented for fine-fraction samples (<0.06 mm, Forssa I, II, IV) and coarser-fraction samples (0–2 mm, Forssa III) (Fig. 17). Note the difference in symbol classification between the northern and the southern parts, especially in higher grades.

In the Forssa–Huittinen area, Au, Cu, Sb, Te and As anomalies in till do not correlate with specific rock types or structures in the bedrock map (Figs. 18–21). Anomalies are found on both the volcanic rocks and granitoids and across various metamorphic grades. Clear Sb and As anomalies are NW-trending in the Forssa–Huittinen area, which may be a result of several overlapping processes. The glacial ice drift and transportation of till was the same, the orientation of volcanic formations is partly the same, and locally the major shear and fault zones have the same NW trend.

Anomalous Au contents occur in the whole area sampled, and grouping of higher grades in some parts of the area is evident (Fig. 18). Anomaly areas are seen at Satulinmäki in the south and at Ritakallio in the north. The largest homogeneous anomaly is in the Kedonojankulma area, where the bedrock is mainly composed of felsic intrusive rocks. Linear features in higher Au grades follow a NE-trending fault zone in the Urjala-Humppila district north of Kedonojankulma. Antimony has the best regional correlation with gold. Tellurium is anomalous in whole Kedonojankulma area, and includes a separate NW-oriented anomaly at Kuuma, south of Kedonojankulma. The latter anomaly occurs along a sequence of intermediate volcanic rocks (Fig. 21).

Table 4. Average concentration of selected elements in the fine fraction (<0.06 mm; Forssa I, II, IV) and coarser fraction (<2 mm; Forssa III) of till.

Element	Forssa I, II, IV, southern part, fine fraction of till (0–0.06 mm)	Forssa III, northern part, coarser fraction of till (0–2 mm)
number of samples	1487	497
Au ppb	3.3	2.5
As ppm	13.6	5.3
Bi ppb	275	432
Cd ppm	0.02	0.00
Co ppm	13.1	8.6
Cu ppm	52.9	31.9
Mo ppm	0.2	0.4
Ni ppm	16.9	17.7
Pb ppm	6.2	2.1
Zn ppm	59.4	53.1
Sb ppb	105.3	52.0
Se ppb	124.9	132.2
S ppm	410.7	360.9
Te ppb	22.0	16.2
depth m	3.2	-

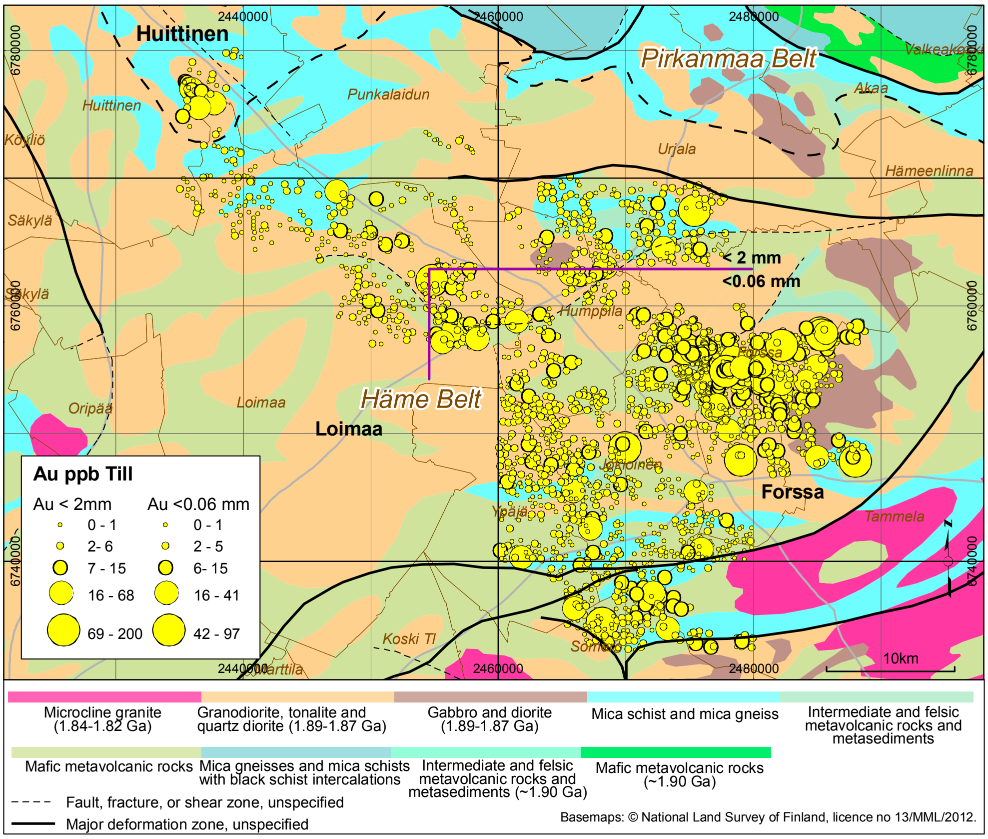


Figure 18. Geochemical map of gold (Au); till fraction <0.06 mm south of the red line, and fraction < 2 mm north of the line. See Fig. 16 for localities and Fig. 17 for the legend.

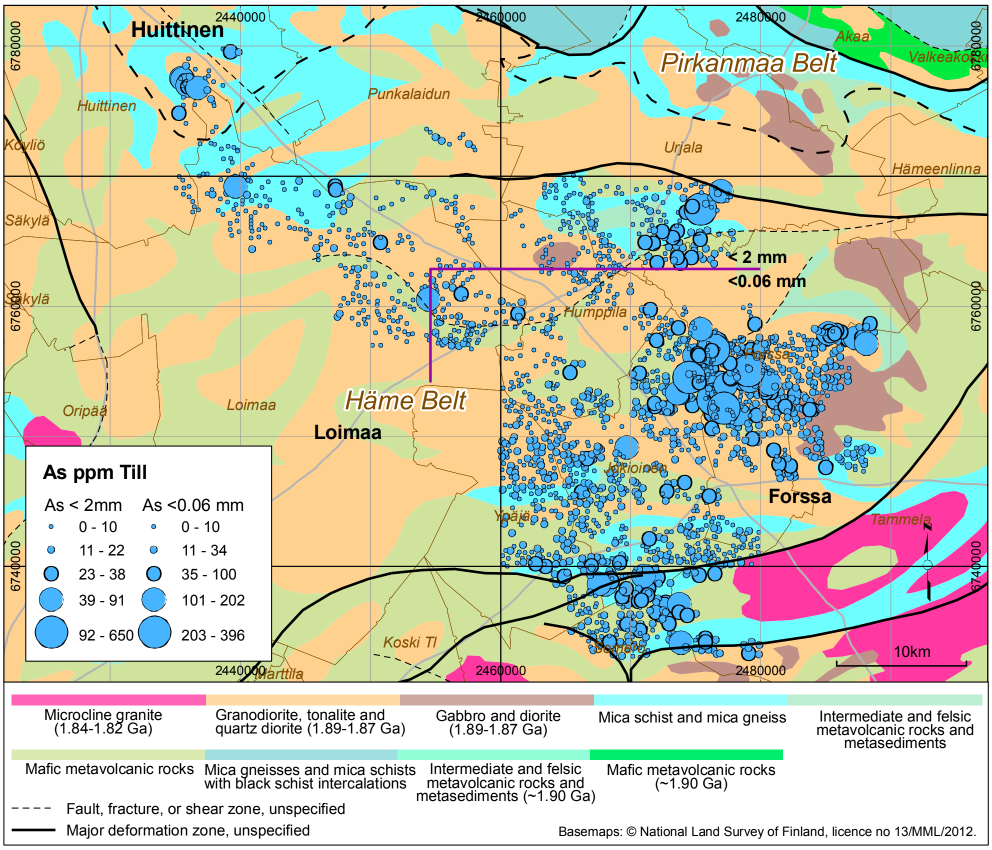


Figure 19. Geochemical map of arsenic (As); till fraction <0.06 mm south of the red line, and fraction < 2 mm north of the line. See Fig. 16 for localities and Fig. 17 for the legend.

Arsenic shows consistently higher values in the southern part, where the anomalies at Satulinmäki and Kedonojankulma are also NW oriented (Fig. 19). At Kedonojankulma, there are probably two parallel anomalies, one following the Au-Sb anomaly within the granitoid and the other in the west following the intermediate volcanic rocks and the Te anomaly. To the north of Kedonojankulma, at Kokkojoki, there is also a relatively clear As anomaly. This is restricted to a small area, if compared to the obscure NE-trending Au anomaly in the same area.

Antimony is anomalously high in the northeastern corner, at Kokkojoki and Kedonojankulma (Fig. 20). At Latovainio, the Sb anomalies overlap the As anomalies, but are smaller in size. At Kokkojoki, the Sb anomaly is restricted to a bedrock area composed of schists and volcanic rocks. Increased Sb contents also occur in the area from Satulinmäki to Kiipu

Tellurium has a clear anomaly in the Forssa area in the nationwide geochemical map, and an anomaly is also prominent in the denser sampling data (Fig. 21). At Kedonojankulma, Te and Sb anomalies practically overlap. Like Sb, the high Te concentrations are present in the northeastern part in the Kokkojoki area, but also in the northwestern part. At Satulinmäki, Te is low in till, but scattered anomalies are seen at Kiipu.

Satulinmäki and Riukka gold occurrences (Kärkkäinen et al. 2006a, 2007), in the southern border of the area, are seen in geochemical maps as an Au-As-Sb anomaly. These occurrences commonly include arsenopyrite and pyrrhotite, and Sb and Bi minerals are common with gold. High gold grades were recovered in drilling, such as 32 ppm Au at 1 m or 3.6 ppm at 22 m in DH391 at Satulinmäki, and 35.5 ppm Au at 1 m (DH353) or 12.3 ppm at 3 m (DH356) at Riukka.

GTK began to systematically investigate the Latovainio multimetal (Au, Bi, Sb, Te, Cu, As) geochemical anomaly in 2006 (Tiainen et al. 2008, 2011). Detailed geochemical mapping has outlined additional Cu-Au-Zn occurrences at Kuuma, Arolanmäki and Kedonojankulma. Kedonojankulma is hosted by subvolcanic rocks and granitoids (Tiainen et al. 2012). Other Au potential regions are being studied at Huittinen, Jokioinen and Urjala.

A natural explanation for these multielement geochemical anomalies is the concentration of extensive hydrothermal activity during the Svecofennian era. Locally, this also seems to be related to late reactivation of certain structures.

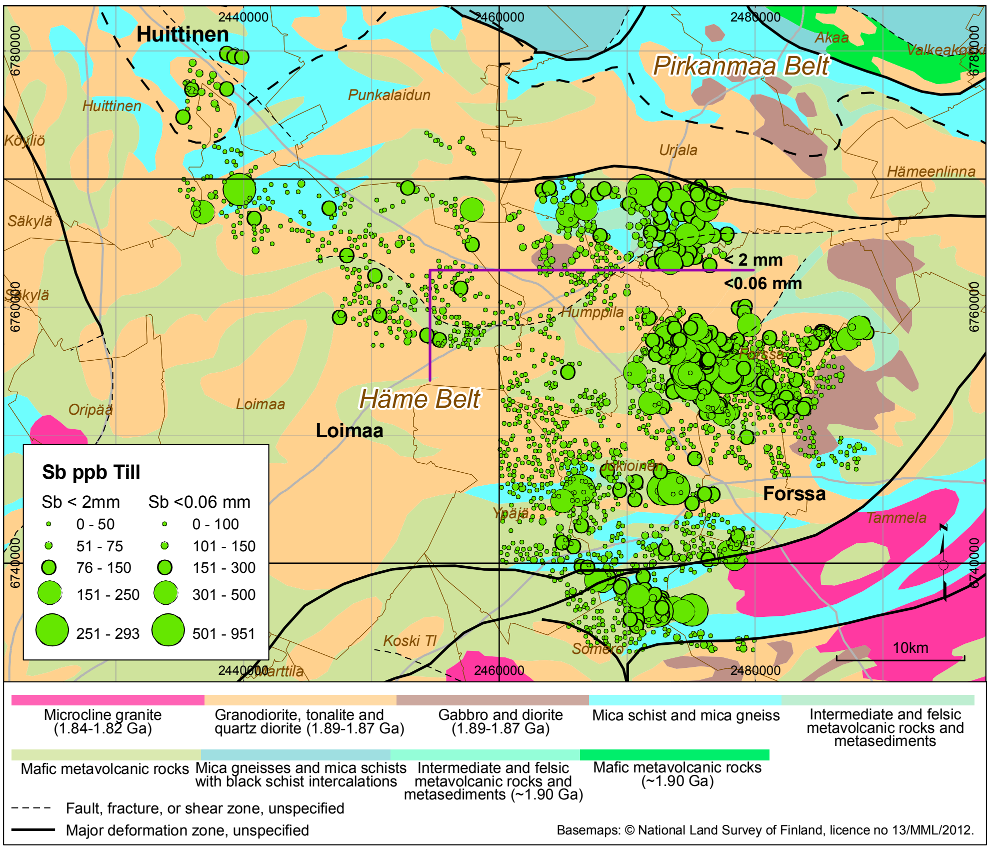


Figure 20. Geochemical map of antimony (Sb); till fraction <0.06 mm south of the red line, and fraction < 2 mm north of the line. See Fig. 16 for localities and Fig. 17 for the legend.

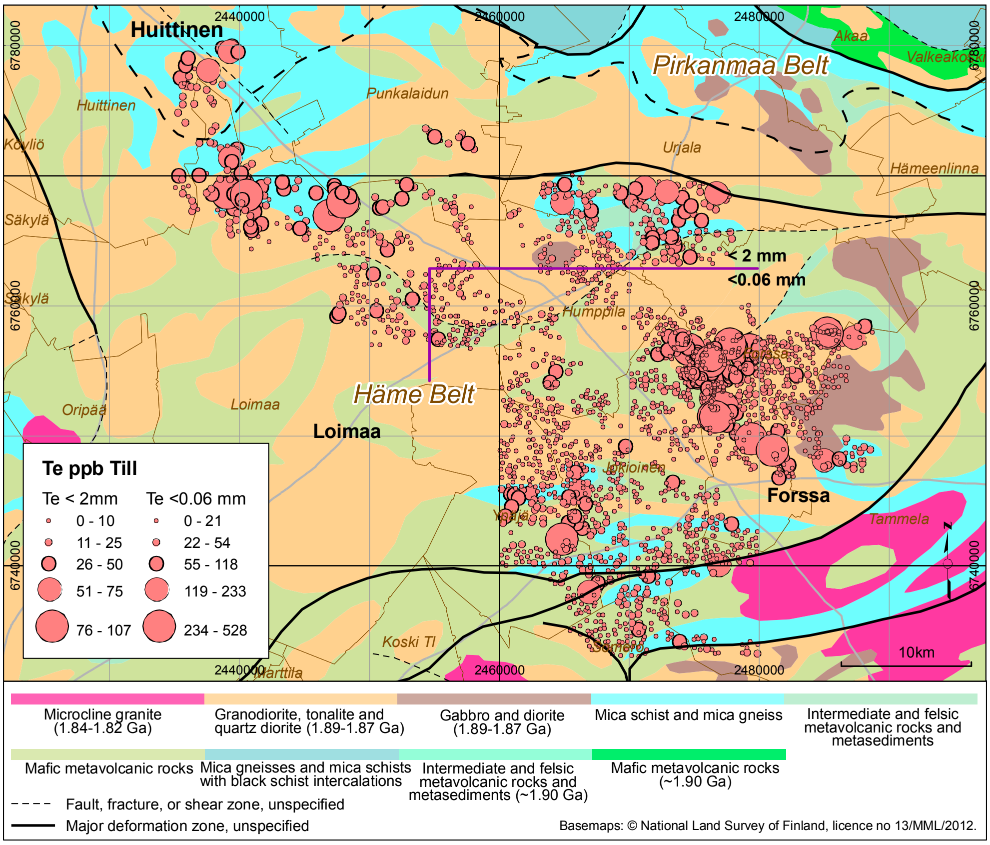


Figure 21. Geochemical map of tellurium (Te); till fraction <0.06 mm south of the red line, and fraction < 2 mm north of the line. See Fig. 16 for localities and Fig. 17 for the legend.

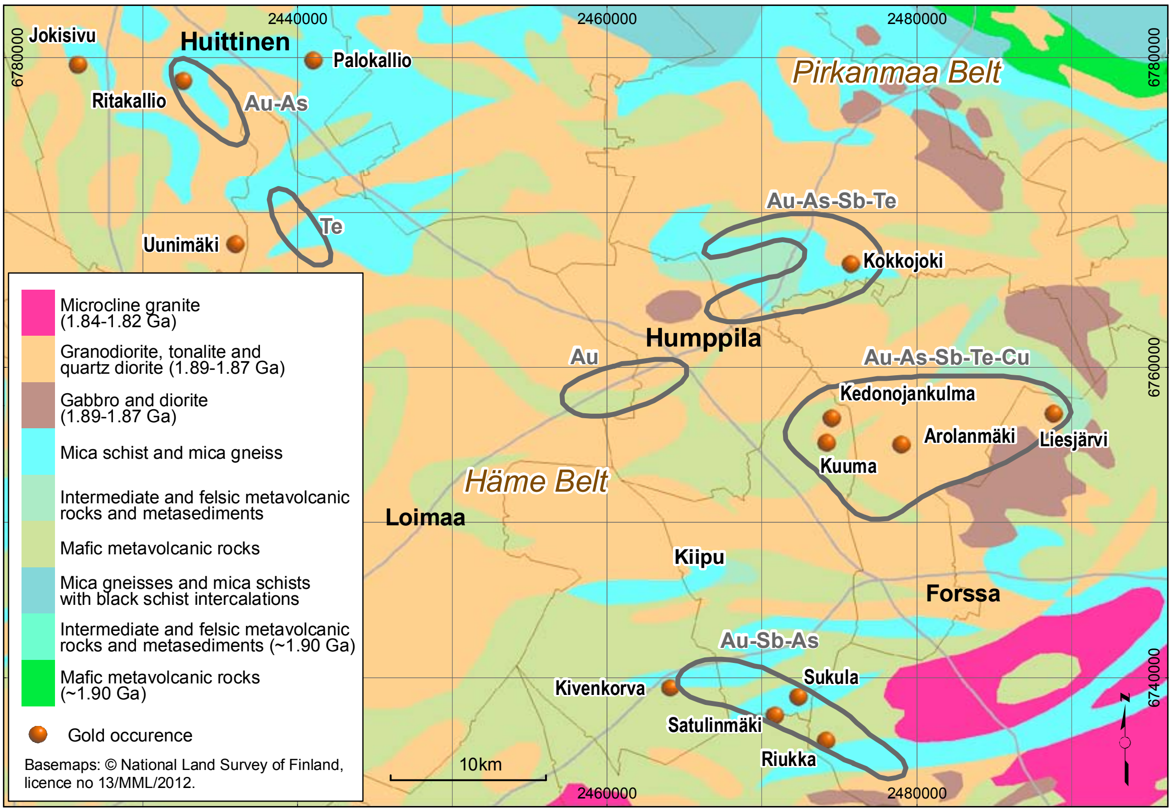


Figure 22. Subareas with the greatest potential for gold in the Forssa–Huittinen area.

At Huittinen and Koijärvi, the anomalies are connected to cross-cutting orogenic or post-orogenic structures, whereas in some cases, such as Latovainio and Kokkojoki, anomalies have a close association with intrusive bodies and related structures. In some cases the hydrothermal activity, mineralization and alteration (Satulinmäki) may have started as pre-orogenic processes.

According to available till geochemical data, the regions with potential for gold mineralisation in the Forssa–Huittinen area are (Fig. 22):

– the Satulinmäki area at Somero, Tammela and Jokioinen (Somero–Tammela Au-critical zone);
– Kedonojankulma–Arolanmäki area at Jokioinen and Forssa, where GTK investigations are also continuing (Tiainen et al. 2008);
– SE extensions of Ritakallio at Huittinen (Korvenmaa etc.);
– the Kokkojoki area at Urjala, which GTK has remapped; and
– the Koijärvi area, which GTK has remapped
– Humppila, not checked area

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Gold in Southern Finland: Results of GTK studies 1998–2011
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NEW DATA FOR EXPLORATION IN SOUTHERN FINLAND – HEAVY MINERAL STUDIES AND ORE SHOWINGS

by
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Huhta, P., Kärkkäinen, N., Hakala, P., Karttunen, K., Nyholm, T., Pelkkala, P., Tranberg, J. & Räsänen, R. 2012. New data for exploration in southern Finland – heavy mineral studies and ore showings. *Geological Survey of Finland, Special Paper 52*, 47–54, 11 figures.

This article describes the use and some results of boulder prospecting and till-based heavy mineral studies in southern Finland. Both activities are commonly used together with till geochemistry to outline anomalies with ore potential. The prospecting of mineralised boulders (or outcrops) and tracing of the boulders along the direction of ice flow are traditional exploration methods in Finland. Heavy mineral studies are especially suitable for identifying gold critical regions.

Heavy mineral studies of basal till have been carried out at approximately 2 000 sites in southern Finland. Gold has been found from 230 sampling sites, and a total of 666 samples from these localities have contained gold grains. The high proportion of gold anomalous points may be related to sampling policy, as most sites are selected according to geochemistry or ore-indicating data.

Prospecting by the general public has historically been an important tool in mapping mineral resources in Finland. A total of 850 000 recorded samples were received by domestic mining companies and the Geological Survey of Finland (GTK) during 1959–1979. Much of this old data has been registered by GTK, which is still active in receiving and examining findings from the general public and amateur prospectors. Since 1980, thousands of new samples of mineralised outcrops and boulders from southern Finland have been examined by GTK. Recently, prospecting by the public has been most active in southern and western Finland. The database of findings since 1980 includes 1124 samples having Au as the major metal and 267 samples with Au as a co-metal.

Keywords (GeoRef Thesaurus, AGI): mineral exploration, gold ores, till, heavy minerals, boulders, outcrops, layman's samples, Southern Finland

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INTRODUCTION

This paper describes till studies applied in mineral potential mapping in southern Finland. We focus to two till fractions, boulders and sand-sized material that is used in heavy mineral studies. The first section concerns heavy mineral studies carried out during 25 years in various mineral exploration projects of the Geological Survey of Finland (GTK). Heavy mineral studies are practically only carried out in gold investigations.

The second section introduces new data on gold ore showings from southern Finland. The ore-showing data are based on mineralised samples sent to GTK by the general public. Abundant observations of gold and other economic minerals have been made from new areas by amateur prospectors and other people.

TILL AS A TOOL IN EXPLORATION

Geochemical surveys, heavy mineral studies and prospecting of mineralised boulders are based on till. Following the boulder trains along the direction of ice flow and tracing the source bedrock is a classic exploration method in Finland. Geochemical mapping has been based on various grain-size fractions. The most common has been the fine fraction (<0.06 mm), but the fraction less than 2 mm is also used to avoid the nugget effect in till. Kärkkäinen et al. 2005.

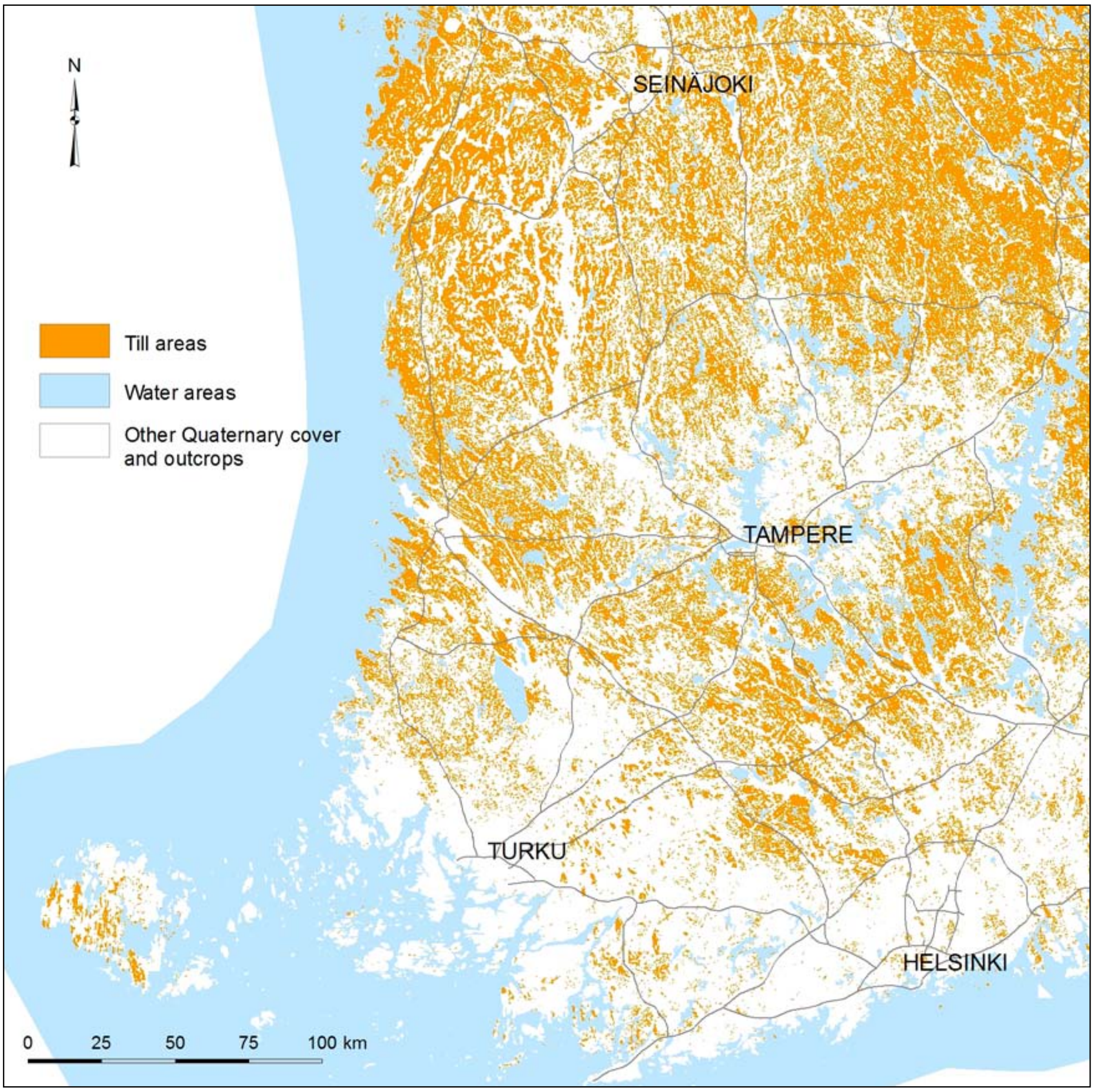

Figure 1. Distribution of till (Quaternary moraine formations) in southern Finland.

Studies on the amount or distribution of various heavy minerals in till are carried out alongside the geochemical studies. Heavy mineral studies on gold work well in most parts of southern Finland if the basal till extends to the bedrock surface, as is the case in Pirkanmaa and Häme (Fig. 1). However, large areas, especially in the SW corner of the country, are overlaid by clay basins or glaciofluvial material above the till layers. Here, sampling from the deep basal till is difficult, because drilling with a strong machine is needed in order to take a 20-kg sample for heavy mineral studies. The maximum depth of a pit or trench that can be dug with a tractor excavator is 5 m in an ideal case when the ground water level is deep.

HEAVY MINERAL STUDIES

Since 1986, till samples for heavy mineral studies have systematically been collected in southern Finland, starting at Pirkkala in the Tampere area. Previously, heavy mineral studies had been carried out as part of nationwide geochemical mapping, for instance at Orivesi (Nikkarinen et al. 1991).

Samples are taken from basal till. In an ideal case, a sample is taken from a 2 to 5 m deep pit made by an excavator (Fig. 2). If the structure of the till is homogeneous, one sample is gathered continuously from the surface to the bottom, representing the whole vertical section. However, if there are many till beds, they are sampled separately. Sometimes, one sample is taken above and another below the ground water table. A typical and rapid approach is to use a spade and take the till sample from a hole close to ground surface. The volume of each sample is generally 10–12 l, having a weight of about 20 kg (Fig. 3).

A heavy mineral sample is first wet sieved to obtain the fraction less than 2 mm. The heaviest minerals (including gold) are first separated with a spiral concentrator (Figs. 4 and 5). The spiral concentrator works as reverse process compared to gold panning, because it first removes the heaviest material, such as gold and sulphides. When panning, the heaviest minerals are the last ones remaining. Panning is sometimes used to obtain fine heavy fractions from the overflow of the spiral separator.

Heavy mineral concentrates are examined under a binocular microscope (Fig. 6). Gold grains are identified and their amount is calculated. The grains are classified into three categories according to the transport distance: (1) angular, with retention of crystal faces, (2) slightly rounded and (3) distinctly rounded and abraded (DiLabio 1991). The size is determined by using the ocular gauge of the microscope. The size of the gold grains is on average 0.12–0.14 mm and they are mostly pure gold without other minerals. The colour is normally yellowish.

Based on the size and quantity of gold grains in various size classes, the total volume of gold and the grade in the primary till sample can be calculated. The quantity of other heavy minerals is also estimated.

Most common heavy minerals in the concentrates are magnetite, ilmenite, zircon and vari-

Figure 2. A typical vertical section in a basal till area of southern Finland.

Figure 3. Till samples for heavy mineral concentration in the backyard of the Ellivuori field base. Photo: Mikko Pelkkala, GTK.

Figure 4. Concentration of heavy minerals is performed by using a spiral separator. First, the till sample (20 kg) is wet-sieved to a fraction less than 2 mm. Photo: Mikko Pelkkala, GTK.

Figure 5. The spiral separator first removes the heaviest particles, which are collected through a funnel to a plastic tube. The washed material remaining in the spiral is panned if several gold grains appear in the heaviest fraction.

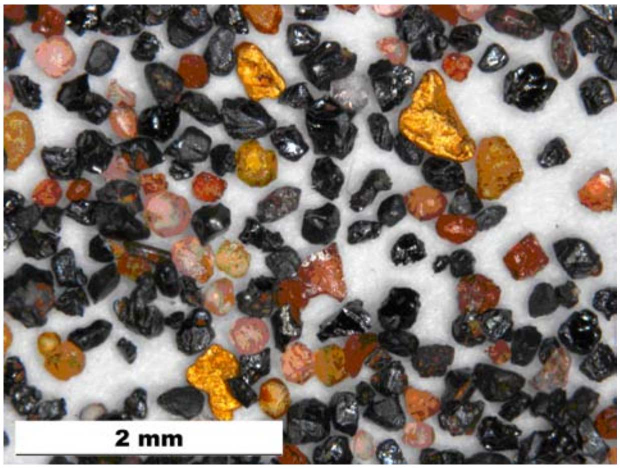

Figure 6. A typical heavy mineral sample from till with gold grains and other minerals. Photo: Kari Kojonen, GTK.

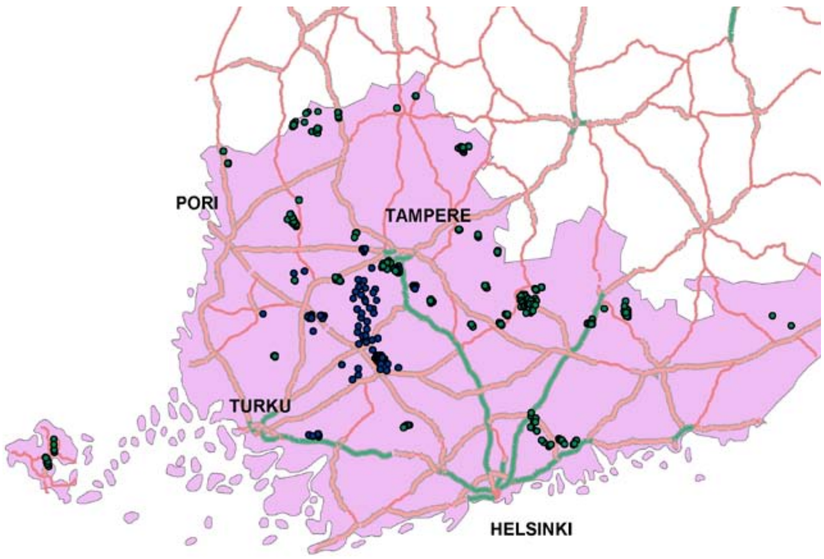

Figure 7. Heavy mineral sampling localities in southern Finland.

ous garnets, mostly almandine. Tourmaline and scheelite occur quite commonly with gold. The most common ore minerals are pyrite, arsenopyrite, pyrrhotite and chalcopyrite. They are usually only met below the ground water level. Close to the ground surface, above the ground water level, sulphides are rare due to weathering.

Sampling has been carried out from about 2 000 sites (Fig. 7). Total of 666 samples contained gold grains. The number of gold grains in each sample varied between 1 and 575, with an average of 2.4 grains. In the 666 gold-bearing samples the average was 7.1 grains. The limit for a general anomaly is regarded to be two grains per sample. The heavy mineral sampling data mentioned in this paper included a total of 230 gold anomalous sampling sites. The high proportion of anomalous points may be related to the sampling policy, as most sites were selected according to their geochemistry or ore-showing data.

GOLD ORE SHOWINGS

Method

Prospecting by the public has historically been an important tool in mapping mineral resources in Finland. Altogether, 850 000 recorded samples were received by domestic mining companies and GTK during the period from 1959–1979, and 6% of these were studied more closely (Hyvärinen & Eskola 1986, Saltikoff 1992). GTK previously received almost all this data from companies and a database was maintained. In practice, ore samples were compared to archaeological findings and all data on new discoveries were gathered at GTK.

The last version of the domestic ore-showing database is from 1987. It includes data from 9327 selected ore boulders and prospects (Saltikoff 1987). The data are classified according to the grade and size of mineralisation, and primary analytical data are not included. Paper copies of field reports on the findings received by GTK are included in the final archive, and hand specimens of the best samples received by GTK have also been archived. The database additionally includes discoveries of mineralised outcrops and boulders made during GTK's mapping and exploration projects. Saltikoff's database includes 322 samples having Au as the major metal and 235 samples with Au as a co-metal.

Recently, prospecting by the general public has been most active in southern and western Finland. Gold has awakened the greatest enthusiasm in ores. Arsenopyrite has been the best indicator mineral, and for amateur prospectors the best way to get the specimen analysed by GTK. Other altered samples have also been recognized as gold critical and analysed.

Since the last update of the database (Saltikoff 1987), thousands of new samples of mineralised outcrops and boulders from southern Finland have been received and registered by GTK. Hundreds of findings have been checked in the field and recorded in a field visit report (M13) in the final archive. GTK currently receives about 6000 samples annually from the public and practically no data from companies. Although the quantity of samples has drastically decreased during the last three decades, the quality of findings has improved. One-third of hand specimens sent to GTK are analysed and about 5–10% of these result in a field control visit. Annually, 2–5 cases in southern or western Finland warrant further investigation, and more if there is a special campaign or sponsored regional competition.

During this project, co-operation with amateur prospectors has been fruitful, and they are primed in areas under investigation by GTK. Collaboration is important to increase the number of field observations in areas with geochemical anomalies and especially in large areas with low potential (before new discoveries).

Recent results

The number of samples from southern Finland received since 1988 and having Au as the major metal is 802. In addition, 32 samples have Au as a co-metal. The average gold grade has been 10.7 ppm Au and the range has been 0.57–612 ppm Au (Fig. 8). Only part of the received samples have been chemically analysed. The reason for analysis of Au-critical samples is often arsenopyrite. In 78% of samples the As content has been > 0.1%, which means at least some visible arsenopyrite grains in a hand specimen (Fig. 9).

Geographically, the recent Au-bearing samples (1989–2008) are better grouped than the older samples, which also include some concentrations but in general are quite evenly distributed (Figs. 10 and 11). The pattern in the Seinäjoki area is similar in the old and new data. This area is characterized by the mature orogeny metallogeny of Sb-Au-W. A NW-oriented Au sample group north of Tampere overlaps with the former Parola W-Cu and Haveri Au-Cu mine fields and Järvenpää Au-Sb-Cu mineralisations at Ylöjärvi. Many new Au showings have been received from the Kullaa area between Tampere and Pori (Fig. 11). A NE–SW-oriented Au sample group is seen in the Häme Belt from Halikko through Forssa to Hämeenlinna.

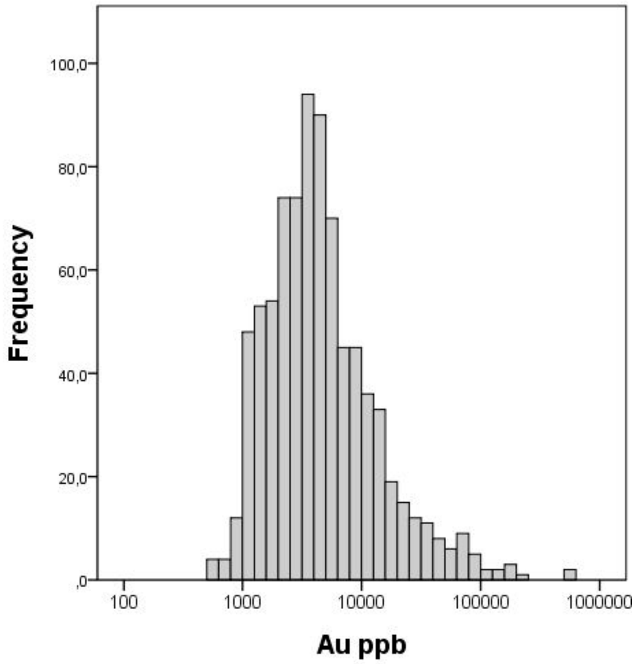

Figure 8. The distribution of Au contents in ore showings received from the general public during 1989–2008.

ACKNOWLEDGEMENTS

The investigations reported here would not have been possible without the extensive work of Boris Saltikoff during the 1980s in gathering and classifying the old ore boulder data from both exploration companies and GTK. Heikki Hirvas and Keijo Nenonen formed the driving force in developing various till studies as an exploration method in Finland. We also wish to thank the hundreds of active prospectors who have sent samples from their discoveries for use by geologists. We are pleased with the team work with the staff of the Layman's Sample Office (Kansannäytetoimisto) at GTK's Kuopio office.

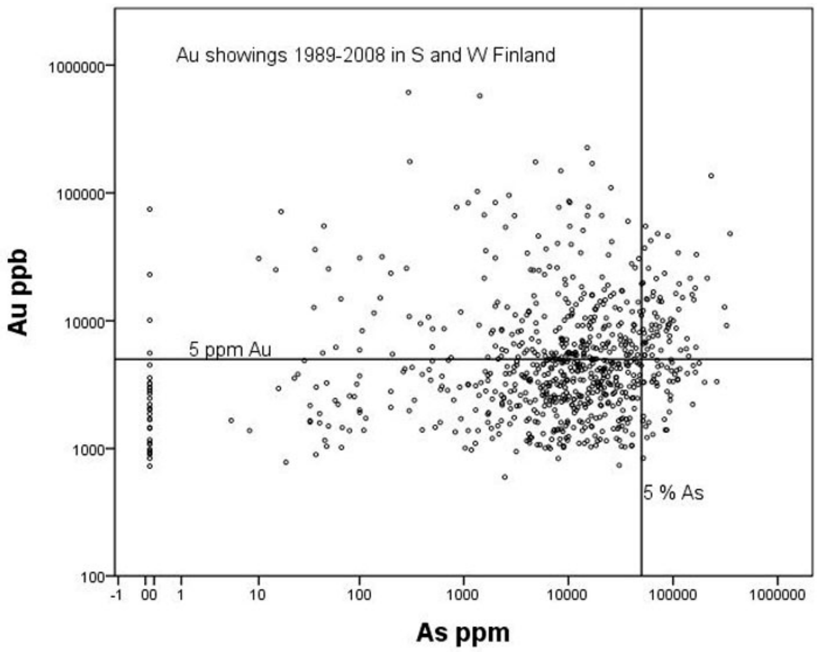

Figure 9. A scattergram of Au and As indicating high variation in the correlation between As and Au in Au ore showings received from the general public during 1989–2008.

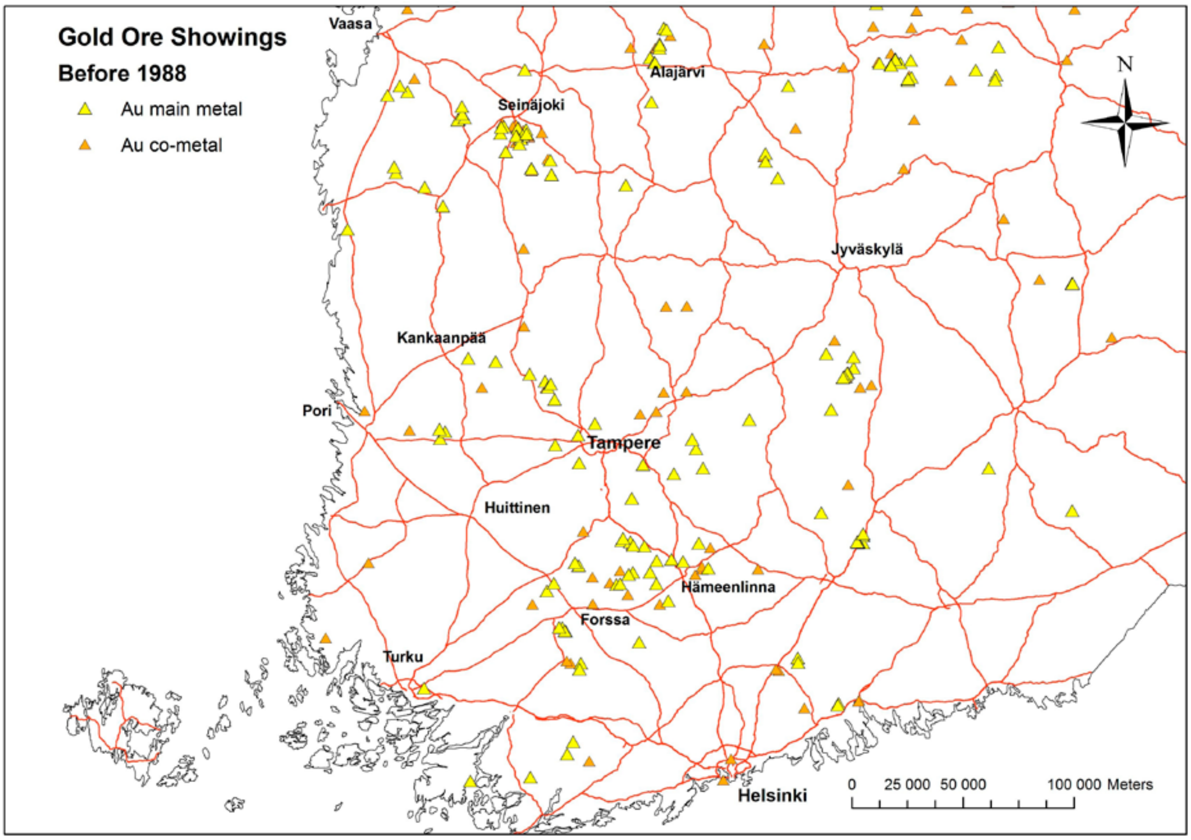

Figure 10. Gold mineralised samples from boulders and outcrops in the ore-showing database maintained until 1988. These data include findings received by companies and only include selected cases (Saltikoff 1987).

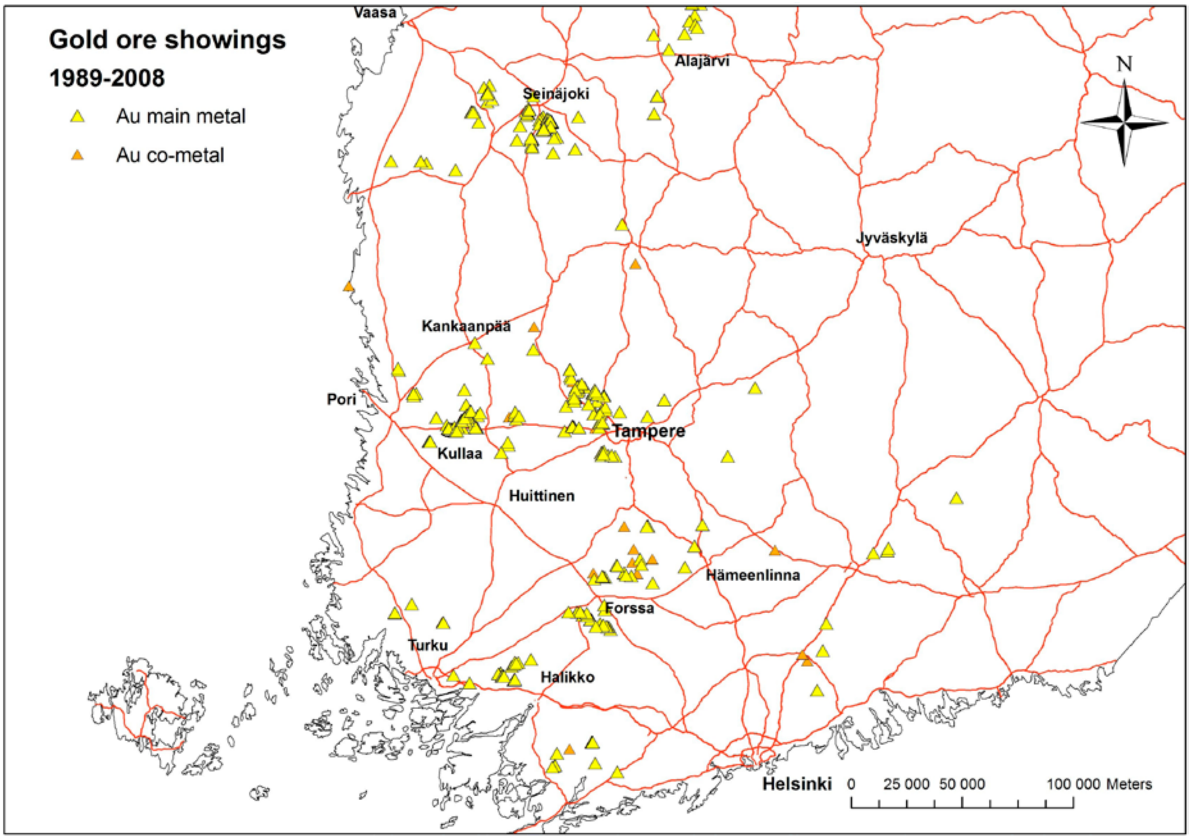

Figure 11. Gold mineralised boulders and outcrops discovered by amateur prospectors and the general public in 1989–2008 and analysed by GTK. These data are based on field reports in GTK's public archive.

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Edited by Sari Grönholm and Niilo Kärkkäinen
Geological Survey of Finland, Special Paper 52, 55–72, 2012

NEW DATA FOR GOLD EXPLORATION IN SOUTHERN FINLAND – DETAILED AIRBORNE GEOPHYSICAL MEASUREMENTS

by
Jaana Lohva and Tarmo Jokinen*

Lohva, J. & Jokinen, T. 2012. New data for gold exploration in southern Finland – detailed airborne geophysical measurements. *Geological Survey of Finland, Special Paper* 52, 55–72, 11 figures.

A brief review of detailed airborne geophysical measurements carried out by the Geological Survey of Finland for gold exploration in southern Finland is presented in this paper.

The whole of Finland has been covered by a nationwide aerogeophysical survey conducted using GTK's three-in-one approach. The nationwide airborne survey by GTK simultaneously measured the Earth's total magnetic field, radioactivity and electrical conductivity, and the measurements were carried out with a line spacing of 200 m and at an altitude of 30 m. In addition to the line spacing of 200 m, detailed airborne measurements with denser line spacing were also carried out in some selected areas in Finland.

In this paper we concentrate on the detailed airborne survey areas in southern Finland: Kullaa, Vampula, Nuutajärvi and Humppila. The detailed flights with a line spacing of 50, 75 or 100 m notably increased the information gathered as compared to the nationwide systematic airborne mapping with a line spacing of 200 m. The dense and detailed high-resolution data enabled interpretation from regional to prospecting scales. In the four survey areas, GTK's three-in-one airborne system has especially been used in gold exploration, combining geophysical data as integrated approach with magnetic, radiometric and electromagnetic data. Geophysics in gold exploration is not based on direct geophysical responses, but on secondary approaches such as delineating alteration zones and geological structural patterns due to the normally low gold concentrations.

Keywords (GeoRef Thesaurus, AGI): mineral exploration, gold ores, geophysical methods, airborne methods, magnetic methods, electromagnetic methods, radioactivity methods, Southern Finland

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INTRODUCTION

The Geological Survey of Finland (GTK) conducted a systematic low altitude airborne geophysical mapping programme covering the whole of Finland between1972–2007. GTK's three-in-one airborne system, i.e. simultaneous measurement of the Earth's total magnetic field, radioactivity and electrical conductivity, were carried out with a line spacing of 200 m and at an altitude of 30 m. The high-resolution airborne data have mainly been applied in mineral exploration and geological mapping, but are nowadays also increasingly used for environmental applications as well as infrastructural planning.

In some of the survey areas, detailed high-resolution airborne surveys have also been carried out, mainly for mineral exploration purposes, with a line spacing of 50, 75 or 100 m (Fig. 1). GTK has operated with two aircraft, a Twin Otter and a Cessna Caravan. Airborne geophysical surveys with the fixed wing Twin Otter aircraft were jointly carried out by GTK and the British Geological Survey (BGS) between 2004–2009. The latest geophysical equipment installation in the Twin Otter consisted of four-frequency electromagnetics, a magnetic gradiometer and 256 channel radiometrics. The standard assembly of the fixed wing Cessna Caravan survey aircraft was two-frequency electromagnetics, a magnetometer on the tail stinger and 256 radiometrics (Hautaniemi et al. 2005).

Application in regional gold potential studies

GTK's three-in-one airborne system has successfully been used in gold exploration, combining geophysical data as an integrated approach in the Central Lapland Greenstone Belt (Airo 2007). Increased K, K/Th and K-Th correlations indicated potassic alteration of ultramafic and mafic rocks. Altered ultramafic and mafic rocks are the hosts having the highest potential for gold. Numerous new targets were identified with the system. Respectively increased U/Th ratios were typically observed near massive sulphide deposits.

In southern Finland, detailed airborne data have been used in identifying gold critical structures and possible alteration zones. Airborne magnetic data are used to identify geological structural patterns such as faults, fractures and shear zones, as well as the variation in rock types. For instance, aeromagnetic anomalies with a rather strong intensity but small size are associated with the Satulinmäki and Riukka gold prospects in the Somero-Tammela area. Anomalies are clearly independent of the variation in rock type. The explanation for this is magnetic pyrrhotite related to the mineralisation of gold, although most of the common pyrrhotite is non-magnetic in these mineralisations (Kärkkäinen et al. 2007). Respectively, one method in seeking gold-critical locations is to identify from bedrock and airborne geophysical maps such major shear or fault zones that penetrate mafic-intermediate intrusive rocks. Critical structures of this kind have resulted in the discovery of many new gold mineralisations in southern Finland.

Airborne radiometric data are valuable together with magnetic data in mapping bedrock alteration zones and lithology. An important restriction is that a soil cover of more than one metre effectively masks radiation. In southern Finland, the overburden is practically ubiquitously thick, whereas weathered bedrock is common in Lapland where radiometric methods have successfully been applied.

Airborne electromagnetic (AEM) data were used in lithological mapping and combined with magnetic data identifying faults and fractures. The detailed AEM data provide new possibilities to interpret the extent of a deposit or mineralised geological structure.1D/2D AEM modelling can be used to estimate detailed conductivity changes.

Detailed airborne measurements in southern Finland

In southern Finland, detailed airborne low-altitude measurements were carried out in four survey areas: Kullaa, Vampula, Nuutajärvi and Humppila (Fig. 1). The detailed flights with a line spacing of 50, 75 or 100 m notably increased the amount of information as compared to nationwide systematic airborne mapping with a line spacing of 200 m. Figure 2 presents a combined detailed aeromagnetic map from Vampula, Nuutajärvi and Humppila, which have recently formed GTK's most important gold potential mapping region in southern Finland (Kärkkäinen et al. 2007). The bedrock in the area is mainly composed of mica gneisses and granitoids (Fig. 3).

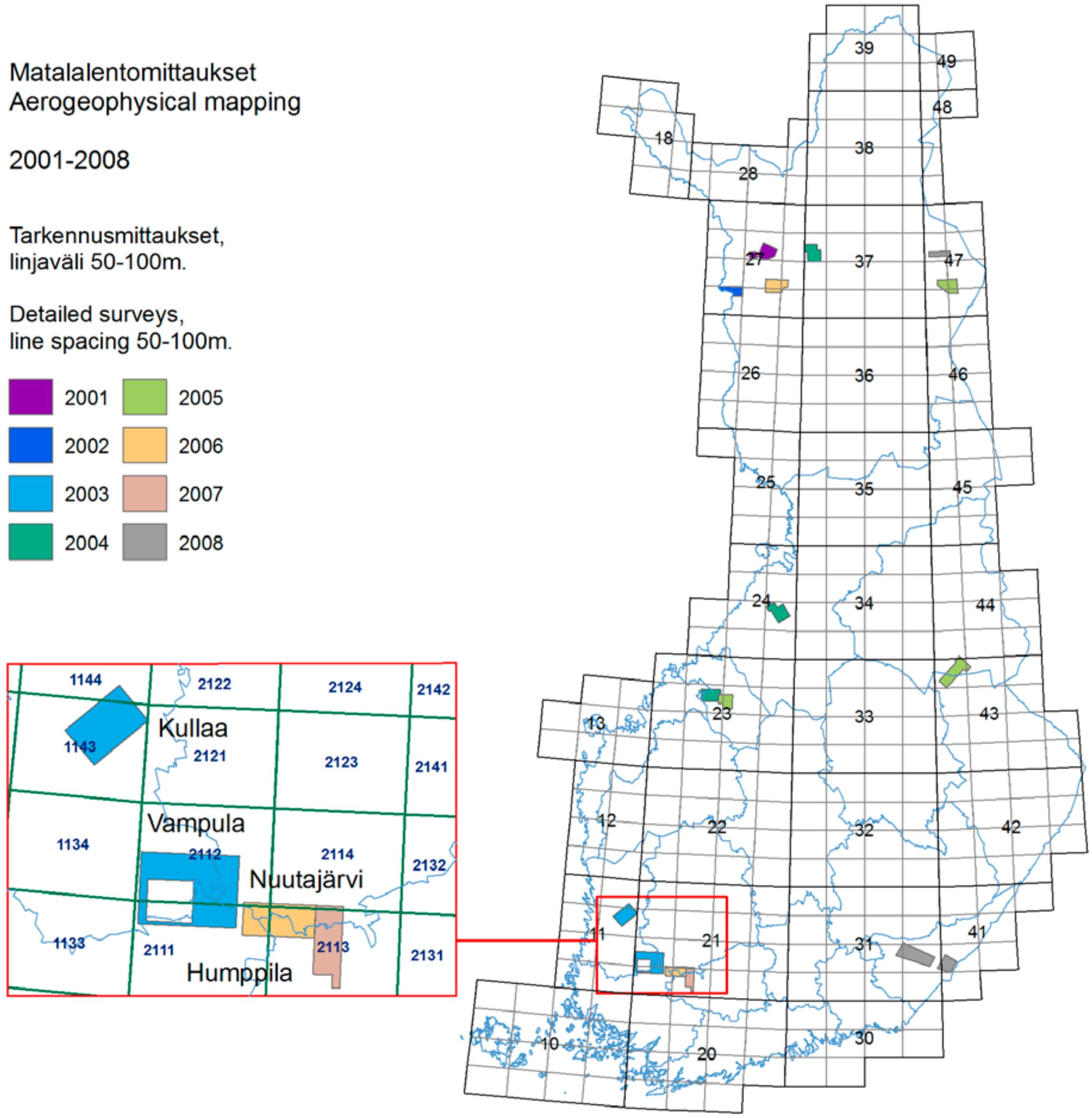


Figure 1. The detailed airborne survey areas in Finland. The framed area includes the detailed flights from southern Finland described in this paper.

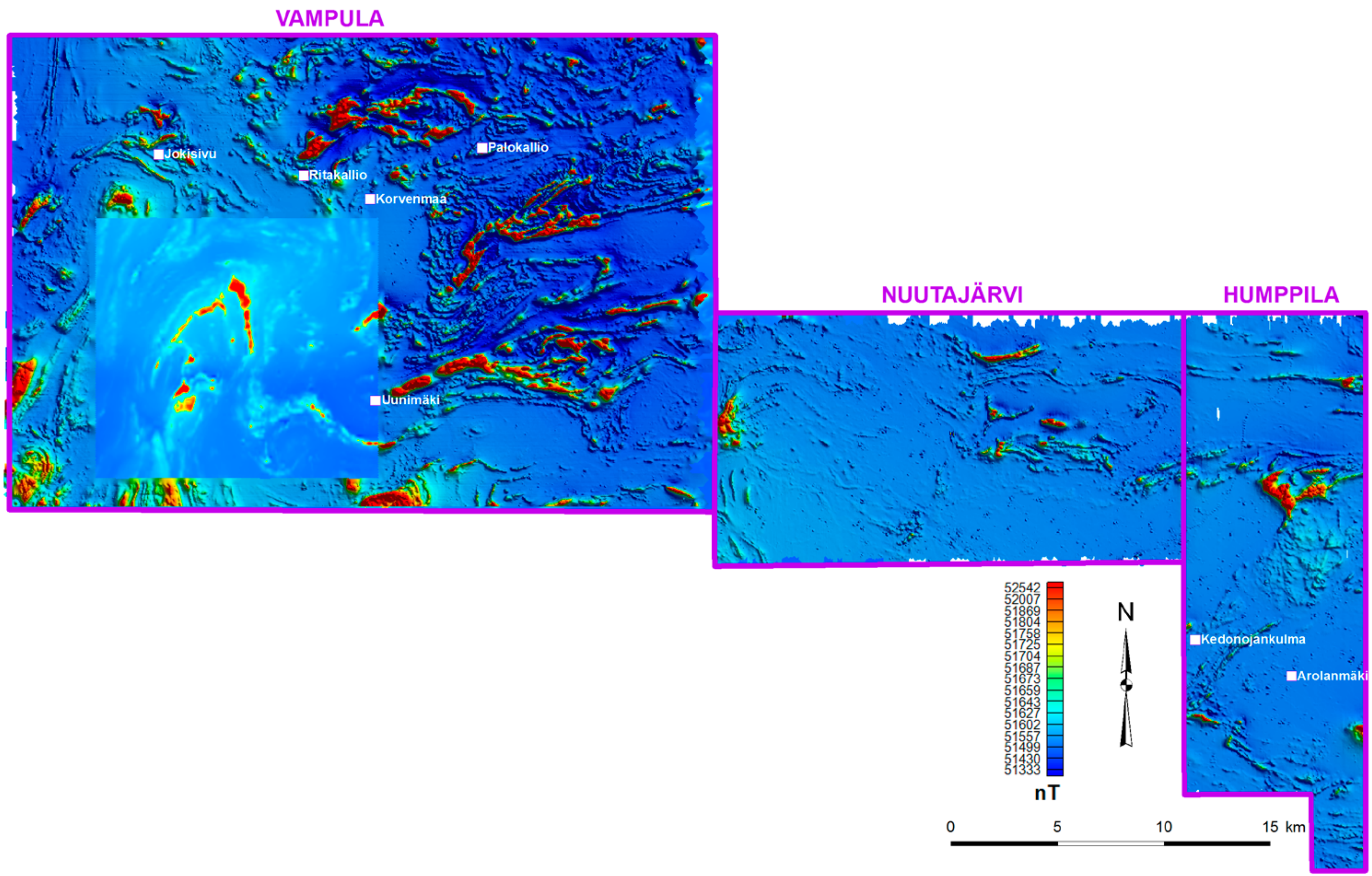


Figure 2. Detailed aeromagnetic map of Vampula, Nuutajärvi and Humppila. Note that the accuracy in the outlined area inside the Vampula flight is the same as in the nationwide data (see text). Gold occurences and Korvenmaa geochemical Au anomaly marked in white.

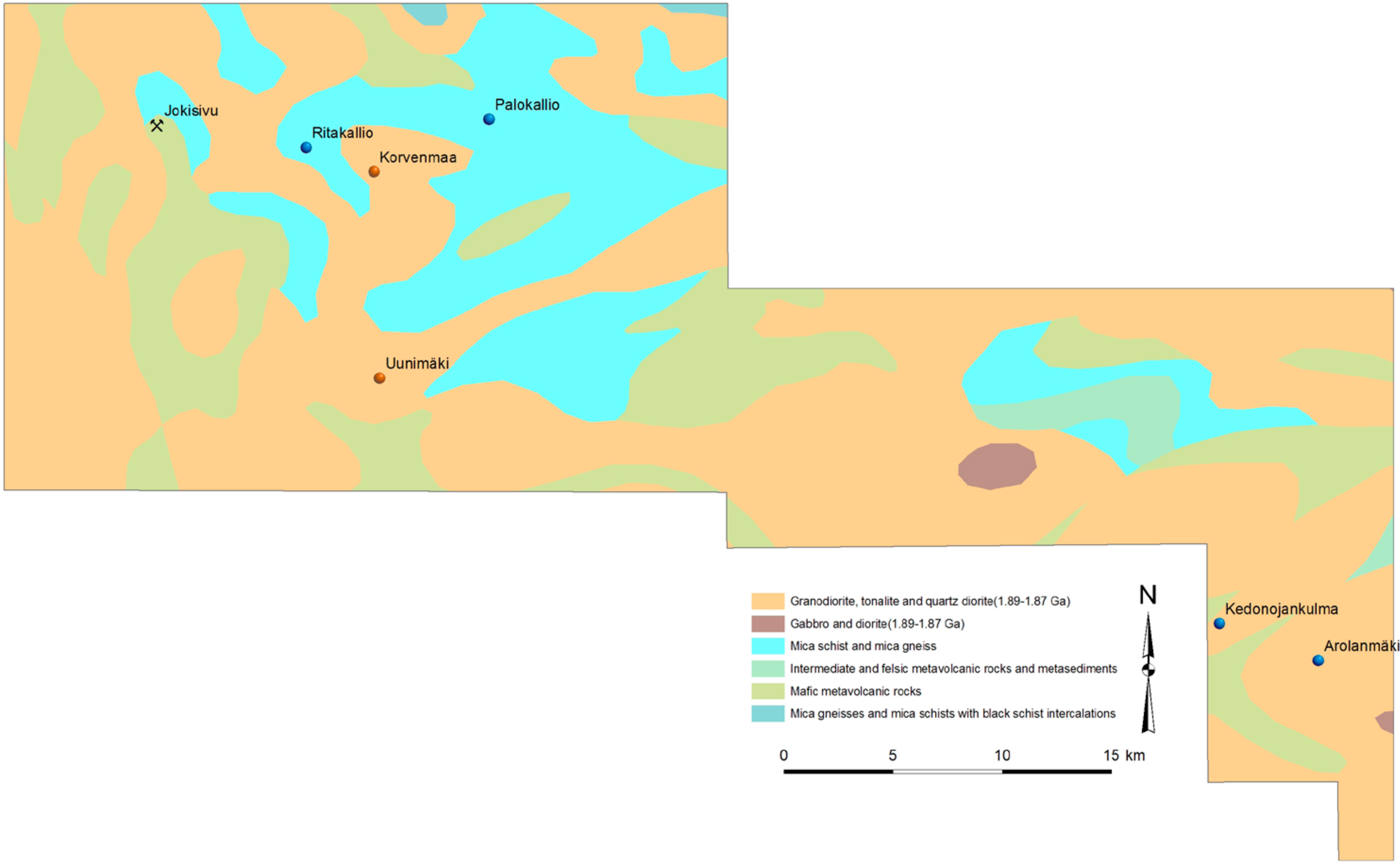


Figure 3. The bedrock in the detailed flight area of Vampula, Nuutajärvi and Humppila. Jokisivu mine, gold occurences (blue dots) Korvenmaa geochemical Au anomaly (yellow) marked.

KULLAA

In autumn 2003, GTK carried out a detailed low-altitude airborne survey in Kullaa with a line spacing of 100 m and a flight altitude of 30 m. The flight direction was NW–SE. In 2003, the Twin Otter aircraft had a two-frequency AEM system. GTK was carrying out gold potential mapping in this poorly exposed area. The main target was at Välimäki, but discoveries of numerous ore showings in other localities referred to a high potential in the Kullaa area (Lehto et al. 2006).

The known gold deposits, Välimäki, Silmusuo and Saarijärvi, are located in the vicinity of the NE–SW-trending highly magnetic and partly conductive amphibolite-hornblende gneiss and mica gneiss zones (Figs. 4 and 5). The magnetic shaded relief image enhances the structural features, and the Välimäki deposit can be seen to be situated in the massive NW–SE fracture zone (Fig. 4).

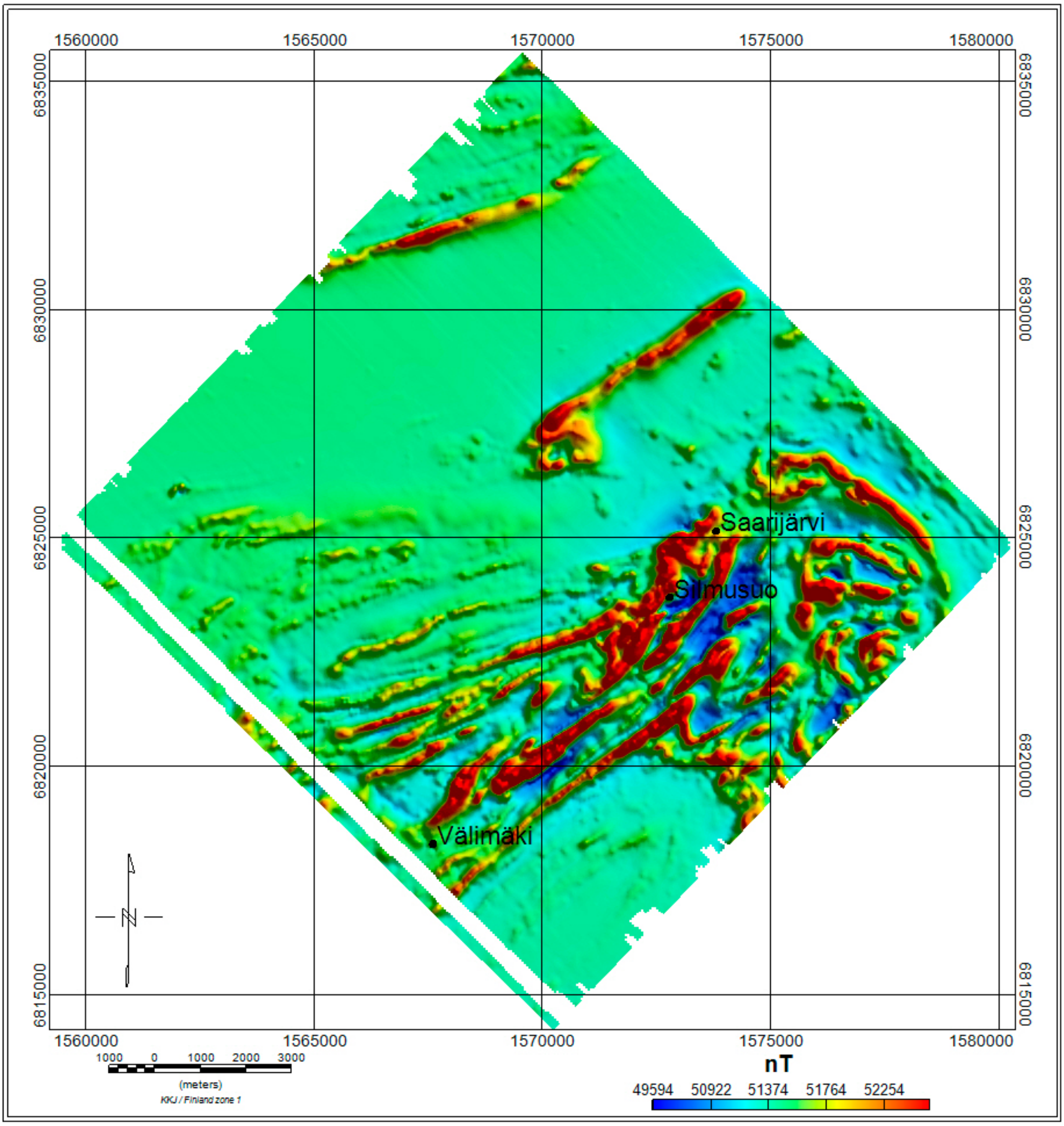


Figure 4. Aeromagnetic map of Kullaa. Known gold occurrences are marked in black.

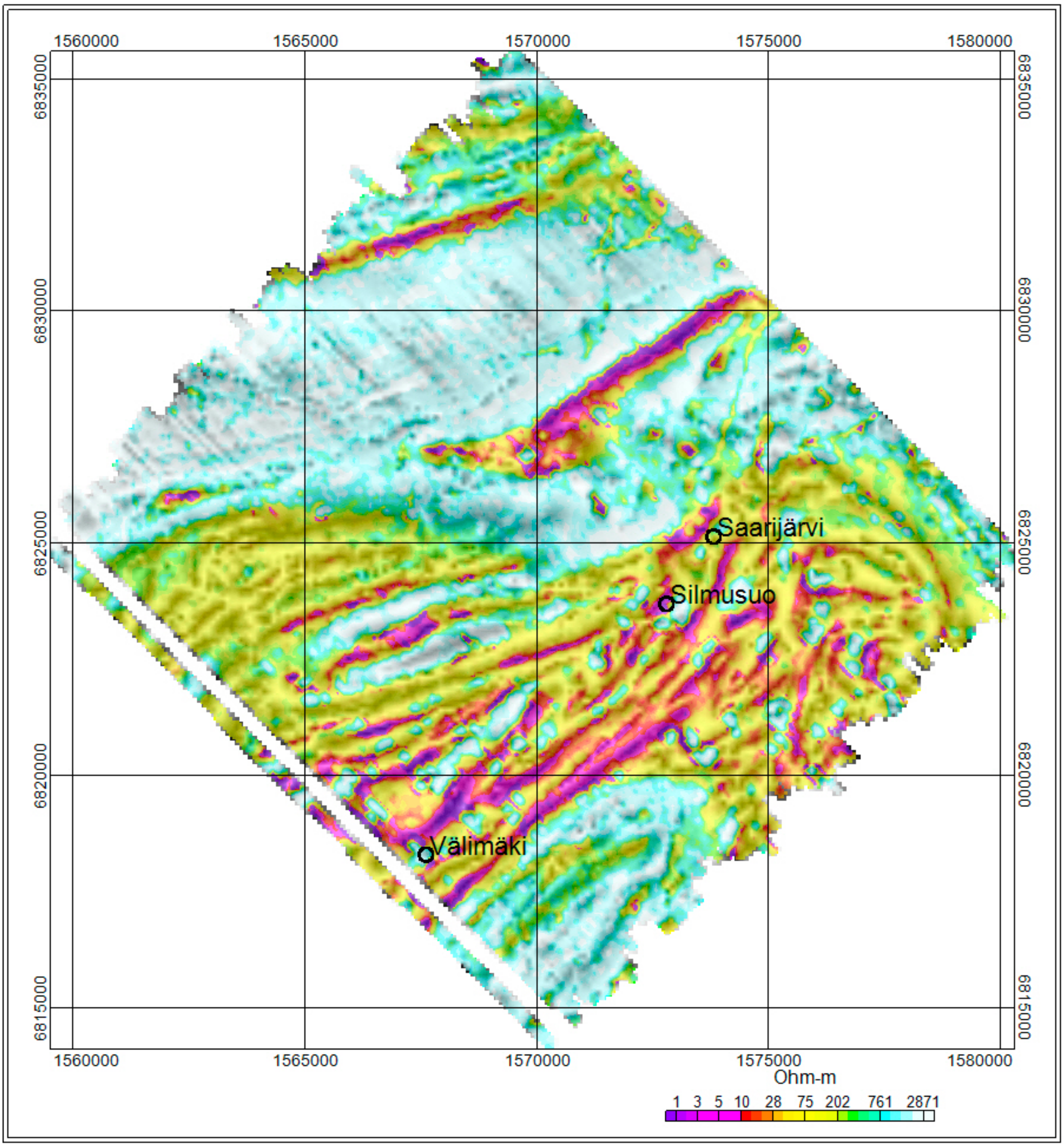


Figure 5. AEM apparent resistivity superimposed on the aeromagnetic tilt derivative.

NUUTAJÄRVI

In autumn 2006, the Nuutajärvi area was mapped with a line spacing 50 m and at an altitude of 30 m using a Cessna Caravan. The flight direction was N–S. The area is seen in Figures 1 and 2. The gold critical structures in the Nuutajärvi flight area have recently been explored in heavy mineral studies, but the results have not yet been reported.

VAMPULA

The Vampula survey area was measured during spring 2003 in an E-W direction with a line spacing of 75 m and a flight altitude of 30 m. The aircraft was a Twin Otter with a two-frequency AEM system. The blank area inside the detailed airborne survey area in Vampula is owned by a private company (Figs. 6 and 7). In the magnetic map (Fig. 6), the blank area is substituted by nationwide aeromagnetic data (line spacing 200 m).

The Ritakakallio gold prospect was discovered as a result of the Vampula flight. A NW–SE-oriented anomalous zone in the magnetic map cutting mafic intrusive and volcanic rocks was interpreted to be a major shear or fault zone. This zone included a weak geochemical gold anomaly. During checking of the structure in the field, numerous Au mineralised boulders and gold grains in till were discovered (Kärkkäinen et al. 2007). Subsequently, other similar gold occurrences have been discovered in an analogous environment in this region. It has been found that in many cases, mafic intrusive rocks are recrystallized so that magnetite content probably decreases by a process of uralitization. In some cases, the decrease in susceptibility seems to be related to sulphurization, which might result from the mineralisation of gold. In these cases, magnetite is replaced by pyrrhotite that is normally of the low susceptibility type. Thus, disturbances in magnetic anomalies may be a result of hydrothermal processes related to mineralisation.

In the Vampula flight area the highly magnetic zones are caused by mafic volcanic rocks and the conductive zones indicate pyrite- and graphite-bearing schist (Figs. 6 and 7). Regionally, the aeromagnetic map of the Vampula area is divided into two parts: in the southwestern side of the survey area the magnetic anomalies are smooth, whereas the eastern side of the area is magnetically grainy. This change may be related to a major difference in the bedrock of these areas. In the southwestern part, magnetic anomalies are related to volcanic rock formations, and on the eastern side the patterns of thin anomalies are caused by frequent changes in the mica gneiss/metagraywacke environment of the bedrock. In a radiometric ternary image (Fig. 8), the clearly NW–ES trending zones are related to Quaternary formations (mainly eskers) and indicate the direction of the ice sheet and topography.

HUMPPILA

In autumn 2007, a gold exploration area in Humppila was surveyed using the Twin Otter aircraft with GTK's three-in-one measurement system. The electromagnetic measurement was carried out for the first time using GTK's new AEM-05 four-frequency airborne system. The system is presented in more detail by Leväniemi et al. (2009). The gold exploration area was covered with a 75 m line spacing at a 30 m flight altitude in a N-S direction. The detailed airborne survey results are presented as aeromagnetic, apparent resistivity and radiometric ternary images in Figure 9.

Most of the gold exploration targets of the Humppila airborne survey area are situated in the Forssa-Jokioinen area. GTK started gold exploration in the area based on till geochemistry and Au-Te anomalies (Kärkkäinen et al. 2007). After the regional exploration phase, several geologically diverse exploration targets were identified in the Forssa area, the major ones known as Kedonojankulma and Arolanmäki (or Latovainio). Detailed ground geophysics such as magnetic, IP, slingram and gravity measurement as well as systematic drilling and a well logging programme were carried out in these areas.

The Kedonojankulma target (see Fig. 9a) is a disseminated Au-Cu-As mineralisation, hosted by quartz-plagioclase-porphyrite in a non-magnetic (granitoid) environment (Fig. 11b). The target is covered by thick clay deposits, as can be seen from the digital terrain model image (Fig. 11a). Attenuation of radiation due to the thick clay deposit is apparent in the radiation images (Figs. 11d, e and f). The clay deposit causes a slight rise in conductivity in the apparent resistivity map (Fig. 11c). The AEM four-frequency anomalies of the Kedonojankulma gold prospect area were quantitatively investigated, and their location is indicated in Figure 11c. The thicknesses and resistivity of overburden, mostly clay fields, were interpreted using 1D inversion of AEM profiles (Suppala et al. 2008). The four-frequency AEM data have been interpreted by regularized inversion using a 1D layered-earth model and 2D model norm to constrain the continuity of the conductivity structure along the flight line. The interpreted clay thickness was approximately 10–20 m and the interpretation is presented in Figure 10. Some highly conductive points on the west side are caused by electric power lines.

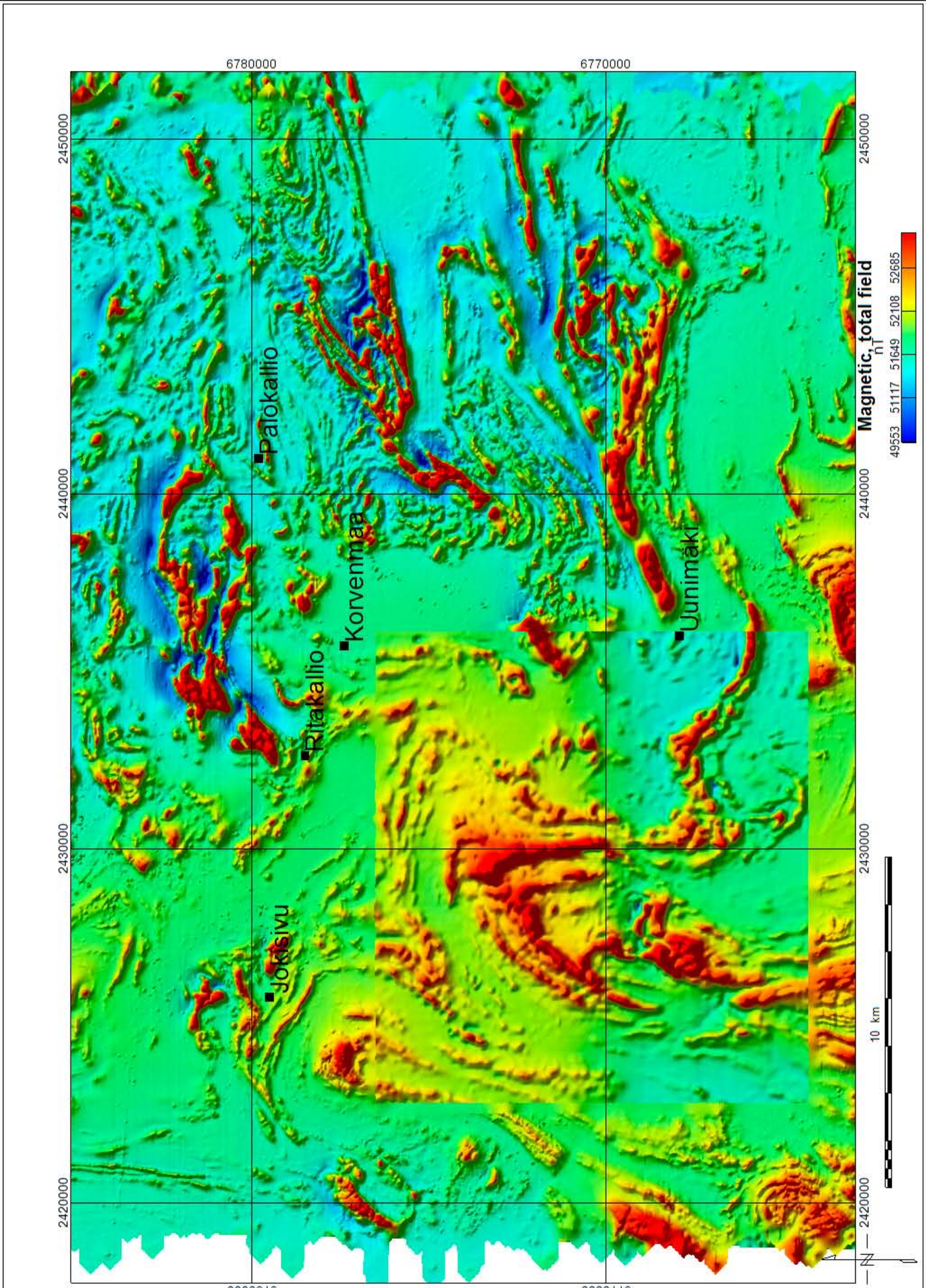


Figure 6. Aeromagnetic map of Vampula. Known gold occurrences and ore prominent geochemical anomaly (Korvenmaa) are marked in black.

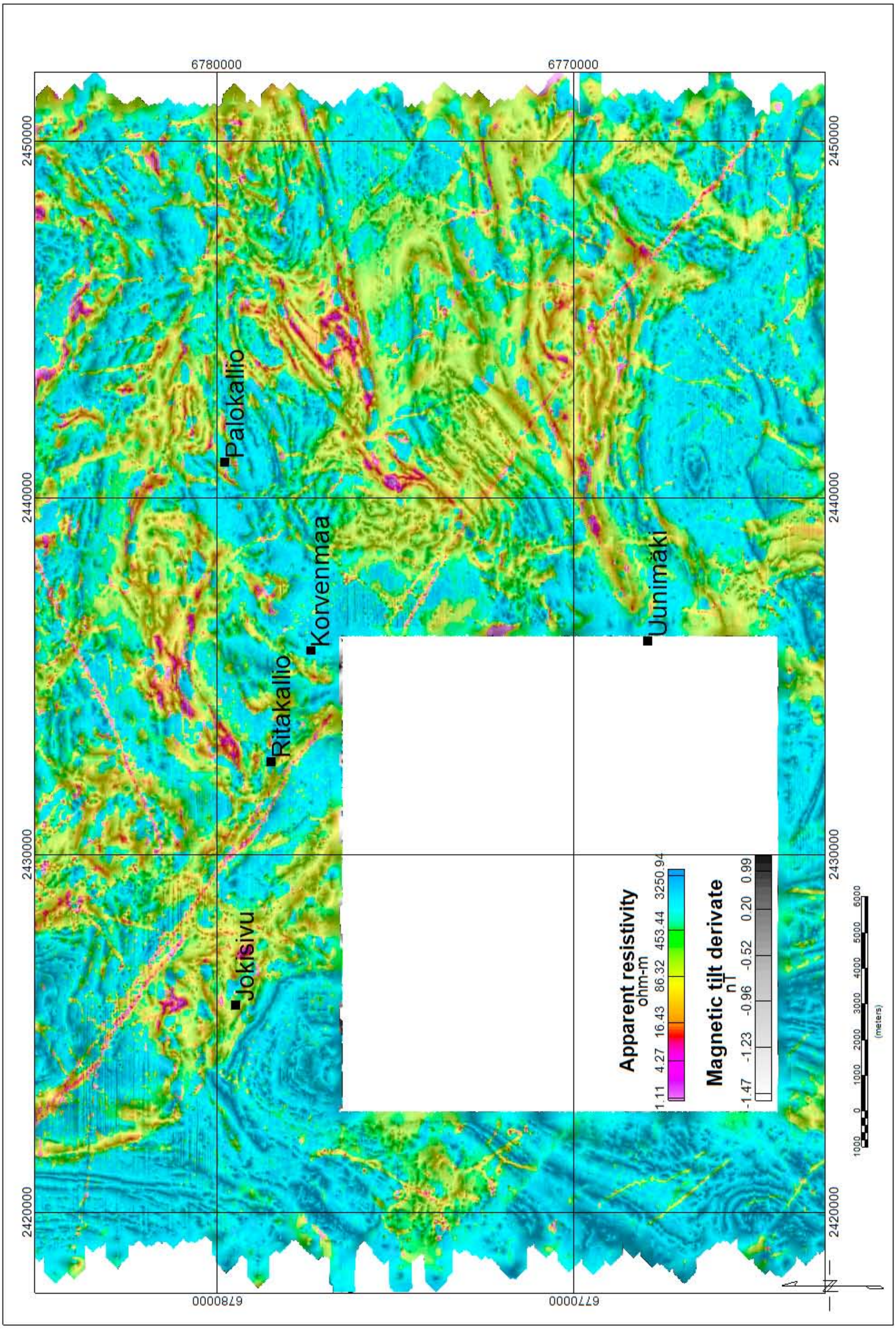


Figure 7. AEM apparent resistivity superimposed on the aeromagnetic tilt derivative in the Vampula detailed flight area. Known gold occureces and ore prominent geochemical anomaly (Korvenmaa) are marked in black.

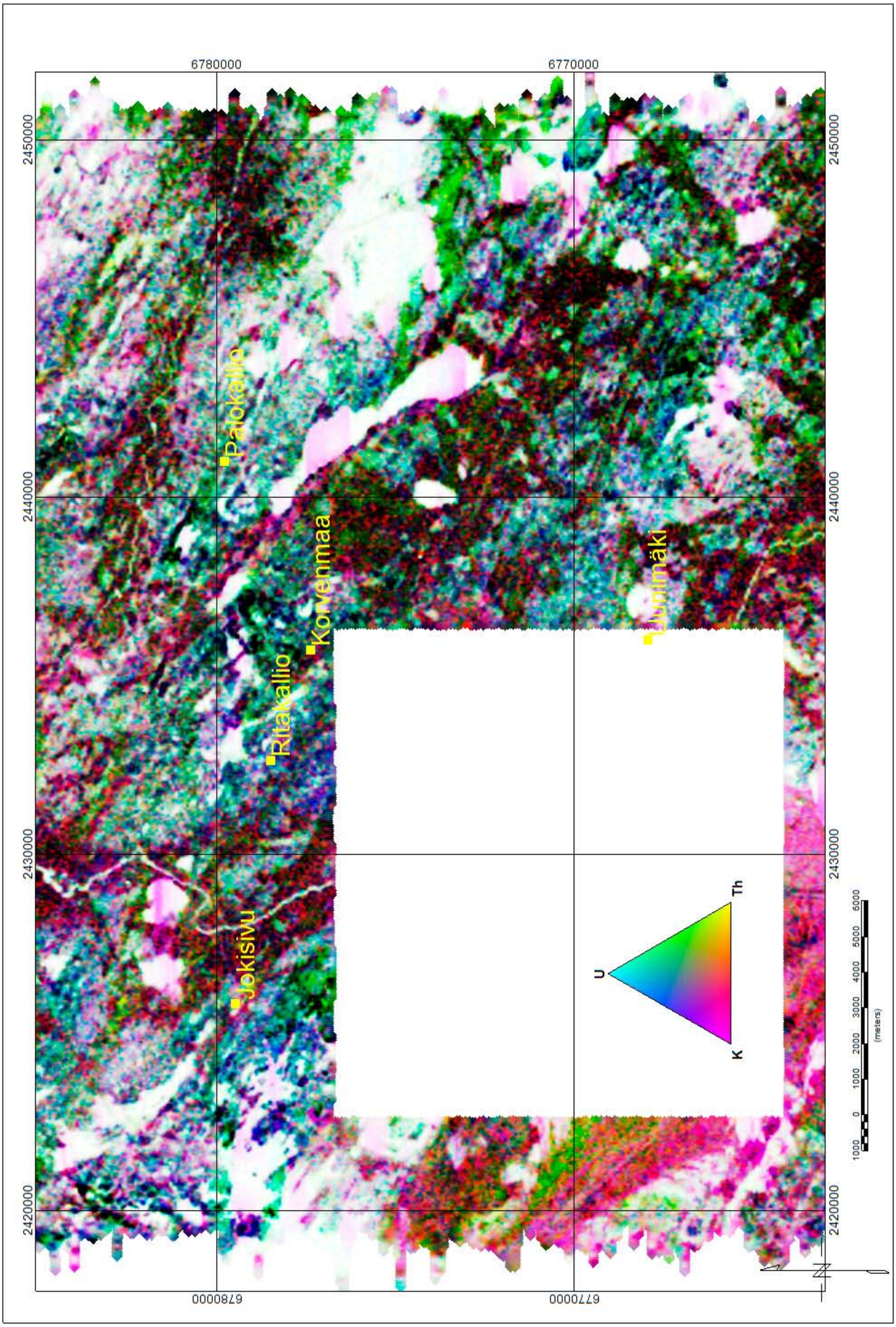


Figure 8. Radiometric ternary map of Vampula. Known gold occurences and ore prominent geochemical anomaly (Korvenmaa) are marked in black.

9a 9b 9c

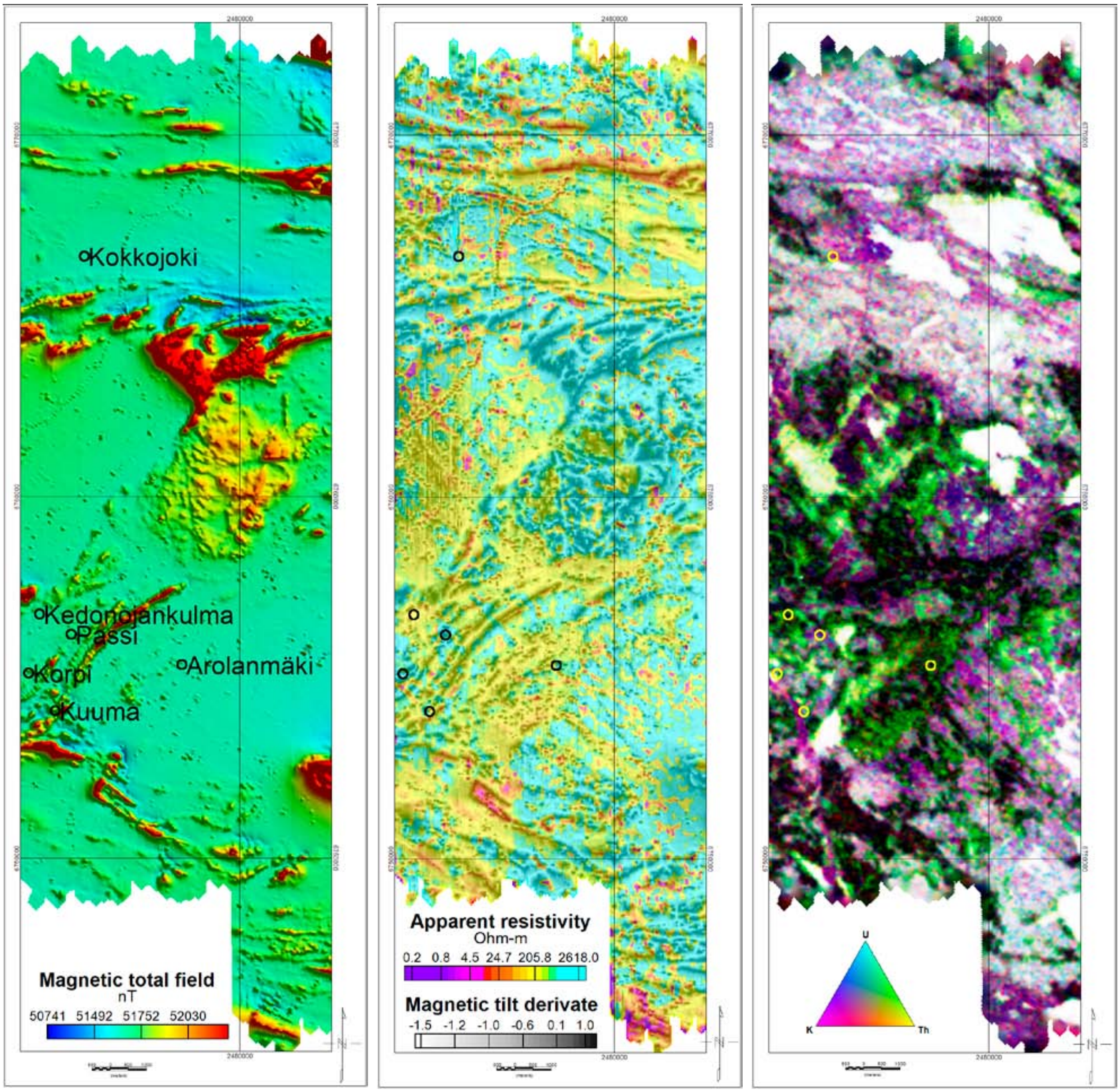


Figure 9. a. Aeromagnetic map of Humppila, b. AEM apparent resistivity superimposed on the aeromagnetic tilt derivative, and c. a radiometric ternary map. Known gold occurrences are marked in black and yellow.

In other targets in the Kedonojakulma area, the interesting geological unit is the sheared sericite schist, altered from intermediate volcanite at the contact of a roundish granodiorite intrusion. Some Au anomalous bedrock samples indicate that the sericite schist might host Au mineralisation. The sulphide disseminated serisite schist zone can be seen in magnetic data (Fig. 11b). Radiation images (Figs. 11d, e and f) from targets in Korpi and Passi show relatively enhanced K/Th and U/Th ratios.

The Arolanmäki target is an Au-Cu-bearing sulphide dissemination in granitoids and sheared granitoids. The target area is clearly shown by till geochemistry and heavy mineral geochemistry. The prospecting area is covered by thick clay deposits. A clear alteration zone can be seen in the radiation images (Figs. 11d, e and f) of Arolanmäki connected with a slight magnetic anomaly (Fig. 11b). Some enhanced K/Th ratios are indicated in Figure 11e.

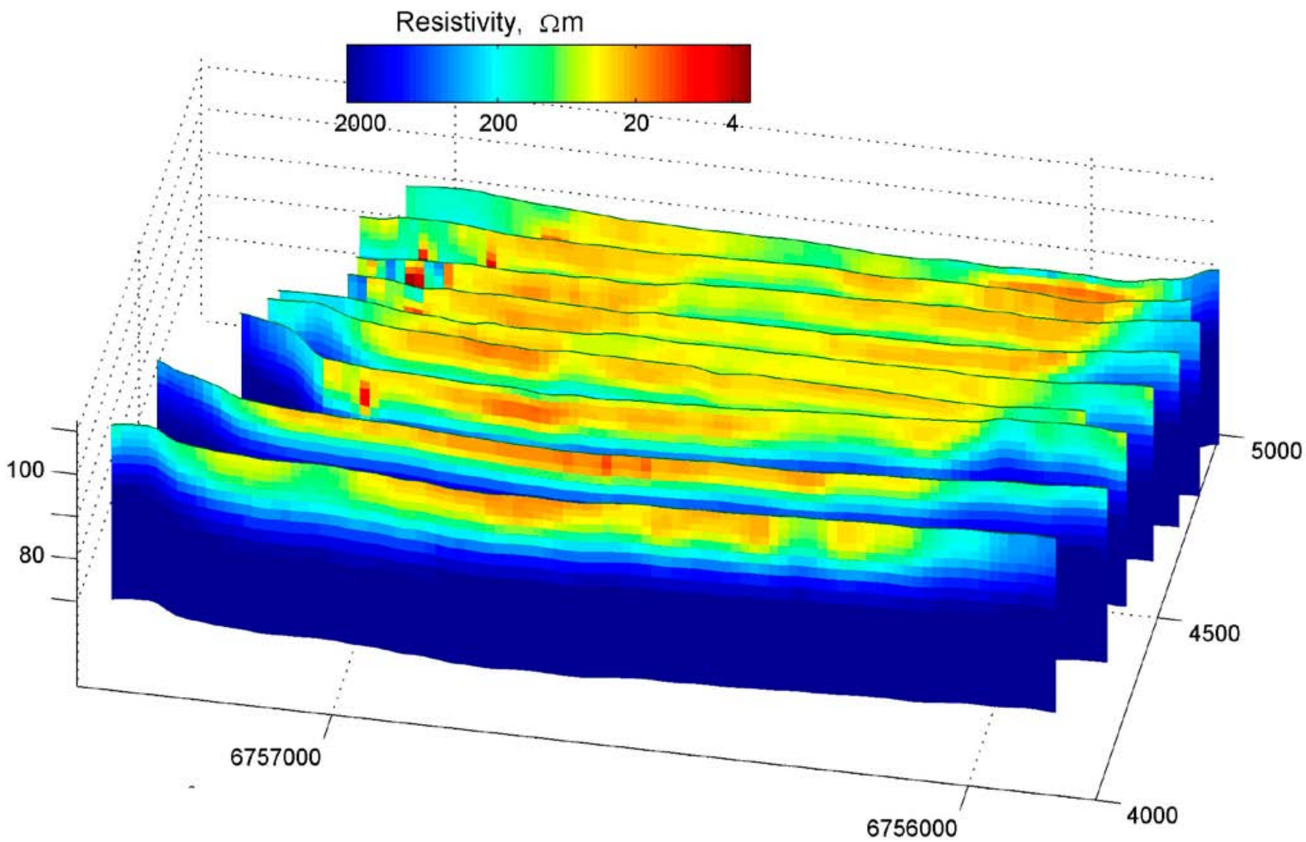


Figure 10. The thicknesses and resistivities of Kedonojankulma overburden, mostly clay fields, were interpreted using 1D inversion of AEM profiles by Ilkka Suppala, GTK.

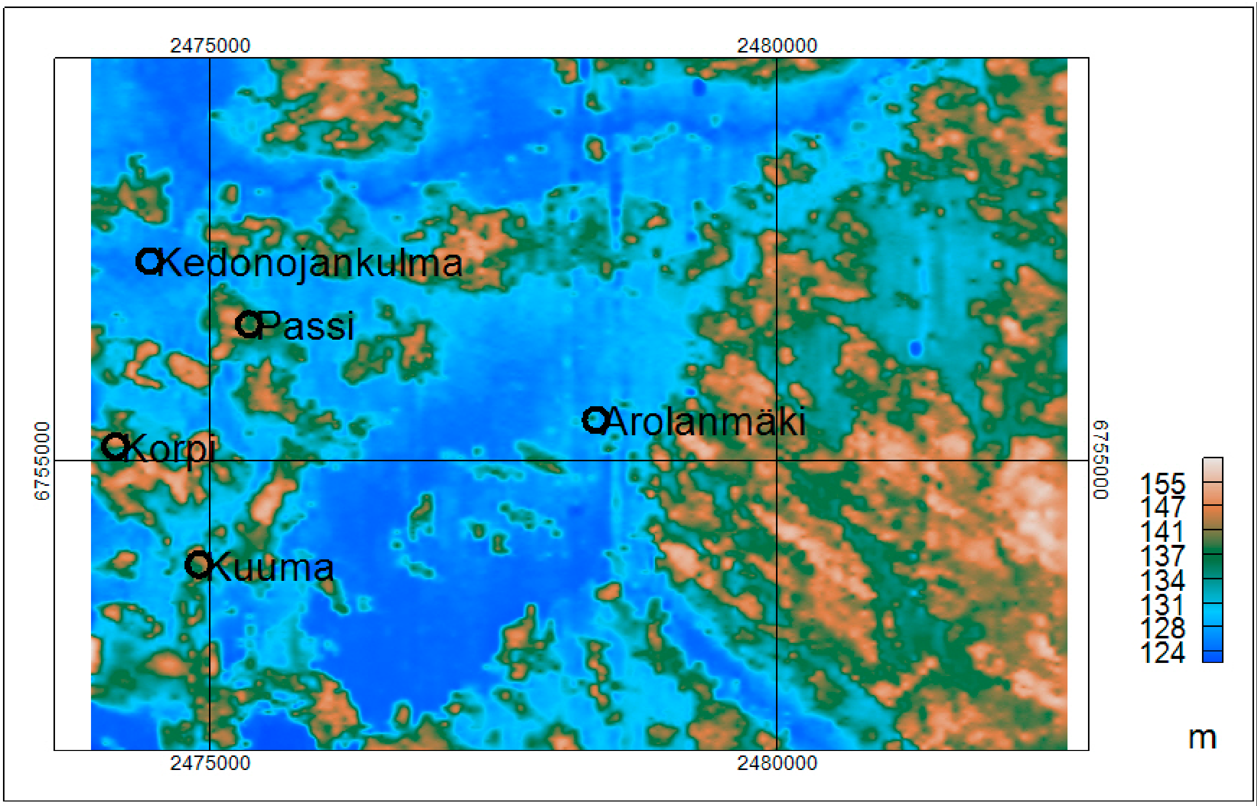
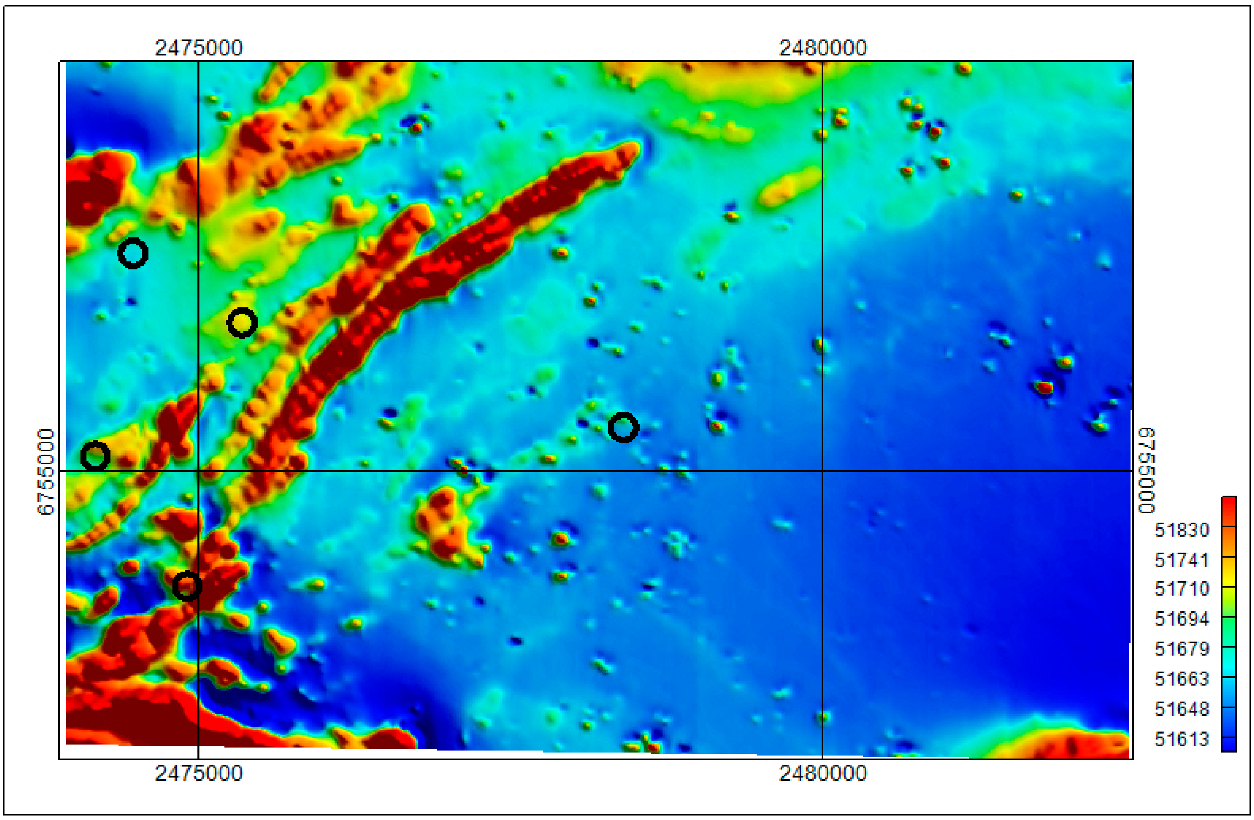
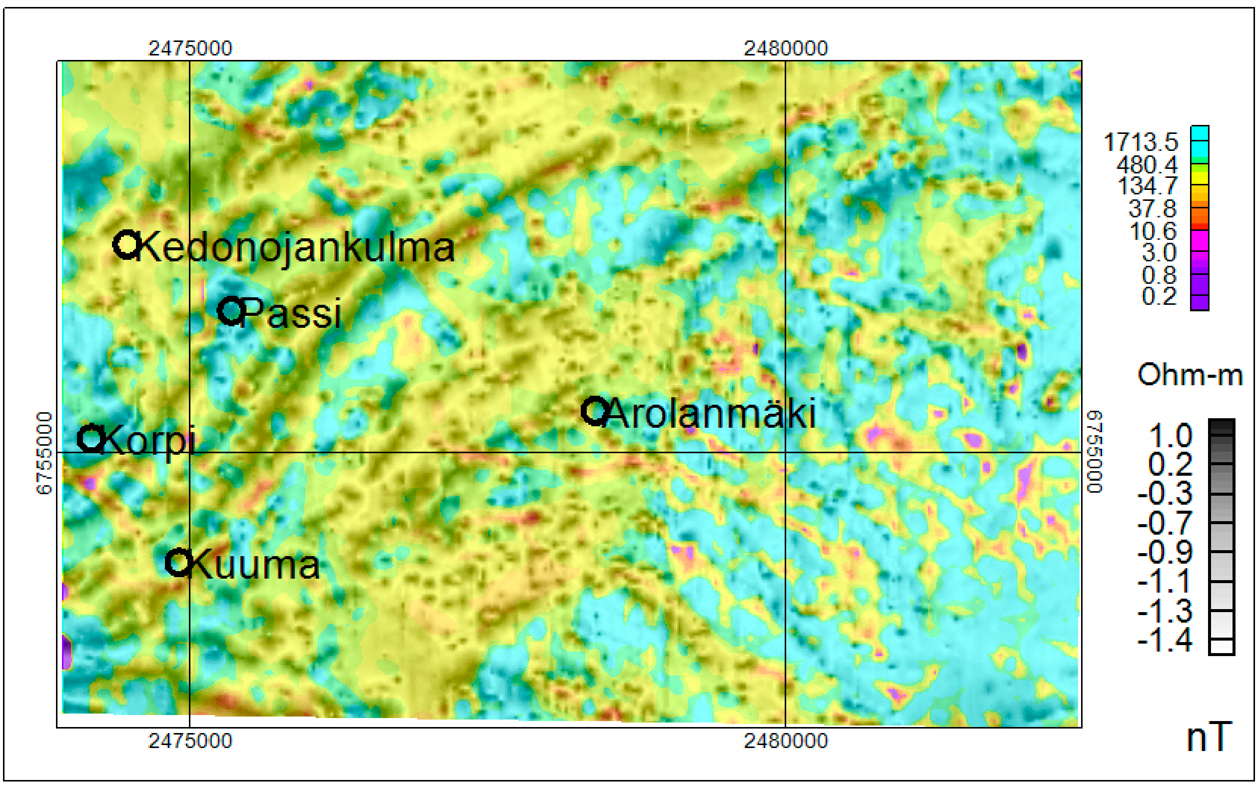


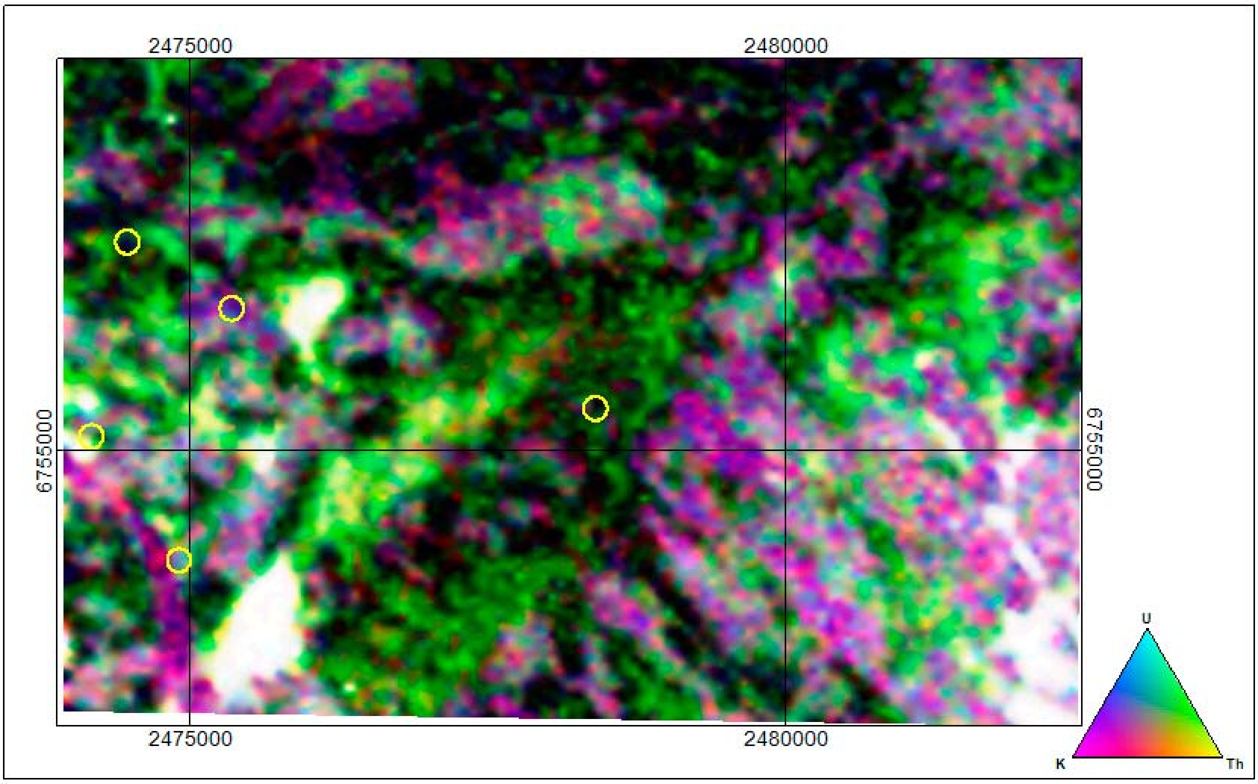
Figure 11. The Kedonojankulma survey area, flown at 75 m line spacing.
a) Digital terrain model



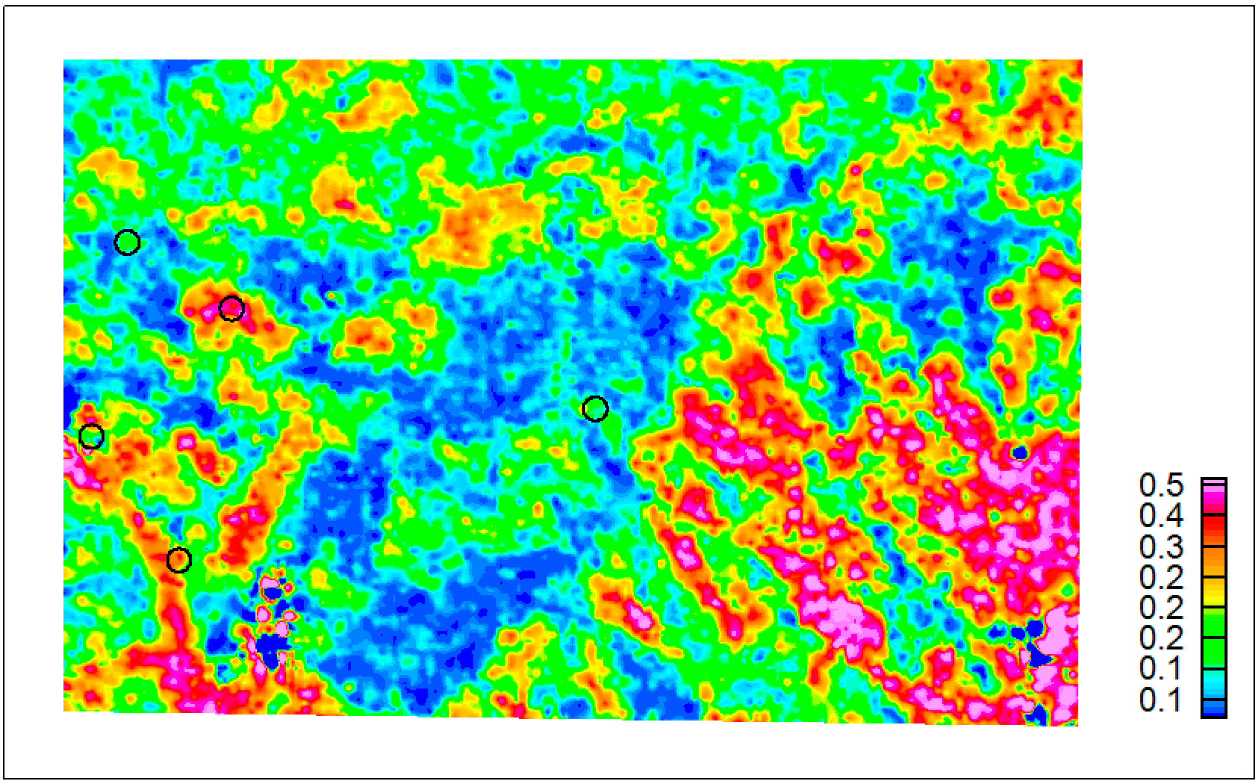
11 b) Aeromagnetic



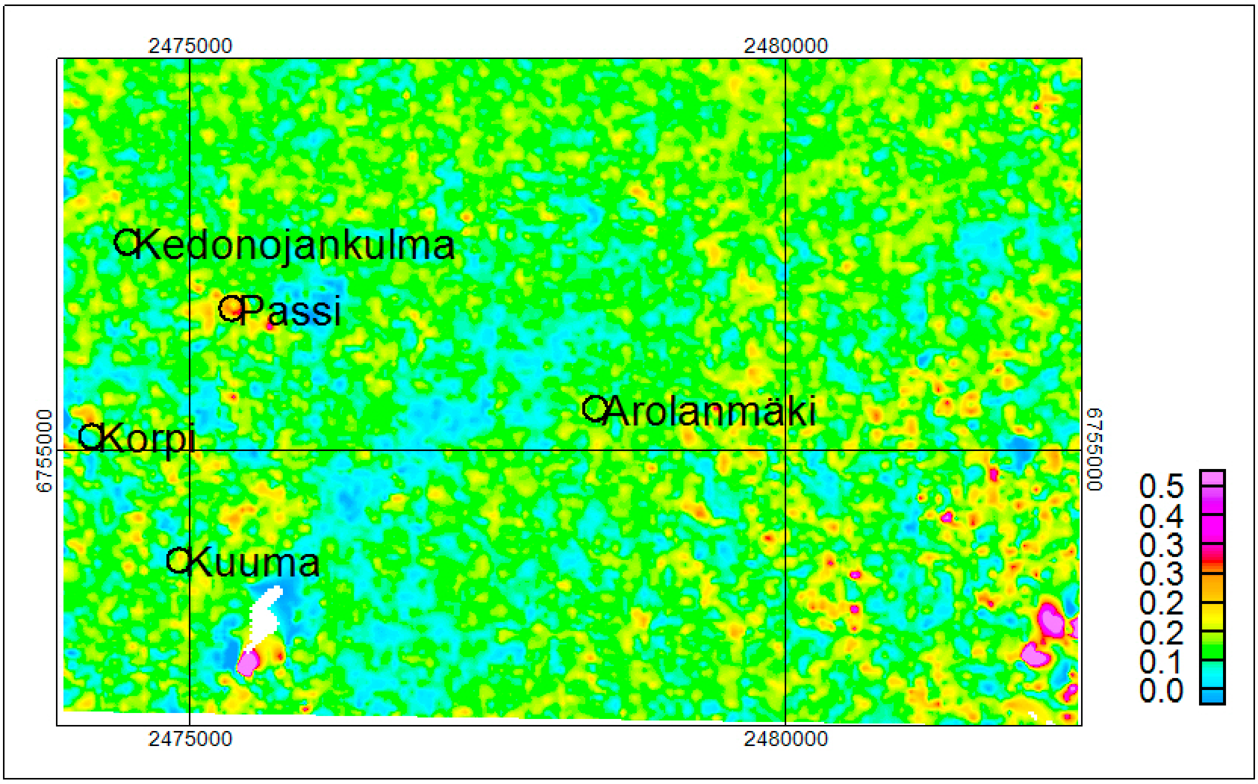
11 c) AEM apparent resistivity, aeromagnetic tilt derivative



11 d) Aeroradiometric ternary



11 e) Calculated K/Th



11 f) Calculated U/Th

SUMMARY

GTK's three-in-one airborne system has been used in gold exploration by combining geophysical data as an integrated approach. Geophysics in gold exploration is not based on direct geophysical responses but on secondary approaches such as delineating alteration zones and geological structural patterns due to the normally low gold concentrations. Airborne magnetics is used in identifying geological structural patterns such as faults, fractures and shear zones, as well as rock types. Airborne radiometric data are valuable together with magnetics in mapping bedrock alteration zones and lithology. Increased K and especially K/Th correlations were indicated in targets with gold potential and potassic alteration of ultramafic and mafic host rocks. Airborne electromagnetic (AEM) data were used in lithological mapping and combined with magnetic data identifying faults and fractures. The detailed AEM data provide new possibilities to interpret the extent of a deposit or mineralised geological structure.1D/2D AEM modelling can be used to estimate detailed conductivity changes.

Airborne measurements are excellent for regional exploration, but more detailed ground geophysical methods are needed to delineate mineralised deposits.

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Gold in Southern Finland: Results of GTK studies 1998–2011
Edited by Sari Grönholm and Niilo Kärkkäinen
Geological Survey of Finland, Special Paper 52, 73–90, 2012

DISCOVERY OF THE KEDONOJANKULMA Cu-Au OCCURRENCE, HOSTED BY A SVECOFENNIAN PORPHYRITIC GRANITOID IN SOUTHERN FINLAND

by
Markku Tiainen, Niilo Kärkkäinen, Esko Koistinen, Jaana Lohva, Pekka Sipilä and Pekka Huhta

Tiainen, M., Kärkkäinen, N., Lohva, J., Sipilä, P. & Huhta, P. 2012. Discovery of the Kedonojankulma Cu-Au occurrence, hosted by a Svecofennian porphyritic granitoid in Southern Finland. *Geological Survey of Finland, Special Paper 52,* 73–90, 22 figures.

The Kedonojankulma Cu-Au occurrence was discovered by diamond drilling after systematic till geochemical studies in the Forssa region, Southern Finland. The starting point for the study was a Te-Cu-As anomaly in the regional till geochemical data. The till geochemical exploration was carried out in two main phases, first in regional-scale anomaly mapping, followed by local-scale anomaly checking and target-scale exploration.

The discovered Cu-Au(-Ag-Mo) occurrence is hosted by a porphyritic tonalite intrusion in the Palaeoproterozoic volcanic-intrusive Häme belt, part of the Southern Svecofennian Arc Complex in southern Finland. The fine-grained Cu-Au(-Ag-Mo) mineralization is controlled by a sheared and fractured, strongly altered zone in the quartz-plagioclase porphyrite. The highest metal contents in one-metre-long samples of drill core are 2.4% Cu, 8 ppm Au, 120 ppm Ag, 0.13% Mo, 0.15% Sb, 0.33% Bi and 1.27% Zn. The Kedonojankulma occurrence has a complex mineralogy, including various Cu, Ag, Au, Bi, Mo, Sb, Sn and Zn minerals. The main ore mineral is chalcopyrite. Other notable ore minerals are arsenopyrite, bornite, chalcocite, sphalerite, pyrite, pyrrhotite, molybdenite, silver sulphides and bismuth.

The Kedonojankulma occurrence has several features that are typical of porphyry-style Cu deposits. Most prominent are the metal contents and zoning, with Cu-Au-Ag-As-Mo in the core, Mo and Cu in quartz veins outside of the core and Zn-Cu-Ag in the outer zone of the intrusion. Various alteration assemblages in the mineralized zone have been identified, with silicification, chloritization, sericitization and epidotization being common.

Keywords (GeoRef Thesaurus, AGI): copper ores, porphyry copper, gold ores, tonalite, mineral exploration, geochemical methods, till, Paleoproterozoic, Kedonojankulma, Finland

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INTRODUCTION

The Kedonojankulma Cu-Au prospect is located in southern Finland in the municipality of Jokioinen, about 13 km north of Forssa. The occurrence is hosted by a porphyritic granitoid in the Palaeoproterozoic volcanic-intrusive Häme belt (Fig. 1).

Exploration history of the Forssa region and Häme belt

The Forssa region has a long but modest history within the mining industry, going back to the 16th century, to the mining of the small copper deposits at Matkajärvi and Tilasinvuori (Puustinen 2003). Outokumpu Oy carried out exploration during the 1970s and 1980s on three main targets: in Kiipu and Leteensuo for base metals and in Somero and Liesjärvi for gold (Mäkelä 1978, 1980, Haga 1984, Kokkola 1990). At the same time, Rautaruukki Oy explored for base metals and tungsten in the eastern part of the Häme belt (e.g. Kinnunen 1984, 1986, 1987, 1988, Sipilä 1980). The Cu potential of the Häme belt was again observed later by Tiainen and Viita (1994) in an ore potential mapping project on the Häme belt and by Lahtinen and Lestinen (1996) in a regional rock geochemistry study of the Tampere–Hämeenlinna area.

The Geological Survey of Finland (GTK) has carried out exploration in the Forssa region since 2000, first for gold in Somero and Tammela and since 2003 for gold and base metals in Jokioinen

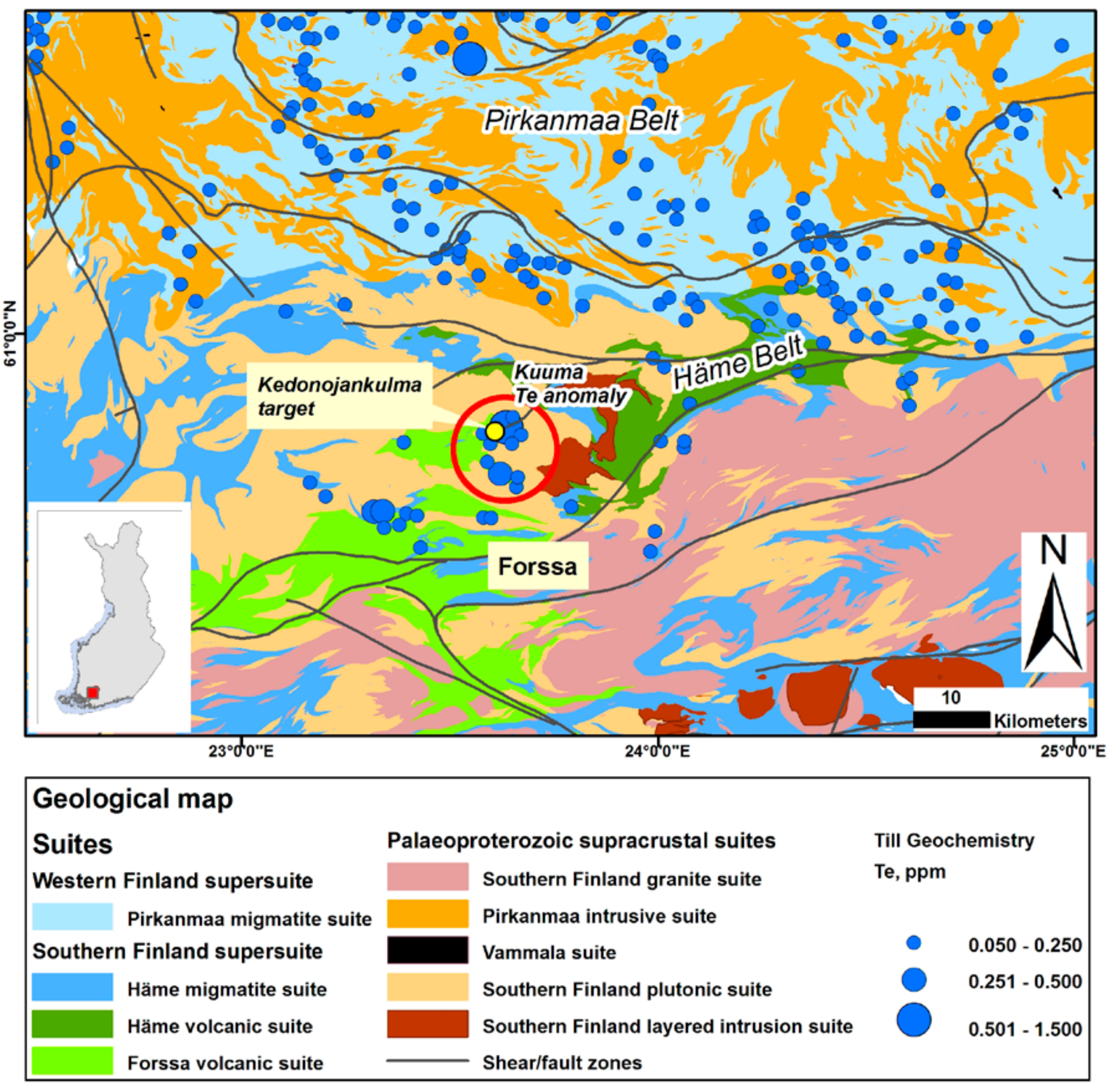

Figure 1. Location of the Kedonojankulma Cu-Au prospect in the Häme Belt. Tellurium (Te) anomaly in the regional (ALMR) till geochemistry data of GTK (Salminen 1995). Geological map by the Geological Survey of Finland (Bedrock of Finland–DigiKP).

and Forssa Kärkkäinen et al. 2003, Kärkkäinen & Koistinen 2006, Koistinen & Kärkkäinen 2006, Kärkkäinen et al. 2008, Kärkkäinen et al. 2010). In the economic sense, the most significant discoveries so far have been the gold deposits of Satulinmäki and Riukka in the Somero gold province. The impetus for the present exploration activities in the Forssa region was a workshop held at GTK in 2002. The topic of the meeting was the gold potential of Southern Finland. It was noted that the Forssa region was clearly underexplored and the region included interesting regional (ALMR) till geochemical anomalies, especially of tellurium (Te). As a result of the workshop, GTK decided to start an exploration project to reveal the ore potential of the Forssa region, and especially to study the Te-Au-As-(Cu) till geochemical anomaly of the Kuuma area (Fig. 1).

Bedrock geology

The study area is located in the western part of the volcanic-intrusive Häme belt, which is part of the Palaeoproterozoic Southern Finland Supersuite (Fig. 1). The age of magmatism in the Häme belt is about 1.88 Ga (Saalman et al. 2009). The volcanic rocks of the Häme belt have been divided into two suites, the calc-alkaline Forssa volcanic suite composed of intermediate and felsic pyroclastic rocks with an arc affinity, and the tholeitic Häme volcanic suite with rift affinity (Hakkarainen 1994, Lahtinen 1996, Heino 2006). The Häme volcanic suite is composed of mafic basaltic lavas and dikes and partly of intermediate pyroclastic rocks. The Forssa gabbro, which is in contact with the Häme volcanic suite, has been interpreted as comagmatic with the uralite porphyrites of the Häme volcanic suite (Neuvonen 1954a, 1954b, 1956).

Based on the new geochemical data, the granitoids of the Häme belt, in the surroundings of the Kedonojankulma occurrence, are volcanic arc-type granitoids (Fig. 2). The chemical composi-

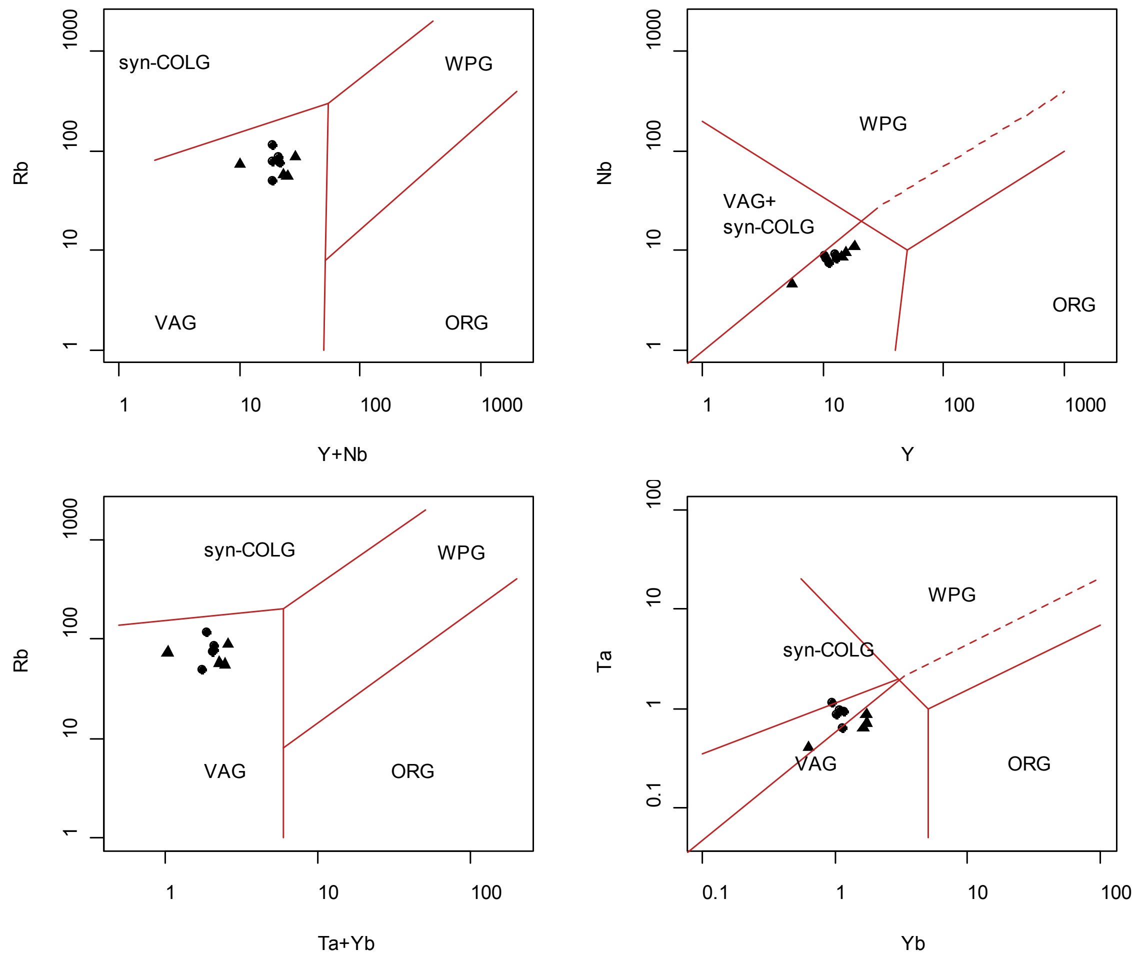

Figure 2. Petrogenetic classification of the granitoids of Kedonojankulma (dot), Koijärvi, Arolanmäki and Passi (triangle) from the diagrams of Pearce et al. (1984). ORG = orogenic granitoid, syn-COLG = syn-collisional granitoid VAG = volcanic arc granitoid, WPG = within plate granitoid. Element units in ppb.

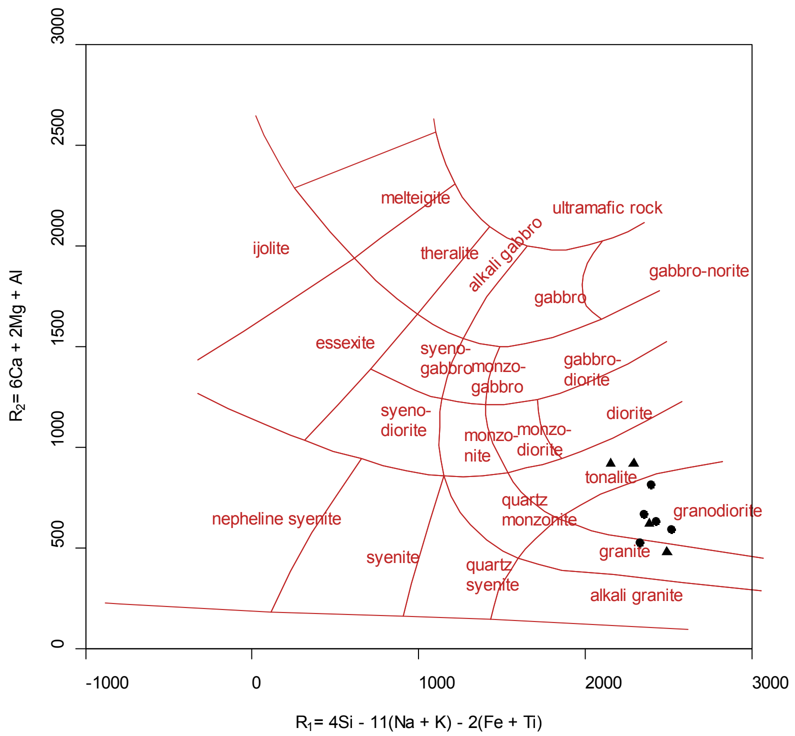

Figure 3. Classification of Kedonojankulma (dot), Arolanmäki, Koijärvi and Passi (triangle) tonalites in the R1-R2 diagram of De La Roche et al. (1980).

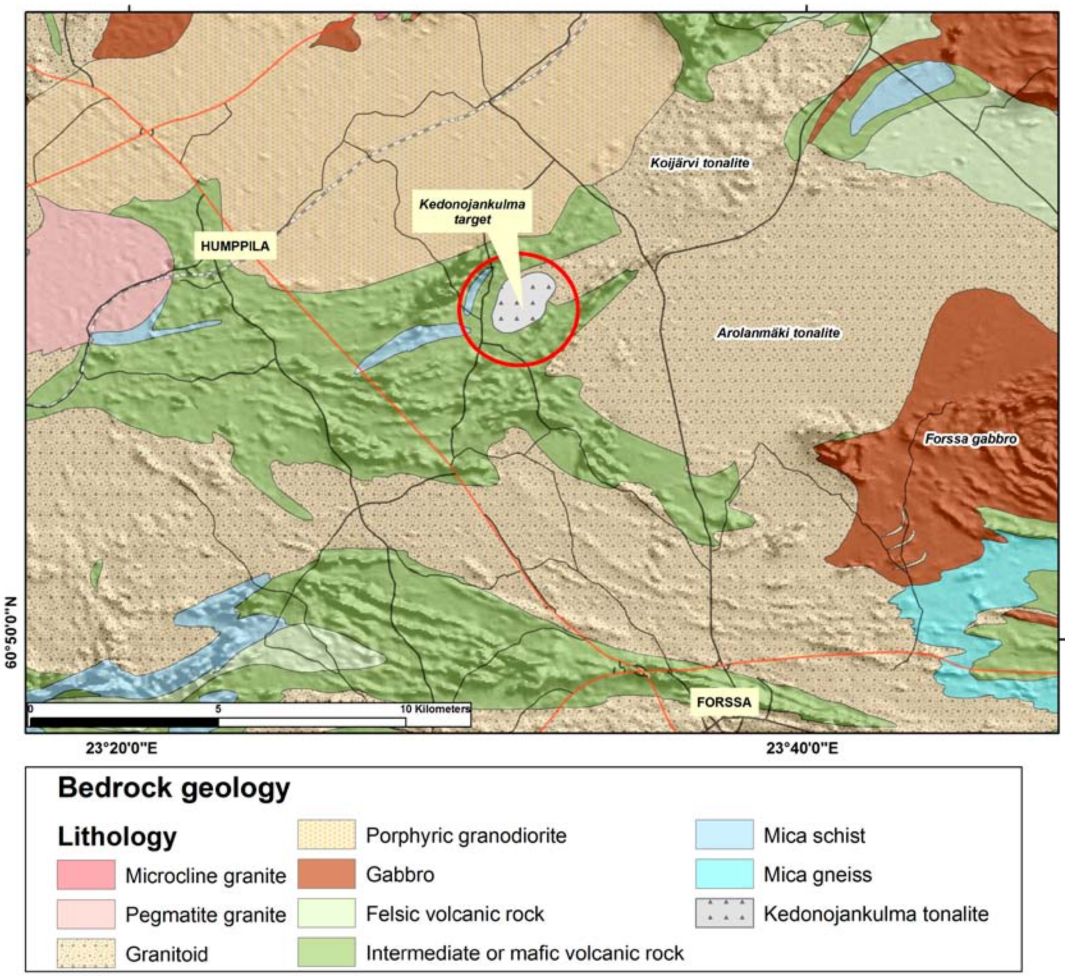

Figure 4. Lithological map of the Forssa region, modified from GTK (Bedrock of Finland–DigiKP). Airborne magnetic map in the background, positive anomalies as highs. Basemap © National Land Survey of Finland, licence no 13/MML/12.

tion of the granitoids in Kedonojankulma, Passi, Arolanmäki and Koijärvi varies from granite to tonalite (Figs. 3 and 4). According to the preliminary petrographic studies, the aforementioned granitoids are tonalites by modal composition.

The Kedonojankulma tonalitic intrusion, hosting the Kedonojankulma Cu-Au occurrence, is a roughly 1.5 x 0.5 km wide, high-level stock within the intermediate and mafic schists of the Häme volcanic suite (Fig. 4). The Kedonojankulma intrusion is composed of porphyritic tonalite, medium-grained phaneritic tonalite and medium-grained quartz-plagioclase porphyrite. Porphyritic phases mainly occur in the northern part of the intrusion and the phaneritic phase in the central and southern parts of the intrusion. In addition, the intrusion includes sub-volcanic porpyritic and aplitic phases. The Cu-Au occurrence is hosted by the strongly altered quartz-plagioclase porphyritic phase of the intrusion.

Quaternary geology

The Quaternary geology of the Forssa region is characterized by large regional clay deposits overlaying the till deposits on the bedrock (Fig. 5; Punakivi 1976, Haavisto-Hyvärinen 1996). The thickness of the clay deposits in the Kedonojankulma area ranges from 5 to 20 m. The narrow and long Kuuma esker cutting Kuuma village in a NW–SE direction is an exception to the flat clay deposit dominating the landscape. The local direction of the ice flow, based on the mapping observations, is roughly 300º, which is more westerly than usual for Southern Finland (Haavisto-Hyvärinen 1996).

Regional till geochemistry

Regional till geochemistry data (ALMR) form the basis for geochemical mineral exploration in Finland. The data represent the aqua regia leached part of the fine fraction (<0.06 mm) of till that has been sampled from below the groundwater surface at a sampling density of one sample

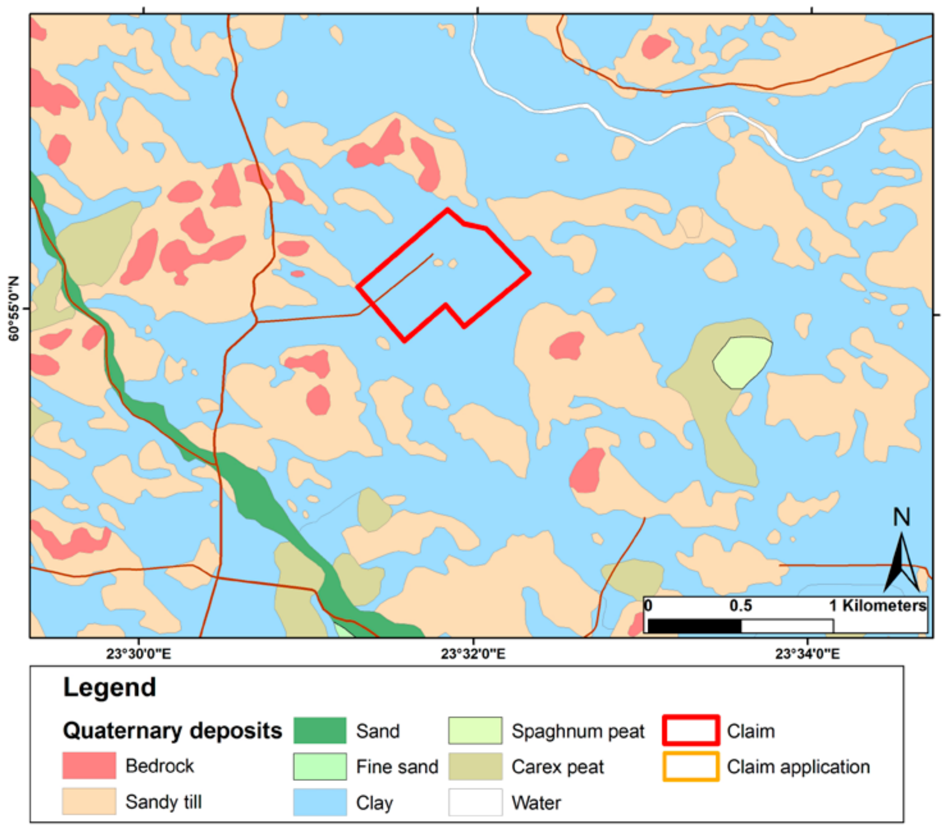

Figure 5. Quaternary geological map of the Kuuma area (Haavisto-Hyvärinen 1996). Basemap © National Land Survey of Finland, licence no 13/MML/12.

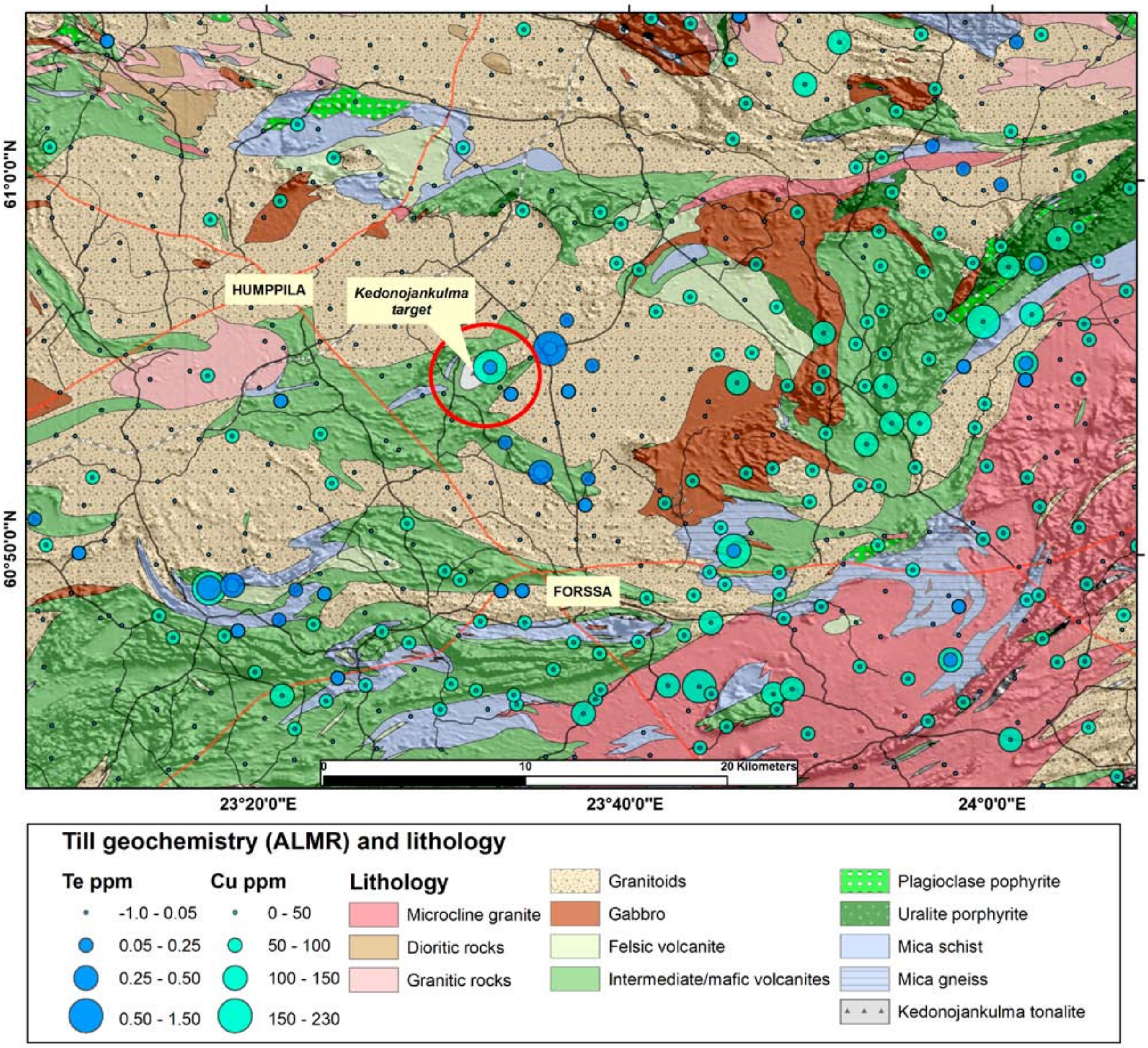

Figure 6. Regional till geochemistry (ALMR), Cu and Te anomalies on a combined geological (Bedrock of Finland–DigiKP) and airborne magnetic map (positive anomalies as highs). Basemap © National Land Survey of Finland, licence no 13/MML/12.

per 4 km^2 (Salminen 1995, Salminen & Tarvainen 1995). Element abundances were determined by inductively coupled argon plasma emission spectrometry (ICP-AES) and AAS. ALMR data are well suited to regional-scale mineral potential evaluation and the identification of possible ore provinces.

In the Häme area, ALMR data reveal a wide regional copper (Cu) anomaly (Fig. 6) that extends from Hämeenlinna in the east to Jokioinen in the west. In addition, several small-sized Cu and Te anomalies are shown in the data. One interesting till geochemical anomaly, selected as a target for more detailed till geochemistry, was the Te-Cu anomaly of Kuuma, situated in the intermediate-felsic volcanic-granitoid environment.

EXPLORATION AT KEDONOJANKULMA

Traditional exploration methods usually applied in exploration for sulphide deposits were also applied at Kedonojankulma. The possibilities of geological mapping were limited because of the sparse outcrops. The tracing of mineralized boulders gave useful information on the existing ore types. Geochemical mapping of till sampled from the base of the till deposit was systematically carried out in the claim area, and with the permission of landowners outside of the claim area. The results of the detailed till geochemical exploration were distinct and could be successfully used to guide the drilling phase. The use of ground geophysics was hindered by the thick clay overburden and locally by an electricity network below the ground surface. Aeromagnetic geophysical surveys were used to delineate lithological units and ground induced polarization measurements (IP) to detect the sulphide mineralizations.

Till geochemistry

Methodology

Till geochemistry was successfully applied in both target selection and target exploration phases. Sampling was conducted by percussion drilling from the base of the till deposit. In the target selection phase the sampling density was approximately 4 samples per km^2. The most interesting anomalies were explored using more dense sampling of about 16 samples per km^2, along roads, paths and dikes in forests and cultivated areas (Kärkkäinen et al. 2008, 2012). In the target exploration phase, sampling was carried out in the first-stage area (claim 8304/1) in a 50-m grid to gain an idea of the spatial extensity of the anomaly. In the later stage, till geochemistry was performed on profiles to map the continuation of the anomaly and the drilled Cu-Au mineralization (Tiainen et al. 2008, Tiainen & Kärkkäinen 2011). The basic sample in till geochemical exploration was the fine fraction (<0.06 mm) of the till. In the target exploration phase the till fraction below <2 mm was also applied. The reason for using the coarser fraction was to find possible gold nuggets. The method had earlier been successfully applied in till geochemical mapping of the Humppila area (Kärkkäinen et al. 2008). The base metals were analysed by multielement ICP-AES and gold by GFAAS.

Results of till geochemical exploration

As a result of the regional till geochemical exploration phase, several interesting Au, Cu, As, Mo, Te and Sb anomalies were detected. One of the most interesting anomalies in target selection phase was a Cu-Au-Te anomaly at Kedonojankulma, including a maximum of 826 ppm Cu (Fig. 7). A till geochemical Cu anomaly at Kedonojankulma was confirmed by 42 follow-up samples (Fig. 8). Almost all the samples were anomalous for Cu, including a maximum of 4.3% Cu, 566 ppb Au and 1740 ppb Te in the fine fraction of till. The samples with the highest copper contents are probably very close to or from the mineralized outcrop.

The confirmed Cu-Au anomaly was mapped forward in the claim area by till geochemistry, analysing the fraction <2 mm and sampling in a 50-m grid. As a result, a rather wide but distinct Cu anomaly was delineated, probably continuing to the southwest (Fig. 9). The highest Cu and Au contents were found in the northern part of the anomaly area, known as Rusakkokallio. The Au anomaly was spatially restricted to the area with the highest Cu contents, while the anomalous Cu and Mo anomalies seemed to extend further outside.

In the final till geochemistry exploration phase, to map the extent of the known Cu anomaly, the mapping was carried out by till geochemistry, based on profile sampling and the fine fraction of till (Fig. 10). Another Cu-Au-Mo anomaly, similar to the Rusakkokallio anomaly, was found 1–1.5 km to the southwest in the Korpi area. The Cu-Au anomalies of Rusakkokallio and Korpi possibly represent the same anomaly, but because of the gap in sampling this remains open.

As a summary of the local till geochemistry, the Cu-anomalous areas were delineated to the Rusakkokallio, Korpi and Passi areas. If the anomalies of Rusakkokallio and Korpi are demonstrated to be connected, the length of the anomalous area will be 1.5 km. The metal contents in till geochemistry indicate polymetallic mineralization, which has metallic zoning with Cu-Au in the core, Cu and Mo outside the core (Figs. 9 and 10) and Zn in the distal part of the mineralization.

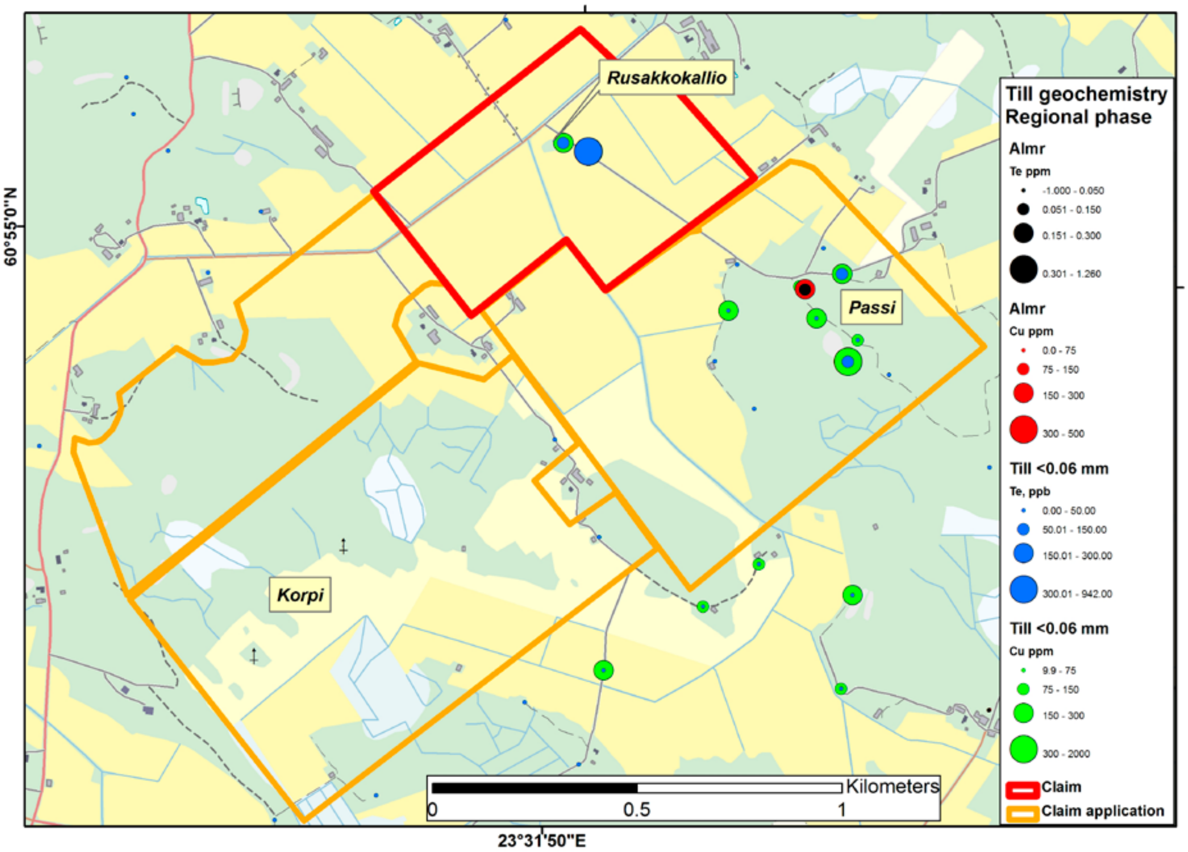

Figure 7. Till geochemistry of the regional exploration phase in the Kedonojankulma area. The red/black symbols indicate the samples of ALMR data. The blue/green symbols indicate the samples of the regional mapping data of the Forssa area. Basemap © National Land Survey of Finland, licence no 13/MML/12.

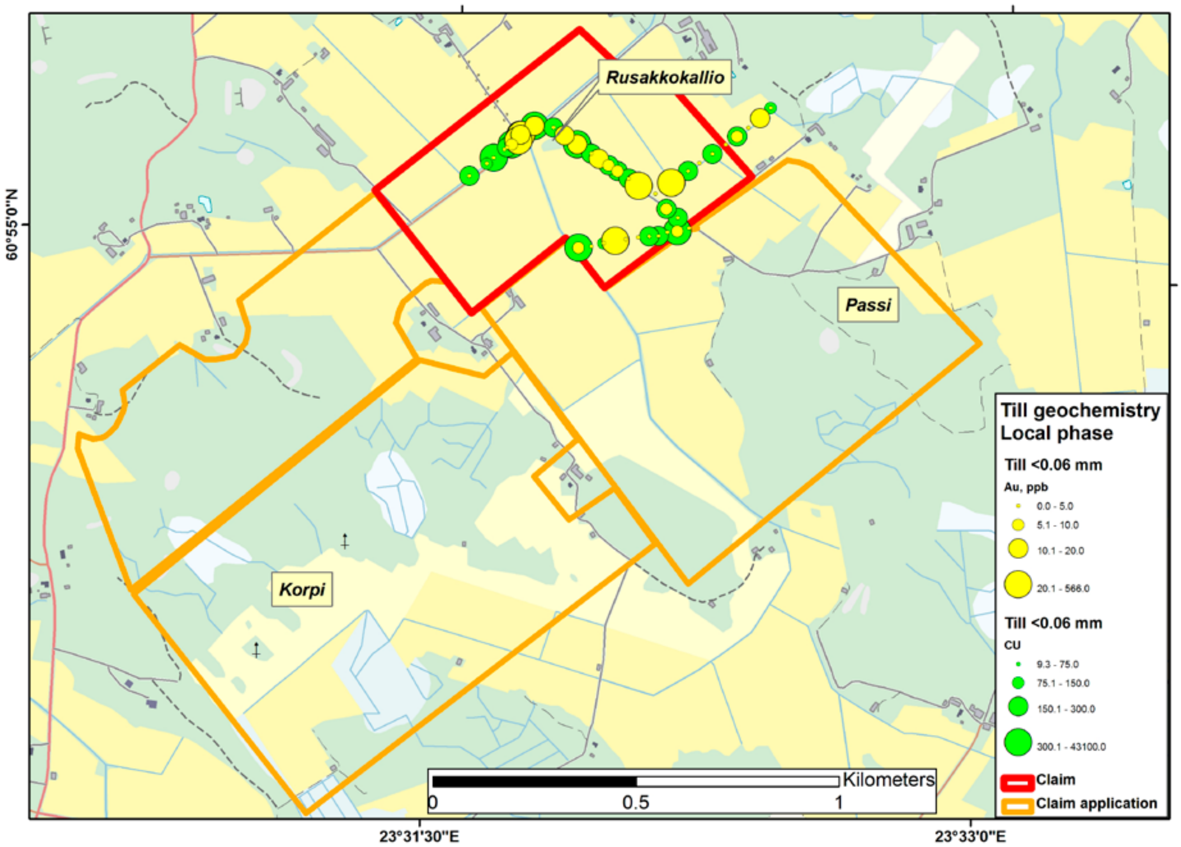

Figure 8. Till geochemistry of the target scale exploration in Kedonojankulma target. Follow-up samples of the regional phase Cu anomaly in the vicinity of Rusakkokallio. Basemap © National Land Survey of Finland, licence no 13/MML/12.

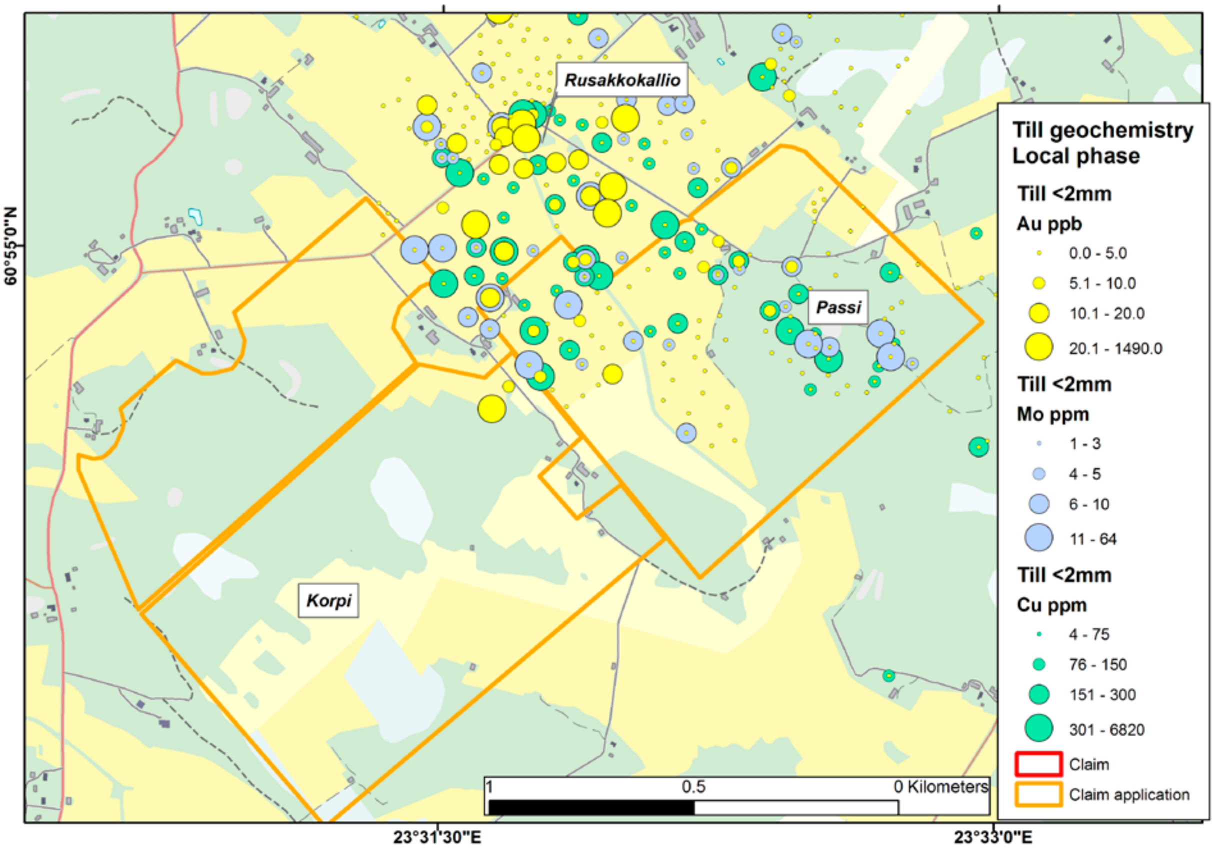

Figure 9. Till geochemistry at Kedonojankulma. Target-scale exploration on a 50-m grid applying the till fraction <2 mm. Basemap © National Land Survey of Finland, licence no 13/MML/12.

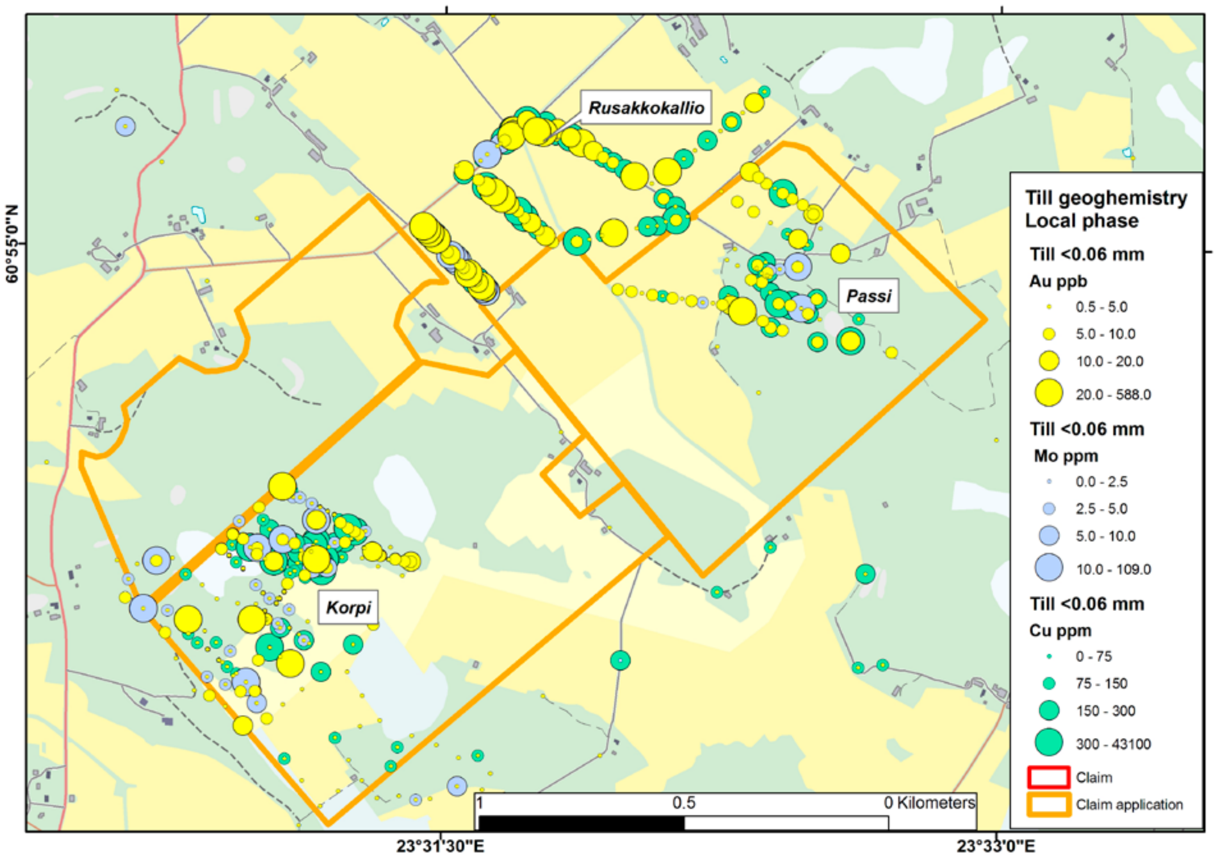

Figure 10. Till geochemistry of Kedonojankulma, Cu and Au contents in fine fraction of till (<0.06 mm). Basemap © National Land Survey of Finland, licence no 13/MML/12.

Geological mapping and ore indications

The bedrock map of the Kedonojankulma area is based on drill core loggings, aeromagnetic anomaly maps and a few outcrops. The outcrops of Rusakkokallio and Korpi, in the northern and western parts of the intrusion, represent mineralized and altered quartz-plagioclase porphyrite. Fig. 11). The third area includes a few outcrops in the Passi hill area, where the rock is slightly altered, equigranular tonalite, and in one outcrop quartz-plagioclase porphyry is found in contact with the tonalite (Fig. 12).

Concurrently with the till geochemical explora-

Figure 11. Altered quartz-plagioclase porphyrite, Rusakkokallio outcrop (x=6761610, y=3311780).

Figure 12. The contact between quartz-feldpar feldspar porphyry (right) and tonalite (left), Passi outcrop (x=6761075, y=3312260).

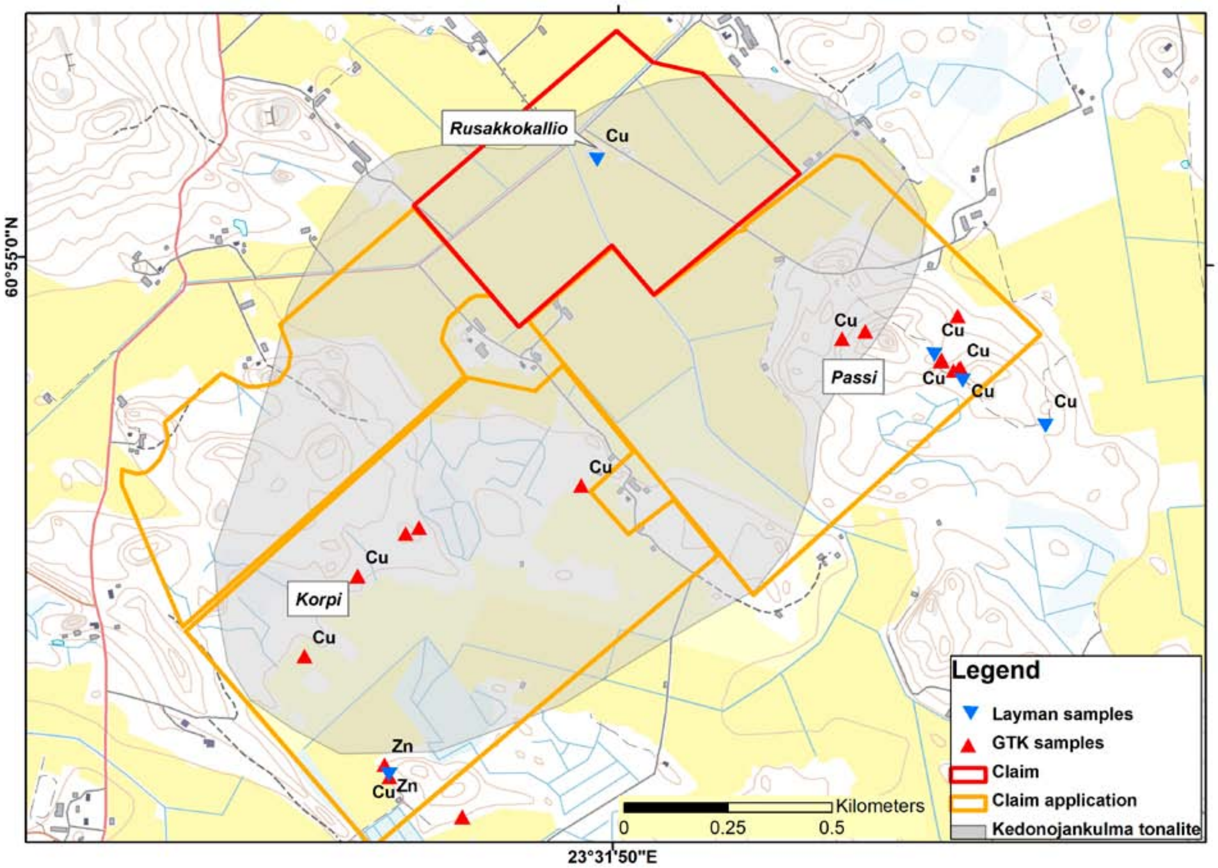

Figure 13. Ore indications of Kedonojankulma area, including mineralized erratic boulders and outcrops. Basemap © National Land Survey of Finland, licence no 13/MML/12.

tion, ore boulder tracing was carried out in the Kuuma area by both GTK personnel and local amateur prospectors. Several mineralized erratic boulders and outcrops were found, indicating the existence of unknown Cu-mineralization at Kedonojankulma (Fig. 13).

Geophysical studies

Geophysical surveys of the Kedonojankulma area comprised both airborne surveys and ground surface measurements. In addition to the standard low altitude airborne surveys, the Kedonojankulma target was partly covered by the detailed airborne survey of the Humppila area (Fig. 14; Lohva & Jokinen 2012). The ground survey methods were magnetic, Slingram and IP.

Airborne magnetic anomaly maps were applied to delineate the geological units. The granitoids with low susceptibility differed from the schist belts indicated by narrow and long positive anomalies. Ground geophysical measurements, particularly IP, were used to locate sulphide mineralization. Sulphide dissemination, mainly chalcopyrite, was revealed by the IP method in the outcrop area of Rusakkokallio, but tracing of the mineralization below the thick clay deposits was difficult (Fig. 15). The Slingram method was not practicable due to the thick clay deposits. Borehole loggings, including gamma-gamma, apparent resistivity and susceptibility, were carried out from most of the drill holes in the mineralized area. Apparent resistivity indicated sulphide dissemination, while gamma-gamma indicated the alteration zones related to the mineralization.

Diamond drilling

The Kedonojankulma Cu-Au occurrence was discovered by diamond drilling in January 2006. The mineralization was intersected by the first drill hole, R325, guided by the till geochemical Cu

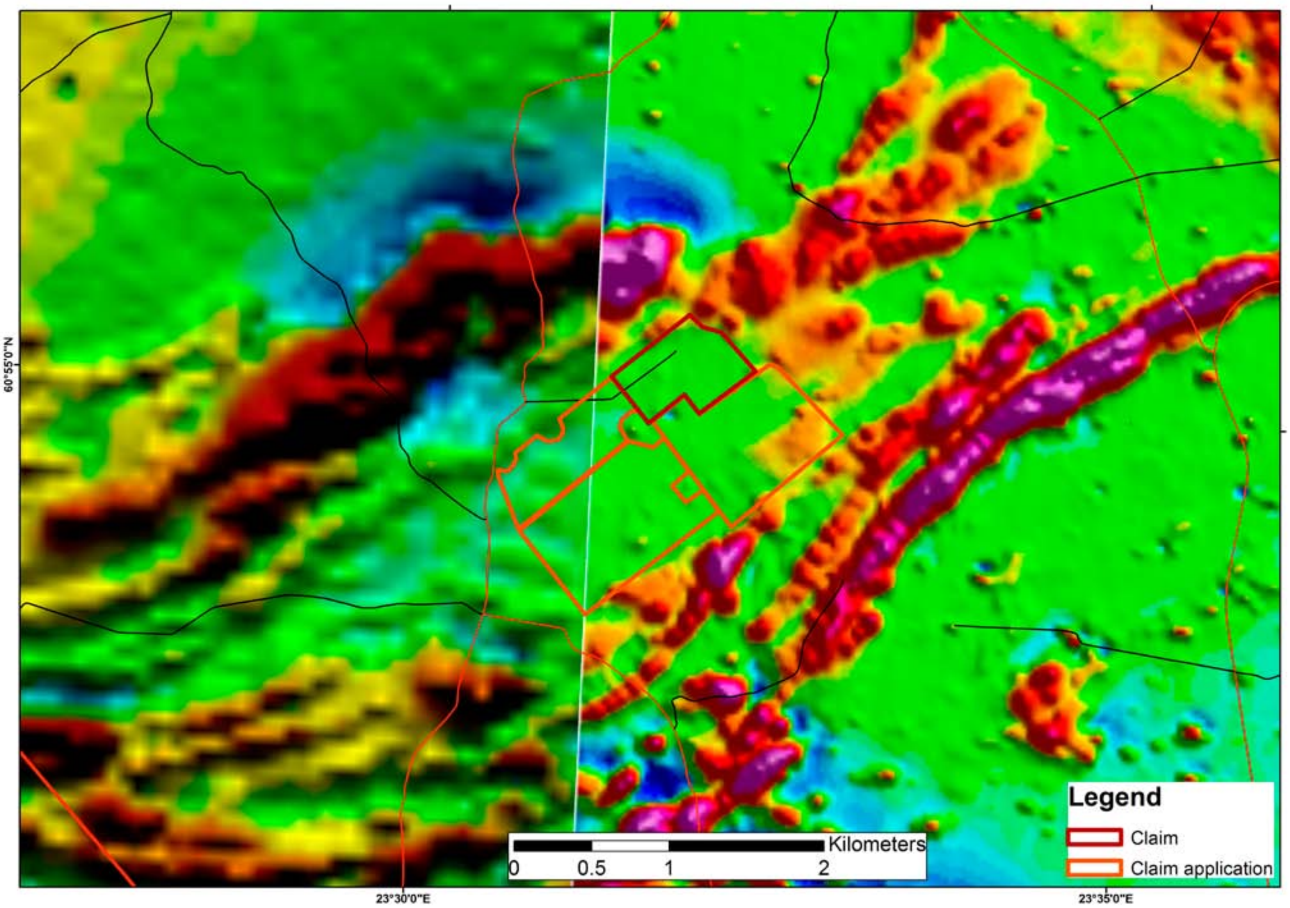

Figure 14. Magnetic anomaly map of the detailed (right section) airborne geophysical data. High total intensity by red and low intensity by green and blue.

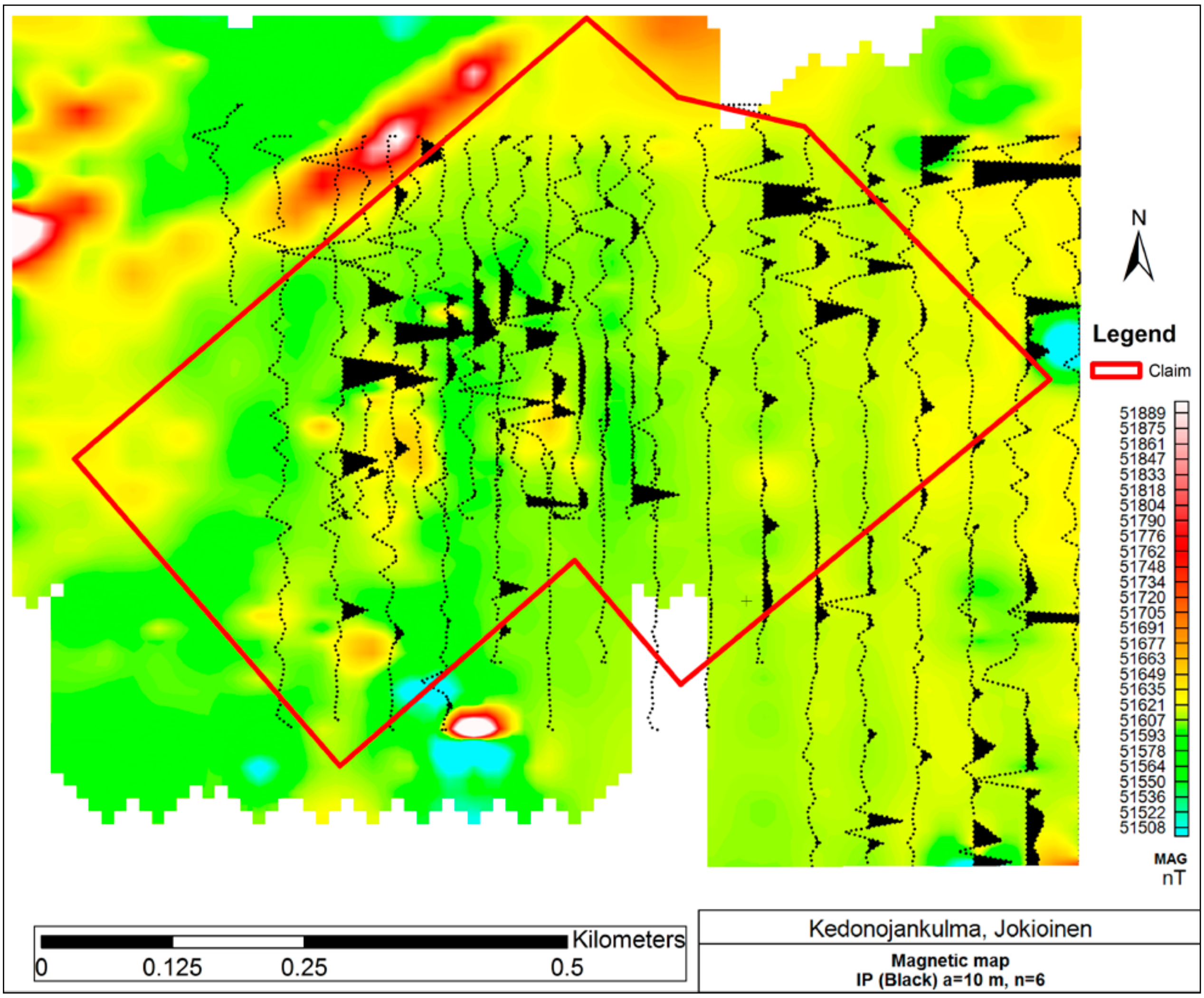

Figure 15. IP profiles (black) on ground magnetic map from the Kedonojankulma survey area. The claim area is marked as aniline red line. Basemap © National Land Survey of Finland, licence no 13/MML/12.

anomaly and the mineralized outcrop of Rusakkokallio (Fig. 16). The discovery hole R325 was already drilled after the first target selection phase of the till geochemical exploration.

After the discovery, drilling was conducted to profile the Rusakkokallio mineralization, to check both till geochemistry and IP anomalies, and to prepare longer profiles for mapping of the Kedonojankulma tonalite intrusion. According to an agreement with the landowners, drilling was mainly conducted during the winter season, because the target is located in a cultivated field area. In the first drilling phase only three drill holes totalling 111.0 m were drilled to check the till geochemical anomaly. Altogether, 58 drillholes, totalling 5198 m, were drilled during 2006–2010 in the Kedonojankulma porphyritic tonalite to evaluate the type and size of the Cu-Au mineralization.

The drill cores were analysed for base metals by ICP-AES/OES and for gold using the Pb fire assay. The best mineralized section in the Rusakkokallio mineralization was 68 m at 0.57% Cu in one drill hole. The highest metal contents in the mineralization, analysed as one-metre-long drillhole samples, were 2.4% Cu, 8.06 ppm Au, 120 ppm Ag, 0.13% Mo and 1.3% Zn. The highest Mo content was detected outside the Rusakkokallio Cu-Au mineralization and the highest Zn content in the south-western part of the Kedonojankulma intrusion. The horizontal extent of the drilled part of the Rusakkokallio mineralization is approximately 150 x 100 m (Fig. 17). The occurrence probably continues to the southwest.

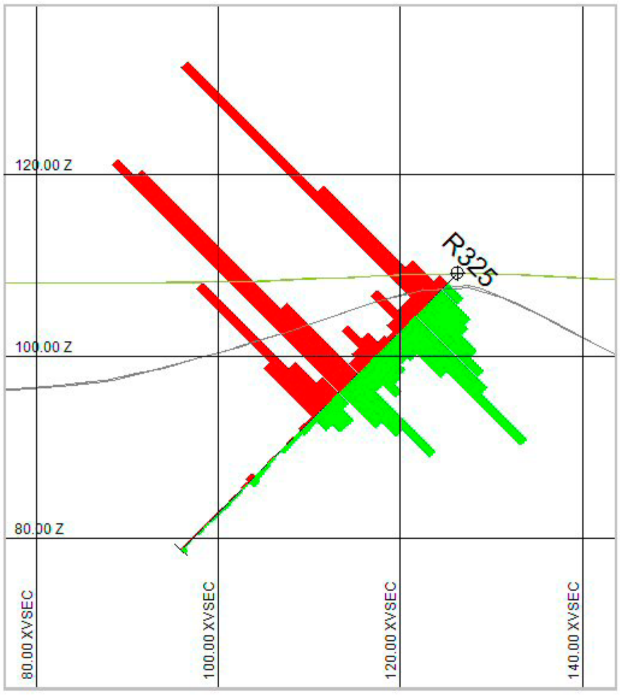

Figure 16. The first drill hole R325 to the Rusakkokallio Cu anomaly in Kedonojankulma. Highest metal contents: Cu 1.83 % (green) and Au 3.75 ppm (red). Ground surface by light green line and bedrock sueface by grey line.

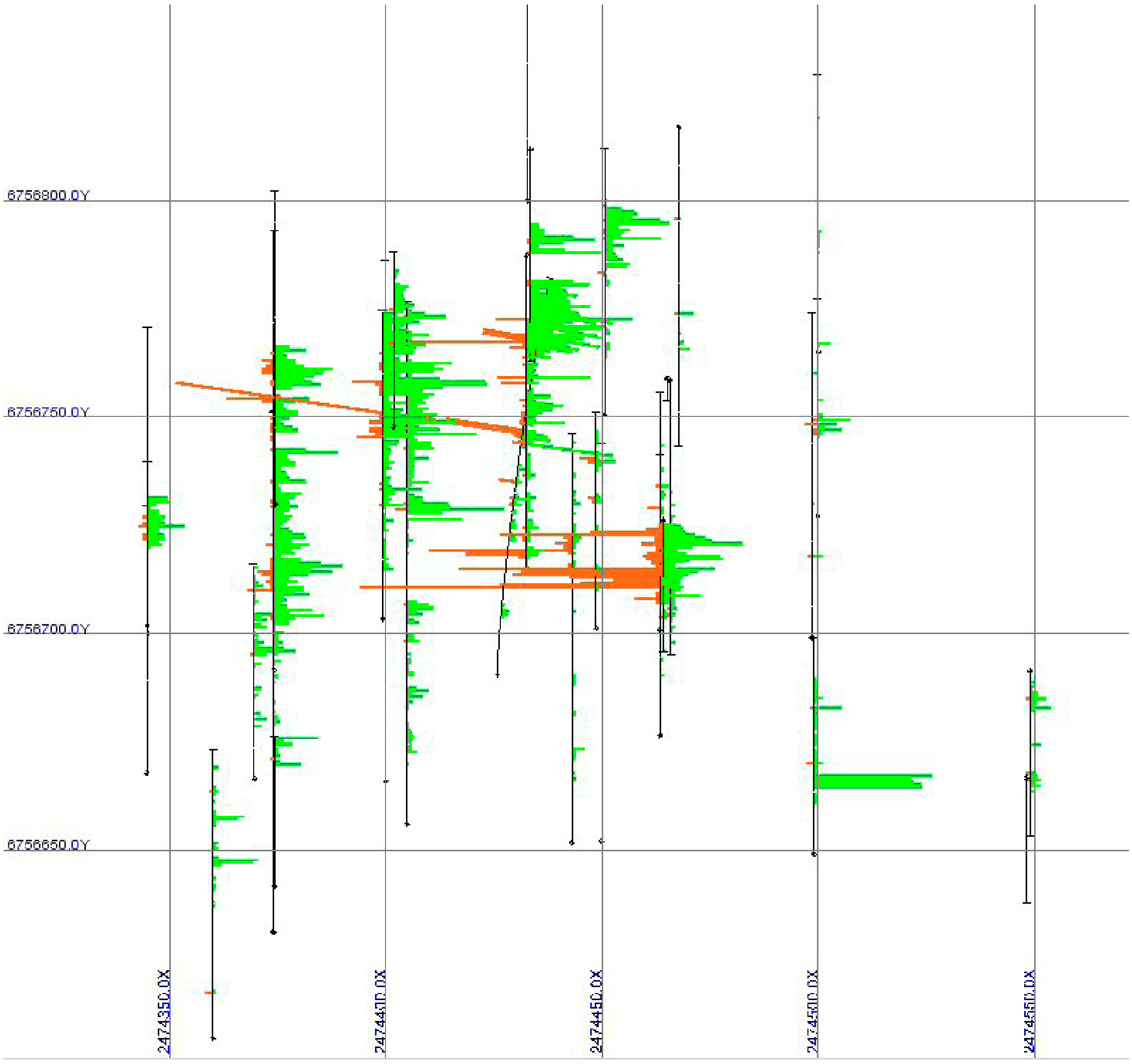

Figure 17. Surface plan view of the vertically projected drill hole intercepts of the Kedonojankulma Cu-Au occurrence. Highest metal contents Cu (green) 2.4 % and Au (red) 8.06 ppm.

KEDONOJANKULMA CU-AU OCCURRENCE

Kedonojankulma intrusion and related rocks

The high-level multiphase Kedonojankulma granitoid stock, hosting the Kedonojankulma Cu-Au occurrence, comprises 3–4 phases that can be distinguished by texture or composition (Fig. 18). The main phases are medium-grained porphyritic tonalite–quartz-plagioclase porphyrite, medium-grained equigranular tonalite, sub-volcanic quartz-feldspar porphyry, aplitic veins and sparse mafic veins. The following lithological description is based on the drill-core loggings, on a few outcrop observations, on a few thin sections and on chemical whole rock analyses. Drilling was focused on the northern, strongly altered and clearly mineralized part of the intrusion.

The chemical composition of the Kedonojankulma intrusion changes from granite to granodiorite (Fig. 3). The compositional variation is partly primary, but can also represent hydrothermal alteration. In texture and by modal composition, the intrusion gradually changes from equigranular–porphyritic rock in the southern and central parts of the intrusion to clearly porphyritic tonalite and quartz-plagioclase porphyrite (Figs. 19 and 20) phases in the northern part of the intrusion. Chemically, porphyritic tonalite and quartz-plagioclase porpyhyrite plot in the granite–granodiorite field. Quartz-plagioclase porphyrite is often hydrothermally altered, also causing variation in the chemical composition of the rock.

The sub-volcanic rock types occur as veins, cutting the porphyritic units near to the northern-northwestern and the even-grained tonalite in the southern contacts of the Kedonojankulma

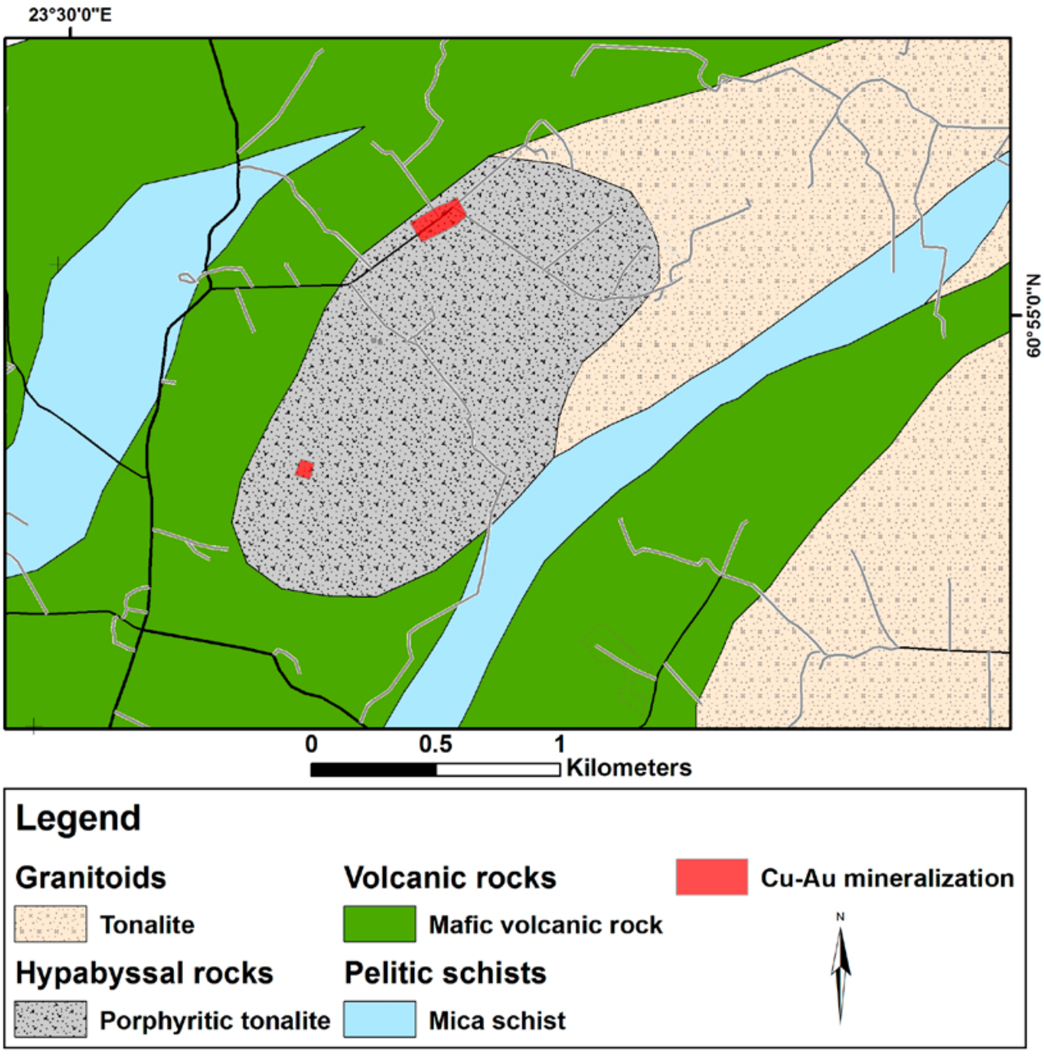

Figure 18. Lithological map of the Kedonojankulma area, modified from the geological map of GTK (Bedrock of Finland–DigiKP). Basemap © National Land Survey of Finland, licence no 13/MML/12.

Figure 19. Quartz-plagioclase porphyrite phase of the Kedonojankulma tonalite, Rusakkokallio outcrop (x=6761610, y=3311780).

Figure 20. Microphoto of quartz-plagioclase porphyrite at Kedonojankulma, crossed nicols.

intrusion. The subvolcanic phases in the ore zone also sometimes host fine-grained sulphide dissemination. The sub-volcanic quartz-feldspar porphyry is porphyritic-aphanitic in texture. Two macroscopically similar types of aplitic rock types were distinguished during the drill-core logging, one occurring as narrow fine-grained veins a few centimetres to a few metres wide having clear contacts with the country rock and the other as a fine-grained reddish rock altered from quartz-plagioclase porphyrite and gradually changing to completely altered rock. Subvolcanic mafic veins are sparse, typically occurring as breccias and veins a few metres in width.

Different types of narrow and thin quartz veins with crosscutting age relationships cut both the porphyritic and the even-grained tonalitic phases of the intrusion. The frequency of the quartz veins is highest in the ore zone. Specific quartz vein types include chalcopyrite stripes, and a certain type of molybdenite dissemination also occurs outside of the most strongly altered and mineralized zone.

Cu-Au mineralized zone

The bedrock hosting the Kedonojankulma Cu-Au occurrence is only visible in one outcrop in the middle of the field area, known as Rusakkokallio (Fig. 21). Sulphide mineralization is visible as a sheared rusty zone, including chalcopyrite and arsenopyrite dissemination.

The mineralized rock is usually sheared, fractured and strongly altered quartz-plagioclase porphyrite. Various alteration assemblages in the Cu-Au mineralized zone have been identified, with silicification, sericitization, chloritization, albitization and epidotization being the most common. Narrow quartz veins, sulphide-bearing veins and alteration connected to the veins are typical features in the mineralization. On a macroscopic scale the completely altered rock is fine grained and dark, dark reddish or dark greenish. Porphyritic tonalite, including narrow quartz veins and/or silicific alteration, is another mineralized rock type, typically hosting Mo mineralization.

In addition to the aforementioned alteration, a wider alteration zone has been mapped. Within this the grey tonalite or quartz-plagioclase porphyrite has been altered to reddish in colour. On a microscopic scale the alteration is visible as the serisitization of plagioclase. The reddish colour is probably caused by hematite pigment. Reddish alteration is often connected to chalcosite, indicating later oxidizing alteration that has caused secondary enrichment of the Cu mineralization.

Ore mineralogy

The Kedonojankulma Cu-Au occurrence has rather diverse ore mineralogy (Tiainen et al. 2008). The main ore minerals are chalcopyrite, arsenopyrite, pyrite, pyrrhotite and in places chalcosite.

Figure 21. The mineralized outcrop at Rusakkokallio (x=6761610, y=3311780). Quartz-plagioclase porphyrite and cutting gray to bluish narrow quartz vein. Drill hole diameter 4 cm.

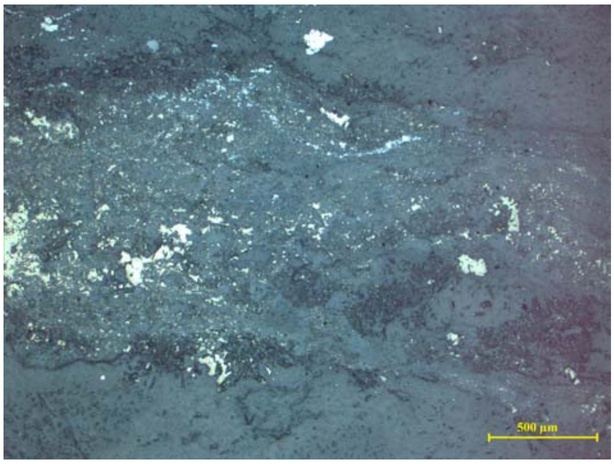

Figure 22. Microphoto of fine grained chalcopyrite-arsenopyrite-chalcosite dissemination in a sheared quartz-plagioclase porphyrite, parallel nicols.

Minor ore minerals are sphalerite, mackinawite, marcasite, scheelite, ilmenite, rutil, bismuth, gold, silver sulphides and tellurides. The sulphide minerals typically occur as fine-grained dissemination in altered, slightly sheared or fractured aphanitic porphyrite (Fig. 22). Medium- and coarse-grained chalcopyrite and arsenopyrite segregations also exist. The highest sphalerite contents have been observed outside of the core mineralization, in the southern part of the Kedonojankulma granitoid.

SUMMARY AND CONCLUSIONS

The Kedonojankulma Cu-Au occurrence was found by drilling after systematic till geochemical exploration. The occurrence is hosted by a strongly altered, sheared and brecciated zone of a multiphase porphyritic tonalite intrusion. The intrusion is composed of porphyritic and equigranular intrusive phases and of sub-volcanic quartz-feldspar porphyry and aplitic phases. The composition of the Kedonojankulma intrusion ranges from tonalite to granite. The Cu-Au(-Ag-Mo) mineralization is a very fine grained sulphide dissemination, controlled by fracturing, shearing and quartz veins. The highest metal contents in one-metre-long drill hole samples are Cu 2.4%, Au 8.06 ppm, Ag 120 ppm and Mo 0.13%. The metal contents of the mineralized intrusion have a zonal distribution, including Cu-Au(-Ag-Mo-Bi-Sb-Zn) mineralization in the core, Mo and Cu alone in quartz veins outside of the main Cu mineralization and Zn in the outer zone of the intrusion. The Cu-Mo-Au anomaly in till geochemistry and the ore indications of erratic boulders and outcrop observations indicate exploration potential for a low grade but relatively large Cu-Au(-Ag-Mo) deposit.

The Kedonojankulma Cu-Au occurrence resembles porphyry-style Cu deposits. The occurrence is hosted by a porphyritic granitoid and has several other features that are typical of porphyry-Cu deposits, including alteration types, zonality in metal contents and metal values typical for porphyry-style Cu-Au deposits (Tiainen et al. 2011). Similar porphyry-style occurrences have been described in the Fennoscandian Shield in the Skellefteo region, such as Tallberg and Älgträsk (Weihed 1992, Bejgarn et al. 2011), and the Au rich deposit of Kopsa in Central Finland (Gaál & Isohanni 1979, Nurmi 1985). The potential to find new porphyry-style Cu deposits is clear in the syn-orogenic granitoids of many subduction-related volcanic-intrusive belts of the Fennoscandian Shield.

ACKNOWLEDGEMENTS

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THE PALOKALLIO GOLD OCCURRENCE AT HUITTINEN, SOUTHERN FINLAND

by
Sari Grönholm and Teemu Voipio*

Grönholm, S & Voipio, T. 2012. The Palokallio gold occurrence at Huittinen, southern Finland. *Geological Survey of Finland, Special Paper 52*, 91–100, 7 figures.

The Geological Survey of Finland investigated the Palokallio gold occurrence at Huittinen during 2006–2009. The occurrence is situated in a gabbro within the Pirkanmaa belt, near the border zone of the Häme belt and the Pirkanmaa belt. The gabbro is penetrated by mafic and pegmatite dykes and quartz veins and is surrounded by mica gneisses and graphite-bearing sulphide schists. Gold mineralisation is hosted by shear zones some centimetres wide in a dioritic gabbro. The strike of these shear zones is variable at Palokallio, but most commonly it is NE–SW. Arsenopyrite, löllingite, pyrrhotite and scheelite are the most abundant ore minerals. The best gold grade detected by drilling has been 41.8 g/t /0.9 m Au. Gold grades in drill core samples are usually under 1 ppm/1 m and the gold occurrence as known so far is not economic. The Palokallio gold prospect is situated near the Jokisivu gold mine and the Ritakallio gold occurrence. Several structural and lithological settings show analogies between the Palokallio and Ritakallio Au occurrences and the Jokisivu Au deposit. These three gold deposits attest that the mafic intrusions with low magnetic anomaly caused by monoclinic pyrrhotite and with sulphide- and scheelite-bearing shear zones are of high gold potential in the Huittinen area.

Keywords (GeoRef Thesaurus, AGI): gold ores, gabbros, shear zones, quartz veins, ore minerals, arsenopyrite, Paleoproterozoic, Palokallio, Huittinen, Finland

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INTRODUCTION

The Palokallio gold occurrence is located in southwestern Finland, about 160 km NW of Helsinki at Huittinen, 13 km SE of the town of Huittinen, and 15 km east of the Jokisivu gold mine. Palokallio lies in the border zone of the southwestern Pirkanmaa belt and the Häme belt (Fig. 1), which marks the supposed suture zone between the Central Svecofennian and Southern Svecofennian Arc complexes. The boundary between these units is not well defined and the Jokisivu prospect is usually regarded as being part of the Pirkanmaa belt (Eilu 2007, Saltikoff et al. 2006). Recent studies (Saalmann et al. 2010, Sipilä et al. 2011) have suggested that the Jokisivu area is part of the Häme belt rather than the Pirkanmaa belt. Palokallio and Ritakallio gold mineralisations are situated in the Pirkanmaa belt (Sipilä 2011). However, several structural and lithological settings indicate that the Palokallio gold occurrence is analogical with the Ritakallio gold occurrence and the Jokisivu Au deposit.

The Jokisivu prospect was investigated by Outokumpu Oy in the 1980s, and since 2009 it has been mined by Dragon Mining. The total ore has been estimated as 338 500 ounces at 5.8 g/t gold (Dragon Mining 2011). The prospect comprises two ore zones, Kujankallio and Arpola. The Kujankallio deposit extends to at least 525 m depth and the Arpola deposit has been drilled down to 200 m. Both deposits remain open at depth (Dragon Mining 2011). The host rock is syntectonic quartz diorite and gabbro with auriferous quartz veins. Mineralisation occurs in approximately WNW–ESE-trending shear zones, which probably branch from regional-scale NW–SE-trending shears. Mineralisation formed during the late stages of the Palaeoproterozoic Svecofennian orogen (Saalmann et al. 2010).

The Ritakallio gold occurrence was found by the Geological Survey of Finland after heavy mineral, geochemical and geophysical studies in 2002 (Vuori et al. 2005). Field mapping and petrographic studies at Ritakallio formed part of a Master's thesis by Lahtinen (2006). Ritakallio is located about 5 km E of the Jokisivu deposit. A quartz dioritic to gabbroic body similar to the Jokisivu host rock hosts moderately NE- to NNE-dipping gold-rich quartz veins in shear zones. 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 investigation in the Palokallio area started in 2006 with a search for gold-critical arsenopyrite-bearing boulders and outcrops east of the Ritakallio area. Gold-enriched shear zones and quartz veins were found in the bedrock at Palokallio. Field mapping and petrographic, ore mineralogical and geochemical studies were carried out as a part of a Master's thesis (Voipio 2008). The Palokallio research area was drilled during 2006–2008. This paper describes lithology and gold mineralisation in the Palokallio area.

GENERAL GEOLOGY

The bedrock of the Pirkanmaa belt mostly consists of turbiditic and partly migmatized mica gneisses. The mica gneisses are intercalated with black schists and graphite-bearing mica schists.

The sedimentation of this supracrustal sequence took place before arc volcanism at 1.9 Ga, and was followed by migmatization during the Svecofennian orogeny at ca. 1880 Ma ago. Complex folding patterns and shear zones developed in different, partly overlapping events during the Svecofennian orogeny. The supracrustal units in the Pirkanmaa belt are intruded by gabbroic to quartz-dioritic rocks of 1.88 Ga (Kilpeläinen 1988).

The complex geometry resulting from polyphase deformation can also be seen on geophysical maps, especially on aeromagnetic maps. The Jokisivu prospect is located on the outer hinge of a NW-trending F_4 fold. F_4 fold axes drag along major NW–SE-trending shear zones (Saalmann et al. 2010).

The mafic gabbros and quartz diorites hosting gold mineralisations do not differ strongly from the surrounding lithology in their magnetic, electromagnetic or radiometric features. Thus, they cannot be localized or recognized from aerogeophysical maps. As the prominent magnetic mineral is monoclinic pyrrhotite, the susceptibilities of these rocks remain low (Huuskonen 2009). In the gravimetric data, NW–SE-trending long gold potential shear zones can be seen as a gravimetric minimum (Vuori et al. 2007). Gold-critical major shear zones are also recognizable in aeromagnetic maps as long 'lineaments'.

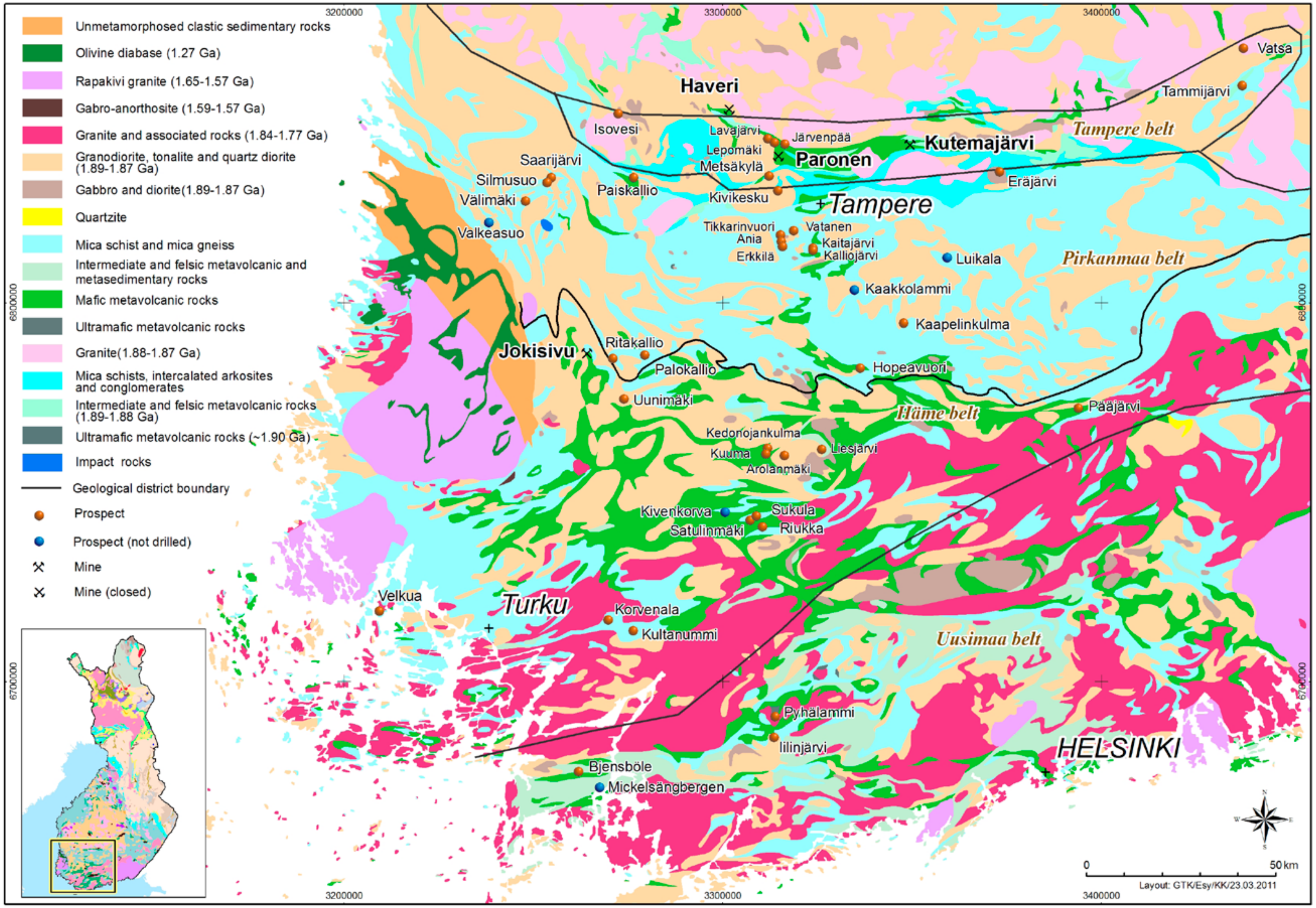

Figure 1. Location of the Palokallio gold prospect. The geology of southwestern Finland and gold deposits and occurrences detected in the Uusimaa, Häme and Pirkanmaa belts. Geology from Vaasjoki et al. (2005), gold occurrences after Eilu & Pankka (2009), and recent exploration by GTK (Kärkkäinen et al. 2003, Kärkkäinen 2007, Sipilä et al. 2011 and unpublished GTK data).

The entire Pirkanmaa belt is considered to have high Ni potential. The Pirkkala–Valkeakoski Au zone overlaps with the Ni zone and contains several minor gold mineralisations represented by gold-bearing quartz veins in synorogenic Svecofennian intermediate intrusives and in pelitic gneisses. The Jokisivu gold mine, the Palokallio occurrence and some other gold occurrences are located south of the Pirkkala–Valkeakoski Au zone. Their relationship with the main group is uncertain and they possibly constitute a separate province (Saltikoff et al. 2006). The gold deposits in the Pirkanmaa belt are classified as orogenic (Eilu 2012). At Jokisivu, ore zone fabrics postdate regional-scale folding, and the metamorphic peak and can be correlated with late Svecofennian regional shear tectonics (D6; 1.83–1.78 Ga). This indicates that mineralisation formed during the late stages of orogenic evolution (Saalmann et al. 2010).

PALOKALLIO PROSPECT

Bedrock and geophysics

The bedrock of the Palokallio area is mainly composed of banded and folded mica gneisses, mafic intrusive rocks and mafic and pegmatite dikes (Figs. 2 and 3). Mica gneisses are usually fine grained and light grey in colour. Bedding structures are sometimes well preserved. Elongated and grey green concretions are sporadically found. Mica gneisses are mainly composed of quartz, biotite and plagioclase. Garnet porfyroblasts are common. Usual accessories are zircon, monazite and sometimes fibrous sillimanite. Numerous pegmatite dikes and mafic dikes truncate

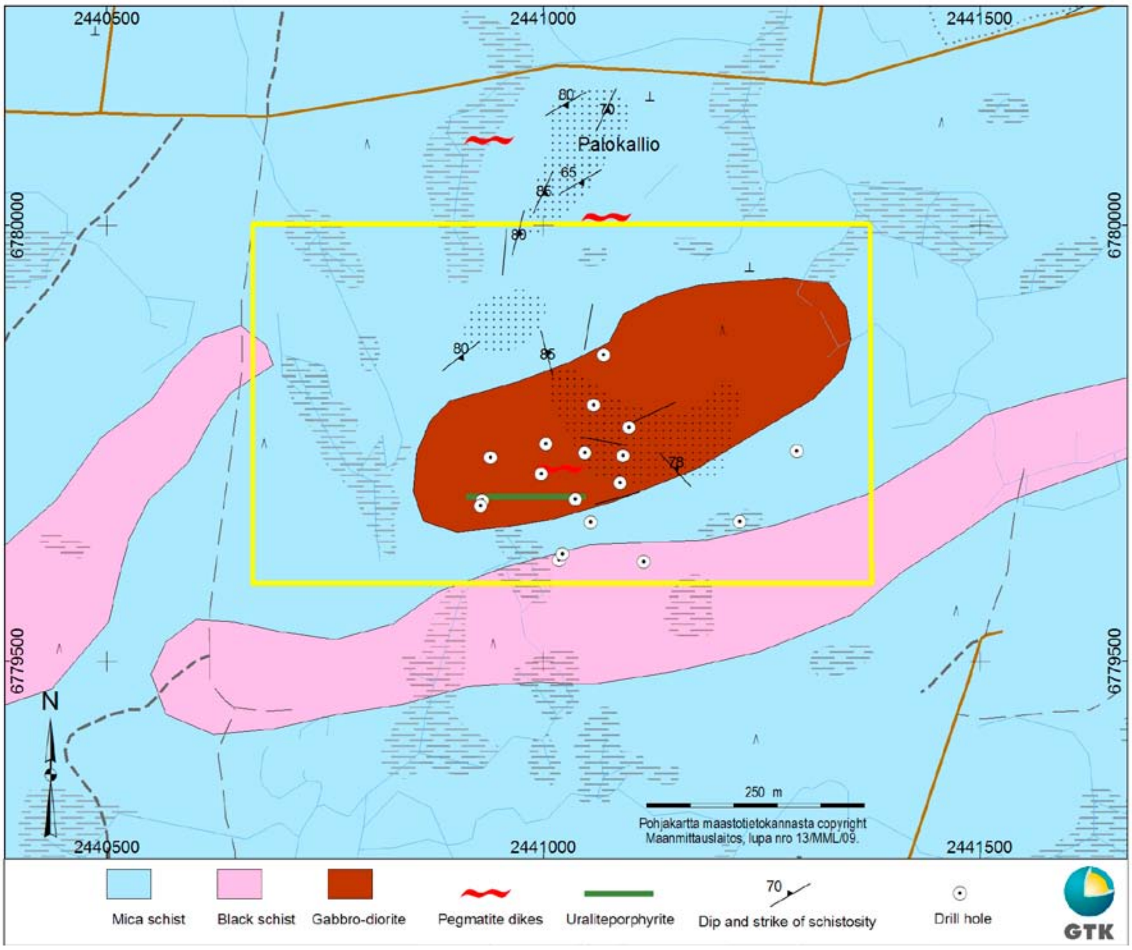

Figure 2. Detailed bedrock map of the Palokallio prospect, showing drill-hole locations and dip and strike of schistosity. After Voipio (2008). The claim area is outlined (yellow line). Basemap © National Land Survey of Finland, licence no 13/MML/12.

Figure 3. The Palokallio gabbro with a mafic dyke.

all rocks in the area. They are typically < 1 m wide, although locally they can reach a thickness of 5 m. Thin carbonate veins also intersect mica gneisses and gabbros. Mica gneisses are rarely intercalated with biotite-ampfibole gneiss.

The Palokallio gabbro is dark green in colour and medium grained, and large parts of the rock are rather homogeneous (Fig. 3). The main minerals in the gabbro are hornblende, plagioclase, biotite and quartz. In the vicinity of pegmatite dykes and in the contact with mica gneiss the gabbro contains garnets and the amphibole has altered to biotite. The main accessories in the gabbro are apatite and zircon. Some chemical variation is possible in intrusions and igneous layering is sometimes present. In the vicinity of the country rock contacts, the gabbro contains large xenoliths of mica gneiss. The intensity of deformation changes from weak to moderate. Arsenopyrite-bearing shears, quartz veins and quartz-feldspar veins and pods are present. Schistosity in the area is mainly E–W, dipping about 70–90° to the north. Some shear zones are NE–SW trending. The geological setting of the Palokallio area is described in more detail by Voipio (2008) and Grönholm et al. (2011).

Strong magnetic anomalies to the west and south side of the gabbro are caused by graphite- and sulphide-bearing schists. These rocks have only been seen in drill cores and they are drawn in the detailed geological map mainly on the basis of geophysical surveys. The gabbro itself is not magnetic, but there is a strong z-shaped, positive IP anomaly within the area of gabbro (Valjus 2010).

Gold mineralisation

The two dominant rock types observed in the Palokallio diamond drill cores are gabbro and mica gneiss. Gold is present in arsenopyrite-bearing shear zones in the gabbro. Shear zones seen on outcrops and drill holes are usually some centimetres wide. Gold contents are sometimes also anomalous in the contact zone of mica gneiss and gabbro. Au grades as high as 1.6 ppm have been recorded by drilling in shears that are in mica gneiss. Mica gneisses that are not close to the gabbro contact do not contain elevated amounts of gold (Grönholm et al. 2011).

The most usual alteration phenomena in the Palokallio study area are serisitization, cloritization carbonatization, silicification, albitization and sulphidization in the gabbro. On gabbro outcrops, the alteration is seen as arsenopyrite-bearing quartz veins in shear zones (Fig. 4). In drill cores the altered rocks are silicified and sulphidized (Fig. 5). Carbonate-bearing veins and patches are typical. Plagioclase is typically serisitized and biotite and amphibole is altered to chlorite. Quartz is usually deformed and polycrystallized. In most altered patches the ilmenite has recrystallized to titanite. Scheelite is often present as disseminated and also as separate grains.

Figure 4. Quartz, sulphides and gold bearing shear zone in the gabbro. Photo: Saku Vuori, GTK.

Figure 5. An arsenopyrite-bearing drill-core sample. R329, Au 6.390 ppm at 0.90 m.

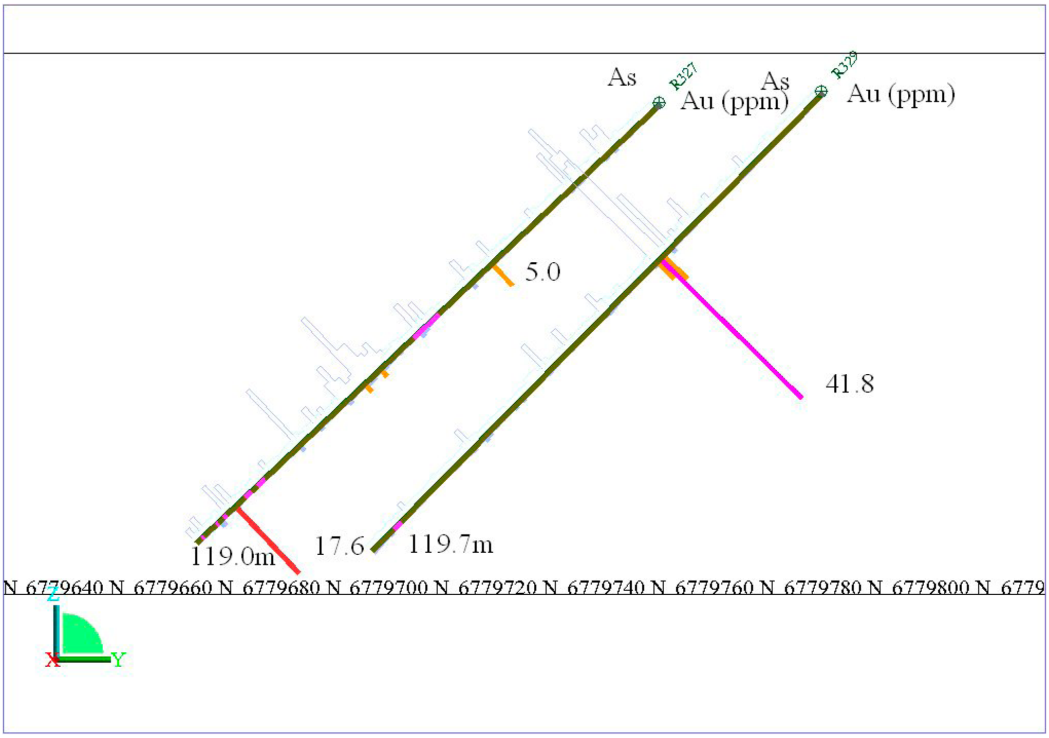

Figure 6. A drilling profile with Au and As contents (drill cores R327 and R329). Rock types: green = gabbro; magenta = granite pegmatite.

Ore minerals

In the mineralized rocks, arsenopyrite is the most common ore mineral. Other common ore minerals include pyrrhotite, löllingite and scheelite. Löllingite and silicate minerals are often present as inclusions in arsenopyrite. Typical silicate minerals are quartz, chlorite and carbonate. Microfractures filled by gold, bismuth, tellurides, chalcopyrite and pyrrhotite are common in arsenopyrite. Scheelite is often found in sulphide-bearing thin sections and in drill core samples. The most common telluride mineral is hedleyite. Pyrite is not very common and it usually occurs as small inclusions in chalcopyrite in the mineralized rocks. Chalcopyrite is the only important copper mineral. Ilmenite is the most common Fe-Ti oxide mineral and is usually met with biotite and amphibole. Au correlates fairly well with As and quite well with Te and Bi (Voipio 2008). Two Au-enriched drill cores (R327 and R329) are presented in Figure 6.

The grain size of gold at Palokallio is usually less than 100 µm (Fig. 7). Gold is present in cracks in arsenopyrite or as inclusions in the arsenopyrite. It sometimes occurs in the borders of the löllingite or arsenopyrite and more seldom with chalcopyrite or pyrrhotite. Bi and Te are always present with Au. The Ag content in the gold grains is 0–62%, and most commonly it is 10–20% Ag (Voipio 2008). Zonation of gold grains in the same way as in the Korvenala deposit (Grönholm et al. 2012) has not been detected.

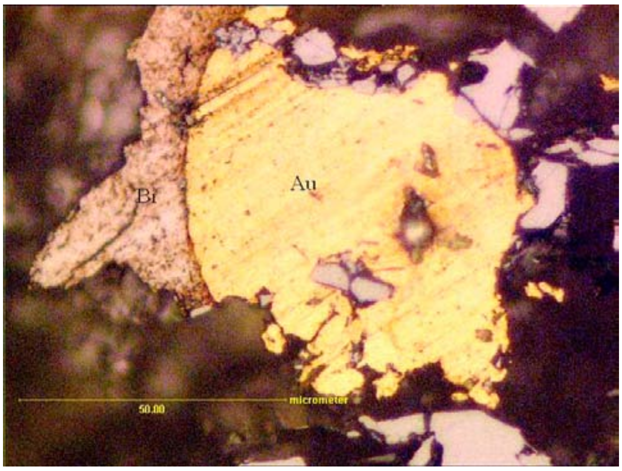

Figure 7. An intergrowth grain of gold and bismuth.

SUMMARY AND CONCLUCIONS

The Palokallio occurrence was discovered by the Geological Survey of Finland during exploration of Au-critical shear zones within a mafic intrusion in the vicinity of the Ritakallio occurrence discovered during 2004. The Palokallio prospect lies in the southwestern part of the Pirkanmaa belt near the border zone of the Häme belt. The sedimentation of this supracrustal sequence took place before arc volcanism at 1.9 Ga and was followed by migmatization during the Svecofennian orogeny at ca. 1880 Ma ago. Complex folding patterns and shear zones developed in different, partly overlapping events during the Svecofennian orogeny. The supracrustal units in the Pirkanmaa belt are intruded by gabbroic to quartz-dioritic rocks of 1.88 Ga.

The Palokallio prospect, Ritakallio prospect and Jokisivu goldmine are similar in that they are situated in mafic intrusions with gold-bearing shear zones. These shears are WNW–ESE trending at Jokisivu and NW–SE trending at Ritakallio. NW–SE-trending long gold potential shear zones at Ritakallio can be seen as a gravimetric minimum and as a lineament in aeromagnetic maps. The orientation of shear zones at Palokallio varies, but shears trending NE–SW appear to be the most common.

At Jokisivu, ore zone fabrics post-date regional-scale folding and the metamorphic peak and can be correlated with late Svecofennian regional shear tectonics (1.83–1.78 Ga). This indicates that mineralisation formed during the late stages of orogenic evolution. The geological similarity between these three deposits attests that Palokallio and Ritakallio deposits have possibly also formed in this way. These three Au deposits demonstrate that the mafic intrusions in the Huittinen area with the low magnetic anomaly are of high gold potential, and particularly the sulphide-, quartz- and scheelite-bearing shear zones in these intrusions.

ACKNOWLEDGEMENTS

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Gold in Southern Finland: Results of GTK studies 1998–2011
Edited by Sari Grönholm and Niilo Kärkkäinen
Geological Survey of Finland, Special Paper 52, 101–114, 2012

GOLD AT KORVENALA, PAIMIO AND KULTANUMMI, HALIKKO (SALO), IN THE HIGH-GRADE METAMORPHIC TERRAIN OF SW-FINLAND

by
Sari Grönholm, Niilo Kärkkäinen, Petri Rosenberg and Meri-Liisa Airo*

Grönholm, S., Kärkkäinen, N., Rosenberg, P. & Airo, M.-L. 2012. Gold at Korvenala, Paimio and Kultanummi, Halikko (Salo), in the high-grade metamorphic terrain of SW-Finland. *Geological Survey of Finland, Special Paper 52*, 101–114, 12 figures and 1 appendix.

The bedrock of the study area belongs to the 1.90–1.82-Ga-old accretionary arc complex of Southern Finland. On aeromagnetic maps the magnetic anomaly groups hosting Kultanummi and Korvenala occurrences form magnetic subprovinces that are outlined by fault and fracture zones. Both gold prospects are located along magnetic lineaments that are related to the main foliation. In the Korvenala prospect, Au mineralization occurs in shear zones a few centimetres wide. Arsenopyrite is a common ore mineral. The sheared rock is usually intermediate plagioclase porphyry or hornblende gneiss. Shear zones are in many cases folded and thus older than the main deformation stage. In Korvenala, anomalous gold values have been found over a relatively wide area, with a mean of 310 ppb for 252 samples. In the most anomalous intervals, grades are usually 0.1–1 ppm Au, with only a few intersections of 5 ppm at 1 m. At Korvenala, alteration is seen as narrow zones around Au-bearing shears. At Kultanummi there is a NE-trending 10–15 m wide and at least 200 m long gold mineralized zone that dips 75º to the NW. The gold grades vary between 0.1–10 ppm. The most prospective lithology for gold at Kultanummi is relatively quartz-rich gneiss that typically contains disseminated sulphides and is characterized by aggregates of sillimanite and sporadic cordierite. Pyrite is the most common ore mineral. It is assumed that the alteration of the host rocks and the gold mineralization are older processes than the regional metamorphism. The composition of native gold grains at Korvenala varies from pure gold to gold-silver alloy. The average composition of gold grains is 92.8% Au and 7.2% Ag. Gold grains are in many cases zoned: the rim is pure gold and the core of the grains is homogeneously silver bearing. The Ag content of the gold grains at Kultanummi is very low and uniform. Native gold grains usually contain less than 1% Ag and at most 4% Ag. No zoning in gold grains has been met at Kultanummi.

Keywords (GeoRef Thesaurus, AGI): gold ores, metamorphic rocks, geophysical methods, magnetic anomalies, gold, grains, zoning, Proterozoic, Korvenala, Paimio, Kultanummi, Halikko, Finland

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INTRODUCTION

The Geological Survey of Finland (GTK) investigated the Korvenala and Kultanummi gold prospects during 1996–2008. The bedrock of the study area belongs to the 1.90–1.82-Ga-old accretionary arc complex of Southern Finland (Korsman et al. 1997). Supracrustal rocks of the southern Svecofennian are divided into the Uusimaa Belt in the south, the Häme Belt in the north, and the Saimaa area in the northeast (Nironen et al. 2002). The study region is on the western part of the SW–NE to WSW–ENE-trending Häme Belt, close to the transition zone to the Uusimaa Belt on the southern side. A suture zone between the Central Svecofennian Arc Complex and the Southern Svecofennian Arc Complex is proposed to be located between the Pirkanmaa and Häme belts. Its precise position and its continuation to the west have recently been studied by Sipilä et al. (2011), and the border zone drawn in Figure 1 is based on these studies. In the Häme Belt, gold

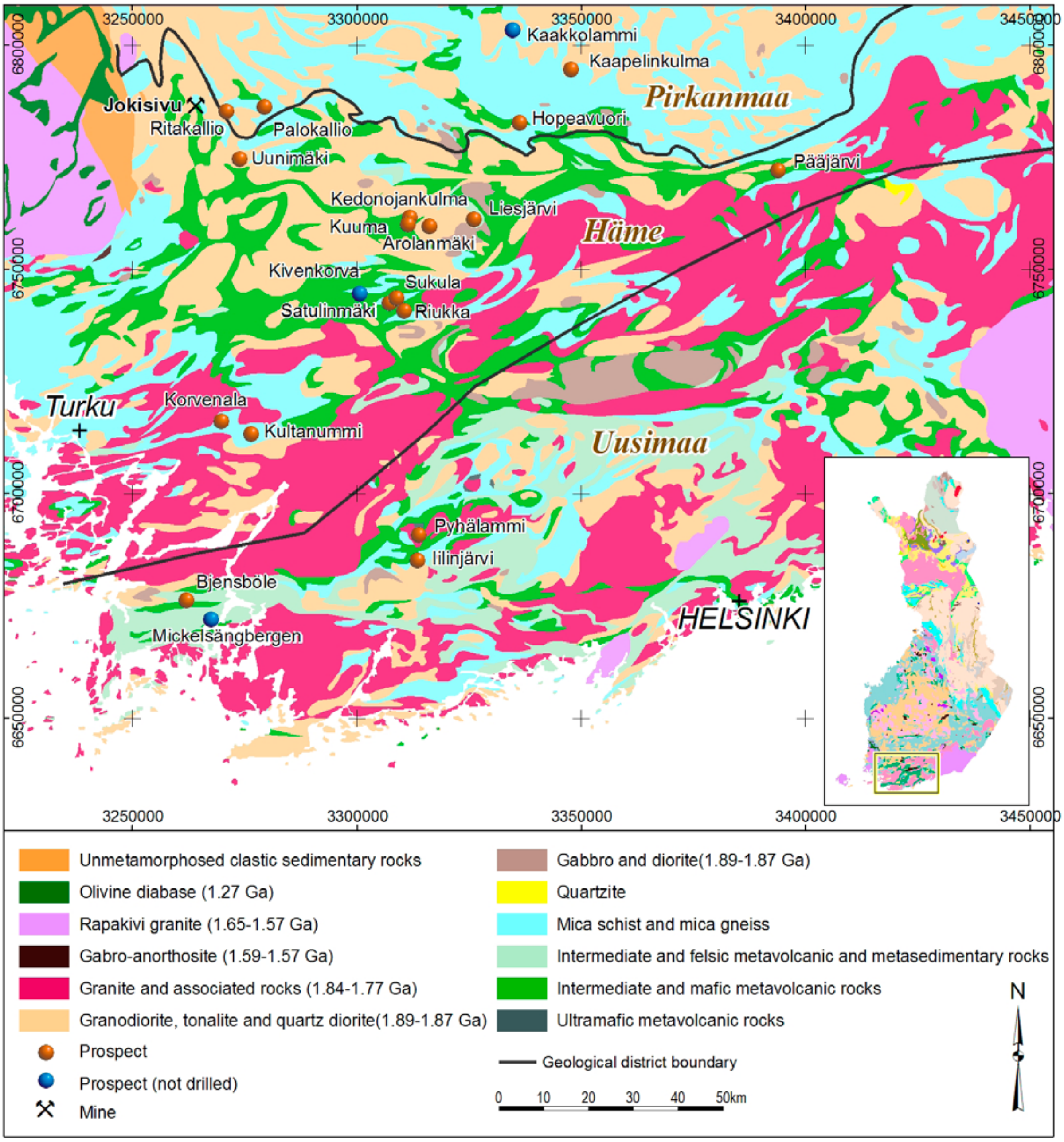

Figure 1. Locations of the Korvenala and Kultanummi gold prospects. The geology of southwestern Finland and gold deposits and occurrences detected in the Uusimaa, Häme and Pirkanmaa areas. Geology from Vaasjoki et al. (2005), gold occurrences after Eilu and Pankka (2009) and recent exploration by GTK (Kärkkäinen et al. 2003, Kärkkäinen 2007, Sipilä et al. 2011 and unpublished GTK data).

occurrence types include intrusion-related and orogenic Au-Cu occurrences and orogenic and possibly epithermal Au occurrences (Eilu 2012).

In 2001, amateur prospector Veli-Matti Koivula recovered indications of gold while panning oxidized regolith material at Kultanummi, near Halikko, in SW Finland. GTK's work at Kultanummi during 2001–2006 resulted in the discovery of a gold-enriched shear zone by drilling (Grönholm et al. 2005, Grönholm & Kärkkäinen 2006). There is a NE-trending 10–15 m wide and at least 200 m long gold mineralized zone that dips 75º to the NW. Gold grades vary between 0.1–10 ppm. The host rock of the gold deposit is silicified and deformed sillimanite gneiss.

Before Kultanummi, numerous samples from Au-bearing outcrops and glacial boulders, also found by Koivula, gave reason for studies in the Korvenala area in Paimio. The distance between Kultanummi and Korvenala prospects is about 10 km. Field work at this area was initiated during 1996–1998 (Rosenberg 2000), and geological remapping and re-logging of the drill cores from the Korvenala prospect was carried out during 2008. Ore mineralogy was analysed from selected mineralized drill core samples. This paper mainly describes the lithologies, geophysical environment and ore mineralogy of the Korvenala prospect, and some comparisons are made between the Kultanummi and Korvenala prospects.

GENERAL GEOLOGY

The Häme Belt is characterized by intermediate and mafic volcanic rocks and various sedimentary rocks (Kähkönen 2005). The western part of the Häme Belt is dominated by metasedimentary rocks that are presumed to be 1.9–1.8 Ga old (Kähkönen 2005). The supracrustal rocks are crosscut and migmatized by 1.88 Ga granitoids as well as 1.84–1.82 Ga granites (Vaasjoki et al. 2005). The supracrustal rocks of the Häme Belt were mainly metamorphosed under amphibolite facies conditions 1.88–1.86 Ga ago. At 1.83–1.81 Ga they largely experienced a high-T event as the late Svecofennian granite-migmatite zone of southern Finland was formed. This event peaked at 1824 ± 5 Ma (Väisänen 2002).

Mica schists and mica gneisses dominate the bedrock of the Kultanummi area. There are minor intercalations of amphibolites and mafic plagioclase porphyrite. Mica gneisses are intruded by aplite and granite pegmatite veins. Rocks are multiphase folded and regional metamorphism corresponds to mid- or high amphibolite facies. Signs of incipient melting of mica gneiss are locally met at Kultanummi. The most prospective lithology for gold at Kultanummi is relatively quartz-rich gneiss, occurring as discrete 10–30 m thick units within the more typical fine-grained massive biotite mica gneisses. The quartz-rich gneiss typically contains disseminated sulphides and is characterized by aggregates of sillimanite and sporadic cordierite, alternating with bands of calc-silicate rock, and multiply-folded thin quartz veins. Pyrite is the most typical sulphide phase occurring as disseminations, as solitary grains and aggregates and along joint planes. Disseminated chalcopyrite and pyrrhotite also occur, and isolated arsenopyrite grains or grain aggregates are present. Magnetite-bearing rocks are common near mineralization. (Grönholm et al. 2005).

The bedrock at Korvenala also contains mid-amphibolite facies mica gneisses, but the volume of metavolcanic rocks, including veins, is prominent when compared to Kultanummi. In this area, granite pegmatites are also common. Regional structural trends tend to be nearly NE–SW, with tight folding.

GEOPHYSICS

The geophysical characteristics of southern Finland comprise well-developed, tectonically deformed aeromagnetic surface anomalies and regional gravity highs corresponding to high density subsurface rocks. The high densities and gravity highs are interpreted to be due to high-grade metamorphic rocks. Strong gravity gradients separate tectonic crustal blocks. Figure 2 displays groups of banded, folded aeromagnetic anomalies with a fold axis striking smoothly to the ENE. The interpreted magnetic lineaments with an ENE strike represent weakness zones related to fold axis planes. The banded magnetic anomaly patterns are cut by NW-trending fault and fracture zones and NE-striking younger sharp fault and shear zones. Zones A–A and B–B in Figure 2 are

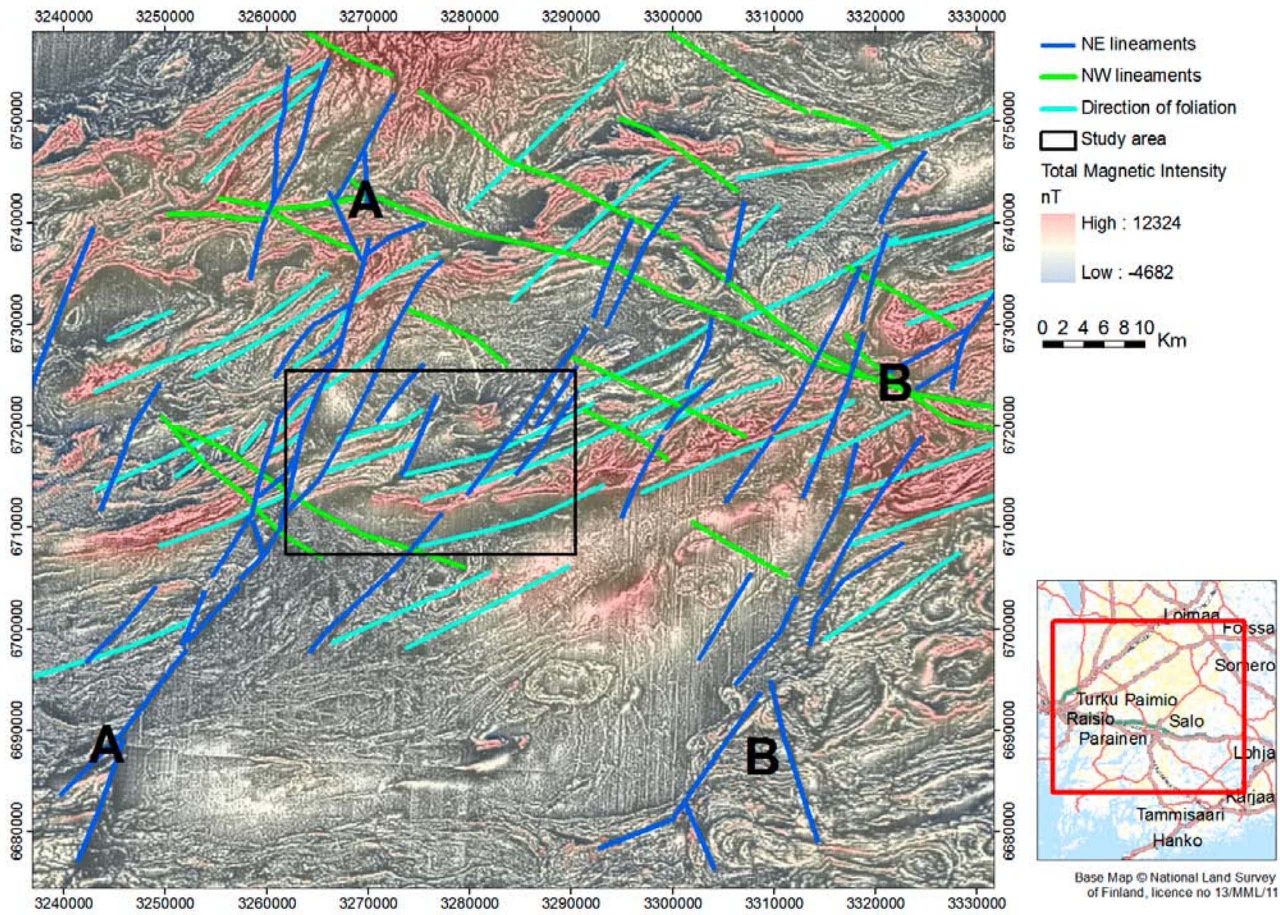

Figure. 2. Magnetic interpretation map from southern Finland. Linear magnetic features with reduced magnetic intensity (magnetic lineaments) were interpreted and divided into three groups, that illustrate important structural trends. The light blue trend is attributed to a regional cleavage trend associated with regional folding; the green lines represent NW-trending weakness zones and faults; the blue lines represent NE-trending weakness zones and sharp faults associated with the boundaries of tectonic blocks. A-A and B-B represent the main tectonic boundaries, and are associated with gravity gradients. The black square shows the map outline of Fig. 3. Processed by Hanna Leväniemi, GTK. Basemap © National Land Survey of Finland, licence no 13/MML/12.

composed of magnetic lineaments aligned with the gravity gradient zones. They can be followed far south from the Finnish coast. West of A–A and east of B–B the metamorphic grade is higher than between these zones, within the block that contains the Halikko and Korvenala target areas (within the black square).

The magnetic anomaly groups hosting Halikko and Korvenala occurrences (Fig. 3) form magnetic subprovinces. They are outlined by fault and fracture zones belonging to the three groups presented in Figure 2. The anomalies are also cut by an ENE-trending cleavage trend, and the location of both occurrences is controlled by these fault zones. The southernmost magnetic anomalies in these packages are of higher magnetic intensity and they are related to negative AEM ratios. The high-intensity magnetic anomalies are caused by magnetite-bearing rocks, as inferred from the airborne electromagnetic (AEM) data: the real (inphase) component shows negative values for high magnetic susceptibility. This feature is termed the 'magnetite effect' and is typically exposed by GTK's frequency-domain AEM method (see Suppala et al. 2005). The lower-intensity magnetic anomalies are caused by rocks that contain less magnetite or, when combined with electrical conductivity anomalies, by monoclinic pyrrhotite (Airo 2005). It can be suggested that magnetite was produced by metamorphic processes. Radioelement distributions of the study areas were expected to indicate some anomalous horizons in association with the mineralized zones, but most of the radioactivity in this region is due to glacial overburden. However, some correlation can be observed between the radioelement distribution and rock types. The radioelement ratios should be investigated in more detail in order to distinguish possible slight variations, e.g. in K/Th or U/Th ratios.

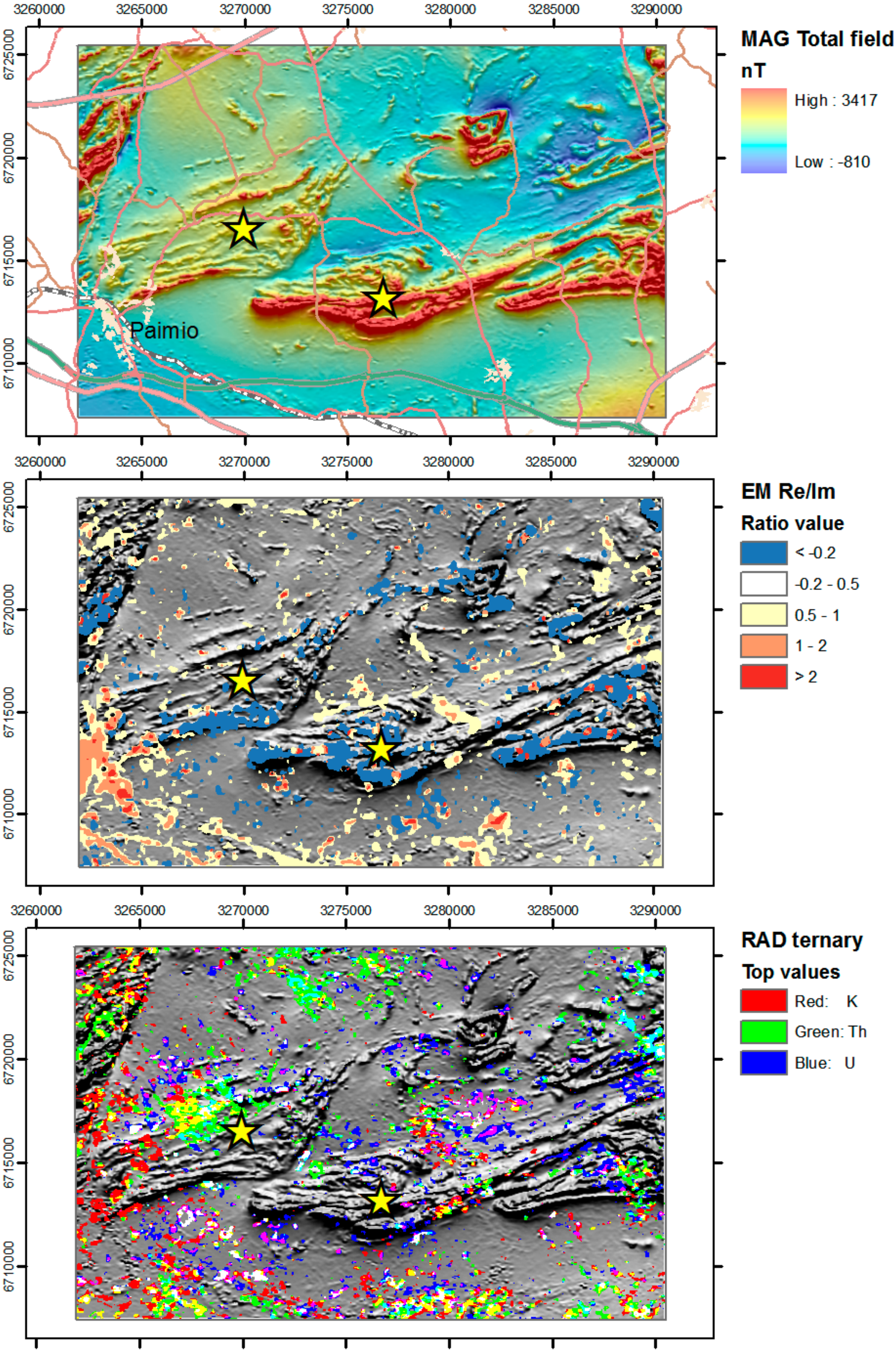

Figure 3. Aerogeophysical maps of the study area. The Au deposits discussed in text are marked with yellow stars.
Top: Magnetic total field map showing banded aeromagnetic patterns associated with metavolcanic rocks and metamorphic schists.
Middle: Thematic aeroelectromagnetic (AEM) ratio map. The blue colour denotes low conductivity plus high magnetic susceptibility due to magnetite. The magnetite content is most prominent in the southernmost banded formations. Yellow to red colours indicate high electrical conductivity of the ground.
Bottom: Maximal cut-offs of airborne radiometric components presented as a ternary image. The radiation is mainly attributed to overburden. Enhanced U radiation (in blue) can be attributed to some of the magnetic anomalies related to metasedimentary layers. Numbers outside the maps are map coordinates. Processed by Hanna Leväniemi, GTK.

KORVENALA PROSPECT

Bedrock

Metasedimentary mica gneisses, intermediate feldspar porphyry gneiss, and granitic and pegmatitic veins are the most common rock types in the Korvenala area (Fig. 4). In the SE part of the area, there are intermediate tuffitic rocks with the intercalations of plagioclase porphyrite, hornblende gneiss and quartz-feldspar schist. The strike of the schistosity is SW-trending and the dip is towards the northwest, with angles varying from almost flat to steep. There are no outcrops in the NW part of the study area.

Mica gneiss

Mica gneiss is a fine- or medium-grained, thinly (1–5 cm) bedded or banded, folded and only weakly migmatized rock. The principal minerals are quartz, plagioclase, potassium feldspar and biotite, with smaller amounts of garnet, zircon, sphene, epidote, apatite and sulphides. The amount of quartz and biotite changes, causing the banding. When sulphides are present, plagioclase is extensively sericitized. Pyrite, pyrrhotite and chalcopyrite are the most common sulphides. Locally, arsenopyrite is also present.

Based on drilling, the mica gneisses contain 5–10 m wide interbeds of intermediate feldspar porphyry and uralite plagioclase porphyrites, as well as hornblende gneisses. Slight skarnitization is sometimes present. Skarn patches are rich in feldspar and stripes with hornblende and diopside. In mica gneisses there are also garnet- and tourmaline-bearing pegmatite dykes, up to 1 m thick, that are poor in mica.

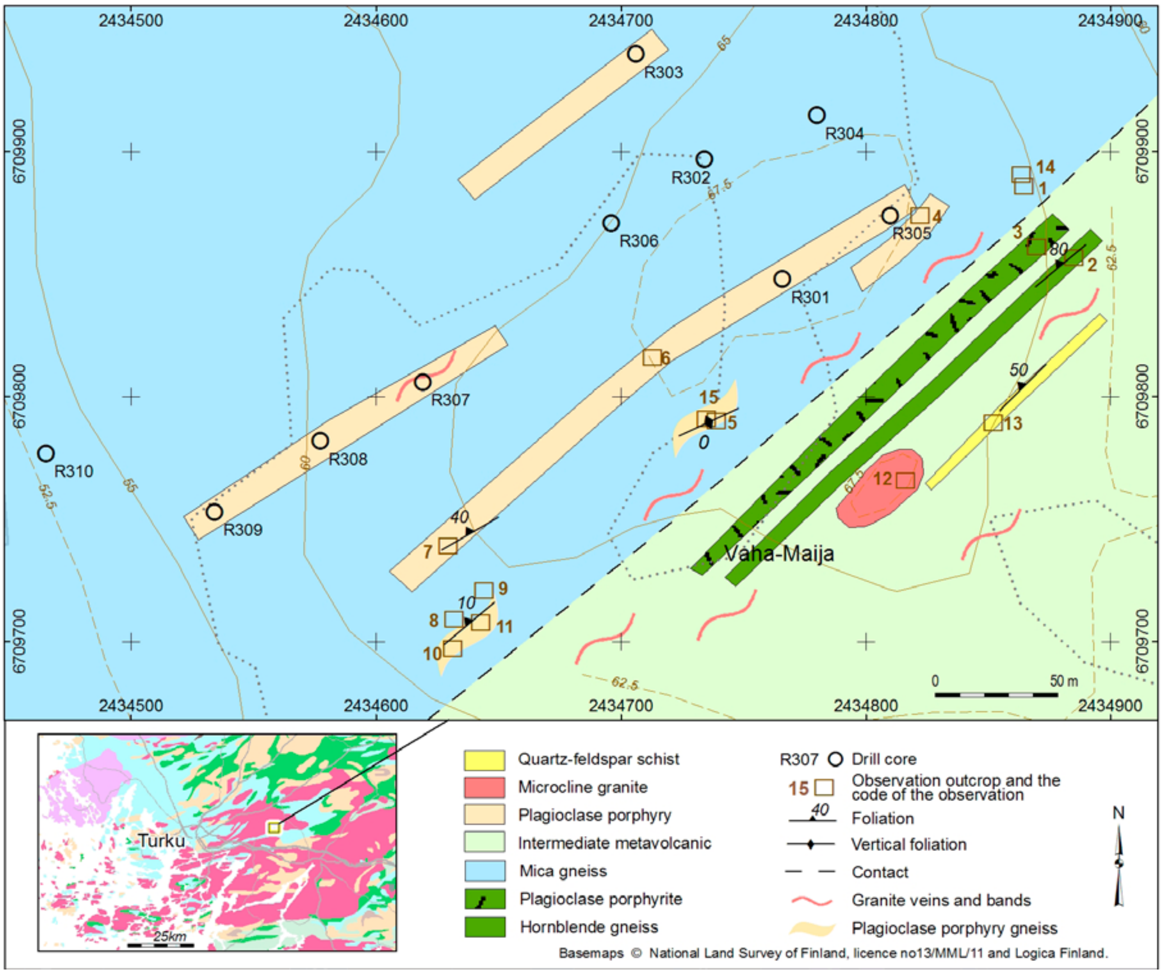

Figure 4. Detailed map of the Korvenala prospect, showing drillhole locations and observation points 1–15. Base map sheet 2021 06. Basemap © National Land Survey of Finland, licence no 13/MML/12.

Intermediate feldspar porphyry gneiss

Most outcrops in the prospect area are granodioritic porphyry gneiss (Fig. 5). These rocks are probably originally dykes or sills. They are oriented along the overall cleavage trend. Porphyry gneisses are pale grey in colour, sheared and silicified. Plagioclase occurs as 1–3 mm long phenocrysts and with the groundmass composed of quartz, plagioclase and biotite. Plagioclase is usually unaltered, but in the shear zones it shows intense serisitization. Biotite has only occasionally altered to chlorite. Skarn stripes and patches in feldspar porphyry contain feldspars, quartz and biotite, and accessories include diopside, titanite, chlorite and apatite. Ore minerals, pyrrhotite, pyrite and arsenopyrite, are common in the sheared parts of the porphyry gneiss. Based on the chemical analysis of drill core samples, this rock is most often the host for gold.

Volcanic rocks

Volcanic rocks can be seen in the outcrops in the NE part of the study area (Fig. 4). These rocks are hornblende gneiss, mafic plagioclase porphyrite and quartz-feldspar schist. Hornblende gneiss is dark green in colour and the grain size is usually 1–5 mm. The main minerals in hornblende gneiss are hornblende, plagioclase, quartz and biotite. Sporadic tourmaline, oxides, pyrrhotite and pyrite are found. There is also magnetite containing many ilmenite exsolution lamellae.

According to drilling results, the hornblende gneiss beds are usually less than 5 m thick. These mafic rocks also include skarn-type inclusions and interlayers. Hornblende gneisses are usually weekly foliated, but strongly foliated parts are also present. Granitic dykes are common. Gold has been found from weakly sheared hornblende gneiss (3.1 ppm/1 m, R304).

Mafic plagioclase porphyrites are also dark green in colour and are usually only weakly foliated. Plagioclase can be clearly seen on outcrops as white laths on the rocks surface (Fig. 6). Plagioclase laths are usually 1–3 mm long.

One outcrop in the study area contains lapilli tuff, the rock now being fine-grained quartz-feldspar schist. The main minerals are biotite, quartz and plagioclase. There are also minor amounts of zircon, titanite, epidote and apatite. The lapillis are some centimetres in diameter, dark green in colour and oriented along schistosity. The main minerals in these lapillis are quartz, hornblende and plagioclase.

Gold mineralization

The Korvenala gold occurrence was found by drilling a gold nugget anomaly in heavy mineral studies of till (Rosenberg 2000). The prospect is also well expressed in Au and As till geochemistry, and has a distinct IP response in the mineralized zone. The Korvenala mineralization is located along the overall cleavage trend and is controlled by fault and fracture zones. In the SE part of the

Figure 5. Feldspar porphyry with a quartz-feldspar vein showing ptygmatic folding in a drillcore sample. R303. x = 6709.940, y = 2434.706.

Figure 6. Plagioclase porphyrite. The white plagioclase laths are 1–3 mm in diameter.

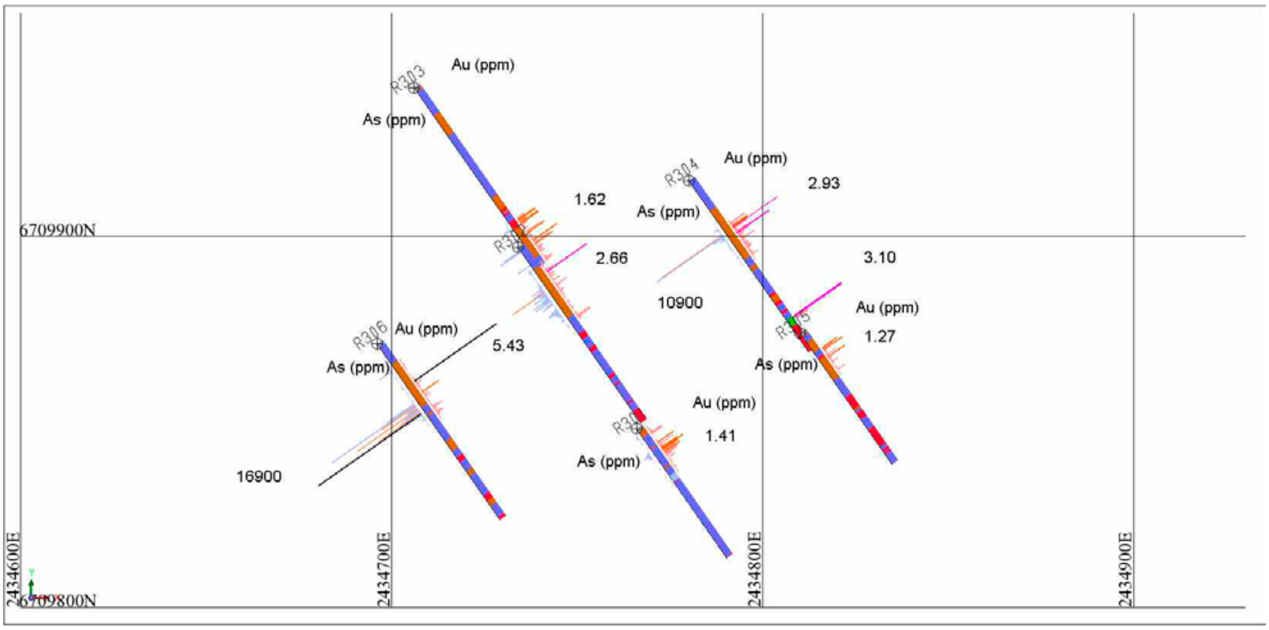

Figure 7. Diamond drilling profiles in plan view. Au and As concentrations are in ppm (g/t). Lithology: brown= feldspar porphyry, blue= mica gneiss, red= granite, green= hornblende gneiss/amphibolite.

study area, magnetite-bearing volcanic rocks and microcline granite are present.

Drill cores analysed from Korvenala show elevated Au values over a relatively wide area, with a mean of 310 ppb for 252 samples (Rosenberg 2000). However, most of the increased Au grades are between 0.1–1 ppm, with only a few analyses of higher grade. The best intersections are 1 m at 5.4 ppm (hole R306) and 5.45 m at 1 ppm (hole R304). Statistically, Au does not correlate well with As (Fig. 7), although spatially, in the same holes, they occur quite closely (Fig. 8). The highest As content recorded in drilling is 1.7%.

Most often, the host rock of the increased gold in drill cores is feldspar porphyry gneiss and hornblende gneiss. The Au grade is commonly low in mica gneisses, although gold is sometimes present in sulphide bearing quartz veins intercalating gneiss. Au has also been found in a granite pegmatite dyke that penetrates the porphyry gneiss. The gold grade of 1.0 ppm Au was recorded in a one-metre section of drill core R 303: 67.50–68.50 m. The pegmatite is grey in colour and contains sporadic arsenopyrite.

On the outcrops of the Korvenala prospect, the Au mineralization occurs in shear zones. The shear zones are a few centimetres wide, rusty and contain quartz veins with some sulphide minerals. The sheared rock is usually intermediate volcanic rock. In the drill core, visible features of Au mineralization are slight. Alteration of the Au-bearing rock is weak and it is not necessarily present in places where gold concentrations are higher.

Alteration includes slight skarn formation, silicification (quartz veins) or sulphurization (arsenopyrite, Fe sulphides) and is locally prominent in sheared Au-bearing sections. Mineralized intersections are light green in colour due to skarn reactions, or contain quartz veins or sporadic arsenopyrite grains. As a result of skarn reactions, plagioclase porphyry locally contains pyroxene minerals, potassium feldspar and sulphides, including sporadic arsenopyrite grains. Locally, plagioclase is strongly serisitized and biotite is altered to chlorite. Potassium feldspar is also present in mineralized rock. Mineralized rocks commonly contain sphene, arsenopyrite, pyrrhotite, magnetite, scheelite and zircon. In mafic rocks, pyrrhotite locally rims mafic silicates. They are interpreted to have been developed in reactions between sulphur-bearing brines and Fe-bearing silicates. Locally, there is dense sulphide dissemination in the drill core, and pyrrhotite is more common than arsenopyrite. These are the most abundant ore minerals in the Korvenala gold mineralization, although pyrite and chalcopyrite are also common. Part of the arsenopyrite is coarse-grained and euhedral.

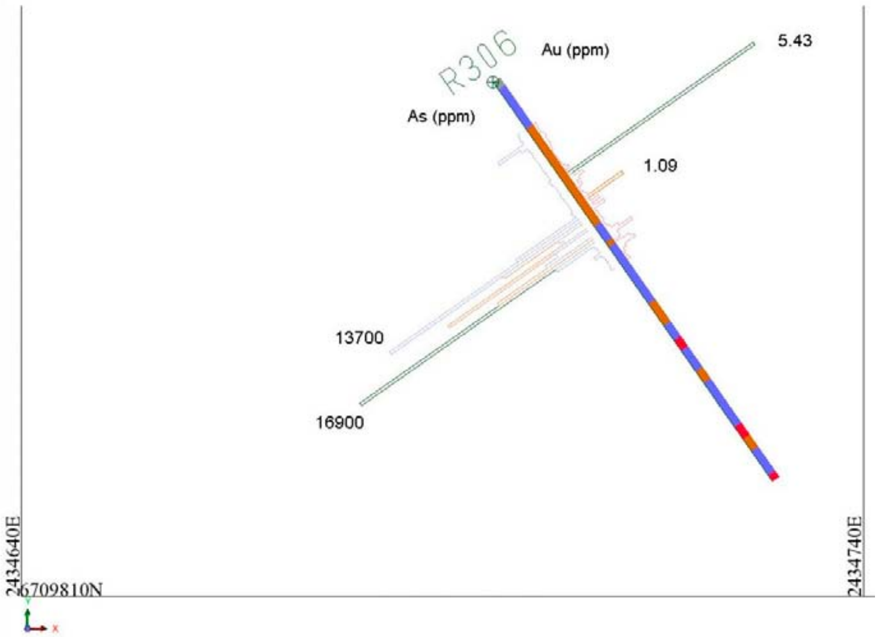

Figure 8. Au and As concentrations in drill core R306. Note that the As concentration is high in the contact zone between mica gneiss and feldspar porphyry. Lithology is the same as in Figure 7.

Gold

Gold was studied from heavy mineral concentrates made of crushed core. These were prepared from two drill core samples: R301/11.00–13.50 m with 0.9 ppm Au and 2320 ppm As, and R303/71.50–73.50 m with 1.1 ppm Au and 520 ppm As. Respectively, 18 and 20 gold grains were identified in the heavy mineral concentrates during binocular microscopy studies. The grain size of gold varied between 0.08 mm and 0.50 mm. According to the total volume of the grains, the grade was estimated to be about 2 ppm Au in both samples, a little higher than in chemical analysis.

For more detailed studies, heavy minerals were cast into epoxy and polished. The concentrates were mainly composed of arsenopyrite and pyrrhotite, with some scheelite and magnetite. Native bismuth was rather common and usually host by sulphides as discrete grains or with gold. SEM-EDS studies also indicated Pb-Bi, Th-Pb-Bi and Pb-Th-U minerals.

In the concentrates, gold usually occurs as individual grains and less voluminously as inclusions in sulphides. The shape of gold grains in attached microphotographs is not necessarily primary, because the grains are separated through several processes from the crushed core. Gold grains are broken and variably rounded, although the sulphides are mainly rather angular. There are usually no inclusions in gold grains. In the concentrates there are no composite grains of gold and sulphides, or fragments or remnants of broken sulphides on the borders of the gold grains. Thus, it is likely that larger gold grains in the concentrates have been more closely associated with silicate minerals than sulphides.

Gold was also found as small inclusions in arsenopyrite and pyrrhotite (Fig. 9). Coarse-grained gold similar to gold met in the heavy mineral concentrates was not met in thin sections.

The composition of native gold grains at Korvenala varies from pure gold to gold-silver alloy (Appendix 1). The average composition of gold grains is 92.8% Au and 7.2% Ag. The gold content varies between 79.5–99.6 % Au and the silver con-

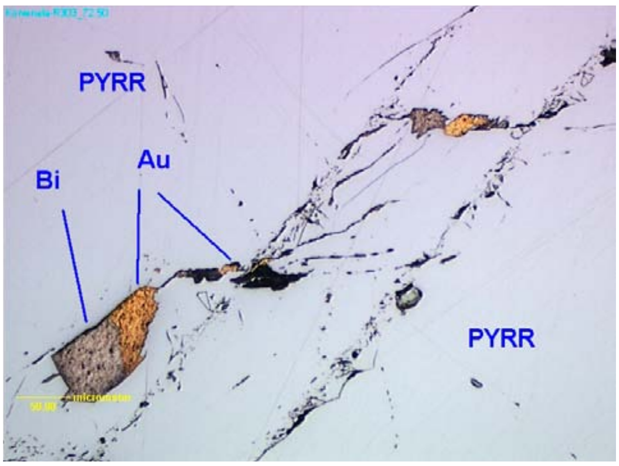

Figure 9. Native gold and bismuth in a sheared crack of pyrrhotite (PYRR).

tent between 0.0–20.6 % Ag. The Cu content is at most 0.14% and Bi at most 0.11%.

The style of zoning varies, but there are always two homogeneous phases. The border zone is pure gold and the primary grain is homogeneously silver bearing. The Ag content of different gold grains is somewhere between 0 and 20% Ag. Locally, pure gold only occurs as a thin overlay bordering the grains, and locally there are broader gold zones or 'veins' of pure gold penetrating the Au-Ag alloy (Figs. 10 and 11). According to the backscatter figure, there are sharp contacts between pure gold and the Au-Ag alloy (Fig. 12). Pure gold fills cracks in the primary Ag-Au alloy grains. For comparison, some chemical analyses of gold grains from Kultanummi at Halikko are included Appendix 1. The Ag-content of the gold grains at Halikko is very low and uniform. There is usually less than 1% Ag and at most 4% Ag in native gold grains.

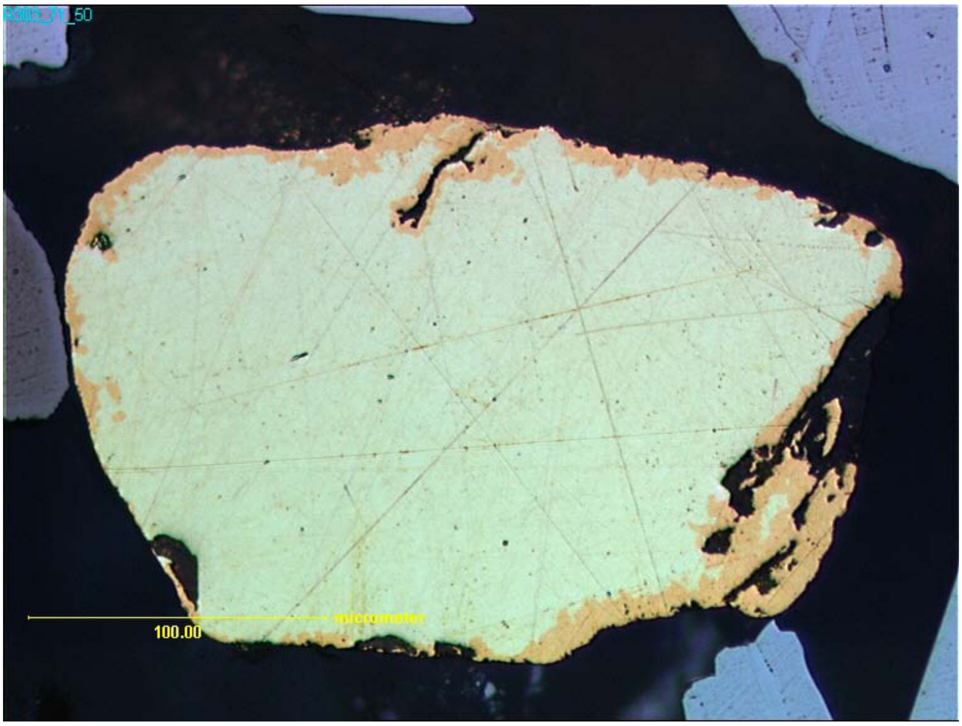

Figure 10. A zoned gold grain in which the lighter centre part contains 10.2% Ag, and the yellow border rim is pure gold. Note that the colour contrast in the gold grain is created with a colour filter of the ore microscope.

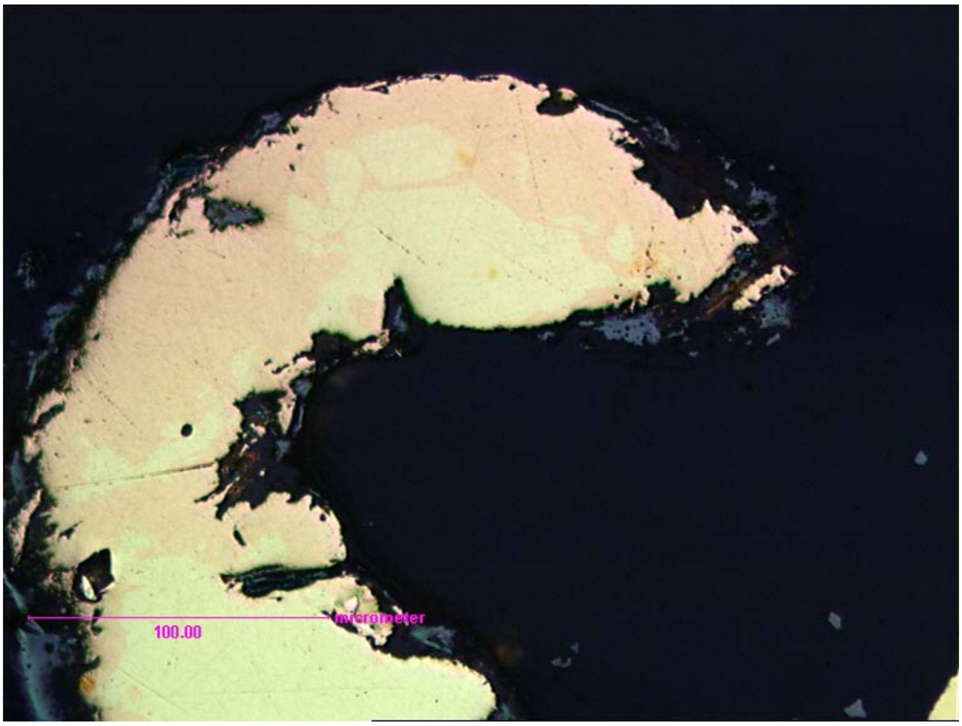

Figure 11. An enlargement of an arc-shaped, Ag-bearing gold grain. The blotched texture due to differing composition is only visible under the microscope when using colour filters.

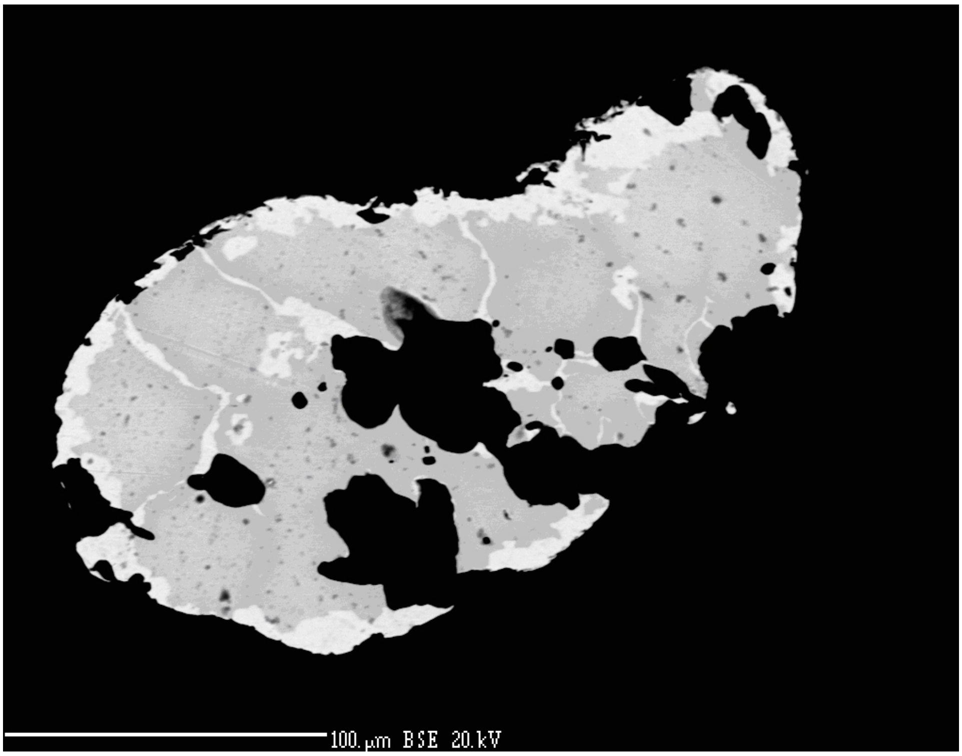

Figure 12. Electron microscope image of a zoned gold grain. The majority of the grain is Ag-bearing (16.8% Ag), but the light-coloured border and cracks of the grain are pure gold (Analysis R303_71.50/ring A / grain 1 in Appendix 1).

COMPARISON OF KULTANUMMI AND KORVENALA DEPOSITS

The gold prospects of Kultanummi and Korvenala occur regionally in similar tectonically separated blocks of supracrustal rocks within a microcline granite complex. The distance between Kultanummi and Korvenala prospects is about 10 km. Both prospects have a distinct IP response in the mineralized zone. On the aeromagnetic map (Fig. 2), the Korvenala and Kultanummi mineralizations are located along lineaments that are related to the main foliation and outlined by fault and fracture zones. Both prospects have native gold.

At Korvenala the gold mineralization is in minor shear zones in plagioclase porphyry and hornblende gneiss. The shear zones are in many places folded and older than the last deformation stage in the area. The As content in the mineralized zone is higher in Korvenala. The genetics of Korvenala are uncertain, but as gold and sulphides are concentrated in shear zones, the origin of gold might be orogenic. The most prospective lithology for gold at Kultanummi is relatively quartz-rich, sillimanite bearing gneiss, occurring as discrete 10–30 m thick units within the more typical fine-grained massive biotite mica gneisses. The As content is low at Kultanummi and pyrite is the most common ore mineral. Magnetite-bearing rocks are common near mineralization at Kultanummi, whereas magnetite is not as common at Korvenala. The close association between gold and the deformed sillimanite-rich zone suggests an early timing and intense argillic alteration during mineralization. There are some similarities with the Enåsen gold deposit in central Sweden and the Kultanummi deposit. The Enåsen gold deposit is a metamorphosed, Palaeoproterozoic analogue to recent epithermal Au deposits associated with acid-sulphate alteration in a high sulphidation environment. Mineralization consists of disseminated chalcopyrite and gold in topaz-bearing quartz-sillimanite gneiss hosted by quartz-feldspar and quartz-mica gneisses (Hallberg 1994).

The gold grains are zoned at Korvenala. The zoned structure of minerals in igneous environment is usually a result of the growth of the mineral grains in a changing melt composition. In a metamorphic (or other hydrothermal) environment, leaching is a more likely reason for the zoning. The zoning of gold grains in the metamorphosed environment of Korvenala is most easily explained by leaching. It is likely that silver has leached from the Ag-Au alloy along the cracks and from the surface of the grains. This is also probable in the Au grain in Figure 12, where one corner of the grain is mainly composed of pure gold and there is only a small inclusion of lighter

Ag-Au alloy. The shape of this part of the grain looks very much like it is corroded, and the leaching is probably related to the corrosion of the gold grain during metamorphic processes. The Ag content of the gold grains at Halikko is very low and uniform, and zonation of the gold grains has not been detected. There is usually less than 1% Ag and at most 4% Ag in native gold grains.

SUMMARY

Recent studies in the Häme Belt, the high-grade metamorphic terrain of southwestern Finland, have delineated several gold occurrences, including the Paimio Korvenala and the Halikko Kultanummi prospects. In this article we have described the lithology, geophysical environment and gold mineralization of these two gold deposits. Some comparisons have also been made between the Kultanummi and Korvenala prospects. The main differences between these deposits are summarized below.

1. Gold mineralization at Korvenala is in minor shear zones in plagioclase porphyry and hornblende gneiss. Alteration is usually rather weak and is mostly seen as silicification, sulphurization and seritization. In Kultanummi, alteration is widespread and most gold is present in a strongly silicified and sulphidised sillimanite gneiss.
2. Arsenopyrite is more common at Korvenala than at Kultanummi. Magnetite and pyrite are more common at Kultanummi.
3. The Ag content in gold grains is higher at Korvenala and gold grains are often zoned. Zonation has not been observed at Kultanummi.

Korvenala might be genetically orogenic on the basis that gold occurs in shear zones, and Kultanummi seems to be metamorphosed epithermal in the same way as the Enåsen gold deposit in Sweden. More research is still needed to resolve the genetic problems involving these deposits. However, the Korvenala and Kultanummi deposits attest to the Au mineralization potential of the high-grade metamorphic terrain of southwestern Finland.

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Appendix 1. Microprobe analyses of the gold grains from Korvenala, Paimio and Kultanummi, Halikko; grades as wt-% . Determination limits, ppm ,Cu 376, Ag 1152, Au 1879, Hg 2137.19, Bi 1109. Acceleration voltage = 20 kV; current = 20 nA; diameter of electron beam = 1 µm. Operator: Lassi Pakkanen, GTK.

Cu	Ag	Au	Hg	Bi	Total	Sample
0.00	20.22	79.63	0.00	0.01	99.86	Paimio- R301 / 11,00-13,50 / grain1
0.00	20.26	79.45	0.00	0.00	99.71	Paimio--R301 / 11,00-13,50 / grain1
0.00	20.60	79.58	0.00	0.00	100.19	Paimio--R301 / 11,00-13,50 / grain1
0.02	2.73	96.28	0.00	0.01	99.03	Paimio-R301 / 11,00-13,50 / grain2
0.01	2.93	97.95	0.00	0.00	100.90	Paimio- R301 / 11,00-13,50 / grain2
0.03	2.82	97.97	0.00	0.06	100.88	Paimio- R301 / 11,00-13,50 / grain2
0.01	10.14	89.26	0.00	0.03	99.43	Paimio- R303_71,50 / ring A / grain1
0.01	10.49	89.27	0.00	0.02	99.78	Paimio- R303_71,50 / ring A / grain1
0.03	10.20	89.14	0.00	0.01	99.38	Paimio- R303_71,50 / ring A / grain1
0.03	10.20	89.14	0.00	0.01	99.38	Paimio-R303_71,50 / ring A / grain1
0.09	5.05	95.53	0.00	0.05	100.73	Paimio-R303_71,50 / ring A / grain2
0.10	4.93	95.82	0.00	0.07	100.91	Paimio -R303_71,50 / ring A / grain2
0.11	5.00	95.80	0.00	0.05	100.96	Paimio-R303_71,50 / ring A / grain2
0.10	4.95	95.30	0.00	0.00	100.34	Paimio-R303_71,50 / ring A / grain2
0.03	15.99	84.16	0.00	0.02	100.21	Paimio-R303_71,50 / ring A / grain3
0.02	16.36	82.98	0.00	0.08	99.44	Paimio-R303_71,50 / ring A / grain3
0.02	16.98	82.39	0.00	0.03	99.43	Paimio-R303_71,50 / ring A / grain3
0.00	17.91	83.00	0.00	0.02	100.93	Paimio-R303_71,50 / ring A / grain3
0.00	0.44	100.18	0.00	0.09	100.71	Paimio-R303_71,50 / ring A / grain3
0.00	0.18	99.72	0.00	0.01	99.91	Paimio-R303_71,50 / ring A / grain3
0.08	9.18	91.26	0.00	0.02	100.56	Paimio-R303_71,50 / ring A / grain4
0.03	9.24	90.64	0.00	0.04	99.96	Paimio-R303_71,50 / ring A / grain4
0.10	9.24	90.90	0.00	0.08	100.32	Paimio-R303_71,50 / ring A / grain4
0.04	8.98	90.67	0.00	0.01	99.70	Paimio-R303_71,50 / ring A / grain4
0.11	9.30	90.96	0.00	0.11	100.47	Paimio-R303_71,50 / ring A / grain5
0.10	9.04	90.84	0.00	0.02	100.00	Paimio-R303_71,50 / ring A / grain5
0.10	9.22	91.19	0.00	0.00	100.51	Paimio-R303_71,50 / ring A / grain5
0.10	9.06	90.87	0.00	0.02	100.05	Paimio-R303_71,50 / ring A / grain5
0.02	6.91	93.18	0.00	0.00	100.10	Paimio-R303_71,50 / ring A / grain6
0.00	6.78	93.06	0.00	0.04	99.88	Paimio-R303_71,50 / ring A / grain6
0.03	6.89	93.23	0.00	0.00	100.14	Paimio-R303_71,50 / ring A / grain6
0.03	6.79	93.48	0.00	0.01	100.31	Paimio-R303_71,50 / ring A / grain6
0.14	1.69	97.69	0.00	0.00	99.52	Paimio-R303_71,50 / ring A / grain7
0.13	1.54	97.53	0.00	0.10	99.29	Paimio-R303_71,50 / ring A / grain7
0.13	1.61	97.49	0.00	0.03	99.26	Paimio-R303_71,50 / ring A / grain7
0.11	1.58	97.79	0.00	0.02	99.49	Paimio-R303_71,50 / ring A / grain7
0.02	4.47	95.03	0.00	0.04	99.56	Paimio-R303_71,50 / ring A / grain8
0.00	4.33	95.10	0.00	0.06	99.49	Paimio-R303_71,50 / ring A / grain8
0.01	4.49	95.33	0.00	0.02	99.85	Paimio-R303_71,50 / ring A / grain8
0.03	4.28	95.23	0.00	0.02	99.56	Paimio-R303_71,50 / ring A / grain8
0.01	4.27	95.60	0.00	0.02	99.90	Paimio-R303_71,50 / ring A / grain9
0.02	4.24	95.52	0.00	0.09	99.87	Paimio-R303_71,50 / ring A / grain9
0.02	4.27	95.13	0.00	0.02	99.44	Paimio-R303_71,50 / ring A / grain9
0.03	4.09	95.49	0.00	0.01	99.62	Paimio-R303_71,50 / ring A / grain9
0.00	0.00	99.57	0.00	0.00	99.57	Paimio-R303_71,50 / ring B / grain1
0.00	0.00	99.23	0.00	0.00	99.23	Paimio-R303_71,50 / ring B / grain1
0.00	0.00	99.26	0.00	0.00	99.27	Paimio-R303_71,50 / ring B / grain1
0.00	0.00	99.29	0.00	0.00	99.29	Paimio-R303_71,50 / ring B / grain1
0.04	4.26	95.50	0.00	0.00	99.81	Halikko 381-1 / ring A / grain1
0.05	4.26	95.64	0.00	0.00	99.94	Halikko 381-1 / ring A / grain1
0.04	4.24	95.52	0.00	0.00	99.80	Halikko 381-1 / ring A / grain1
0.07	0.74	98.36	0.00	0.00	99.17	Halikko 381-1 / ring B / grain1
0.06	0.76	98.60	0.00	0.00	99.42	Halikko 381-1 / ring B / grain1
0.08	0.80	98.66	0.00	0.00	99.54	Halikko 381-1 / ring B / grain1
0.08	0.75	98.54	0.00	0.00	99.36	Halikko 381-1 / ring B / grain1
0.08	1.02	98.89	0.00	0.00	99.99	Halikko 381-1 / ring C / grain1
0.08	0.90	98.70	0.00	0.00	99.69	Halikko 381-1 / ring C / grain1
0.08	0.92	98.59	0.00	0.00	99.59	Halikko 381-1 / ring C / grain1
0.07	0.71	98.68	0.00	0.00	99.46	Halikko 381-1 / ring C / grain2
0.05	0.74	98.89	0.00	0.00	99.68	Halikko 381-1 / ring C / grain2
0.05	0.71	98.72	0.00	0.10	99.58	Halikko 381-1 / ring C / grain2
0.00	0.55	99.01	0.00	0.00	99.57	Halikko 381-1 / ring C / grain3
0.02	0.54	99.08	0.00	0.00	99.65	Halikko 381-1 / ring C / grain3
0.02	0.62	99.49	0.00	0.00	100.13	Halikko 381-1 / ring C / grain3

Gold in Southern Finland: Results of GTK studies 1998–2011
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DISCOVERY AND MINERALOGY OF GOLD OCCURRENCE AT VELKUA, SOUTHWESTERN FINLAND

by
Niilo Kärkkäinen, Raimo Lahtinen and Lassi Pakkanen*

Kärkkäinen, N., Lahtinen, R. & Pakkanen, L. 2012. Discovery and mineralogy of gold occurrence at Velkua, Southwestern Finland. *Geological Survey of Finland, Special Paper 52*, 115–130, 13 figures and 1 appendix.

The first indication of gold in the Velkua area came from a nationwide lithogeochemical study by the Geological Survey of Finland. During follow up exploration, the gold occurrence was discovered in 2006 from a sulphide-rich outcrop. The Au occurrence is hosted by an amphibolite with intercalations of felsic and intermediate gneisses. Amphibolite is surrounded by migmatitic greywackes and coarse-grained microcline granites. Two major types of mineralizations are identified. Higher grade (1 to 24 ppm Au) ore comprises gold that occurs as native grains associated with silicate minerals. In lower grade (0.2–2 ppm Au) zones, gold is closely associated with sulphides. Larger gold grains are locally zoned, the core being an Ag-Au alloy and the border being pure gold.

The Velkua area belongs to southern Svecofennia, which went through two events of deformation and metamorphism at 1.88–1.87 Ga and 1.83–1.80 Ga, respectively. Gold in high grade ores occurs as inclusions in metamorphic silicate minerals in amphibolites and gneisses. The gold occurrence is metamorphosed, and is probably older than the younger regional peak metamorphism. Whether it was originally an orogenic Au deposit, epithermal deposit or a mixture of these two remains unresolved.

Keywords (GeoRef Thesaurus, AGI): gold ores, mineral exploration, amphibolites, gneisses, mineralogy, ore minerals, Proterozoic, Velkua, Naantali, Finland

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INTRODUCTION

The Velkua Au occurrence is situated in the archipelago of southwestern Finland (Fig. 1). The first indication of gold in this area was an Au-anomalous sample in the nationwide lithogeochemistry database (Rasilainen et al. 2008). This sample formed part of an east–west-oriented line of samples with elevated gold concentrations (> 5 ppb) (Fig. 2), also including the Paimio and Halikko Au mineralized areas (Grönholm et al. 2005). Anomalous values seem not to be controlled by any known geological or geophysical factor. These Au anomalous sample points were re-sampled during 2006.

The original sample from Velkua contained 23.6 ppb Au (N9208576), which is a substantially higher value than normally found in the nationwide geochemical database (Rasilainen et al. 2008). The sampled rock consisted of typical mica gneiss without any sulphide enrichment. Four new samples collected from the same location also contained anomalous concentrations of gold (16.8–61.9 ppb Au). The analysed samples did not contain high amounts of arsenic (maximum 170 ppm As) or sulphide minerals (maximum 0.11% S). During follow-up mapping in the vicinity of the sampling site, a rusty outcrop of arsenopyrite-bearing amphibolite was found (Fig. 3). Chemical analyses from this outcrop indicated grades of 1–2 ppm Au, and a heavy mineral concentrate of a crushed rock sample contained numerous gold grains.

No previous observations of gold have been described (Eilu & Pankka 2010), and no mineral exploration in general has been carried out in the re-

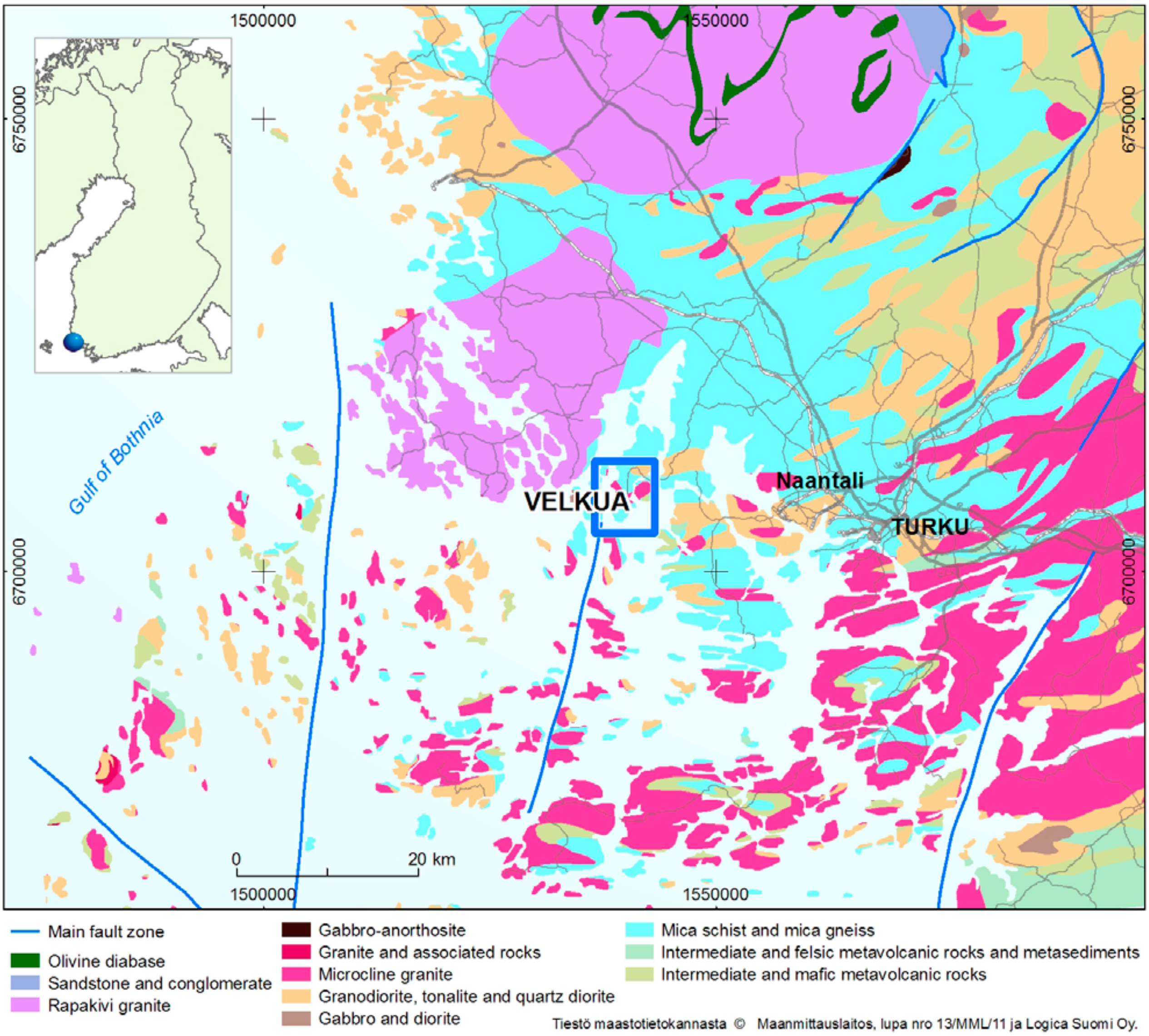


Figure 1. Location of the Velkua area. Bedrock map of Finland according to Korsman et al. (1997). Basemap © National Land Survey of Finland, licence no 13/MML/12.

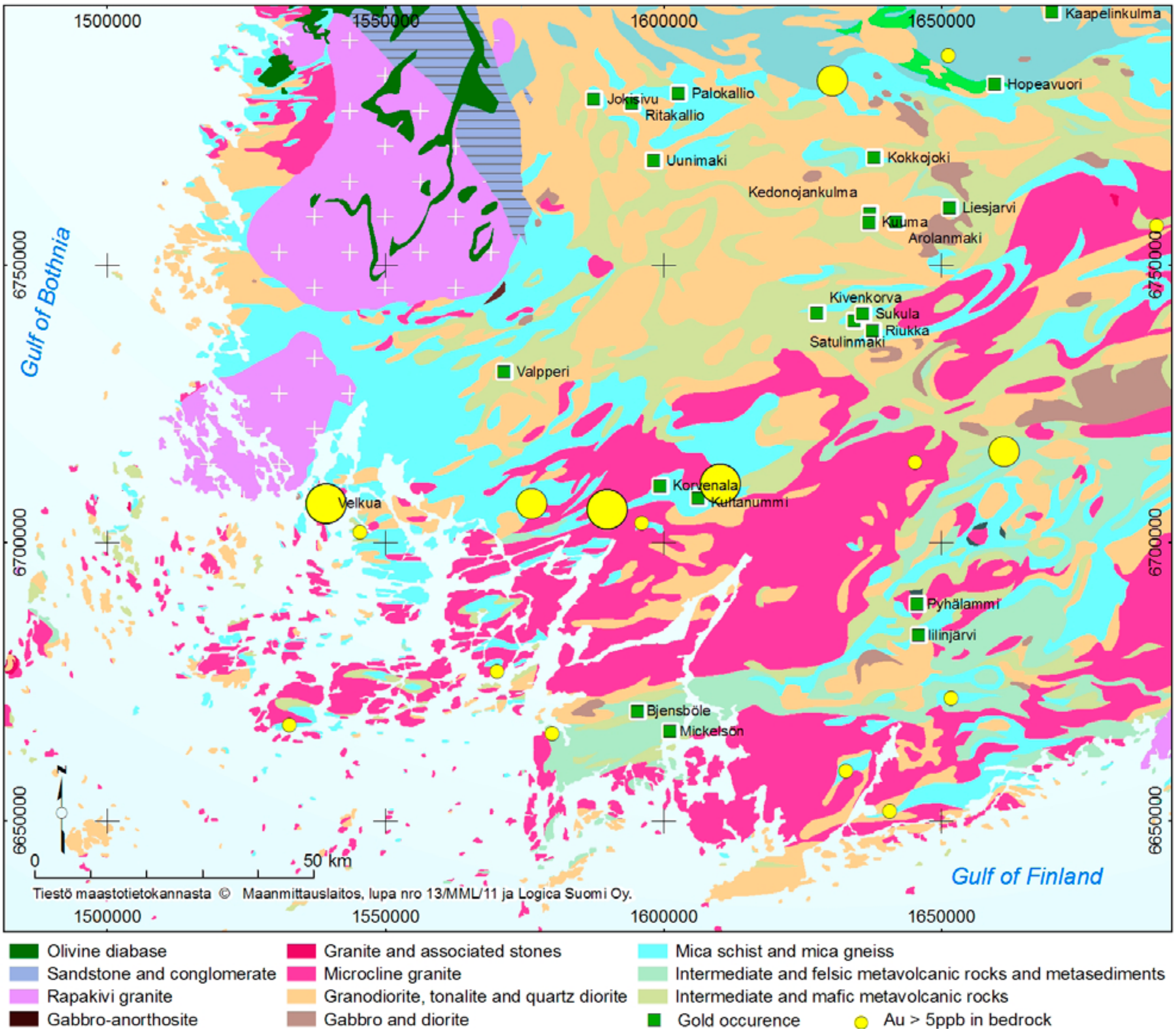


Figure 2. Anomalous Au (>5 ppb) in bedrock in southwestern Finland based on the nationwide lithogeochemical database of Finland (Rasilainen et al. 2005). The geological map is according to Korsman et al. (1997) and green squares indicate gold prospects. Basemap © National Land Survey of Finland, licence no 13/MML/12.

gion according to the archives or databases of the Geological Survey of Finland (GTK). Historical iron mines and some occurrences of pyrrhotite in a gneiss-amphibolite zone in the western part of the Velkua area have been reported (Karhunen 2004).

Typically, Svecofennian orogenic gold deposits are related to shear zones formed syn- to post-peak metamorphism (Eilu & Pankka 2010, Saalmann et al. 2009, 2010), and their variable timing reflects the multiphase orogenic evolution of Fennoscandia (Lahtinen et al. 2005). Examples of metamorphosed epithermal Au deposits include Enåsen (Hallberg 1994) and Orivesi (Eilu et al. 2003, Talikka & Mänttäri 2005). Kultanummi also represents an Au occurrence in high grade gneisses formed during pre- or early orogenic stages (Grönholm et al. 2005).

Figure 3. The arsenopyrite and pyrrhotite mineralized amphibolite in the discovery outcrop of the Velkua occurrence (observation JA – 07- 29, x = 6718627 and y = 3209288; common KKJ coordinates)

The most favourable depth for precipitation of gold from orogenic hydrothermal fluids within crustal scale shear systems is in the transitional zone from greenschist to amphibolite facies (Groves 1993). Svecofennian orogenic gold occurrences in the Pohjanmaa, Tampere, Pirkanmaa and Häme belts are mainly met in bedrock metamorphosed under mid-amphibolite facies conditions (Eilu & Pankka 2010). In contrast, high amphibolite to granulite facies metamorphic conditions occurs at Velkua.

The purpose of this article is to describe the discovery history and the characteristic features of the Velkua gold occurrence. The work is a continuation of mapping of the gold potential in the high metamorphic zone of southwestern Finland (Rosenberg 2000, Grönholm et al. 2005, Lehto & Kärkkäinen 2007).

Location and research methods

The Velkua gold occurrence is located 30 km west of Turku, and 1 km north of the village of Teersalo in the centre of Velkua archipelago, in the municipality of Naantali (Fig. 1). The discovery was made in a rocky hill surrounded by small fields and forest.

Exploration at Velkua started with mapping and sampling of the mineralized outcrops. Crushed bulk rock samples were chemically analysed and their heavy mineral contents were determined. Later, a ground geophysical survey, bedrock mapping, till heavy mineral studies, diamond core drilling and mineralogical studies were conducted.

Gold was analysed from the outcrop samples by ICP-MS using aqua regia leach and from drill core samples using the Pb fire assay method. Other metals were analysed by ICP-OES from aqua regia leach. Analyses were conducted by Labtium Oy.

Heavy mineral concentrates from drill core and outcrop samples were prepared from samples that were selected based on chemical analyses. Rock samples were first crushed to fine-grained material (90% < 1 mm). Gold and ore minerals were concentrated using a spiral separator and by panning the overflowed material several times to obtain both the gold-enriched fraction and the sulphide-rich fraction. Sulphide concentrates and hand-picked gold grains were mounted in epoxy resin and polished. These were studied by ore microscopy and with an SEM-EDS electron microscope and microprobe at the laboratories of GTK (Appendix 1). The mineralogy of three heavy mineral samples is included in this article.

BEDROCK

General geology

The Svecofennian in southern Finland has been divided into central and southern arc complexes (Korsman et al. 1997), also known as southern and central Svecofennia, where the latter is characterized by migmatites with trondhjemite leucosomes and metamorphism culminated at c. 1.88 Ga (Korsman et al. 1999, Mouri et al. 1999, Rutland et al. 2004, Lahtinen et al. 2009). In contrast, southern Svecofennia went through two events of deformation and metamorphism, at 1.88–1.87 Ga and 1.83–1.80 Ga, the latter characterized by granite leucosome in migmatites (Korsman et al. 1999, Väisänen et al. 2002, Mouri et al. 2005, Skyttä et al. 2006, Skyttä & Mänttäri 2008, Pajunen et al. 2008). Major unconformity between these two events is seen in the occurrence of lateritic paleosols (Lahtinen & Nironen 2010) and ≤ 1.87 Ga quartzites and meta-arkoses (e.g., Bergman et al. 2008) in southern Svecofennia.

Velkua is situated in the 1.90–1.80-Ga-old accretionary arc complex of southern Finland (Korsman et al. 1997), which comprises arc-type volcanism at 1.90–1.88 Ga with partly coeval plutonism at 1.89–1.87 Ga. Velkua is also located within the northern part of a microcline granite belt characterized by pre-, syn- and late-tectonic granites of the younger metamorphic event. Anorogenic rapakivi granite (1.59–1.57 Ga) is located less than ten kilometres north of the Velkua area.

The bedrock at Velkua is composed of mica gneisses, volcanic rocks and granites, and either belongs to the western extension of the Häme belt or is part of the Uusimaa belt. Volcanic rocks include amphibolites and quartz feldspar gneisses with carbonate rock interlayers (Karhunen 2004), but similar associations are met in both belts (Kähkönen 2005). The central part of the Uusimaa belt comprises arc-type rocks varying from an island arc (1.895 Ga) to mature arc affinity (1.878 Ga) (Väisänen & Mänttäri 2002), and ages of 1.89–1.88 Ga have been recorded from the Häme belt (Kähkönen 2005, Saalmann et al. 2009). Syntectonic (c. 1.88–1.86 Ga) Kakskerta enderbite obtained a new metamorphic overgrowth in the Turku area (Fig. 2) during granulite facies metamorphism, with peak metamorphism dated at 1824 ± 5 Ma (Väisänen et al. 2002). It is assumed that the supracrustal rocks at Velkua have an age of 1.90–1.88 Ga and that they have been affected by both metamorphic peaks, where the high grade metamorphism correlates with the younger 1.83–1.81 Ga event detected in the Turku area.

Local bedrock

The host rock of the Velkua Au prospect is a 100–300-m-wide N–S-oriented amphibolite-hornblende gneiss surrounded by mica gneisses cut by microcline granites (Fig. 4). Gneisses are often either migmatized or intruded by numerous granitic pegmatites (Fig. 5).

Mafic metavolcanic rock (amphibolite) is bordered on its eastern side by layered metagreywacke and on the western side by light-coloured massive mica gneiss (originally a psammite). Gneisses also occur within the surrounding microcline granite as relict bands and lenses that show different degrees of melting. A 10-m-wide north–south-oriented mylonite zone runs along the eastern slope of the hill.

Amphibolite is a dark-grey or green, massive or banded and fine- to medium-grained rock that locally shows remnants of volcanic structures, such as layering and phenocrysts. Biotite and clinopyroxene are common mafic minerals in addition to the most abundant hornblende. Quartz occurs in a granoblastic matrix and as lenses and usually thin veins. Tourmaline and apatite are locally abundant in the amphibolite. There are 1–20-m-thick interlayers of intermediate and felsic rocks: quartz-plagioclase or biotite-plagioclase gneiss and clinopyroxene-bearing gneisses. Clinopyroxene-bearing gneiss occurs in the eastern contact zone of the amphibolite against migmatitic greywacke. The contact between amphibolite and the clinopyroxene-bearing gneiss is gradual.

The strongly metamorphosed and partly melted metagreywacke is composed of gently folded 10–40-cm-thick alternating psammitic and pelitic layers. The rock hosts subconformable but irregular leucosome veins, bands and lenses. Younger leucosome and pegmatite veins cut the rock in the direction of second phase schistosity. Pelitic layers comprise large garnet aggregates and cordierite porphyroblasts.

The volume of granite pegmatite varies between 22 and 30% within the mineralized amphibolite unit. Tourmalines and garnets are common in both pegmatite and gneisses. Pegmatite also contains löllingite, pyrrhotite and sporadic lenses of sericite.

Typically, the colour of the mylonite is greenish or bluish, and characteristic secondary minerals are carbonate, sericite after totally saussuritized feldspar, blue quartz and chlorite. Locally, pyrrhotite and arsenopyrite also occur, probably as remnants of sulphides in the primary rock. All

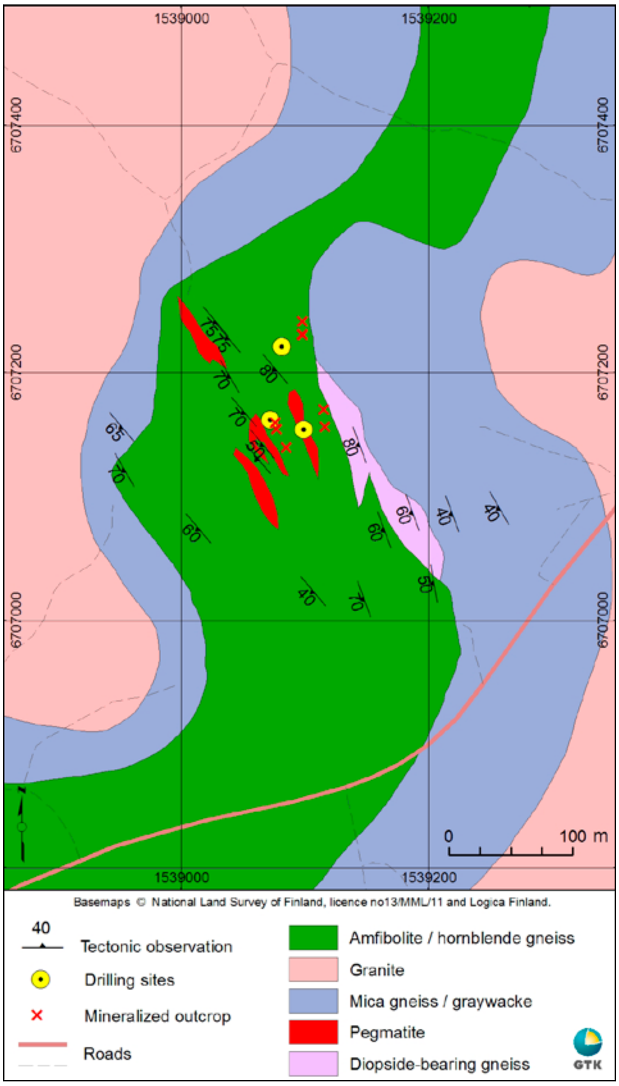


Figure 4. Bedrock map of the study area. Basemap © National Land Survey of Finland, licence no 13/MML/12.

Figure 5. Amphibolite containing a leucosome vein network and a pegmatite vein intruding along the strike of the second stage schistosity.

these features and their crosscutting nature indicate that the mylonite formed rather late and during retrograde metamorphism.

The orientation of layering and predominant schistosity is 140–150° and the dip is 40° SW or steeper. Schistosity is cut by almost east–west-striking (100–110°) second schistosity, in which direction minor pegmatite veins and apophyses intrude. The amphibolite unit is gently folded. About 1 km north of the mineralized outcrops the strike is locally east–west oriented and the outcrops contain numerous quartz veins but no sulphides. Instead, patches of garnet and a network of leucosome, aplite and pegmatite veins are common (Fig. 5).

GOLD MINERALISATION

Discovery

The hill where the discovery occurred is composed of a 30–50-m-broad, locally rusty amphibolite that locally contains narrow quartz veins and disseminated pyrrhotite and arsenopyrite. Amphibolite has interlayers of felsic or intermediate biotite-plagioclase and quartz-plagioclase gneiss, and is intruded by a network of granite pegmatites. On the northern end of the hill, within felsic gneiss, there is two-meter-wide quartz–feldspar rock with abundant arsenopyrite.

Anomalous Au contents are found in almost every sample from the discovery hill. Chemical analyses from sulphide-bearing outcrop samples indicated grades between 1.1 and 3.7 ppm Au. One whole rock sample was crushed for heavy mineral studies (JA-07-29). The heavy mineral concentrate (0.66 kg) contained 55 gold grains, 17 of which were rather large, being 0.26–0.66 mm in size. The total volume corresponds to a grade of 31 ppm Au in the sample (Pekka Huhta, personal communication). Another concentrate was also prepared because the chemical analyses did not correspond with the results of the heavy mineral test. The new sample contained 86 gold grains, but the proportion of large grains was small. The calculated grade according to the volume of grains was as 2.5 ppm Au in the sample, which correlates well with the chemical analysis.

Mineralized rocks

Amphibolite hosts several parallel 0.5–8-m-thick zones with disseminated arsenopyrite, pyrrhotite, scheelite and tourmaline. Biotite-plagioclase gneiss interlayers also contain tourmaline and arsenopyrite. Scheelite is met as individual grains and thin stripes most commonly associated with clinopyroxene. Tourmaline and biotite are most abundant in arsenopyrite-enriched zones.

Chemical analyses from drill cores indicate increased gold contents (>100 ppb Au) in a drilling section at least 30 m long. Clearly Au mineralized rocks (>0.5 ppm) occur in three parallel 1–9-m-wide zones that are separated by barren rock or rock with only slightly elevated Au contents (>0.02 ppm).

Two main types of Au mineralization can be distinguished: a) lower grade ore with disseminated arsenopyrite and pyrrhotite in rocks of variable composition, and b) higher grade ore in banded amphibolites with only weak arsenopyrite and pyrrhotite dissemination but having individual scheelite grains and visible gold. The rocks hosting high-grade ore are similar in appearance to barren rocks. An 8-m core section of the high grade ore contained an average of 5.3 ppm Au. The highest grade was 24.2 ppm Au at 1 m. In the lower grade Au-mineralised zone the gold content is usually 0.5–2 ppm in sections from 1 to 4 m.

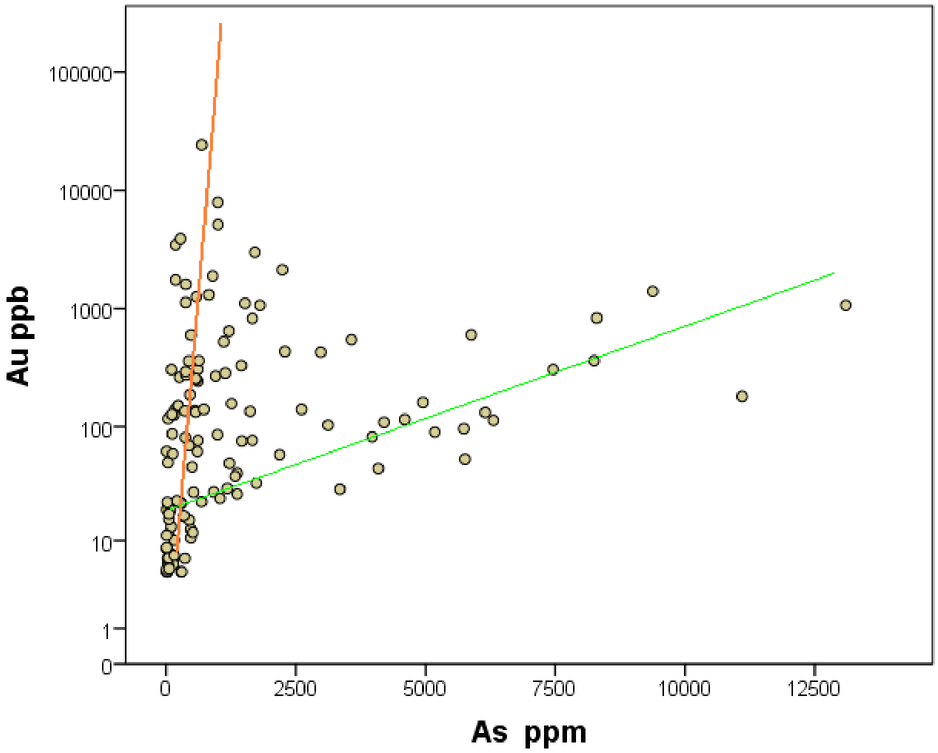


Figure 6. A correlation diagram of gold (ppb) and arsenic (ppm) in drill-core samples from Velkua; values on the y axis (Au) are logarithmic. Correlations of As and Au in low grade mineralization (green) and high grade mineralization (red) are shown as lines.

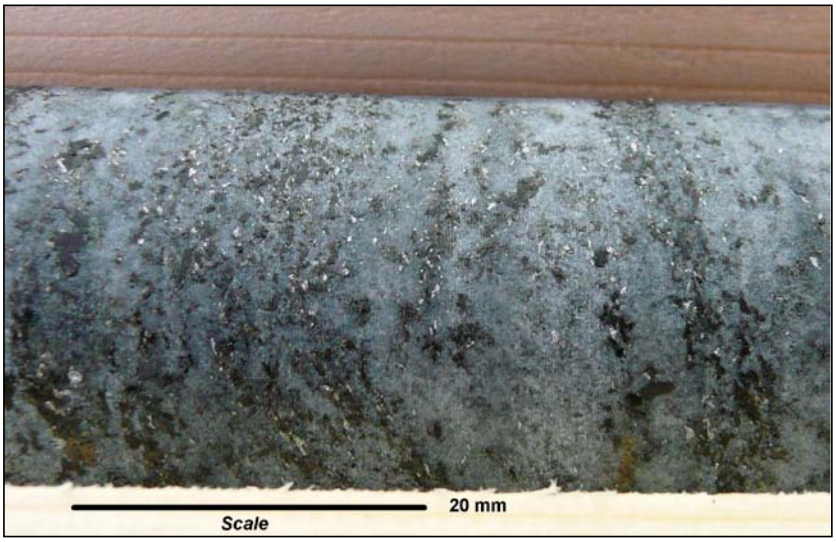


Figure 7. A typical arsenopyrite dissemination in a hornblende gneiss, drill hole R302.

Arsenic contents are typically between 0.18 and 1.3% As. Gold correlates to some extent with arsenic when As values are high and Au values are relatively low, but in samples with more than 1 ppm Au the As values are usually less than 0.2% (Fig. 6).

Characteristic features for both mineralized and barren rocks are thin quartz veins, clusters of quartz and feldspar-quartz veins, patches of coarse-grained clinopyroxene in quartz-feldspar veinlets, biotitization and tourmaline.

Typically, the high-grade mineralization is bordered by an increased amount of tourmaline and alteration of hornblende (uralite) to biotite. Locally, quartz and feldspar-quartz veins are also bordered by tourmaline prisms. Light bands are comprised of leucosome material or common coarse-grained clinopyroxene in feldspar-quartz matrix and veins (Fig. 8). Locally, there is an increased amount of coarse-grained biotite.

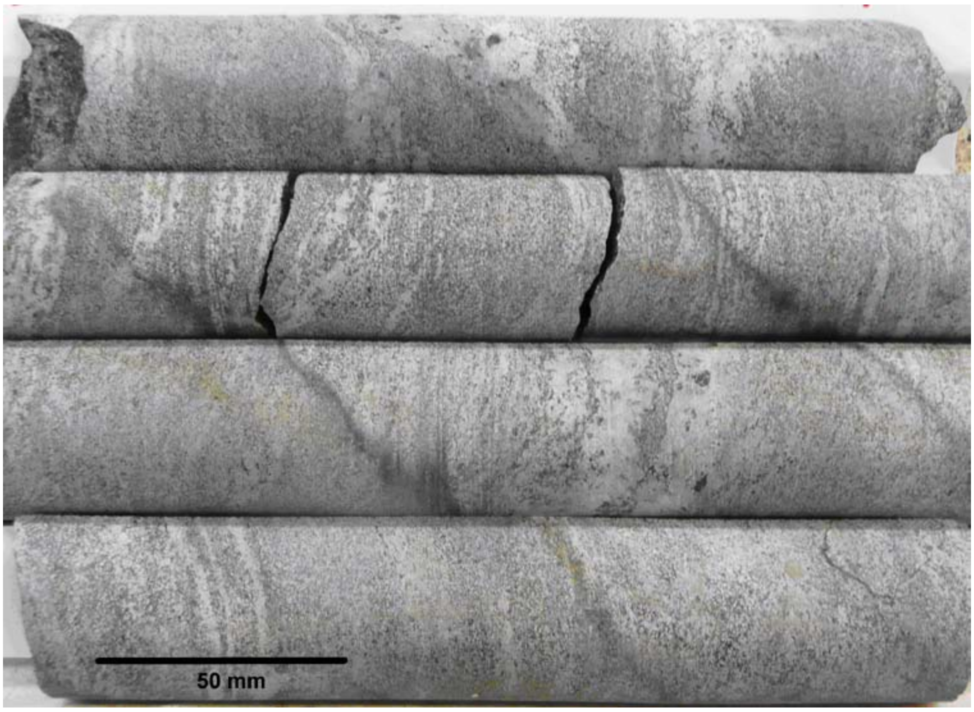


Figure 8. Au-mineralized amphibolite from Velkua (24.2 ppm Au, R301 35.25–36.25 m). There are only small amounts of sulphides in this section. Light bands are leucosomes and quartz veins.

Ore minerals

The major ore minerals in Au-mineralized rocks are pyrrhotite and arsenopyrite. Other common minerals are löllingite, ilmenite, chalcopyrite and ilmenomagnetite. Accessory minerals include gold, native bismuth and ullmanite.

Sulphide minerals occur as evenly distributed fine-grained dissemination (Fig. 7) or as minor networks composed of different sulphide minerals. Sulphides commonly occur in bands with abundant mica. In most cases, pyrrhotite is more abundant than arsenopyrite, which occurs locally as well-developed crystals. In strongly deformed rocks, pyrrhotite intrudes into and between biotite flakes and cuts veins that fill micro faults. Chalcopyrite typically occurs as inclusions in pyrrhotite and locally also as inclusions in arsenopyrite.

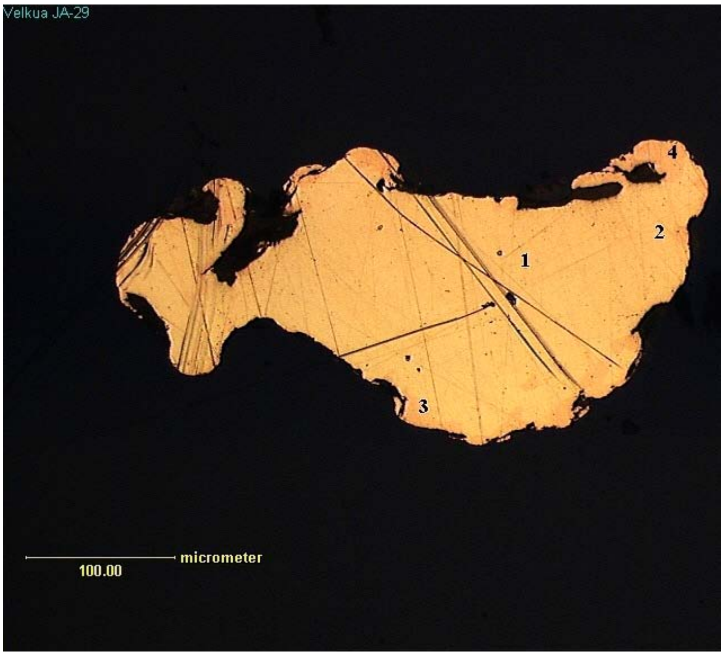
Mineralogy of gold

Gold occurs as discrete grains with silicates and arsenopyrite. The grain size typically varies between 10–200 µm (Fig. 9). Arsenopyrite and löllingite occur locally in small composite grains with gold in silicates. More often, coarse-grained As sulphides host gold inclusions or in some cases make gold up a core for enveloping arsenopyrite (Fig. 10), or make up a group of minute inclusions within arsenopyrite (Fig. 11). Native bismuth is a typical trace mineral with gold.

Gold is rather pure, and according to 77 microprobe analyses the mean composition is 93% Au (usually 92–94%) and 7% Ag (Appendix 1). Silver is more abundant (10–30% Ag) in coarse-grained gold grains (100–300 µm) in the sulphide-rich low-grade ores, where some gold grains also contain traces of copper (3% Cu). Small gold inclusions in arsenopyrite also usually contain higher contents of silver.

Gold is met as inclusions in quartz, plagioclase and hornblende in the high-grade ores (Fig. 12). In transmitting light, the gold grains look like normal minute opaque dissemination in quartz, plagioclase and hornblende and at the contact of tourmaline (Fig. 12). The composition and texture of the metamorphosed host rock of the high-grade ore does not differ from the surrounding equigranular amphibolite, with only a few gold grains. There is practically no arsenopyrite in this section. Locally, gold grains are arranged in dissemination bands oriented along the main schistosity (R301-35.00). The gold grains inside silicate minerals are small with a typical grain size of 10–30 µm. The shape is partially euhedral and gold sometimes occurs as composite grains with löllingite or bismuth (Fig. 13).

a)



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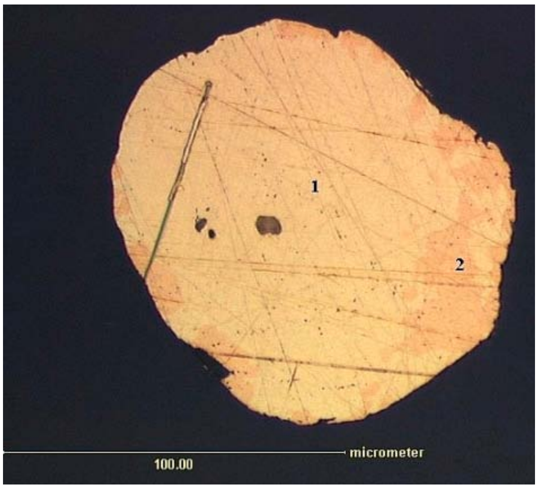

Figure 9. Gold grains separated from a crushed bulk rock sample from the discovery outcrop. Fig. 9a points 1 and 2 have 93% Au and 7% Ag, and points 3 and 4 have 100% Au. Fig. 9b point 1 (lighter inner side) has 91% Au and 9% Ag and point 2, showing deep yellow patches on the outer rim, has 99.7% Au and 0.3% Ag;

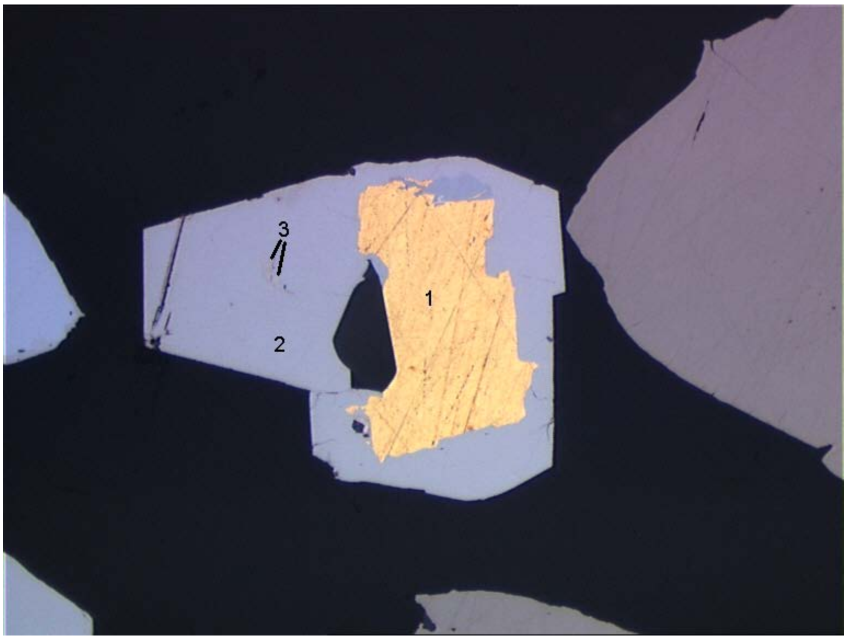

Figure 10. A composite grain of gold (1) and arsenopyrite (2) with small maldonite inclusions (3). The composition of gold is 94% Au and 6% Ag and the composition of maldonite (Au_2Bi) is Au 63% Au and 33% Bi.

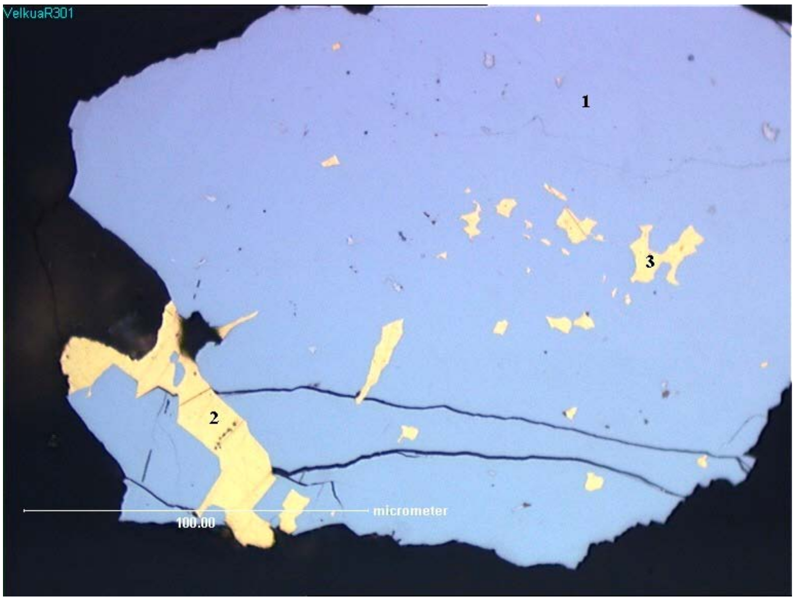

Figure 11. Gold inclusions in arsenopyrite (1). The composition of gold (2–3) is 95% Au and 5% Ag. (Heavy mineral concentrate R301-35.25–36.25.)

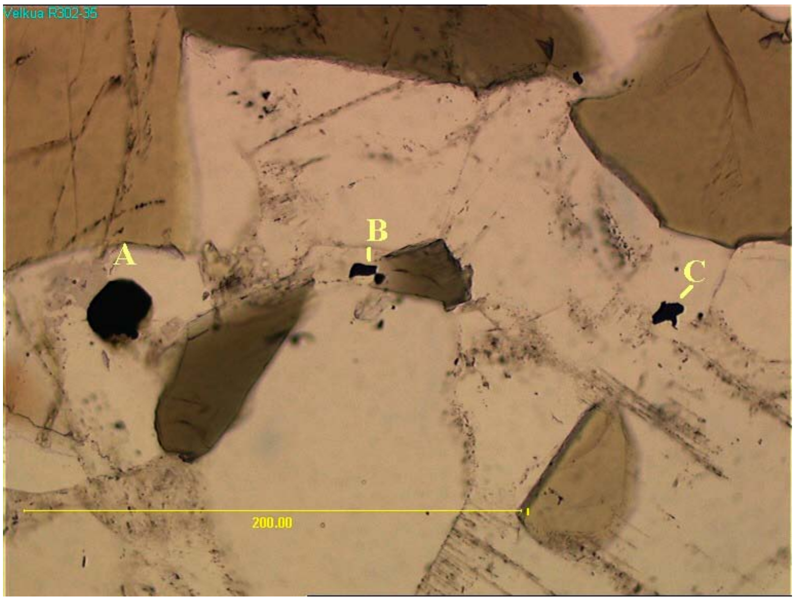

Figure 12. Gold grains (A–C) in a granoblastic matrix of an amphibolite. The composition of grain A is 94% Au and 6% Ag. Grain B is composed of 94% Au and 6% Ag; grain C is composed of 95.5% Au and 4% Ag; grain D is composed of 94% Au and 6% As (polished thin section R301-35.00).

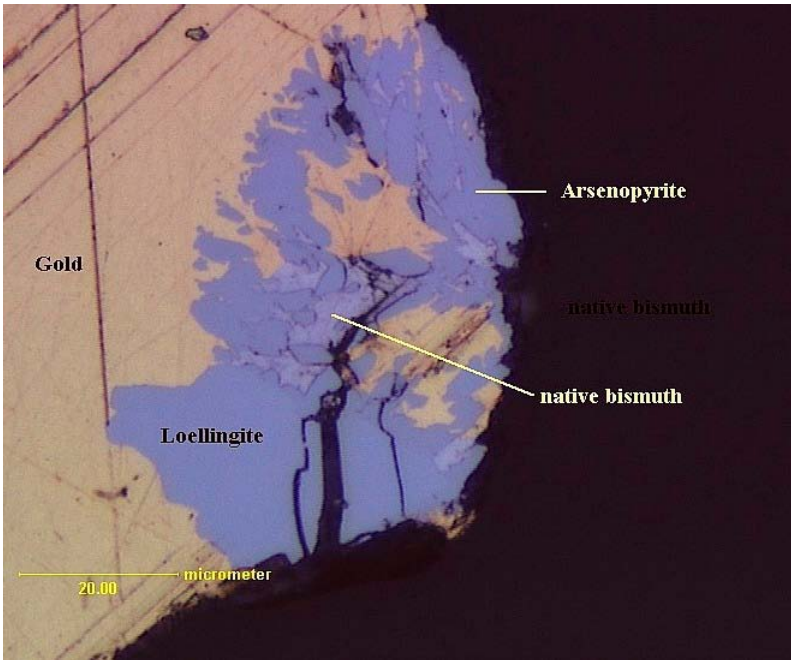

Figure 13. A composite gold grain including löllingite, native bismuth and arsenopyrite. The composition of gold is 95% Au and 5% Ag. (Heavy mineral concentrate R301-35.25–36.25).

Gold is also met as a swarm of inclusions in arsenopyrite in the low-grade mineralizations. Arsenopyrite is usually rather coarse grained and euhedral and commonly has several clear zones or irregular patches of löllingite in the core. Native bismuth and rarely ullmanite were met with gold and arsenopyrite.

A curious feature of the gold grains separated from a crushed outcrop sample of the low-grade arsenopyrite-dominated ore is that the coarse gold grains were clearly zoned. They had a rim or patches of deep yellow (pure) gold surrounding the grains of lighter-coloured Ag-bearing gold (Fig. 9b).

DISCUSSION

Arsenic is a common constituent in late-orogenic or post-peak metamorphic orogenic gold deposits of Southern Finland (Luukkonen 1994, Saalmann et al. 2009). At Velkua, the occurrence of gold is bimodal when compared to arsenic (Fig. 6). Spatially, arsenopyrite is common in a broad zone within and around the Au mineralized zone. However, the Au content in arsenopyrite-rich rocks is usually low, being <0.5–2 ppm. The high grade gold ore contains only small amounts of arsenopyrite and sulphides in general.

Arsenopyrite and Fe sulphides also occur in the mylonite rock located in the eastern part of the Velkua Au prospect. The rock has a retrograde mineral composition: chlorite instead of biotite and hornblende and carbonate instead of plagioclase. Based on retrograde silicate mineralogy, mylonite must be clearly younger than the Au mineralization, and the sulphides are probably remnants of primary sulphides.

In the high-grade ore, gold occurs as inclusions in silicates crystallized during prograde high-grade metamorphism that also caused partial melting of host rocks. Gold is thus older than the peak metamorphism, which we correlate with the younger 1.83–1.81 Ga metamorphic event. Based on available data, it is not possible to state whether the gold mineralized during the early stages of this younger metamorphism or during the earlier tectono-metamorphic event at c. 1.87 Ga (Väisänen et al. 2002). The early metamorphic evolution could have taken place in the greenschist-amphibolite transition zone, similarly to what has been proposed for the metamorphosed Griffins Find Gold deposit in Australia (Tompkins & Grundy 2009). However, gold mineralization at Velkua is closely associated with mafic volcanic rocks, and a synvolcanic environment for the gold enrichment cannot be ruled out. An interesting observation is the zoning of gold in the large gold grains of the Velkua occurrence. Leaching of Ag from the surface of Ag-Au alloy grains or precipitation of authigenic gold on the surface of grains due to surface weathering is unlikely, because the same outcrop sample contained fresh, unaltered arsenopyrite and pyrrhotite. Zoning of the gold grains could be explained as resulting from at least two hydrothermal stages.

CONCLUSIONS

The discovery of gold at Velkua proves that elevated gold contents in bedrock samples may indicate the occurrence of gold mineralization somewhere in the vicinity. The Velkua discovery was made on the western end of an E–W-trending Au anomaly in the nationwide lithogeochemical Au map. This anomaly runs through the Vaskio area close to the Korvenala and Kultanummi gold prospects at Paimio and Halikko, and defines a new Au province in Finland.

An important focus of future studies at Velkua is the assessment of the dimensions and grade of the deposit to determine its economic significance. There have been positive results concerning both the quality and grade, but only based on a few drilling profiles. Gold occurs as discrete grains, and grades up to 3–5 g/ton have been met in sections of 3–9 meters.

An open question that requires further investigation is the genesis of the mineralization. The relationship between high- and low-grade ores and the role of arsenic in the mineralization should be looked into more closely. A key question is the metamorphic history and the metamorphic mineralogy of the gold mineralization. The Velkua Au occurrence is a metamorphosed Au deposit, but whether it was originally an orogenic Au deposit, epithermal deposit or a mixture of these two remains unresolved. Further data on the mineralogy of gold could also provide information on the history of the mineralization.

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Appendix 1. Electron microprobe analyses of gold and other ore minerals of Velkua. Samples were as polished thin sections and concentrates in epoxy slabs. Analyses were made at Research laboratory of the Geological Survey of Finland.
Analysing conditions: acceleration voltage = 20 kV, electron beam current and diameter = 10 nA and 1 µm respectively. Natural minerals and metals were employed as standards.
Electron Microprobe / operator: Cameca SX100 & Lassi Pakkanen, GTK.

Ag wt-%	S wt-%	Fe wt-%	Cu wt-%	Ni wt-%	Sb wt-%	Cd wt-%	Au wt-%	Bi wt-%	As wt-%	Se wt-%	Hg wt-%	Total wt-%	Sample / ring (r) and grain (gr) or group (gp) / point (p)	Mineral
0	20.62	35.76	0	0.01	0.02	0	n.d.	0	43.8	0.27	n.d.	100.51	R301con.E/r A/p1	arsenopyrite
6.19	0.04	0.02	0	0	0.01	0.14	93.4	0	0.02	0	n.d.	99.83	R301con.E/r A/p2	gold
0.08	0.05	1.75	0	0	0.01	0.02	62.98	33.34	0.14	0.03	n.d.	98.45	R301con.E/r A/p3	maldonite
7.43	0.07	0.07	0.02	0	0.01	0.1	92.82	0	0.08	0.03	n.d.	100.69	R301con.E/r A/p4	gold
11.3	0.04	0.8	0	0.02	0	0.11	87.69	0.01	0.07	0	n.d.	99.93	R301con.E/r B/p1	gold
11.1	0.11	1.12	0	0.02	0	0.12	87.41	0	0.31	0.02	n.d.	100.32	R301con.E/r B/p2	gold
5.1	0.02	0	0.13	0	0.01	0.02	94.2	0	0.03	0.01	n.d.	99.65	R301con.A/r A gr a/p1	gold
0	1.65	26.53	0.03	1.37	0	0	n.d.	0	87.53	0.42	n.d.	100.09	R301con.A/r A gr a/p2	löllingite
0	0.04	0.58	0	0.02	0.03	0	n.d.	95.02	0.18	0.01	n.d.	95.89	R301con.A/rA gr a/p2	löllingite,
0.04	17.25	32.88	0.02	0.26	0	0	n.d.	0	48.32	0.3	n.d.	99.16	R301con.A/r A gr a/p4	arsenopyrite
5.95	0.03	0	0.01	0	0	0.07	93.62	0.06	0.02	0	n.d.	99.78	R301con.A/r A gr b/p1	gold
0.03	37.49	62.55	0.01	0.05	0	0	n.d.	0.12	0.6	0.03	n.d.	100.44	R301con.A/r A gr b/p2	pyrrhotite
0.02	17.56	33.74	0.01	0.25	0.01	0	n.d.	0	47.68	0.29	n.d.	99.66	R301con.A/r A gr b/p3	arsenopyrite
0.03	14	1.32	0	25.39	52.63	0	n.d.	1.91	2.35	0.44	n.d.	99.31	R301con.A/r A gr b/p4	ullmannite
5.35	0.01	0.17	0	0	0.01	0.07	94.18	0	0	0	n.d.	99.82	R301con.A/rA gr b/p5	gold
6.99	0.2	0	0	0	0	0.04	93.05	0.11	0.03	0	n.d.	100.27	R301con.A/rA gr c/p1	gold
0.03	17.85	33.52	0.01	0.32	0	0	n.d.	0	48.07	0.3	n.d.	99.72	R301con.A/rA gr c/p2	arsenopyrite
0	0	33.67	0.01	0.25	0.01	0	n.d.	0	48.18	0.31	n.d.	99.76	R301con.A/rA gr c/p3	arsenopyrite
0.02	36.35	61.09	0	0.17	0	0	n.d.	0	0.03	0.01	n.d.	97.8	R301con.A/rA gr c/p4	pyrrhotite
0.02	18.5	33.38	0.04	0.5	0.02	0	n.d.	0	47.7	0.25	n.d.	100.59	R301con.A/r B/p1	arsenopyrite
7.87	0.02	0	0.03	0	0	0.13	92.09	0.07	0	0.01	n.d.	100.33	R301con.A/r B/p2	gold
2.63	0.03	0	0.04	0	0	0.06	96.7	0.05	0.04		n.d.	99.61	R301con.A/r B/p3	gold)
0.01	18.44	35.04	0.02	0.02	0.03	0	n.d.	0	46.79	0.3	n.d.	100.79	R301con.A/r C/p1	arsenopyrite
4.41	0.03	0.31	0.01	0	0	0.02	94.36	0.02	0.01	0	n.d.	99.25	R301con.A/r C/p2	gold
4.38	0.04	1.2	0	0	0	0.03	92.58	0	0	0	n.d.	98.28	R301conc.A/r C/p3	gold
7.16	0	0.01	0.08	0	0	0.13	92.91	0.13	0	0	n.d.	100.49	JA-29Acon./gr A/p2	gold
0.32	0.02	0.01	0	0.02	0		99.29	0.13	0.01	0	n.d.	99.83	JA-29Acon./gr A/p4	gold, border
18.46	0.02	0	0	0.03	0	20	81.44	0	0	0	n.d.	100.54	JA-29Aconc./gr B/p1	gold
0.55	0.01	0	0.01	0.01	0	0	99.38	0.06	0	0	n.d.	100.1	JA-29Aconc./gr B/p2	gold

Appendix 1. cont.

Ag wt-%	S wt-%	Fe wt-%	Cu wt-%	Ni wt-%	Sb wt-%	Cd wt-%	Au wt-%	Bi wt-%	As wt-%	Se wt-%	Hg wt-%	Total wt-%	Sample / ring (r) and grain (gr) or group (gp) / point (p)	Mineral
0.84	0.01	0.01	2.80	0.01	0	0.06		0.05	0	0	n.d.	99.16	JA-29Aconc./gr C/p1	gold, core
0.23	0	0	0.06	0	0	0.05	99.53	0	0.01	0	n.d.	99.94	JA-29Aconc./gr C/p2	gold, border
0.73	0.04	0.01	0.02	0	0	0.08	98.07	0	0	0	n.d.	99.02	JA-29Aconc./gr D/p4	gold
30.09	0.04	0.01	0	0	0.02	0.31	69.83	0.02	0	0	n.d.	99.37	JA-29Aconc./gr E/p1	gold, core
1.74	0.03	0	0.02	0	0.01	0.03	97.26	0.08	0	0	n.d.	97.21	JA-29Aconc./gr E/p2	gold, border
7.41	0.02	0	0.14	0.01	0	0.01	92.7	0	0.02	0.01	n.d.	100.32	JA-29Aconc./gr F/p1	gold, core
0.35		0.01	0	0	0		98.54	0	0.01	0.01	n.d.	99.00	JA-29Aconc./gr F/p2	gold, border
38.6	0.11	0	0	0.01	0	0.44	60.44	0	0.03	0	n.d.	99.73	JA-29Aconc./gr G/p1	Gold, core
1.64	0.12	0.01	0.01	0	0.01	0.05	97.96	0	0.02	0	n.d.	99.86	JA-29Aconc./gr G/p2	gold, border
9.37	0.03	0	0.01	0	0	0.07	90.22	0.1	0	0	n.d.	99.95	JA-29Aconc./gr H/p1	gold , core
0.33	0.02	0	0	0	0	0.03	99.5	0	0	0	n.d.	99.97	JA-29Aconc./gr H/p2	gold ,border
30.64	0.06	0.78	0	0.01	0	0.34	68.29	0	0	0	0	100.44	R302-61.00/r1/p2	Gold
0	0.01	0.96	0	0.08	0.38	0	n.d.	96.81	0.1	0.06	0.01	98.51	R302-61.00/r1/p3	Bismuth
0	0.85	25.05	0.01	1.25	0	0	n.d.	0	70.63	37	0	99.65	R302-35:00/rY/p1	löllingite
8.46	0.03	0.05	0.16	0	0.01	0.2	90.67	0.08	0.01	0	0	99.76	R302-35.00/rY p2	gold
6.13	0.01	0.83	0.19	0	0	0.17	92.71	0.03	0	0	0.05	98.14	R302-35.00/r1	gold in hbld
0	0.03	0.01	0.04	0	0.01	0.09	90.19	0.04	0.02	0	0	98.65	R302-35:00/r2/p1	gold
6.14	0.02	0	0.17	0.01	0	0.12	93.13	0.17	0.01	0.01	0	99.89	R302_35:00/r3/gr 3/p1	gold
6.19	0.02	0.18	0.19	0	0.01	0.13	93.7	0.03	0.01	0	0	99.18	R302-35:00/r3 gr 3/p2	gold
5.85	0.04	0	0.18	0	0.02	0.04	92.8	0.18	0	0.011	0	99.03	R302-35,00/r4 gr A/p1	gold)
4.95	0.02	0.06	0.05	0.02	0	0.04	93.03	0.06	0	0	0	98.32	R302-35.00/r4 gr B/p1	gold
4.65	0.06	0.07	0.14	0	0.01	0.08	92.48	0.04	0	0.01	0	97.61	R302-35,00/r4 gr C/p1	gold
5.73	0	0.24	0.01	0	0	0.03	91.81	0.01	0	0	0.01	97.90	R302-35,00/r4 gr D/p1	gold
5.23	0.01	0.3	0	0.01	0.04	0.05	91.18	0.03	0	0	0	96.91	R302-35.00/r5 gp A/gr1	gold
6	0.01	0.3	0.05	0	0	0.06	92.82	0.07	0.02	0	0	99.36	R302-35.00/r5 gp A/gr2	gold
7.78	0.02	0.14	0	0	0	0.06	92.15	0	0.02	0	0.02	98.25	R302-35,00/r5 gp A/gr3	gold
5.69	0.01	0.06	0.07	0.01	0	0.1	91.99	0.02	0	0.01	0	98.01	R302-35.00/r5 gp B/gr1	gold

Note: Zn, Mn, Co, Sn and Te were analysed; all results below detection limits.

Average elemental detection limit:

Ag	S	Fe	Cu	Zn	Mn	Ni	Co	Sb	Cd	Au	Bi
3244	629	868	1171	1350	927	977	651	1136	1932	3932	5407

As	Sn	Te	Se	Hg
1662	3175	2197	935	5286

Gold in Southern Finland: Results of GTK studies 1998–2011
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EXPLORATION AND THE MINERALOGY OF GOLD IN THE KULLAA AREA, SOUTHWESTERN FINLAND

by
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Kärkkäinen, N., Lehto, T., Pakkanen, L. & Rosenberg, P. 2012. Exploration and the mineralogy of gold in the Kullaa area, southwestern Finland. *Geological Survey of Finland, Special Paper 52*, 131–148, 15 figures, 1 table and 2 appendices.

This study formed part of the regional gold potential studies of the Geological Survey of Finland (GTK) in the high-grade metamorphic areas in southwestern Finland. The Kullaa area is located in the Palaeoproterozoic Pirkanmaa migmatite belt. The western end of the Pirkanmaa belt, delimited at its ends by NW–SE-oriented faults, is here named the Kullaa zone. It is within a structurally controlled area referred to in the literature as the Pomarkku tectonic block. The Kullaa zone is mainly composed of strongly metamorphosed migmatitic greywacke and mafic subvolcanic and intrusive rocks, and the metamorphic grade corresponds to upper amphibolite facies.

One objective of this exploration study has been to trace the source of tens of gold-mineralized boulders. GTK's main target has been the Välimäki gold occurrence, although observations of gold have been made along the whole zone, including drillings at Saarijärvi, 15 km NE of Välimäki. Prior to the presently-described studies, exploration in the Kullaa area was minimal, and the only known mineral deposit was a small Silmusuo gold occurrence that was studied in the 1950s and 1980s. In addition to the Välimäki, Silmusuo and Saarijärvi occurrences, there are other groups of mineralized boulders and boulder fans that originate from unknown sources.

Gold mineralization mainly occurs in mafic rocks related to shear zones, within or close to narrow quartz veins of different generations. The altered rocks related to gold mineralization are characterized by garnet, biotite, arsenopyrite, Fe sulphides and quartz. Gold commonly occurs in its native form and locally in composite grains with Bi and Te minerals. Individual gold grains are locally zoned so that a large proportion of the grain is Ag bearing and the border zone is pure gold.

Keywords (GeoRef Thesaurus, AGI): gold ores, mineral exploration, shear zones, gneisses, quartz veins, mineralogy, sulfides, geochemistry, Paleoproterozoic, Kullaa, Finland

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INTRODUCTION

Kullaa is located in southwestern Finland (Fig. 1) in the Svecofennian, 1.87–1.90-Ga old accretionary arc complex of central and western Finland (Korsman et al. 1997). The area named as the Kullaa zone in this paper is part of a larger structural area referred to in the literature as the Pomarkku block (Pietikäinen 1994, Pajunen et al. 2001, 2008). The Pomarkku block is a lithologically variable area surrounded by NW–SE oriented major faults and characterized by tectonic elements related to these structures (Fig. 2). The Kullaa zone is at the western end of the E–W-trending Pirkanmaa migmatite belt, which is characterized by turbiditic psammites, tonalite veined migmatites, black shales, various plutonic rocks and Ni occurrences in small ultramafic intrusions (Kähkönen 2005, Peltonen 2005). The basement of the sedimentary rocks has not been identified (Lahtinen et al. 2009).

The aeromagnetic map of the Kullaa zone and surrounding areas includes features that refer to asymmetrical folds, faults and shears that may be favourable for the mineralization of gold (Fig. 2). The Kullaa zone is cut at its western end by the NW–SE-oriented Kynsikangas (or Pori) shear zone (Pietikäinen 1994). The eastern end of the Kullaa zone is bordered by a group of fault/shear zones that is sub-parallel with the Kynsikangas zone (Pajunen et al. 2008).

Historically, the only known ore deposit in the Kullaa zone is the Silmusuo gold occurrence, which was studied by Outokumpu Oy during the 1950s and 1980s (Eilu & Pankka 2009). In general, mineral exploration in the Kullaa area was minimal before the gold studies carried out by the Geological Survey of Finland (GTK) since the late 1990s. The initial aim of these studies was to trace the source of tens of gold mineralized boulders and many boulder fans, which were found by amateur prospectors from several localities within the Kullaa zone (Fig. 3). GTK's main target has been the Välimäki gold occurrence close to the

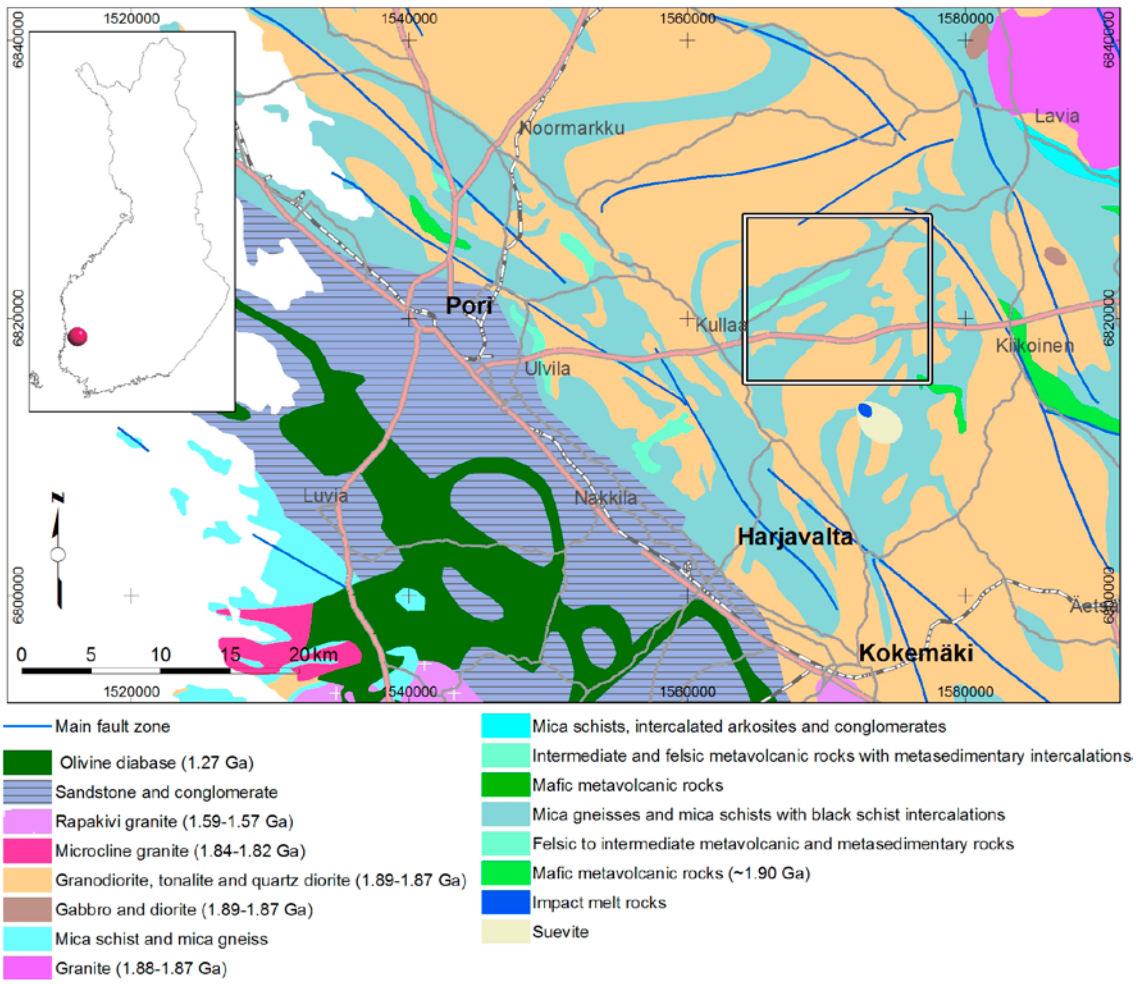

Figure 1. Location of the Kullaa area on the bedrock map of Finland. Framed area is the Välimäki target. Basemap © National Land Survey of Finland, licence no 13/MML/12.

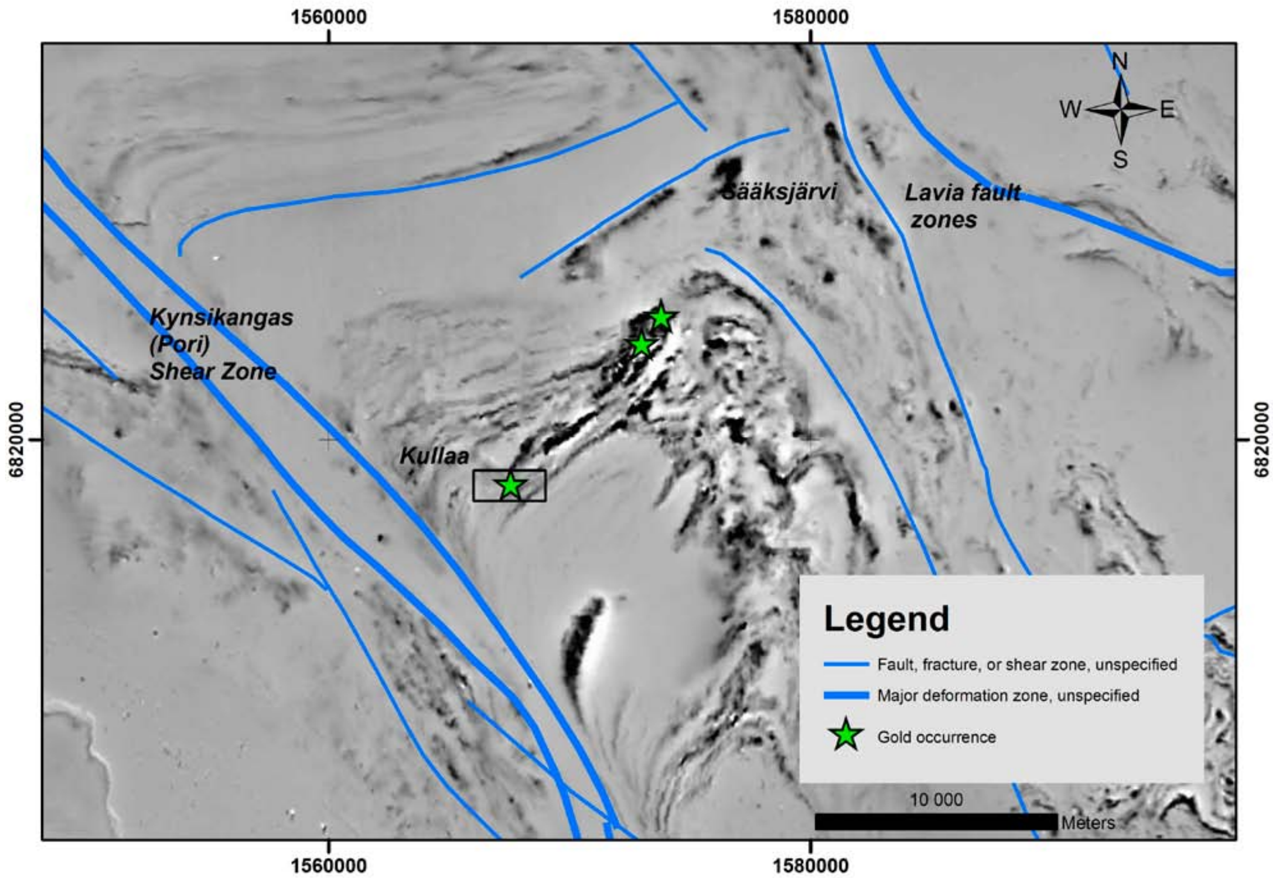

Figure 2. Airborne magnetic map of the Kullaa area. The Välimäki area is framed. Note the transversal orientation of the Kullaa schist zone as compared with the NW–WE-oriented major fault and shear zones according to bedrock map of Finland 1:1000 000 (Korsman et al. 1997).

village of Kullaa. In addition, intersections of ore-grade gold have been met in drillings at Saarijärvi, 15 km NE of from Välimäki.

Kullaa is one of the locations where GTK has carried out gold potential mapping in high grade metamorphic areas in southwestern Finland described in this volume (Kärkkäinen et al. 2012a, Grönholm et al. 2012). The purpose of this paper is to introduce the Kullaa research material available in GTK's databases, and present the key results for use in further studies. The work in the Kullaa area has periodically been carried out during more than 10 years, and the only public archive reports concern studies on the Välimäki gold occurrence (Rosenberg 2000, Lehto & Kärkkäinen 2006). A special study performed for this article described the mineralogy of the gold. The result of the microprobe analyses are presented in the appendix of the paper.

RESEARCH HISTORY

GTK started gold studies at Kullaa during 1997, and the main target area was Välimäki, close to the Pori shear zone. It was chosen due to numerous gold bearing boulders found by amateur prospectors. The results of preliminary till studies and a ground geophysical survey were positive (Rosenberg 2000), and later drillings during 2000 led to the discovery of a gold occurrence (Lehto & Kärkkäinen 2006).

Studies at Kullaa were continued with a reconnaissance gold geochemical survey in the Tampere and Pirkanmaa belts during 2001 and 2002 (Kärkkäinen et al. 2003, 2012b). During 2006, a detailed aerogeophysical survey was carried out at a line spacing of 100 metres (Lohva & Jokinen 2012). Unfortunately, the flight area was smaller than planned and did not cover the western end of the Kullaa schist zone, or the Kynsikangas shear zone.

The Saarijärvi gold occurrence, 15 km NE of the Välimäki occurrence (Figs. 2 and 3), is the other Au discovery by GTK in the Kullaa schist zone, and tentative drillings were carried out there during 2007. Gold at Saarijärvi was first found in an outcrop. During 2008, GTK continued work at Kullaa by conducting heavy mineral studies on till (Fig. 4). Since then, new data have been obtained each year from amateur prospectors through the layman's office of GTK.

Till studies

The bedrock of the Kullaa area is exposed in a few places. It is covered by basal till a few metres thick and small clay basins. Targeting was based on studies of various till materials. Methods included boulder prospecting (mineralized stones of till), heavy mineral studies (sand-sized till material), and regional and targeted geochemical surveys (clay-sized fine fraction of till).

The gold mineralized boulders make up several ice-driven boulder fans within the 20 km long Kullaa zone (Fig. 3). One of the boulder concentrations is clearly related to the known Silmusuo gold occurrence. The main interest in this work has focused on the source cluster of boulders in the Välimäki area close to the Kynsikangas fault. In addition to these ore showings, there are other groups or fans of mineralized boulders that originate from unknown sources. There is no boulder concentration at Saarijärvi.

Between the years 1995 and 1998, 54 boulder samples from the Kullaa area were analyzed by the layman's office of GTK. The average gold concentration in these analyses was 6.8 ppm Au, and the highest concentration was 42.4 ppm (Lehto & Kärkkäinen 2006). The host rock types of the boulders are various arsenopyrite-bearing biotite and hornblende gneisses, which include quartz veins and often pyrrhotite. One gold and arsenopyrite-rich sample (9.2 ppm Au and 34.4% As) contained a large amount of cobalt (e.g. 0.13% Co, K/981525).

The number of gold grains in till was deter-

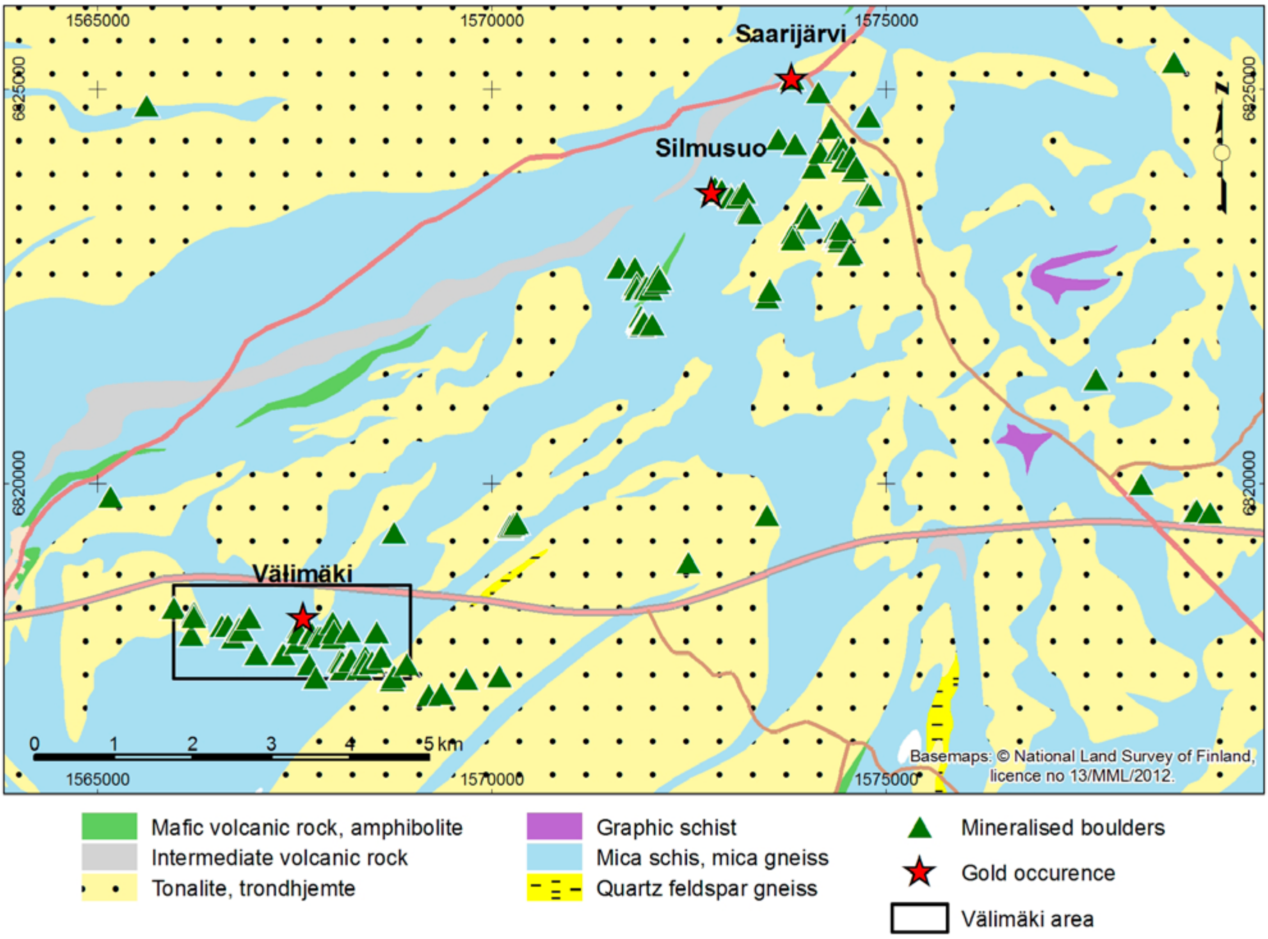

Figure 3. Lithological map of the Kullaa schist zone (DigiKP200 of GTK). Gold occurrences, mineralized boulders and the Välimäki area are included.

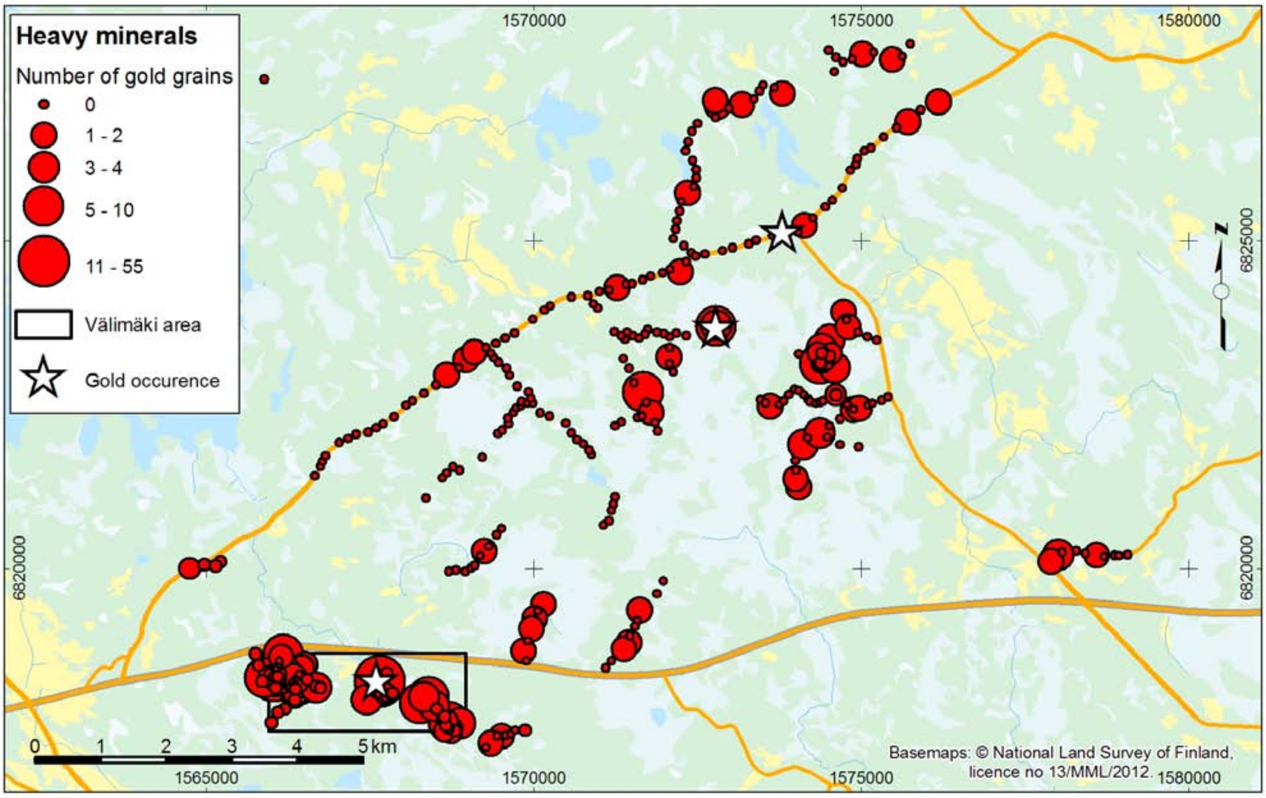

Figure 4. Distribution of gold grains (nuggets) in till of the Kullaa area. Numbers refer to the number of grains in a 10-l till sample. Samples from the Välimäki area are according to Rosenberg (2000). The Välimäki area is framed.

mined from heavy mineral concentrates that were prepared from 10-litre samples. Gold grains are common in till within the whole Kullaa zone (Fig. 4). Spatially, the number of gold grains correlates well with the geochemistry of gold in the fine fraction of till (Rosenberg 2000). Detailed geochemical surveys have revealed elevated Au concentrations in a restricted area SE of Välimäki (Rosenberg 2000).

Drilling

Observations of the lithology and mineralization from Välimäki have mainly been based on drill core data. Drilling at Välimäki was targeted at geochemical and heavy mineral anomalies, where the ground magnetic anomaly is weak compared to further east along the strike of the schists (Lehto & Kärkkäinen 2006). The change in the magnetic field was thought to be related to a fault zone and the alteration of magnetic minerals to non-magnetic during hydrothermal activity. It is assumed that in the hydrothermal process related to mineralization, iron leaches from magnetite and reacts with silicates to form metamorphic mafic silicates, and simultaneously pyrrhotite alters to form pyrite.

At Saarijärvi, drilling was used to estimate the dimensions of the mineralized rock within and outside the discovery outcrop.

Mineralogical studies

Mineralogical studies were conducted on polished thin sections and polished epoxy slabs that were formed from heavy mineral concentrations of crushed Au-rich core. Samples for the concentrates were selected according to the chemical analyses. The core was first jaw crushed to a fine fraction (more than 70% < 2 mm). Gold and sulphide minerals were then concentrated by a spiral separator. The outflow was panned many times to obtain all the fine-grained gold. The gold grains were picked out under binocular microscope and mounted in epoxy, which was polished for ore microscopy, SEM-EDS studies and microprobe analyses (WDS). Other polished epoxy slabs were made from the rest of the heavy mineral concentrate, mainly composed of sulpides, to study gold inclusions in the sulphides.

Microprobe analyses (WDS) were performed from 11 gold grains and 6 Au-Bi-Te composite grains. Electron microprobe analyses of minerals were performed by the wavelength dispersive technique using a Cameca SX100 instrument at the Geological Survey of Finland (GSF) in Espoo. Natural minerals and metals were employed as standards. Analytical results were corrected using the PAP online correction program (Pouchou & Pichoir 1986). Several determinations were made from 3 to 6 points of each grain, and the results are presented in Appendices 1 and 2.

BEDROCK OF THE KULLAA ZONE

The Kullaa zone belongs to Svecofennian Pirkanmaa migmatite belt, and is part of a structurally controlled area referred to in the literature as the Pomarkku tectonic block (Pietikäinen 1994, Korsman et al. 1999, Pajunen et al. 2001, 2008). The Kullaa zone is composed of mica schists and gneisses, mafic and intermediate volcanic and subvolcanic rocks, graphite-bearing schists and subconformable elongated felsic and mafic intrusions (Pihlaja 1994) (Fig. 3). The NE–SW orientation of the zone curves on its western end sub-parallel to the Kynsikangas shear zone (Fig. 2). Tectonic structures, namely layering and foliation, in the Kullaa area are very gently sloping (Pajunen et al. 2008).

The airborne geophysical map clearly displays the structure of the Kullaa schist zone, which makes up the northern limb of a complex fold of supracrustal rocks (Fig. 2). Slightly magnetic hornblende gneisses and amphibolites are seen as narrow magnetic anomalies (Fig. 5). Mainly low-magnetic mica gneisses are present in conductive zones in electromagnetic maps, because mica gneiss contains pyrite and graphite-bearing interlayers. Strongly recrystallized pyrrhotite-bearing metacherts are met close to Silmusuo.

The bedrock of Kullaa has recrystallized in the regional metamorphism under upper amphibolite facies conditions (Pietikäinen 1994). Most of the mica gneiss of the Kullaa zone is fine or medium-grained massive or banded migmatized rock with remnants of greywacke. Typical aluminium silicates are garnet and sillimanite and K-feldspar. Partial melting of the mica gneiss has occurred (Fig. 6a). In mafic igneous rocks, all pyroxenes (and olivine) are metamorphosed to hornblende and biotite, and garnet is a typical metamorphic mineral (Fig. 6b). Hornblende gneiss (medium-coarse grained) and amphibolite (fine grained) are interchanging and the rocks are mainly named ac-

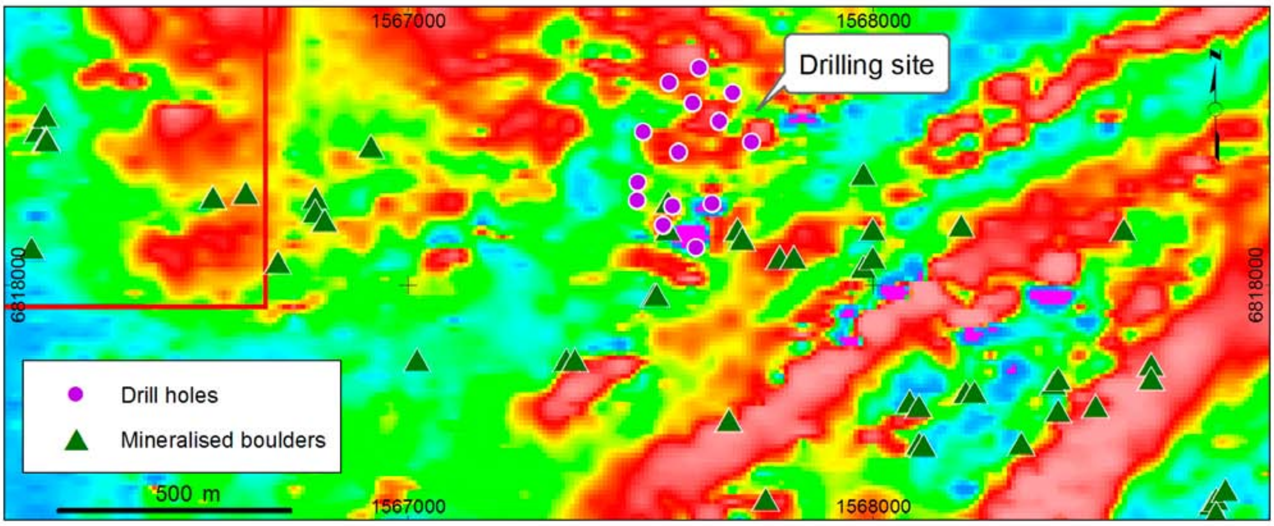

Figure 5. Ground geophysical magnetic map of the Välimäki area; the density of data points is 100 x 10 m. Warm colours indicate highly magnetic areas.

a)

b)

Figure 6. Typical rock types in the Kullaa schist zone: a) mica gneiss (diameter of core = 40 mm) and b) garnet amphibolite with relict phenocrysts of mafic minerals and plagioclase (size of coin = 26 mm).

cording to the grain size. Some of the hornblende gneiss clearly originated from metagabbro. The chemical composition corresponds to a mafic volcanic rock or gabbro (Table 1). Hornblende gneiss in the mineralized zones is strongly deformed and variably biotitized. Mafic rocks are also locally migmatitic due to leucosome veins and irregular granite pegmatite veins and lenses. Respectively, some felsic gneisses banded by leucosome veins are likely to have derived from granodiorite or tonalite.

Quartz veins are common at Välimäki, and locally the banded texture of mafic gneisses is due only to thin laminated quartz veins. Some of the thin veins are folded, the folded veins usually containing feldspar, and the contact against the host is gradual. Pyrrhotite, pyrite and commonly also arsenopyrite occur both in quartz veins and the surrounding host rock. Pyrrhotite is common in hornblende gneiss and amphibolite, and pyrrhotite-disseminated rock also locally contains arsenopyrite.

Table 1. Selected chemical analyses of mafic rocks of Välimäki: major elements and Cr, Ni and Cu determined by XRF, trace elements by ICP-MS, except gold >500 ppb by the Pb fire assay.

	R309 15.00–16.00	R309 16.00–17.00	R309 20.00–21.00
SiO_2 %	54.5	52.5	51.5
TiO_2 %	1.01	1.01	1.28
Al_2O_3 %	17.0	17.1	17.3
Fe_2O_3 %	9.86	10.4	11.01
MnO %	0.09	0.15	0.17
MgO %	3.63	4.02	4.23
CaO %	5.01	7.57	7.95
Na_2O %	2.70	2.50	2.67
K_2O %	2.22	1.14	0.89
Au ppb	12700	230	52
As ppm	651	550	159
Cr ppm	24	25	25
Cu ppm	233	101	141
Ni ppm	17	22	29
Te ppb	3160	144	15.6
S ppm	10100	3910	6310

THE VÄLIMÄKI GOLD OCCURRENCE

Gold mineralization occurs at Välimäki in shear zones and narrow sulphide veins within hornblende gneiss, amphibolite and mica gneiss, which alternate as beds some tens of metres thick (Fig. 7). In addition, the bedrock in the Välimäki area contains metagabbro (hornblende gneiss), granodiorite or tonalite (biotite-plagioclase gneiss) and partly assimilating thin granite pegmatite veins. The strike of bedding and schistosity is almost E–W-oriented and the dip is gently southwards.

The most intensive shearing is seen as biotite seams and thin sulphide veins. Some shear zones are brecciated or mylonitised and characterized by the entry of potassium feldspar and pyrite, and re-crystallization of biotite to coarse-grained flakes. Often the shears are only a few metres thick, but they are usually surrounded by thicker alteration zones, seen as arsenopyrite, pyrite and biotitization. They have clearly cutting or folded quartz veins or swarms of laminated quartz veins and garnet in mafic rock types.

There are gold-bearing sections in the whole drilling area of Välimäki (Fig. 8). High gold concentrations generally occur within intersections a couple of metres long. Arsenic correlates rather well with gold, although some Au-rich sections are low in As. For instance, in one drill hole there is an Au-rich section (13.9 ppm Au/1 m section) related to a 10-cm-thick massive arsenopyrite-chalcopyrite-pyrrhotite vein (Fig. 9). In the same drill hole (R309), another Au-rich section (12.7 ppm Au/m) contains only traces of arsenopyrite. However, the latter section contains some narrow quartz veins and Au-Te-Bi composite grains of microscopic size. The host rock in both cases is hornblende gneiss.

No characteristic feature has been recognized in the core to explain the elevated gold content in chemical analysis. In many sections there is barren rock that is clearly altered or strongly deformed and contains elevated numbers of quartz veins. As an example, one drill hole (R301) contains three different sections enriched in gold. None of the three Au-rich sections contains quartz veins, although the Au-enriched zones are surrounded by quartz vein swarms. Between 85.00–88.50 m, the slightly mineralized (150–550 ppb Au) garnet-bearing hornblende gneiss is sheared and partly mylonitized. In the mineralized rock, coarse-grained biotite replaces hornblende. Here, the surrounding low-Au rock contains quartz veins, disseminated arsenopyrite and fissures filled by arsenopyrite and pyrite, and it appears more promising for gold than the mineralized rock. Between

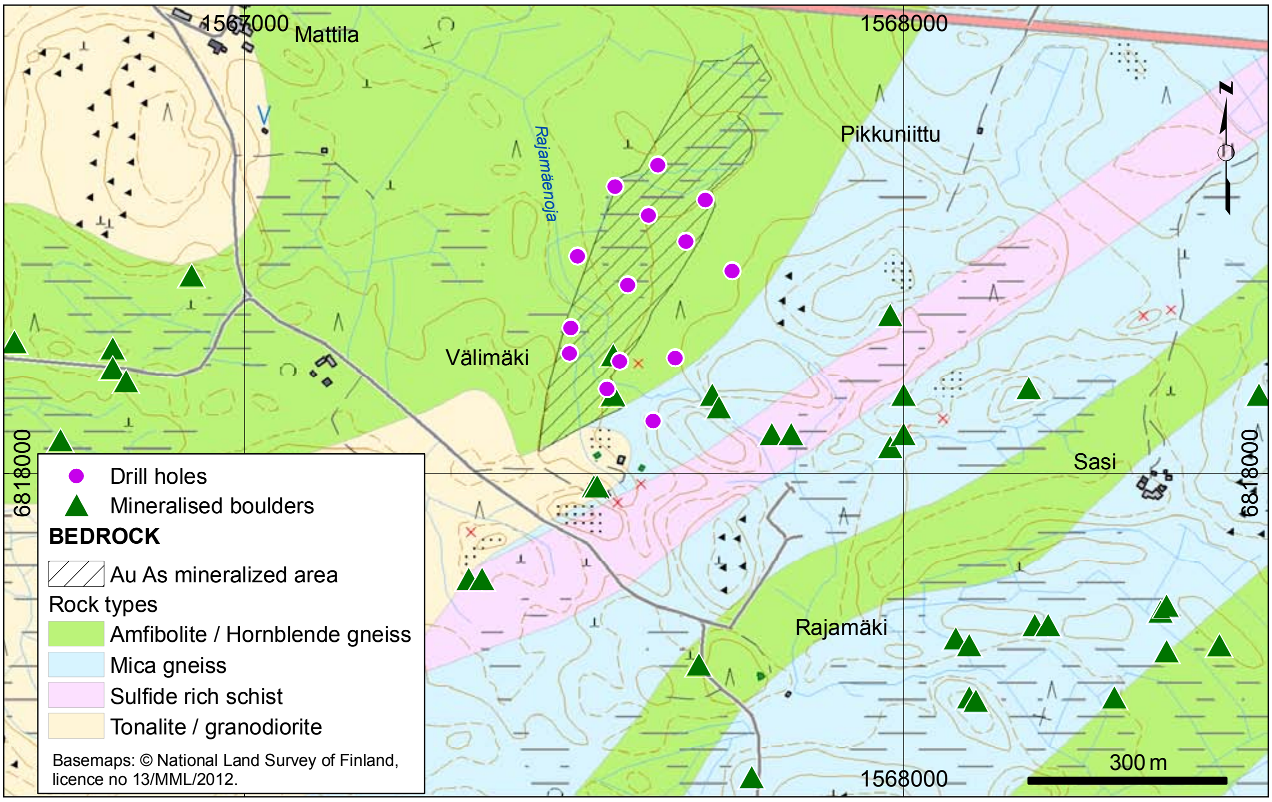

Figure 7. Lithological map of the Välimäki area.

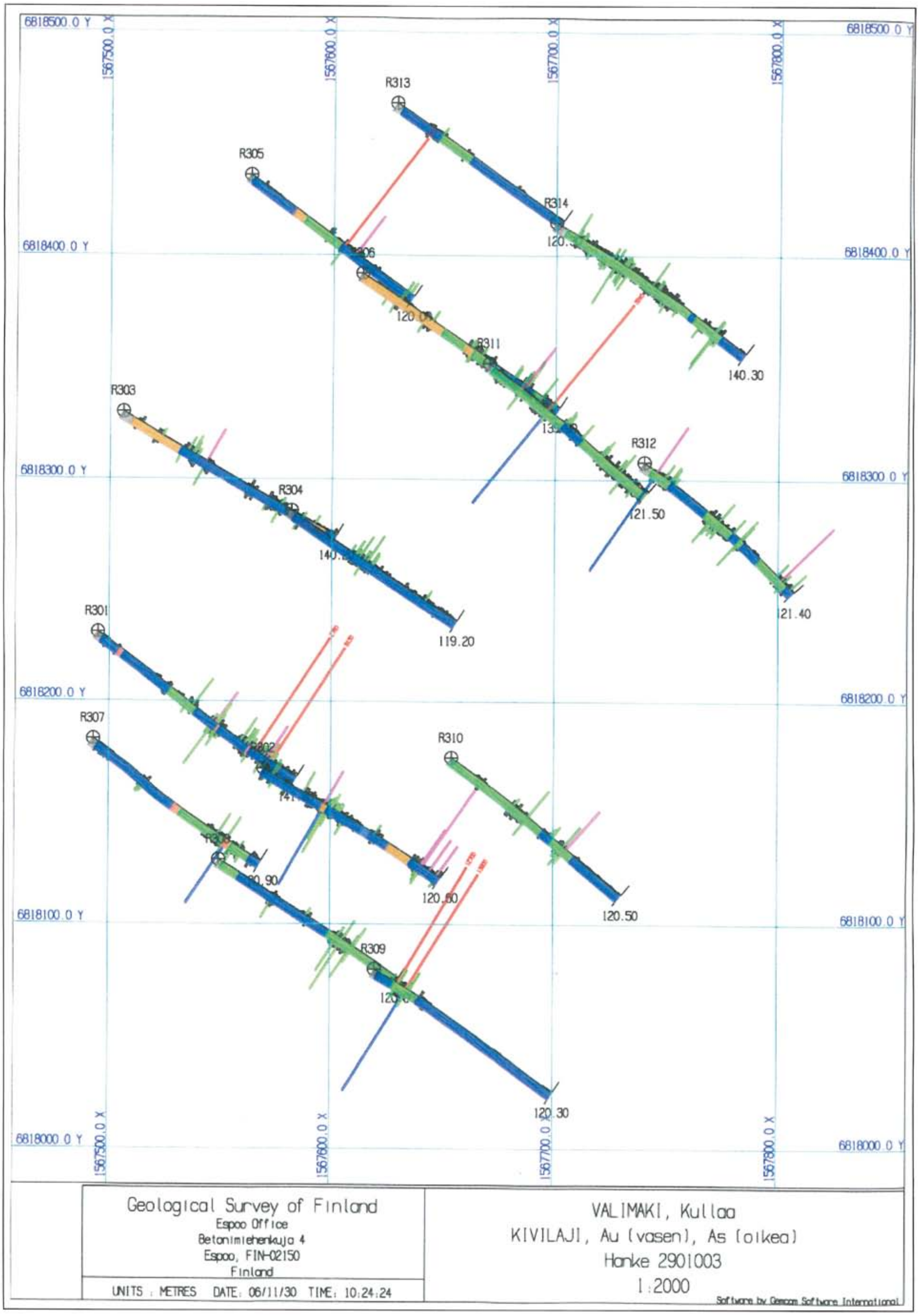

Figure 8. A map of Au distribution in drilling at Välimäki, projected to the surface. Gold is on the left and arsenic on the right right in the logs. Chemical analyses are usually performed on one-metre sections. Colour codes in the logs: blue = mica gneiss and metagreywacke, green = hornblende gneiss and amphibolite, light brown = tonalite (biotite-plagioclase gneiss); colours in Au bars: green < 500 ppb, magenta 500–1500 ppb, red 1500–13500 ppb (bars cut in grade ≥ 2500 ppb).

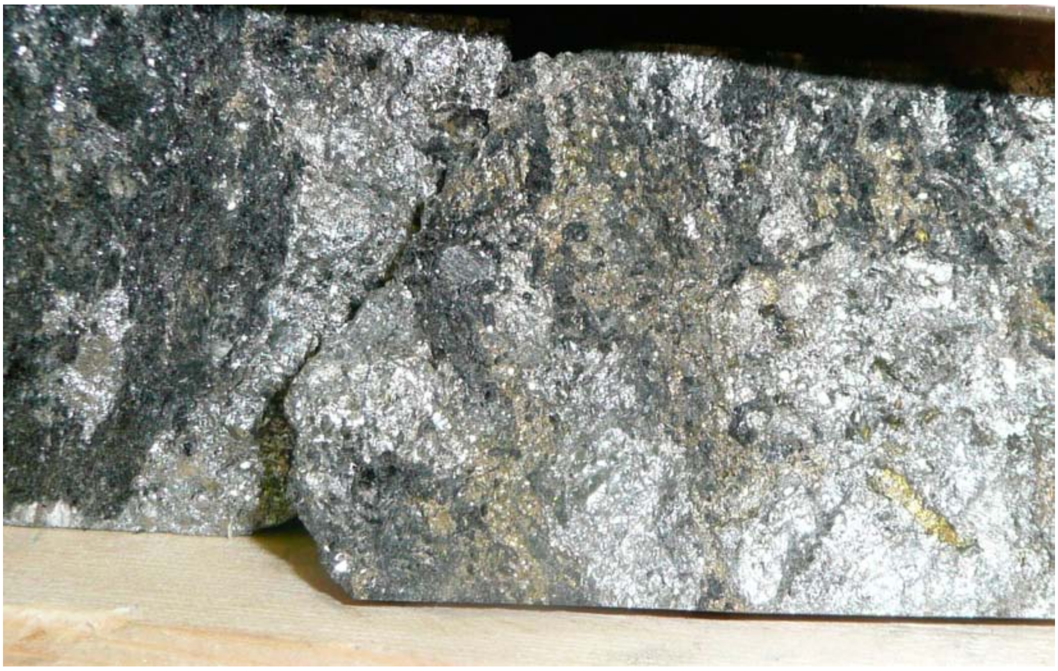

Figure 9. A massive sulphide vein composed of arsenopyrite, pyrrhotite and chalcopyrite at Välimäki, Kullaa. (Hole R309, depth 21.90 m).

113.50–114.50 m in the same hole, gold-rich rock (2800 ppb Au) is composed of coarse-grained biotite and quartz mylonite within amphibolite. Here, the mineralized zone is also surrounded by barren amphibolite, including a swarm of thin quartz veins. Between 124.50–125.80 m there is 8100 ppb Au in arsenopyrite-bearing granite pegmatite. Here, the surrounding empty rock is amphibolite containing a few quartz veins. In two last cases, there is coarse-grained, almost transparent microperthitic feldspar in irregular pegmatitic rock close to the Au-rich section.

Arsenopyrite is common and occurs as dissemination within Au-mineralized rocks, in barren rocks and in barren quartz veins. Garnet of the hornblende gneiss disappears as the quantity of arsenopyrite or quartz veins close to Au-rich zones increases. The increase in potassium is seen as the replacement of hornblende by biotite, the growth of biotite to coarse-grained scales and possibly also the appearance of translucent microperthitic K-feldspar. Quartz veins, usually thin and laminated, are most common close to gold-rich zones, but these veins seldom contain much gold. Part of these quartz veins and arsenopyrite rich veins are younger when sharply intersecting the host rock.

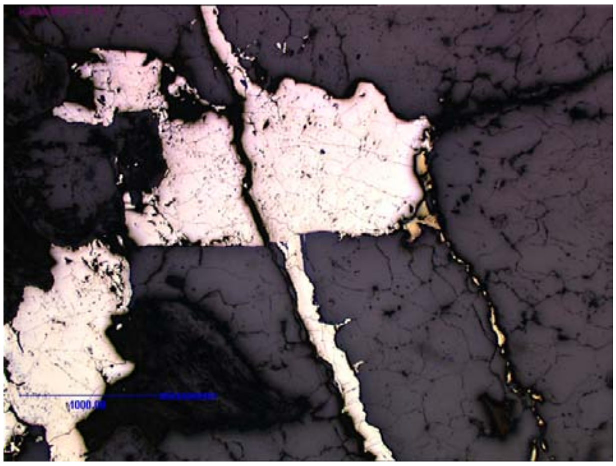

Figure 10. Typical late veins at Kullaa; fault-fill pyrite and chalcopyrite veins cutting the foliation of the mica gneiss; the large pyrite grain is a pseudomorph after disseminated pyrrhotite (reflected light).

There are commonly secondary fault or shear veins that are either sub-parallel with the main schistosity or appear as fault fissures that cut the schistosity at sharp angles. Some of these veins are cracks a few millimetres thick that are filled with saussurite or pyrite and chalcopyrite. Sulphides and probably some of the gold have remobilized within these microstructures (Fig. 10).

THE SAARIJÄRVI GOLD OCCURRENCE

Gold at Saarijärvi was first found in an outcrop disseminated by pyrite, arsenopyrite and chalcopyrite. Samples taken from a sulphide-enriched part of the outcrop contained 4.4–10.6 ppm Au. Till covering the mineralized rock contains a large number of minute gold grains. The strike of the rocks here is almost east–west and the dip is vertical. There is a narrow shear zone cutting the schistosity at a shallow angle. The shear contains rusty seams and commonly arsenopyrite.

Mica gneiss is dominant in the southern part and mafic biotite-hornblende gneiss in the northern part of the mineralized outcrop. The host of the gold mineralization is biotite-hornblende gneiss containing sub-parallel quartz veins (Fig. 11). White graphic textured granite pegmatite veins occur in the contact of the major rock types. Mica gneiss contains sillimanite and metamorphic potassium feldspar.

Figure 11. Quartz veins in Au-mineralized biotite-hornblende gneiss at Saarijärvi Kullaa.

The mineralization of gold in Saarijärvi is highly similar to mineralized sections in the Välimäki gold occurrence. The highest Au contents in the Saarijärvi occurrence are 2310 and 1060 ppb Au in a one-metre section of drill core. In addition to these sections, there are many parallel zones a few metres thick that contain elevated concentrations of gold (>200 ppb Au). The highest arsenic contents are between 0.2 and 0.8%. Here, arsenic is also enriched in much broader zones than gold, and for instance arsenic is anomalous (> 10 ppm) practically throughout the length of drill hole R316 (99.40 m).

Figure 12. Folded arsenopyrite-quartz veins in Au-mineralized mica gneiss from Saarijärvi, Kullaa (1 m @ 2.3 ppm Au, R316-40.70 m). Veins are bordered and partly corroded pyrite and contain some feldspar. Shearing is well indicated by pyrite cutting the quartz vein and partly also by bands of disseminated arsenopyrite. Thickness of core is 40 mm.

There are some differences at Saarijärvi compared to Välimäki, namely the more common appearance of pyrite than pyrrhotite, and carbonate is a common mineral. Pyrite and arsenopyrite are commonly enriched in zones a few metres thick and narrow quartz veins in at least a 100-m-wide section. The veins are either clearly cutting or folded (Fig. 12).

The texture of the mica gneiss varies from coarse-grained migmatitic pyrite-biotite gneiss to fine-grained massive rock. Mica gneiss contains pegmatite veins, folded quartz veins and white needles of fibrolitic sillimanite. The texture of the (biotite-) hornblende gneiss is mainly massive or banded, and the fine or medium grained types can mostly be named as amphibolite, especially when they contain uralite spots, remnants of mafic phenocrysts. In hornblende gneisses there are commonly zones with an abundance of garnet or strongly deformed saussurite rich zones, chlorite, carbonate and biotite seams and narrow quartz veins.

MINERALOGY OF GOLD

The most common ore minerals in the gold mineralized rocks of Kullaa are pyrrhotite, pyrite, arsenopyrite and chalcopyrite (Fig. 13). Hornblende gneiss locally contains abundant ilmenite and some magnetite. Ilmenite is also mobilized into fracture-filled veins together with pyrite. Chalcopyrite is a common inclusion in pyrrhotite. In the non-mineralized rocks, pyrrhotite is common in hornblende gneiss and pyrite is more common in mica gneiss.

Arsenopyrite is the mineral that characterizes the gold mineralized zones, but is not necessarily present in all Au-rich sections within these zones. Arsenopyrite occurs as sporadic grains or a sparse finer-grained dissemination both in mica gneisses and in various versions of hornblende gneiss, often together with pyrrhotite and pyrite, or irregularly in quartz veins and thin massive sulphide veins. In sheared and fractured hornblende gneiss, pyrite replaces pyrrhotite and saussurite replaces feldspar. Pyrite is common in fracture filling together with minor chalcopyrite.

Gold occurs as rather large (50–200 µm) individual native gold grains (Fig. 14) and as small (10–50 µm) inclusions in arsenopyrite. In some cases, native gold is within composite grains with Bi and Te-Bi minerals (Fig. 15). Native bismuth is common and occurs as individual grains and in composite grains. Hedleyite (Bi_7Te_3) and an unnamed Bi telluride have been met in Au-Bi-Te composite grains together with native gold (Appendix 2).

Gold of the Välimäki prospect is rather pure, and is alloyed with only a small amount of silver. Large (0.1–0.3 mm) gold grains contain 96% Au and 4% Ag on average. The highest concentration of silver recorded in a large gold grain is 17.5% Ag. This grain contains a small amount of mercury (2% Hg).

Some of the gold grains are zoned, usually so that under an ore microscope there is a narrow deep-yellow shell capping the light yellow, more voluminous inner part (Fig. 14). The inner part of the grain contains up to 17% silver and the border is composed of pure gold. Some of gold grains separated from the drill core were not zoned or were only slightly or partly zoned. Zoning was also observed in one complex native gold- native bismuth grain, where the gold close to the contact to bismuth contained 10.5% Ag (WDS analysis R309-21.00-22.00 ring C in Appendix 1). Small (<30 µm) native gold inclusions in arsenopyrite also contain silver (8% Ag). Thus, the composition of gold inclusions in arsenopyrite corresponds to the inner part of large discrete gold grains.

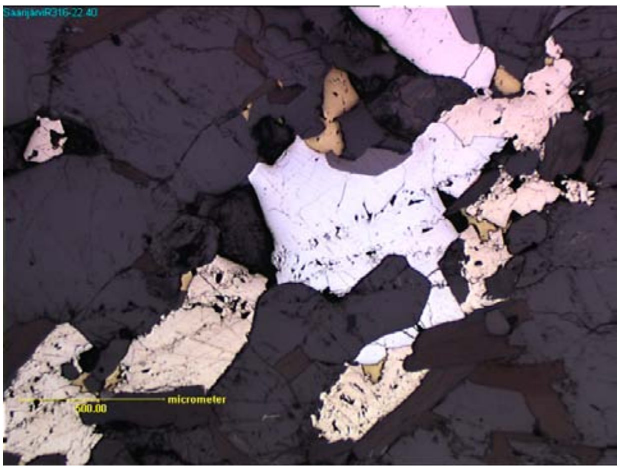

Figure 13. Typical sulphide minerals in Au-mineralized hornblende gneiss of Kullaa. Chalcopyrite (yellow) is as inclusion in pyrrhotite (brownish) and arsenopyrite (white). Saarijärvi, drill hole 1143/07/R316, depth 22.40 m.

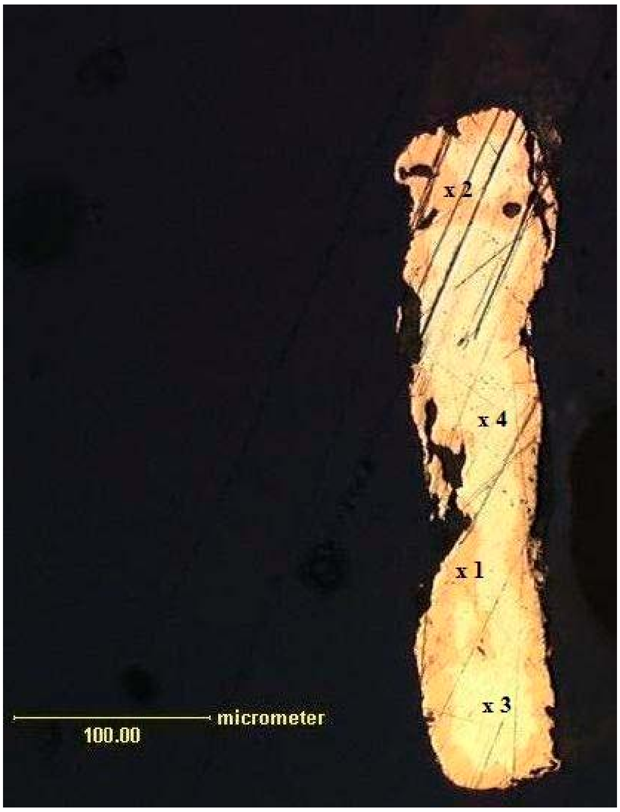

Figure 14. A gold grain of the Välimäki gold mineralization in a heavy mineral concentrate from a crushed core (R309 15.00–16.00 m). At points 3 and 4 the composition is 90% Au and 10% Ag, and darker patches at the borders (points 1 and 2) are pure gold. (Each numbered point represents at least 3 determinations by microprobe).

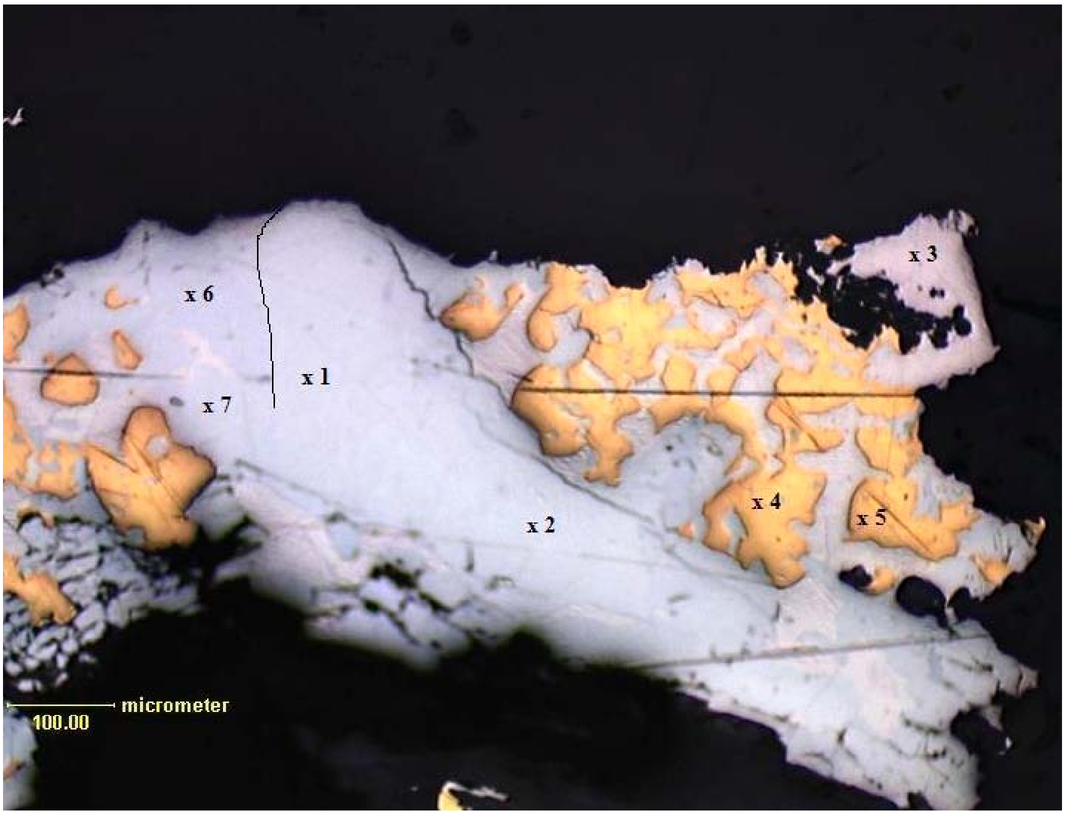

Figure 15. An Au-Bi-Te composite grain; the grey area at the centre of the grain is hedleyite (Bi_7Te_3) (points 1–2), on the right rim of the grain there is native bismuth (point 3), and darker grey areas on the left side of the grain are un-named Bi-tellurides, Bi2Te (points 6–7); the yellow mineral is pure native gold, 99–100% Au (points 4–5). Sample R309-15.00–16.00.

DISCUSSION

The gold occurrences of the Kullaa zone can be classified as orogenic gold deposits. The Kullaa area represents a deep level of the earth's crust. The metamorphic grade is upper amphibolite facies. Leucosome veins and biotite-rich pegmatites assimilating into their host rocks indicate partial melting of the bedrock. Melting of mica rich rocks started during metamorphism. Thus, it is likely that the gold of Kullaa also mineralized in a rather deep environment, during late stage of the Svecofennian orogeny. In the mineralized rocks, K-feldspar and coarse grained biotite in shear zones, as well as the folded quartz veins partially mixing with the gneissic host rock and Au-bearing pegmatite veins, refer to a great depth.

Mineralization probably developed during a long period of the Svecofennian orogeny, and the major controlling features were tectonic processes and metamorphic fluids, although the environment rich in mafic rocks may also have been significant. The mineralization was probably related to secondary fault and shear zones connected to the crustal-scale Pori (Kynsikangas) shear zone.

The Au mineralized shear zones at Kullaa are in many cases more or less mylonitized. The bedrock had already cooled to a rather rigid rock when it thrusted or imbricated (e.g. in relation to the Pori shear zone) and reactivated gold-bearing fluids from previously mineralized zones or outside from the surrounding host rocks. Shearing is locally thorough. During the late stages the Svecofennian orogeny or after it, it is probable that the rocks locally suffered retrograde alteration. This is seen as biotitization and mobilization of sulphides in numerous seams related to shears and faults.

Gold has crystallized from the same fluids as arsenopyrite, which is common in mineralized zones. The early generation of gold is seen in the Ag-bearing inner (and major) part of gold grains, and Ag-bearing gold inclusions in arsenopyrite. Early-stage arsenopyrite occurs as rather even dissemination in the host hornblende gneiss, and is locally enriched in folded veins. Fault-fill pyrite, ilmenite and chalcopyrite, as well as Te-Bi minerals, probably represent the latest hydrothermal stage. The late phase gold contains practically no Ag, and this probably reflects the composition of the hydrothermal fluids. Pyrite replacing pyrrhotite is also related to late processes.

Some of the ore minerals, such as pyrrhotite, chalcopyrite and ilmenite, are probably igneous in origin, and older than the hydrothermal processes. The lack of magnetite in mafic rocks may be a result of sulphurization, and thus part of pyrrhotite may be contemporaneous with arsenopyrite.

Garnet is common in hornblende gneiss, which points to the proportional enrichment of aluminium. This may indicate alteration related to an early-stage hydrothermal process. Close to Au-rich zones, garnet disappears and the number of arsenopyrite or quartz veins increases. The disappearance of garnet may be a result of leaching of garnet and precipitation of quartz veins.

As a result of GTK's studies at Kullaa, two new gold occurrences, Välimäki and Saarijärvi, were discovered. These gold occurrences and numerous Au-mineralized boulders elsewhere indicate that the Kullaa schist zone can be regarded as a gold potential area.

Diamond drilling was conducted in too few profiles to enable the recognition of unique, economic gold-rich zones. More drilling is needed in the future, and particularly at Välimäki, other drilling directions should be tested.

SUMMARY

The bedrock at Kullaa is composed of gneisses and migmatites that recrystallized during high-grade regional metamorphism, corresponding to upper amphibolite facies. The Kullaa zone makes up a tectonic block that is bounded by NW–SE-oriented major fault and shear zones. The bedrock at Kullaa has local mineralizations of gold, arsenopyrite, Fe sulphides, chalcopyrite and Bi-Te minerals.

In the Kullaa zone, where the only earlier gold discovery was at Silmusuo, GTK has localized two new gold occurrences at Välimäki and Saarijärvi. In drillings, the best sections contained 13 ppm Au/m at Välimäki and 2.3 ppm Au/m at Saarijärvi. The Au content is high in narrow zones that are bordered by anomalous Au contents (100–500 ppb Au) in sections a few metres thick. Mineralization is related to tectonic processes, and is also probably controlled by the mafic host rocks. There are shear and fault zones subparallel to major schistosity, and they are likely to be secondary relative to the major Pori shear zone. Arsenopyrite, quartz veins, shear zones, biotitization, the alteration of pyrrhotite to pyrite, and locally-occurring carbonate are all features related to gold mineralization. The gold mineralization can be classified as mesothermal orogenic type. There are still several Au-bearing boulder fans that have been transported from unknown sources.

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Appendix 1. Microprobe analyses of gold and complex Au-Bi-Te minerals of Kullaa. Each analysis is average of 2-5 determinations. Acceleration voltage = 20 kV, electron beam current = 20 nA and diameter = 1 µm. Electron Microprobe = Cameca SX100 , operator Lassi Pakkanen

	Cu %	Ag %	Au %	Hg %	Bi %	Total %	Sample/(grain)/point	Note
Native gold	0.03	1.5	98.33	0	0.04	99.9	R309 21.00-22.01A grain1	
Native gold	0.04	1.58	98.87	0	0.03	100.53	R309 21.00-22.01A grain2	
Native gold	0.03	1.57	98.62	0	0.03	100.5	R309 21.00-22.01A grain3	
Native gold	0.06	3.24	97.27	0	0.07	100.64	R309 21.00-22.01B grain1	
Native gold	0.04	2.67	96.58		0.03	99.97	R309 21.00-22.01 C grain1	
Gold inclusion	0.06	8.16	91.11		0.02	99.35	R309 21.90, in arsenopyrite	
Native gold, core	0.08	9.65	89.34			99.4	R309 15.00-16.01A, core1	
Native gold, core	0.09	9.65	89.31	0	0	99.36	R309 15.00-16.01A, core2	
Native gold, rim	0	0.17	99.22	0	0	99.4	R309 15.00-16.01A, rim	
Complex grain	0	0	0.03	0	99.45	99.48	R309 15.00-16.01B/G1/3	
Complex grain	0	0.06	98.84	0	0	98.91	R309 15.00-16.01 B/G1/5	1
Complex grain	0.01	0.07	98.54			98.62	R309 15.00-16.01 B/G1/5	1
Zoned gold - rim	0	3.1	96.13	0	0	99.23	R309 15.00-16.01 C/G1/1	
Zoned gold – rim	0	0.35	98.09			98.46	R309 15.00-16.01C/G1/2	
Zoned gold – core	0.09	17.37	80.59	1.98	0	100.04	R309 15.00-16.01 C/G1/3	
Zoned gold – core	0.11	17.24	80.38	1.97	0	99.69	R309 15.00-16.01 C/G1/4	
Complex Au-Bi-Te	0.01	0.76	97.71	0	0.04		R309 15.00-16.01 C/G2/1	2
Complex Au-Bi-Te	0.01	0	0.24	0.03	98.91	99.18	R309 15.00-16.01 C/G2/2	2
Complex Au-Bi-Te	0.07	7.55	91.95	0	0	99.5	R309 15.00-16.01 C/G2/3	2
Complex Au-Bi-Te	0	0	0.06	0	99.12	99.26	R309 15.00-16.01 C/G2/5	2
Complex grain	0.01	0.29	97.62	0	0	97.96	R309 15.00-16.01 C/G3/1	
Complex grain	0	0.7	97.96	0	0	98.04	R309 15.00-16.01 C/G3/2	
Complex grain	0	0	1.34	0.04	97.42	98.8	R309 15.00-16.01C/G3/3 (Bi)	

1 = For other minerals in complex grain see Appx. 2 R309 15.00-16.01C/G1/P1-2
2 = For other minerals in complex grain see Appx. 2 R309 15.00-16.01C/G2-3

Detection limits (ppm):

Cu	Ag	Au	Hg	Bi
376	1152	1879	2137	1109

Appendix 2. Microprobe analyses of Bi-Te minerals in complex Au-Bi-Te grains of Kullaa. Each analysis is average of 2-5 determinations. Acceleration voltage = 20 kV, electron beam current = 20 nA and diameter = 1 µm. Electron Microprobe = Cameca SX100 , operator Lassi Pakkanen.

Co	Sb	Au	Te	Se	Bi	Total	Sample/grain(g)/point (p)	Mineral	Note
0.02	0.02	0.67	0	0	98.22	98.95	R309/21.00-22.01C/G5	Bi	1
0	0	0	0	0.04	98.63	98.72	R309/21.00-22.01C/G6	Bi	
0	1.67	0	19.12	0.04	79.39	100.24	R309/15.00-16.01B/G1/P1	Bi7Te3 (Hedleyite)	
0.01	1.61	0.01	19.12	0.05	92.08	99.67	R309/15.00-16.01B/G1/P2	Bi7Te3 (Hedleyite)	
0	0.05	0.22	0.01	0.01	99.21	99.29	R309/15.00-16.01B/G1/P3	Bi	1
0	0.05	0	22.72	0.09	77.36	100.37	R309/15.00-16.01B/G1/P6	Bi2Te (Unnamed)	
0	0.19	0.01	23.22	0.08	77.03	100.55	R309/15.00-16.01B/G1/P7	Bi2Te (Unnamed)	
0.01	0.11	0	0	0.06	98.76	99.15	R309/15.00-16.01C/G2/P2	Bi	
0.01	0.18	0	23.02	0.07	76.72	100.06	R309/15.00-16.01C/G2/P4	Bi2Te or (Bi,Sb)2Te	
0.01	0.07	0	0.01	0.02	98.36	98.5	R309/15.00-16.01C/G2/P5	Bi	
0.02	0.18	0.01	0	0.02	97.23	98.54	R309/15.00-16.01C/G3/P3	Bi	
0	0.19	1.17	22.67	0.17	73.04	98.70	R309/15.00-16.01C/G3/P4	Bi2Te or (Bi,Sb)2Te;	1
0	0.22	1.22	22.45	0.17	75.33	99.35	R309/15.00-16.01C/G3/P5	Bi2Te or (Bi,Sb)2Te;	1

Note: 1 = Au probably from surrounding

S, Ni, Ag, Fe, Cu, Cd, Sn, Zn and As were analysed, all values below detection limit
Detection limits, ppm:

Ag	S	Fe	Ni	Co	Cu	Sb	Cd
1968	318	569	664	488	825	911	1090
Au	**Mn**	**Sn**	**Te**	**Se**	**Zn**	**Bi**	**As**
4293	600	1202	1395	1005	974	6997	1561

Gold in Southern Finland: Results of GTK studies 1998–2011
Edited by Sari Grönholm and Niilo Kärkkäinen
Geological Survey of Finland, Special Paper 52, 149–176, 2012

SOIL GEOCHEMICAL STUDIES IN GOLD EXPLORATION AT THREE TARGETS IN HAAPALUOMA, SEINÄJOKI, W-FINLAND

by
Aimo Hartikainen

Hartikainen, A. 2012. Soil geochemical studies in gold exploration at three targets in Haapaluoma, Seinäjoki, W-Finland. *Geological Survey of Finland, Special Paper 52,* 149–176, 13 figures and 7 tables.

A Project of the Geological Survey of Finland entitled "Evaluation of ore reserves of Southern Finland", led by Project Manager Niilo Kärkkäinen, began to investigate the gold potential of three tentatively studied gold targets in the Haapaluoma area in 2008. A part of the investigation involved sampling from the bottom of the glacial till and from the bedrock surface more intensively and over a wider area than previously. Till exists as a 1–8-m-thick bed over the gold potential Middle-Proterozoic volcanic-sedimentary sequence intruded by felsic intrusions. The samples studied visually and then analysed by ICP-OES and GFAAS or by ICP-MS in the laboratories of Labtium. Altogether, 2281 samples were collected, of which 1167 were from till and 1114 from the bedrock surface. In a 200-m grid the samples were around the felsic Haapaluoma intrusions. According to the gold and arsenic distributions of this sampling phase, the earlier-known gold targets proved to have wider extents than previously thought and new anomalies were also found. The target-scale soil sampling in Pasto revealed two notable anomalies, one of which was drilled. Diamond drillings revealed arsenopyrite in numerous narrow quartz veins and patches in a shear zone several metres thick. Gold contents at the 1 ppm level were common, while the maximum content was 5 ppm in one-metre length of drill core. A gold-containing zone in Timanttimaa, confirmed by diamond drillings, continues in both directions according to the results from intensive soil sampling. In addition, it is evident that parallel gold-containing zones exist. In Tiilikallio, in the interface of till and bedrock, two parallel Au anomalies also occur, which are probably connected to shears in uralite-plagioclase-porphyrites. The sampling method was shown to be successful delineating the gold potential at local and target scale in a cost-effective manner.

Keywords (GeoRef Thesaurus, AGI): mineral exploration, gold ores, geochemical methods, till, bedrock, weathering crust, chemical composition, gold, arsenic, tellurium, Haapaluoma, Seinäjoki, Finland

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BACKGROUND

Gold prospecting in Finland, apart from in Lapland, is relatively young. The oldest gold investigations in Seinäjoki and its surrounding areas were not carried out before the1980–1990s (Kontas 1981a, Kärkkäinen 1989, 1990, 1992, 1993a, 1993b, 1993c, Kärkkäinen & Huuskonen 1992, Oivanen 1985, 1987, Lestinen 1988, Lestinen et al. 1991). Many of the targets were initially examined because of antimony or tungsten (Pääkkönen 1966, Oivanen 1982a, b, Yletyinen & Haapala 1980). Developments in gold analysis in the beginning of the 1980s prepared the way to rapidly analyse samples at a reasonable cost (Kontas 1981b). Some promising gold mineralizations have been located and thoroughly investigated, but, have so far, been uneconomic. However, numerous gold-containing boulders, gold in till and some patches of gold in outcrops have encouraged further exploration for gold in southern Ostrobothnia (Huuskonen 1991, Turkka & Kanto 1996).

The three targets in Seinäjoki explored by the Geological Survey of Finland (GTK), Pasto, Timanttimaa and Tiilikallio, are located about 30 km southeast of the centre of Seinäjoki (Fig. 1). A decisive factor initiating the exploration of these targets was the discovery of several gold-containing boulders by two amateur geologists, Reijo Perälä and Pekka Hietala.

The soil geochemical project began in 2008 and formed part of a more extensive project led by Niilo Kärkkäinen. The samplings was planned by the geologists Niilo Kärkkäinen, Jorma Isomaa and Aimo Hartikainen, and an assistant Mikko Pelkkala. Pauli Schroderus collected the majority of the samples, with Viljo Bäck as his foreman.

SOIL

A layer of till with a thickness of a few metres ubiquitously covers the slightly undulating surface of the bedrock. Outcrops are abundant in the Tiilikallio area, but are less common at Pasto, and just a few are present at Timanttimaa. Modest layers of sorted sediments occur beneath peat and in river channels.

According to the drumlins, striations and till studies, the most recent ice flow movement took place from the north (350°–360°) (Nenonen & Hakala 1982, Nenonen & Johansson 1981, Nenonen & Liippo 1984). Only a small number some observations of older ice flow movements, from 315°–340°, have been reported in the Seinäjoki area (Nenonen & Huhta 1981, Nenonen & Liippo 1984). The sorted sediments beneath the till cover are probably Eem interglacial in age (Nenonen & Huhta 1981). According to the aforementioned till studies, boulders containing ore minerals form fans, which are oriented in the direction of the youngest ice movement.

Nevertheless, the possibility of complex transportation of till does exist, because the uppermost till could be the final result of complex glacigenic and glaciofluvial processes. An example of this is seen at Karhukangas in Kauhajoki, some 60 km from Seinäjoki, where the soil profile consists of at least four, and perhaps even seven till beds separated by sorted sediments. The lowest layers must be several hundred thousands years old (Huhta 1997, Pitkäranta 2009).

According to Pääkkönen (1966), about 90 % of the boulders in the Seinäjoki area were transported only a short distance in a glacier. The tin anomalies in till are also of local origin, with a transport distance even less than 100 m (Nenonen & Hakala 1982). The observations of Oivanen (1982b) support these interpretations. When the till cover is thick, the surface part of the till mainly appears to have a much more distant source area, even up to 1.5–2 km from its present location (Lestinen 1988).

According to Mölder and Salmi (1954), it is difficult to find weathered bedrock in the Seinäjoki area. However, Lestinen (1988) reported that preglacial weathering was common, and although its thickness is nowadays modest, usually being less than 30 cm. Weathered bedrock can exceptionally be up to even 4 m in thickness (Lestinen 1988). The sampling data presented in this paper proves that bedrock beneath till often is weathered, but usually not more than 20 cm in thickness.

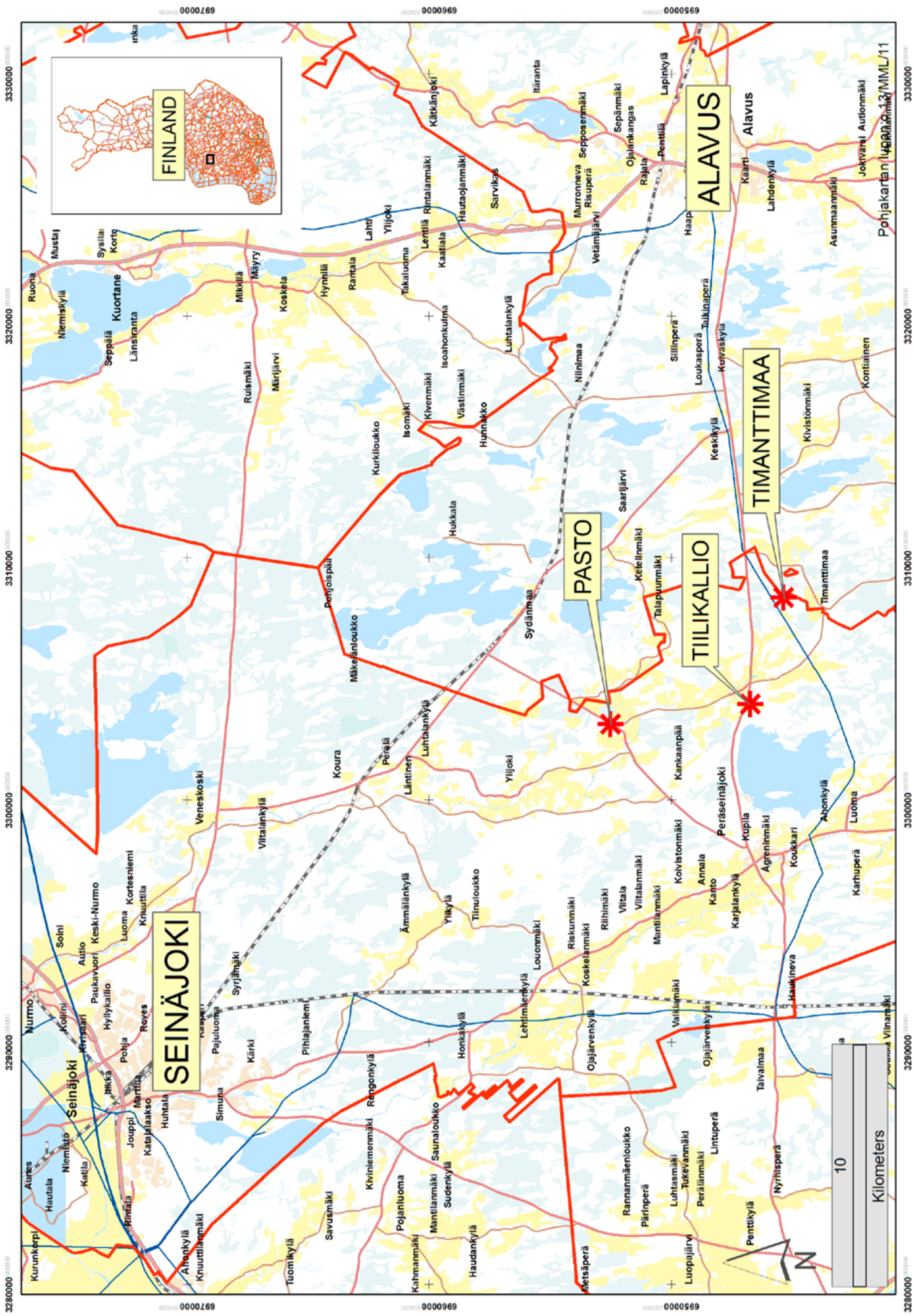

Figure 1. The locations of soil geochemical studies for gold exploration in the Seinäjoki–Alavus area, western Finland. The location of the study area in Finland is indicated in the inset map. Basemap © National Land Survey of Finland, licence no 13/MML/12.

GENERAL FEATURES OF THE BEDROCK

This chapter summarises the descriptions of the bedrock of the Seinäjoki area by Oivanen (1982b) and Mäkitie and Lahti (2004) Simplified map of the bedrock (Fig. 2) is based on the digitalized data-base "Bedrock of Finland – DigiKP 200" (Bedrock of Finland–DigiKP).

The area is dominated by <1.89-Ga-old paragneiss, known as mica gneiss or biotite-plagioclasegneiss, which is variably metamorphosed, from amphibolite facies even to granulite facies. The name mica gneiss includes several rock types based on the degree of metamorphosis, chemical composition, the degree of coarseness, porphyroblasts and volcanism occurring during sedimentation. Among these are phyllite, metagreywacke, graphite bearing schist, porphyroblastic mica schists and gneisses, quartz or/and plagioclase-bearing schist and vein gneiss. They are all coloured in blue in Figure 2. The foliation of the supracrustal rocks is usually close to NW–SE, as well as the most strongest shears.

Metavolcanics are less abundantly found within previous rocks. Originally, mafic volcanics probably mainly consisted of lava and layer dykes, but nowadays consist of homogenous amphibolites. Intermediate layers, some metres thick and containing hornblende also intercalate mica gneiss. Heterogenous ryolitic tuffites are also usually minor. They are often very migmatized and can resemble rocks of the mica gneiss group.

Deformed andesitic uralite and plagioclase porphyrites have a variable appearance. Presumably, they have been hypabyssal layer dykes and can reach a thickness of tens of metres. Porphyrites occur as boudinaged lenses and beds in mica gneiss. Especially the margins of the porphyrites are deformed and contain boudinaged quartz veins.

Tonalites and granodiorites several square kilometres in width are variably deformed and the rock types interchange with each other and with quartz diorite. Tonalites commonly includes mica gneiss xenolites. Diorite remnants in tonalite probably represent the oldest preserved rock in the Seinäjoki area. In places, granodiorite cuts tonalite. Tonalite is often potassium metasomatized, in which case it is lithologically porphyritic granodiorite.

As the youngest granitoids, porphyritic granite intrusions cut other rocks. They are wide and at most slightly deformed. Small intrusions and veins are usually coarse grained and follow schistosity. Granites often contain supracrustal xenolites. Some granite pegmatites carry tourmaline, spodumene, beryl, columbite, antimony minerals and cassiterite.

METHODS AND STUDIES

Sampling

Soil geochemical studies in gold exploration were performed in several stages. The earliest of these was during 1987−1988 (Table 1: "old"). This paper includes the results of this sampling, although they have been presented earlier (Kärkkäinen 1993b, 1993c). The majority of the samples were collected during 2008–2010 using a Terri hydraulic percussion drill installed on a snow-mobile. This equipment produced till samples weighing 100−150 g, while weathered bedrock samples were smaller and fresh bedrock samples smaller still.

The three target areas were Pasto, Timanttimaa and Tiilikallio (Figs. 1 and 2). Two samples were taken at each sampling site, the first sample from the bedrock surface and the second from till about half a metre above the previous sample.

At the local scale, samples were collected in a 200-m grid above areas of supracrustal rocks. Sampling was subsequently focused on anomalous areas observed at the local scale. Samples were then collected along sampling lines, the distance between sampling sites initially being 20 m and finally 10 m. Altogether, 2281 samples were taken, a half of which consisted of till, with the rest being either weathered or fresh bedrock samples (Table 1). According to the local sampling, the mean depth of the soil cover is 4.0 m in the Haapaluoma area.

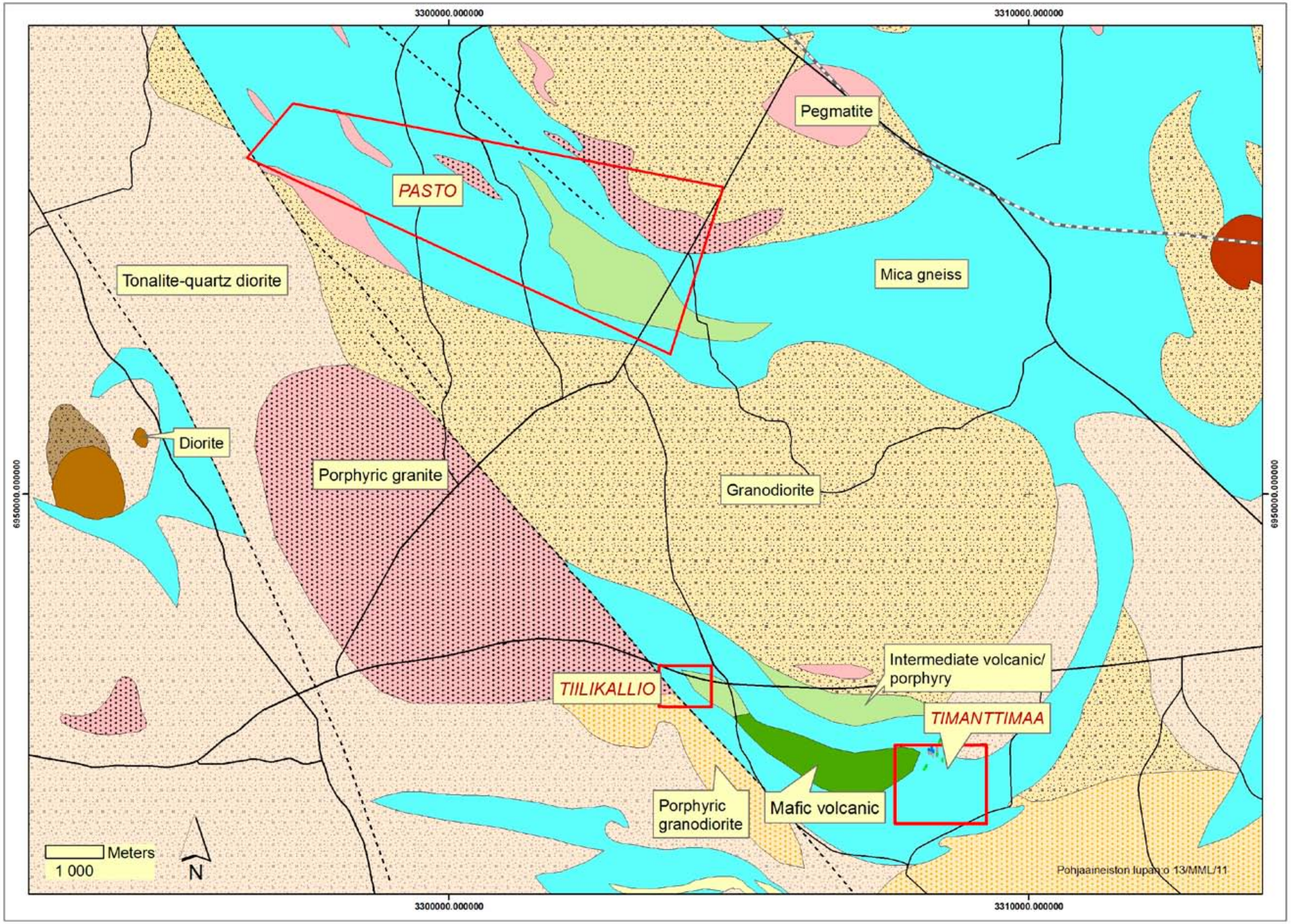

Figure 2. Simplified map of the bedrock around the study areas (from the bedrock data base of GTK, 2011). Basemap © National Land Survey of Finland, licence no 13/MML/12.

Table 1. The numbers of geochemical soil samples collected at three targets in the Haapaluoma area, Seinäjoki, western Finland. W bedrock=weathered bedrock, Bedrock=bedrock surface, Lab=samples analysed in the laboratory, Depth=mean depth of soil cover (m), Local=local sampling, old=earlier collected samples.

Area / stage	Till	W bedrock	Bedrock	Total	Lab	Depth
Local	86	9	63	158	104	4.0
Pasto	644	102	513	1259	1259	4.3
Timanttimaa	299	144	151	594	339	4.6
- re-analyses					33	
- old				342	342	3.4
Tiilikallio	138	25	107	270	142	2.2
Total	1167	280	834	2281	2219	

Laboratory studies

All the samples collected during 2008–2010 were visually examined. From the till samples the following were defined soil type, colour, grain size, compactness, wetness and ore minerals, if possible. From weathered and fresh bedrock samples the rock type, colour, grain size and interesting minerals were recorded. It is a challenging to determine the rock type of a small and/or often dirty weathered sample, for instance because amphibole is often altered to biotite during weathering. For various reasons, the map based on the determination of these fairly small fragments, unreliably illustrates the proportion of mica gneiss.

All the samples from the Pasto target were analysed separately. To save costs a similar weight (2.5 g) of homogenized till and bedrock samples was combined to form one sample for analysis from each sampling site at the local scale and at theTimanttimaa and Tiilikallio targets. However, if ore minerals or other interesting minerals were observed, the two samples were analysed separately.

All the samples were completely ground, homogenized and a subsample was taken for analysis.

The samples of local scale, Pasto and Tiilikallio and majority of the samples from Timanttimaa were analysed by inductively coupled plasma optical emission spectrometry (ICP-OES) for the following 31 elements (0.15 g weight): Ag,Al,As, B,Ba,Be,Ca,Cd,Co,Cr,Cu,Fe,K,La,Li,Mg,Mn, Mo,Na,Ni,P,Pb,S,Sb,Sc,Sr,Ti,V,Y,Zn and Zr. Because partial leaching (aqua regia) was used, the recorded concentrations of the main elements, in particular, were too low. However, the concentrations of chalcophylic elements were reliably determined. Gold and Te were analysed by atomic absorption spectrometry with electrothermal atomization (5 g weight).

The 142 combined samples from the final sampling stage at Timanttimaa were analysed by inductively coupled plasma mass spectrometry (ICP-MS) for the following 42 elements (aqua regia, 5 g weight): Ag,Al,As,Au,B,Ba,Be,Bi,Ca, Cd,Co,Cr,Cu,Fe,K,La,Li,Mg,Mn,Mo,Na,Ni,P, Pb,Pd,Pt,S,Sb,Sc,Se,Sn,Sr,Te,Ti,Th,Tl,U,V,W,Y, Zn and Zr. Of these, the most important in gold exploration are Au and its pathfinders, As, B, Bi, Cu, Sb, Te and W.

LOCAL SCALE SOIL GEOCHEMICAL STUDY FOR GOLD

The soil geochemical study for gold began with local-scale sampling, during which 158 samples were collected from supracrustal rocks around the Haapaluoma intrusive. The till and weathered/ fresh bedrock samples were combined to form one sample. If anything interesting was observed the samples were analysed separately (Table 1).

At this scale gold, arsenic and tellurium are often present at fairly high concentrations in the same samples and form a distinct factor: Au-As-Te. On the concentration map of Au and As, the Tiilikallio and Timanttimaa targets can be distinguished from barren areas (Fig. 3). Gold- containing boulders were earlier observed in these areas, and at Tiilikallio also in bedrock (Huuskonen 1991). In addition to these, a wide and previously, unexamined anomaly exists to the ESE of the Pasto target. The concentration maps of Te and B (no figures) closely resemble those of Au and As.

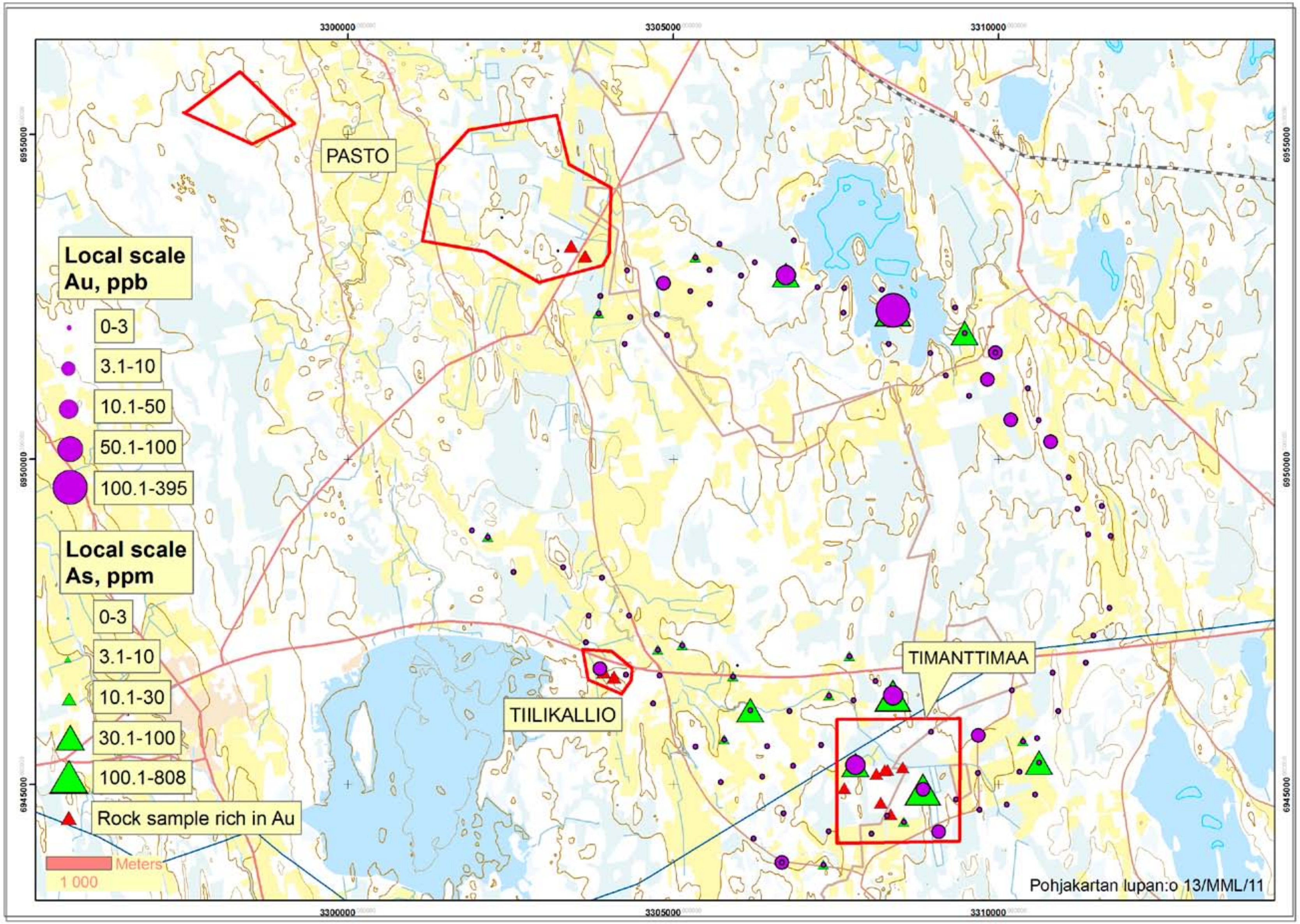

Figure 3. The distribution of Au and As in the till/bedrock interface on supracrustal rocks around the Haapaluoma intrusion according to local geochemical sampling with combined samples (till and rock samples form one sample for analysis). Basemap © National Land Survey of Finland, licence no 13/MML/12.

TARGET-SCALE SOIL GEOCHEMICAL STUDIES FOR GOLD

Pasto

Colour of till samples

Altogether, 1259 till, weathered bedrock and bedrock surface samples were gathered in the Pasto area. The soil type was determined and the colour, grain size and possible deviations were visually recorded.

Tills were divided into 24 classes according to colour. Transitional cases were removed for further consideration and the rest were formed into three main groups: greyish, brownish-multicoloured and greenish tints. Table 2 provides the mean contents of nine elements in these three colour groups.

Table 2. Mean contents of some elements in till according to the colour of the till samples, Pasto, Seinäjoki. N=number of samples. Au and Te in ppb, others in ppm. Analysed by ICP-OES and GFAAS (Au and Te), aqua regia leaching.

Colour class	N	As	Ca	Cu	Fe	Mg	Ni	S	Au	Te
Greyish	472	44	2873	23	17996	6031	17	632	7.7	23
Brownish-multicoloured	33	44	2665	18	21485	6669	17	433	6.8	18
Greenish	26	20	3118	44	25754	9881	26	1772	4.8	25

The notable variation in the colour of tills was mainly a consequence of the mineralogy of the samples. A greyish colour revealed that the sample consisted of granitoids and/or mica gneiss group rocks. Multicoloured and brownish till samples were probably derived from the oxidizing horizon of the surface level of ground water, where iron partly occurs as brownish iron hydroxides. This interpretation is supported by the low sulphide content. In Finland, the Eh-pH-conditions and low Cl content in till do not favour the hydromorphic mobilization of gold (e.g. Brookins 1986).

A greenish colour of till and high Ca, Cu, Fe, Mg and Ni contents in a sample indicate that it is to a great extent a composite of local mafic material. As a whole, strong variation in till was observed, showing that till is heterogeneous and has only been transported a short distance by the glacier. All three control groups were found to have almost as high a mean Au content, which also suggests immobility of gold in till in this area.

Grain size of till samples

The grain size was visually determined from 366 till samples. Most of them were imprecisely defined sandy till samples, 8 were fine sandy till samples and 43 were coarse sandy till samples. Some grain-size studies on till have demonstrated that fine fractions have higher contents of elements such as Cu and Zn (Nikkarinen et al. 1984). As can be seen in Table 3 the levels of the chalcophylic elements As, Cu, Fe, Te and also the 'mafic elements' Ca, Fe and Mg were higher in fine sandy till samples than in coarser groups. This results from easy pulverization of sulphides, biotite and some mafic minerals during glacial processes, and probably partly occurred even before the Pleistocene. The highest mean content of gold was recorded in the coarsest till. The difference could be due to the small number of fine sandy till samples, and first of all of the nugget effect.

Table 3. Mean contents of some elements in till according to the grain size of the till samples. N=number of samples. Au and Te in ppb, others in ppm. Analysed by ICP-OES and GFAAS (Au and Te), aqua regia leaching.

Grain size	N	As	Ca	Cu	Fe	Mg	Ni	S	Au	Te
Fine sandy till	8	30	4324	33	21863	8724	18	578	3.7	27.4
Sandy till	315	25	2636	20	17766	5857	17	573	5.1	16.7
Coarse sandy till	43	16	2031	17	14927	4802	15	335	6.8	11.7

Depth of the soil cover

The depth of the soil cover is commonly greatest in bog areas. In higher, dry areas the soil cover is thin and outcrops even exist. The direction of forms of the terrain is almost the same as the general direction of supracrustal rocks and the schistosity. The till cover in drumlins is more than 10 m. The mean depth of the soil cover in Pasto was found to be 4 m, while the maximum sampling depth was 14.4 m.

The bedrock surface and weathered bedrock samples

The rock type was determined from 608 bedrock samples. A proportion of the weathered bedrock samples were completely weathered and their type determination was impossible. Moreover, some samples were so small that, for instance, it was difficult to differentiate tectonized feldspar porphyry from mica schist. Furthermore, foliated mafic rock often is biotitized and therefore resembles mica schist, although an ophitic texture can still exist. A small proportion of the rock samples were certainly derived from boulders. For these reasons, the data presented in Figure 4 are not entirely valid.

According to studied rock samples, the detailed bedrock is naturally much more complex than presented at the 1:100 000 scale (Lahti & Mäkitie 1990). The strongest magnetic anomaly is probably caused by narrow graphite/black schist-containing pyrrhotite. The mica gneiss group rocks are commonly intruded by relatively small granodiorite-tonalite, gabbro-diorite and by pegmatitic granite intrusives, dykes and veins. Evidently, some of these had a role in the settling of gold in its present location.

Some observations from the visual study of bedrock surface samples

Amphibolite: 24 samples; greenish-grey; a little pyrite, pyrrhotite and arsenopyrite; some biotitization, silicification and chloritization; several anomalous As and Te contents; Au low or weakly anomalous.

Andesite-intermediate volcanic-quartzfeldspar schist: 11 samples; greyish tints; no ore minerals; low or weakly anomalous As, Te and Au.

Black schist: 2 samples; greyish black; ore minerals not observed; but a high Fe content; As, Te and Au slightly anomalous.

Chlorite schist: 8 samples; greenish tints; no visible ore minerals; low As, Au and Te contents; in one sample Ag 4.7, Cu 2070, Pb 410 and Zn 478 ppm.

Diorite: 8 samples; greyish tints; a little pyrite; often As anomalous, weakly Au-Te anomalous.

Feldspar porphyry: 15 samples; greyish tints; a little pyrite; three samples very As and Te anomalous, but low Au.

Gabbro: 19 samples; greenish or greyish tints; arsenopyrite in one sample and pyrite in two; commonly As-Te anomalous; weakly/moderately Au anomalous.

Granite: 43 samples; red tints; no ore minerals; usually low Au, As and Te, but one sample As-Cu-Te anomalous.

Granodiorite-tonalite(gneiss): 33 samples; greyish tints; sometimes a little deformed; some pyrite or pyrrhotite in 5 samples; four samples clearly As anomalous and high Cu in one sample; Au and Te low.

Mafic volcanic: 8 samples; greenish or blackish tints; pyrrhotite and chalcopyrite in one sample; relatively high As, Pb and Te in one sample, Au low.

Mica schist-mica gneiss: 393 samples; partly misinterpreted feldspar porphyres and biotitized mafic rocks; greyish tints; often pyrite and pyrrhotite; sometimes sericitized and/or chloritized; As > 500 ppm 15 cases, Au > 300 ppb 4 cases and Te > 300 ppb 2 cases.

Pegmatite granite: 30 samples; reddish tints; no ore minerals; low As, Au and Te.

Quartz: 5 samples; greyish tints; a little pyrite; low As, Au and Te contents.

Anomalies

The samples from the Pasto area were taken in three stages. The intention of the second and third stages was to clarify the distribution of gold in the area.

The highest gold contents were recorded in fairly concise anomalies and close to the known gold- containing outcrops. The distributions of arsenic and tellurium (no figures) were very simi-

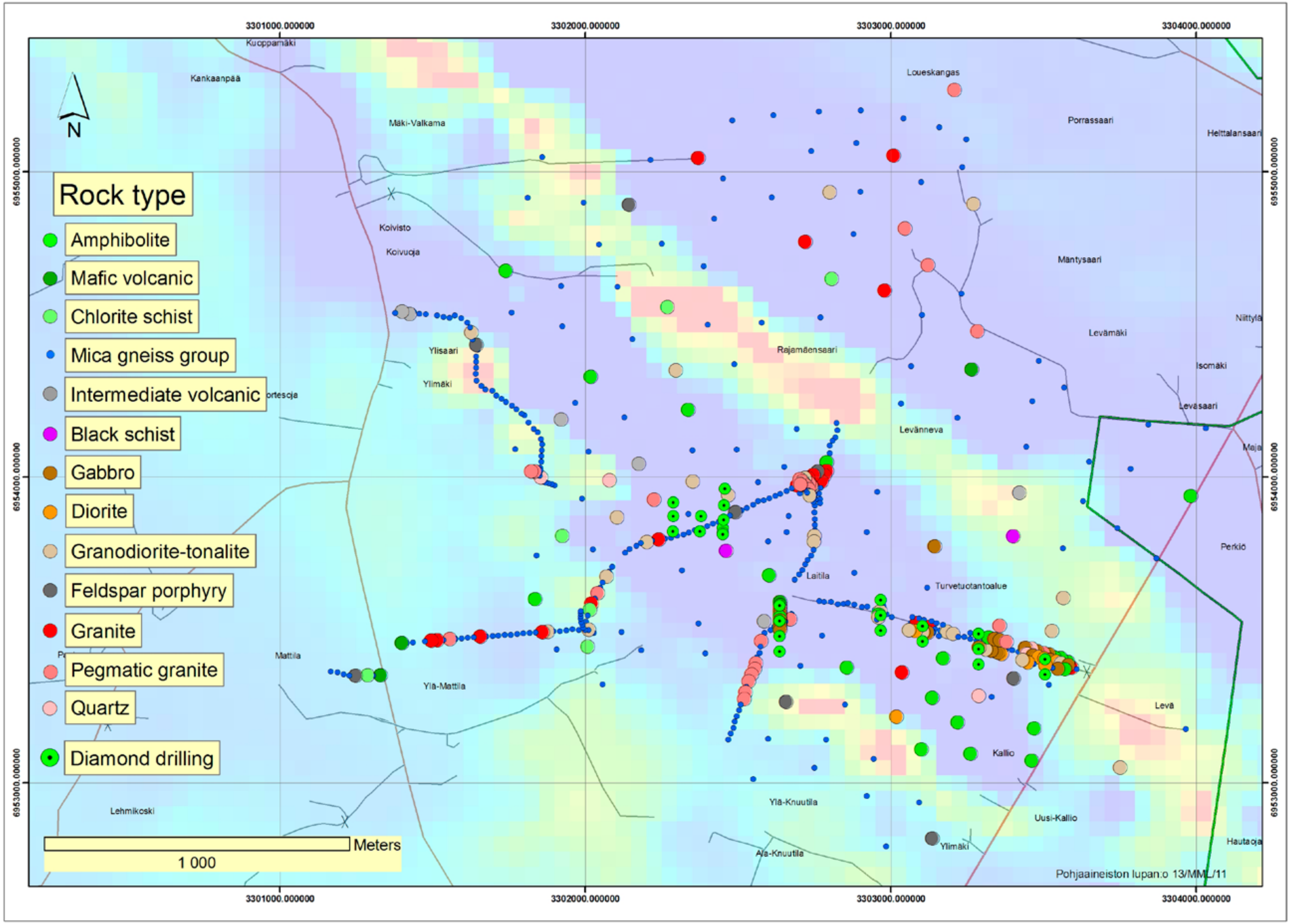

Figure 4. The rock types of the weathered and bedrock surface samples collected in the Pasto area. An aeromagnetic map is presented as background. Basemap © National Land Survey of Finland, licence no 13/MML/12.

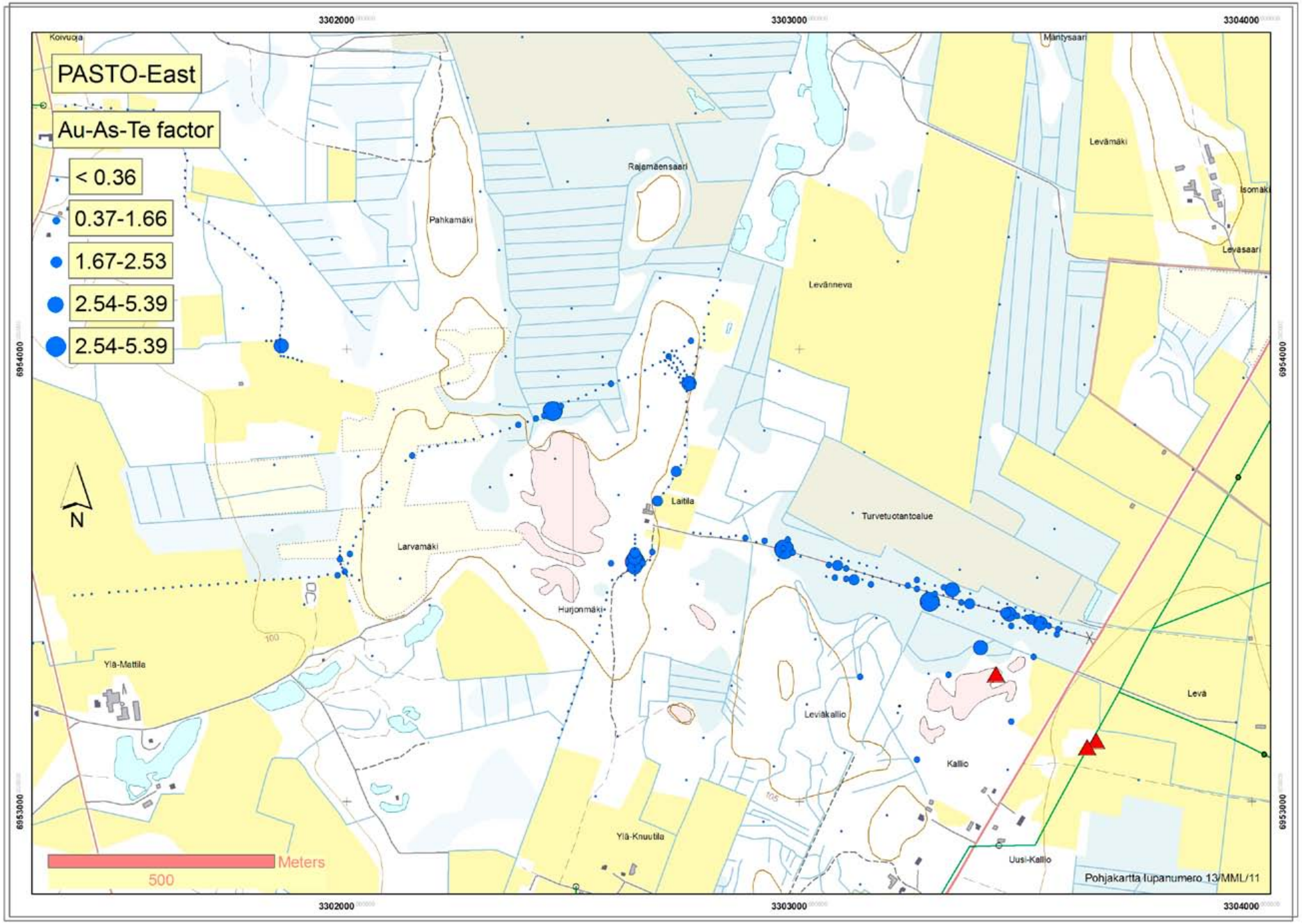

Figure 5. The Au-As-Te -factor in weathered and bedrock surface samples from the eastern part of the Pasto area. Red triangles indicate the locations of two bedrock samples and a boulder rich in gold. Basemap © National Land Survey of Finland, licence no 13/MML/12.

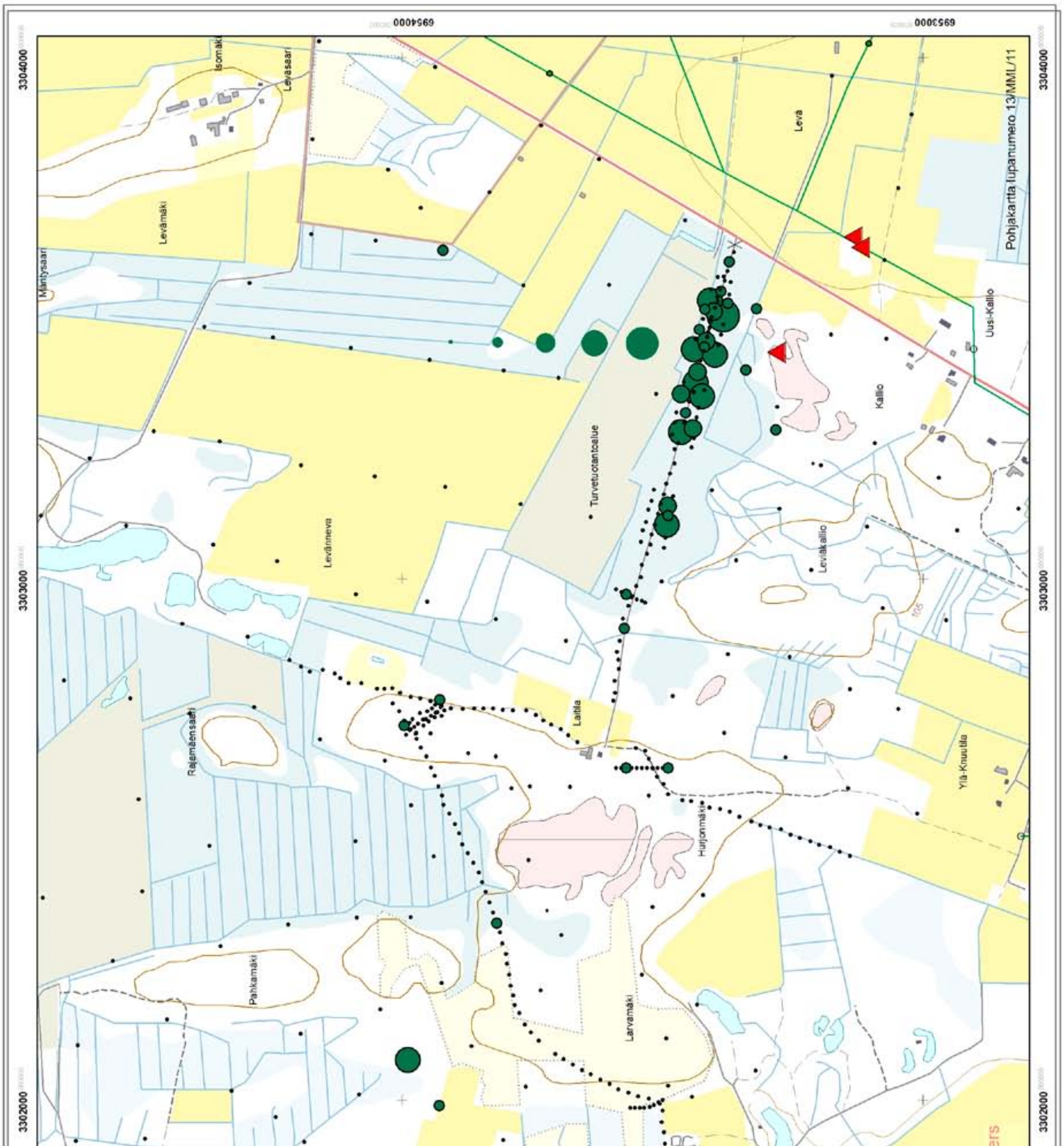

Figure 6. The Au-Te -factor in till samples from the eastern part of the Pasto area. Basemap © National Land Survey of Finland, licence no 13/MML/12.

lar. In factor analysis (principal components, correlation matrix, Varimax rotation) of bedrock and weathered bedrock samples, the factors were very typical of those seen in soil chemical exploration for gold: F1 = Al-Ba-Fe-K-Rb-Ti (mica-mafic factor); F2 = Ca-Na-Sr (plagioclase factor); F3 = Cr-Mg-Ni = (ultramafic factor); F4 = Ag-Cu-S (sulphide factor); F5 = As-Au-Te (gold factor); and F6 = B (tourmaline factor?). The factor analysis for till samples produced similar, but less distinct factors.

Tellurium loaded entirely on the gold factor, which means that significant sulphide deposits do not exist in the area. The ultramafic factor was rather strong, despite ultramafic rocks being elsewhere. Gold and boron were wholly located in different factors, which could indicate that pegmatite granites contain tourmaline, but not gold. Tourmaline veins can certainly exist in any rock type.

Figure 5 displays the Au-As-Te -factor of the bedrock surface and weathered bedrock samples (factor 5) and Figure 6 the Au-Te -factor of till samples (factor 6). According to these maps, the most sensible drilling target seems to be E–W-trending anomaly, which is also likely to be approximately in the direction of mineralization. Gold-containing boulders are probably derived from this horizon or close to it.

The most interesting samples

The highest Au, As and Te contents in bedrock and till samples from the Pasto area are presented in Table 4. In almost all of the presented samples, Au, As and Te were anomalous, while B and Sb contents in these samples were low. Cu and Mo were occasionally anomalous. The sulphur content was fairly low, which probably indicates the mobilization of sulphur during the Holocene.

Table 4. Contents of some elements in selected bedrock and till samples. Au and Te in ppb, others in ppm. Analysed by ICP-OES and GFAAS (Au and Te), aqua regia leaching. MC=mica schist, GB=gabbro, AFB=amphibolite.

X	Y	Material	Rock type	As	Cu	Fe	Mo	S	Au	Te
6953558	3302967	Bedrock	MC	5710	99	32500	1.5	3340	139	250
6953864	3302455	Bedrock	MC	10200	50	27900	1.0	5490	171	225
6953442	3303288	Bedrock	GB	6090	287	52200	0.5	6980	69	1540
6953540	3302637	Bedrock	AFB	1440	70	34900	0.5	663	68	534
6953530	3302637	Bedrock	GB	1240	45	41900	0.5	538	372	463
6953384	3303505	Till		506	52	29400	2.0	1400	932	1000
6953492	3303104	Till		5570	797	29100	39.1	6920	169	1180

Figure 7 illustrates the locations of the samples presented in Table 4. One of these was monitored with nine diamond drill holes (geologist Jorma Isomaa). In these drillings, tens of metres of weakly disseminated arsenopyrite were observed, mainly in quartz veins and as patches. The gold content was often at the ppm level, with the maximum being nearly 5 ppm/2 m.

Figure 7 also shows the locations of the gold-containing samples collected using a hammer: one of a boulder and two from the bedrock surface. The exact sampling sites are uncertain.

In 1984 Malmikaivos Oy drilled three holes each about 100 m long in the surroundings of these samples. Arsenopyrite was observed in quartz veins and in deformed diorite (according to the drill reports of O. Taikina-aho), but nothing is known of the gold contents in these drill cores.

Timanttimaa

Background

The Geological Survey of Finland explored for gold at Timanttimaa because gold-containing boulders were found in the area by an amateur geologist (Reijo Perälä) during 1987−1991 (Kärkkäinen 1993b, c). Based on nine drill holes, a several-metres-wide shear zone could be delineated in the contact zone of an intermediate intrusion and supracrustal rocks, which was cut by abundant quartz veins. The gold content of the shear horizon was about 1 ppm, while the maximum

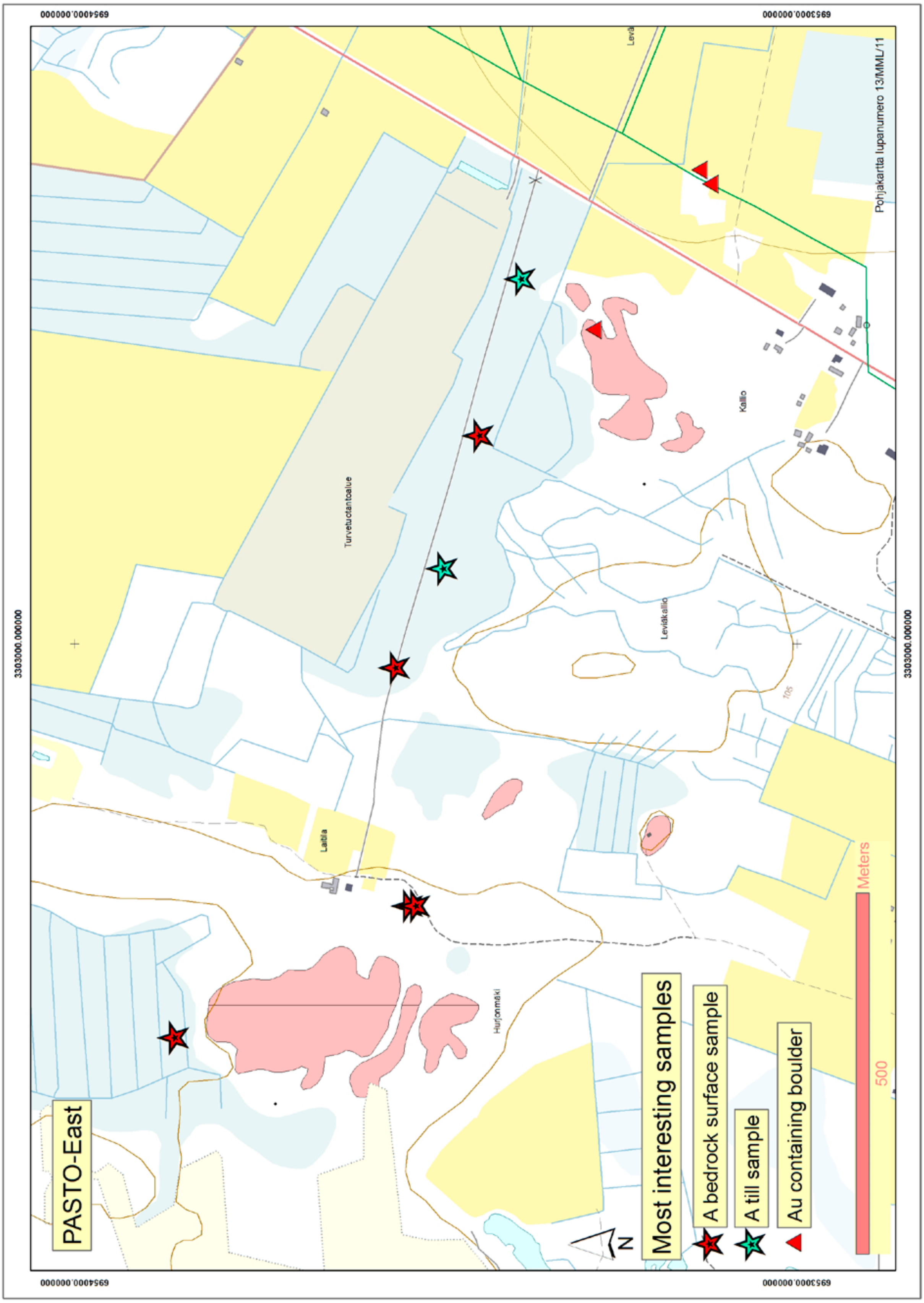

Figure 7. The locations of the samples presented in Table 4. Basemap © National Land Survey of Finland, licence no 13/MML/12.

was 15.5 ppm/1.5 m. The ore horizon seemed to continue in both directions, and indications of parallel also zones existed. To verify this, samples of the bottommost part of the till blanket and of bedrock surface were collected.

Samples

Altogether 594 till, bedrock surface and weathered bedrock samples were taken in the Timanttimaa area (Table 1). As in the Pasto area, the samples were taken using a 35 mm a Terri hydraulic percussion drill. Earlier, in 1987–1988, 342 samples were taken from the interface of bedrock and till. The results of this sampling have previously been presented (Kärkkäinen 1993b). The mean depth of the soil cover was found to be 4.55 m in the Timanttimaa area, the maximum depth being 10.8 m.

The soil type was confirmed and the colour and grain size were determined from the till samples. Because till and bedrock samples were usually combined, a similar comparison of the colour and element contents could not be performed to that in the Pasto area. The same concerns the grain size of till. The till samples were mostly greyish, but often also brownish or brown sandy till.

Altogether, 368 rock type determinations were carried out. As at Pasto, some of the weathered bedrock samples were so completely weathered or the samples were so small that they remained without a name. A small proportion of the bedrock samples were probably derived from boulders.

According to the bedrock surface samples, the bedrock at Timanttimaa largely resembles that in the Pasto area, although the rock types exist in different proportions. Amphibolite and granodiorite-tonalite samples were more common than at Pasto, but granite, pegmatite granite, diorite, gabbro, mafic volcanic, chlorite schist and feldspar porphyry were less common. In real terms, the amphibolite samples were probably from plagioclase-uralite porphyries, within or in the contacts of which gold has at least partly enriched (Kärkkäinen 1993b). It may be important that sericitization is common in the Timanttimaa area.

Anomalies

The samples collected during 1987–1988 were analysed by AAS (As, Cu, Pb and Zn) and GFAAS (Au). During 2009–2010, samples were taken in two stages. The first set of samples were analysed by ICP-OES and GFAAS and the second by ICP-MS- and ICP-OES. A list of the analysed elements is presented in the earlier section 'Laboratory studies'.

The characteristics of the most interesting samples are listed in Table 5. Of the six bedrock samples, one was from amphibolite, one from gabbro and the rest were from mica schist. Three nonweathered samples contained pyrite and one arsenopyrite. Almost all were anomalous for Au, As and Te. In contrast, gold-containing weathered bedrock samples were anomalous for As, but only occasionally for Te.

A significant difference was detected between fresh and weathered bedrock samples in the sulphur content, which in weathered samples was generally only 100–800 ppm. As at Pasto, this indicates that hydromorphic mobilization of sulphur, arsenic and tellurium has occurred during weathering and oxidation, while gold has remained. The aforementioned sericitization is probably a result of mineralogical alteration during weathering and not hydrothermal alteration occurring at depth.

The antimony and molybdenum contents in the samples presented in Table 5 are low. In many of the samples in the table, tungsten contents are slightly anomalous, which may be an indication of scheelite in the samples (not checked by UV). The distribution of gold in combined samples from Timanttimaa is illustrated in Figure 8.

The highest gold contents were recorded in a fairly restricted area on a magnetic anomaly and on a gentle fold.

In the factor analysis of combined samples (22 elements, Varimax rotation, correlation matrix, principal components, 6 factor model) the mica-mafic factor was the strongest, as usual. The second strongest was the Au-Te-As factor, which describes the notable gold potential of the area. Silver and copper also had moderate loading on this factor. Other factors evidently did not have any role in gold exploration: the potassium feldspar factor, plagioclase factor, Pb-Zn factor and apatite(?) factor.

Figure 9 illustrates the locations of diamond drilling sites and the gold mineralizations reflected directly in the bedrock surface (Kärkkäinen 1993b). The largest red spheres in the figure indicate high Au, Te or As values in the combined till/surface bedrock/weathered bedrock samples. Based on the known mineralizations and the largest spheres, probable gold mineralized bedrock in the Timanttimaa area is outlined with red lines.

Table 5. Element contents of some selected soil geochemical samples from Timanttimaa. BDTL=combined sample of bedrock surface and till, WBTL=combined sample of weathered bedrock and till, MC=mica schist, GB=gabbro, AFB=amphibolite, SERC=sericite schist, SP=pyrite, AsP=arsenopyrite, q=silicification, sq=smoke quartz, ser=sericitization. Minerals=interesting minerals. Au and Te in ppb, others in ppm.

Material	Rock type	Minerals	Ag	As	B	Cu	S	Au	Te	W
BD	MC	SP, q	0.3	808	3	100	10900	395	217	-
BD	MC	SP, q	1.1	3	21	64	36000	135	131	-
BD	GB		0.6	750	3	30	6390	39	242	-
BD	AFB	AsP, sq	1.8	1880	3	263	5150	491	442	-
BD	MC	SP	1.0	797	6	165	37300	296	117	6.7
BDTL	MC		0.1	313	3	22	687	707	197	0.5
WBTL	MC	ser	0.1	31	10	29	131	114	80	0.4
WBTL	MC		0.1	30	15	36	221	217	51	0.9
WBTL	MC	ser	0.2	31	9	38	294	160	113	0.8
WBTL	MC	ser	0.1	28	19	37	206	358	74	1.2
WBTL	MC?		0.9	245	14	484	3770	135	31	1.6
WBTL	SERC		0.1	50	6	118	786	118	38	0.3
WBTL	SERC		0.2	32	8	35	411	609	217	1.6
WBTL	MC		0.1	14	9	35	323	417	50	1.5
WP	SERC		0.1	29	8	21	54	115	37	1.1
WPTL	MC?		0.1	29	9	15	140	415	59	0.4
WPTL	SERC		0.1	29	6	33	289	505	275	0.6
WPTL	MC?		0.1	38	5	31	310	293	364	1.3

Element contents of combined vs. separate till and bedrock samples

A high content of As, Au, B or Te was detected in 17 combined samples. For these, the original completely ground till and bedrock samples were then separately analysed by ICP-MS. This was carried out to clarify, which one consists a high content, and also to check the influence of the nugget effect on gold values.

High As, B or Te contents in combined samples did not reveal any new high Au contents. Thus, according to this small data set, the nugget effect is not significant in this area. A high Au content in combined samples can be explained by a high content either in till or, more typically, in a bedrock surface sample. Therefore, gold in this area is probably very fine grained, or is perhaps present in ore minerals, as arsenopyrite or pyrite. Furthermore, the high (or low) contents of other elements, for example Bi, B and Sb, in combined samples were comparable to the contents of separately analysed samples. According to the results, ICP-MS is well suited to soil geochemical studies in gold exploration.

When only the most important pathfinders are considered gold-containing samples (Table 6) can be divided into five combination groups:

1) Au-B (3 weathered bedrock samples)
2) Au-Te (2 weathered bedrock samples)
3) Au-As (1 small bedrock chip)
4) Au alone (2 weathered bedrock samples and 1 bedrock chip)
5) Au-Te-B-Zn (1 weathered sericite schist sample).

According to the data in Table 6, Sb, Cu and W are not pathfinders in gold exploration in this area. Only one sample is clearly Au anomalous out of six As anomalous samples. This could, however, indicate the nugget effect. It is clear that high As and Te in this area demonstrates the existence of gold horizons as well as gold itself. In many areas, black or sulphide schists, often high in As and Te, confuse comprehension of the distribution of these elements in gold exploration, but fortunately they, do not occur in Timanttimaa.

Ten Au anomalous samples consisted of weathered bedrock, while only one fresh bedrock chip and none of the till samples were anomalous. This may indicate that Au has somehow enriched in weathered bedrock. The sulphur content was low, except in one bedrock sample. In oxidized circumstances, Au and possibly Te have remained in weathering bedrock, while sulphur and arsenic have mobilized. The only gold-containing fresh bedrock sample had high contents of both Au and S content.

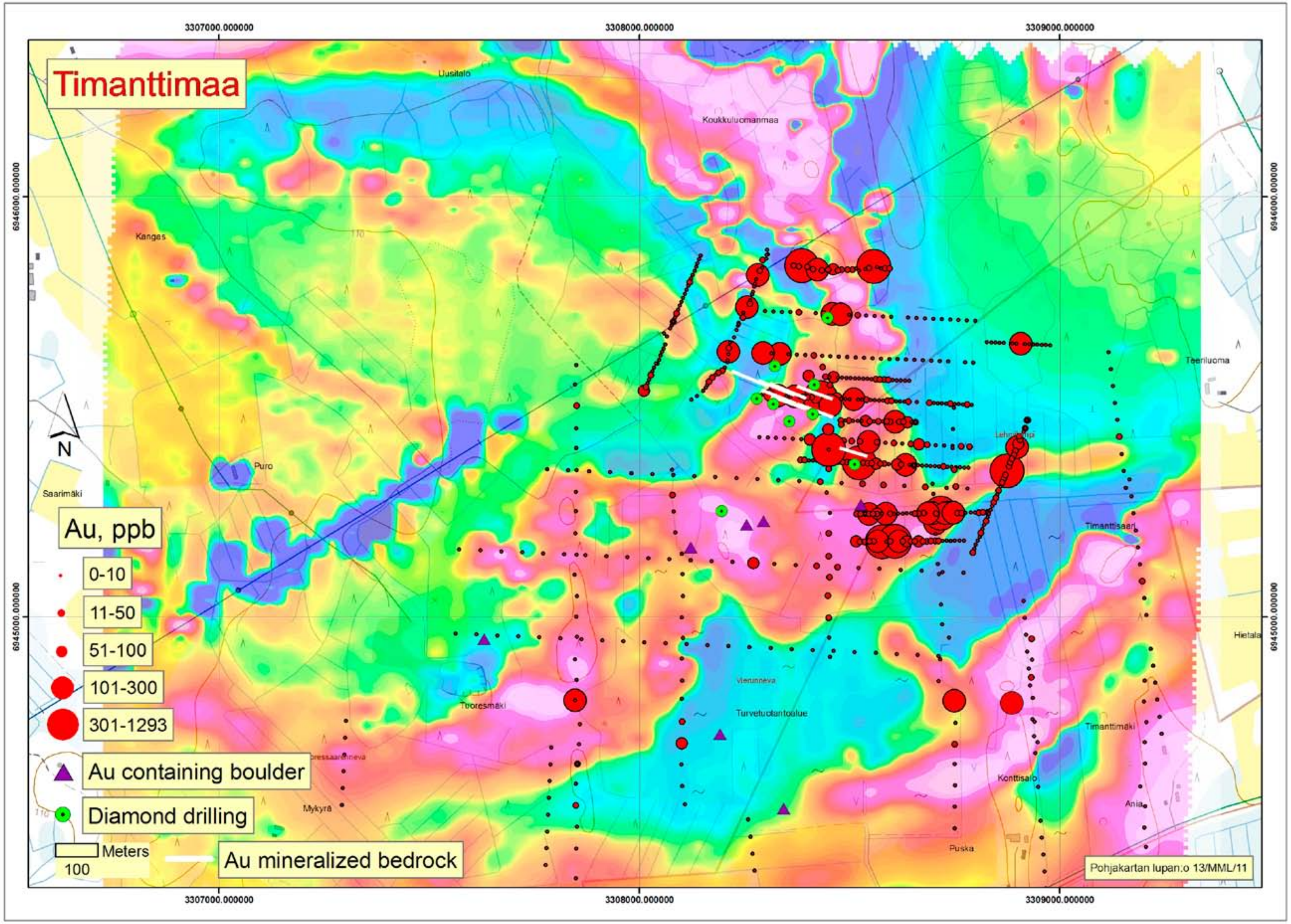

Figure 8. Gold content in the combined samples taken from the bottom of the till cover and from the bedrock surface in Timanttimaa, Seinäjoki. A map of the magnetic field measurements is presented as background. Basemap © National Land Survey of Finland, licence no 13/MML/12.

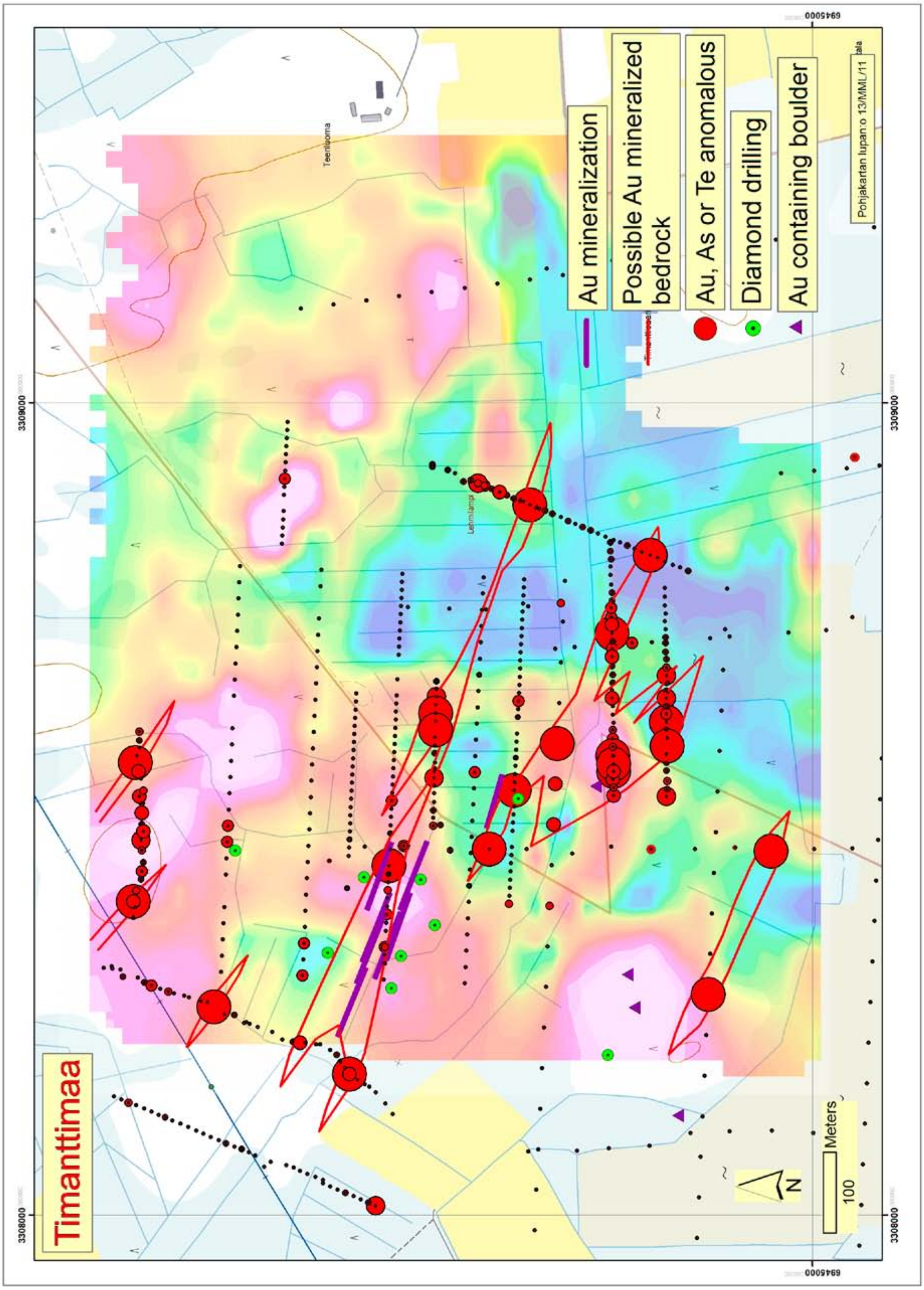

Figure 9. Gold, arsenic and tellurium content in combined samples (till samples and samples taken from the bedrock surface). Red lines delineate the highest contents of all of these elements. A map of induced polarization chargeability is presented as background. Basemap © National Land Survey of Finland, licence no 13/MML/12.

Table 6. The contents of some elements in combined samples and in separate samples from Timanttimaa, Seinäjoki. WB=weathered bedrock, BD=bedrock chip, CHLS=chlorite schist, MC=mica schist. SERC=sericite schist, AFB=amphibolite. TLWB=combination of till and weathered bedrock samples, TLBD=combination of till and bedrock chip. Anomalous values are in red. Au and Te as ppb, others as ppm. Analysed by ICP-MS.

ID	As	Au	Bi	Sb	Te	W	B	Ca	Cu	Na	S	Zn
30292 TLWB	778	11	1	5	135	0	12	3170	45	270	218	36
10 30292 80 Till	5	22	0	0	11	0	3	2250	15	349	342	47
10 30292 89 WB **CHLS**	**1370**	19	1	7	**211**	0	13	4000	58	273	156	25
30300 TLWB	20	251	1	1	147	1	23	2440	50	211	315	40
10 30300 40 Till	5	11	0	0	7	0	3	2470	10	299	585	36
10 30300 54 WB **MC**	21	**267**	1	1	177	0	**19**	1910	55	167	83	38
30310 TLWB	38	293	7	1	364	1	5	2520	31	224	310	49
10 30310 41 Till	5	19	0	0	8	0	3	2210	9	281	466	33
10 30310 51 WB **MC?**	55	**594**	**15**	1	**993**	1	10	2500	44	143	176	60
30328 TLBD MC	313	707	1	0	197	1	3	2580	22	783	687	32
10 30328 35 Till	5	41	0	0	34	0	3	2160	11	273	3	30
30343 TLWB	29	505	1	0	275	1	6	1680	33	330	289	49
10 30343 33 Till	5	8	0	0	3	0	3	2220	8	325	465	26
10 30343 43 WB **SERC**	53	**785**	2	0	**617**	0	12	1030	52	309	131	69
30361 TLBD	301	20	1	1	557	1	3	3850	107	558	1160	46
10 30361 32 Till	52	31	2	0	**1290**	1	3	1940	17	351	647	35
10 30361 44 BD **AFB**	539	31	0	2	56	0	7	5710	**183**	744	1820	56
30363 TLBD	424	42	0	8	47	1	3	3660	253	534	563	51
10 30363 36 Till	105	17	0	1	40	0	10	2750	122	286	272	46
10 30363 45 BD **AFB**	709	35	0	**20**	51	3	10	5240	**401**	922	993	62
30381 TLWB	29	415	0	0	59	0	9	2120	15	165	140	36
10 30381 50 Till	5	84	0	0	10	0	8	1650	7	222	213	42
10 30381 64 WB **MC?**	45	**546**	1	0	85	0	15	2460	10	122	78	29
30397 TLWB	**261**	**13**	3	**0**	**30**	**0**	**9**	1930	30	280	188	56
10 30397 42 Till	**538**	35	4	0	22	0	3	1510	24	240	270	24
10 30397 52 WB **MC**	21	8	1	0	35	0	12	2190	22	301	125	80
30413 TLWB	90	13	2	0	37	0	17	2030	36	169	927	49
10 30413 40 Till	5	6	0	0	3	0	3	2090	7	274	470	21
10 30413 53 WB **MC**	152	42	3	0	81	0	**29**	2090	59	85	1340	78
30420 TLWB	14	417	1	0	50	1	9	2790	35	153	323	67
10 30420 40 Till	15	38	0	0	48	1	8	2170	23	207	557	64
10 30420 52 WB **MC**	12	**628**	1	1	98	2	13	3410	28	53	80	67
30423 TLWB	32	609	2	1	217	2	8	1750	35	247	411	504
10 30423 40 Till	5	30	0	0	3	0	3	1910	10	263	471	23
10 30423 61 WB **SERC**	45	**778**	3	1	**531**	1	**17**	1320	43	187	307	**858**
30435 BD	**490**	**66**	**0**	**1**	**13**	3	**3**	8430	38	2060	4190	98
10 30435 20 BD **MC**	**500**	45	0	1	15	2	5	**7610**	35	**1770**	**4250**	95
30437 TLBD	27	236	0	1	12	1	3	3850	56	892	4610	196
10 30437 23 Till	5	7	0	0	6	0	3	1480	6	314	25	44
10 30437 34 BD **MC**	49	**388**	0	1	13	1	8	5610	89	1230	**9080**	**342**
30450 TLWB	28	358	0	0	74	1	19	1850	37	148	206	44
10 30450 40 Till	18	38	0	0	28	0	8	1810	12	228	251	43
10 30450 50 WB **MC**	37	**470**	1	0	142	1	**33**	1760	45	65	124	44
30452 TLWB MC	**30**	**217**	**0**	**0**	**51**	**1**	15	**2460**	**36**	**166**	**221**	**31**
10 30452 35 Till	5	25	0	0	3	0	3	2250	7	281	343	22

Tiilikallio

Background

The Geological Survey of Finland explored for gold because of samples collected from outcrops by an amateur geologist (Reijo Perälä) in the Tiilikallio area during 1983–1984 (Oivanen 1985). The bedrock is mainly intensely deformed uralite-plagioclase porphyrite, acid volcanic and mica schist. The silicified parts of the faults often contain arsenopyrite, but representative samples collected from the fault were low in Au, the maximum concentration being 1.2 ppm. In diamond drillings (154.30 and 94.00 m), gold contents were even lower (Oivanen 1985).

Samples

Samples were collected using a Terri hydraulic percussion drill during the winter of 2010. Altogether 270 samples were collected, 138 of which were till, 107 bedrock and 25 weathered bedrock. The soil cover was found to be thin in the area, and the mean depth of bedrock samples was 2.2 m.

The till samples were mainly dry, brownish grey, mean grey or brown grey sandy till. Two of the samples were greenish, which probably indicates a mafic origin. The preserved greenish colour of till also implies that the till consisted of local, not homogenized material on the proximal of the side on the sampling site. Most of the samples were loose, but ten of the samples were very tight. The latter samples probably represented old, highly consolidated till.

A notable proportion of the bedrock samples consisted of mica schist. Biotite was sometimes chloritized and sericitization was common. Occasionally, the amphiboles of the mafic rocks were biotitized, and samples in this case may sometimes have been wrongly determined as mica schist. Thus, for instance, uralite porphyrites are presumably more widespread and common than interpreted from the samples.

Mafic volcanics are more incoherent according to the rock samples taken during the soil geochemical sampling (Fig. 11) than they appear in the bedrock map of scale 1:100 000 (Lahti & Mäkitie 1990, Fig. 10). Intermediate porphyries seem to be fairly common in the area.

Only small amounts of ore minerals were detected in bedrock samples. Arsenopyrite was observed in two samples: in a porphyry and in a mica schist sample. Smoke quartz and pyrite were also recorded in the latter. Pyrite and pyrrhotite were detected in some samples.

Anomalies

In the factor analyses of combined samples from Tiilikallio (principal components, correlation matrix, Varimax-rotation), arsenic and tungsten most closely followed gold. Bismuth also had a fairly strong loading on this factor (F5). Tellurium located with sulphur (F2) and the highest Te contents located in areas, where gold occurs at low levels. The other factors were mica-mafic (F1), plagioclase (F3), potassium feldspar (F4), lanthanum-thorium (F6) and tin (F7). In one sample, the tin content was 59.7 ppm.

In Figures 12 and 13, the highest values of Au, As and W form two NW–SE-trending anomalies. Sampling was not performed between the anomalies because of the thin soil cover, but in this area several samples of bedrock have been collected by hammer. In addition, two drill holes exist, but the gold content in drill cores was reported to be low (Oivanen 1985). The anomalies that were now detected have not been verified by diamond drilling. It is difficult to distinguish any correlation between anomalies and magnetic field measurements (Fig. 12). In addition, only a weak resemblance could be observed between anomalies and IP measurements (Fig. 13).

The element contents of ten soil geochemical samples are presented in Table 7. Only three samples had gold content of over 100 ppb, but several samples clearly had anomalous values for As, B, Sb, Te and W. Arsenic and tungsten are mainly responsible for the delineation of the most potential areas for gold with red lines in Figures 12 and 13.

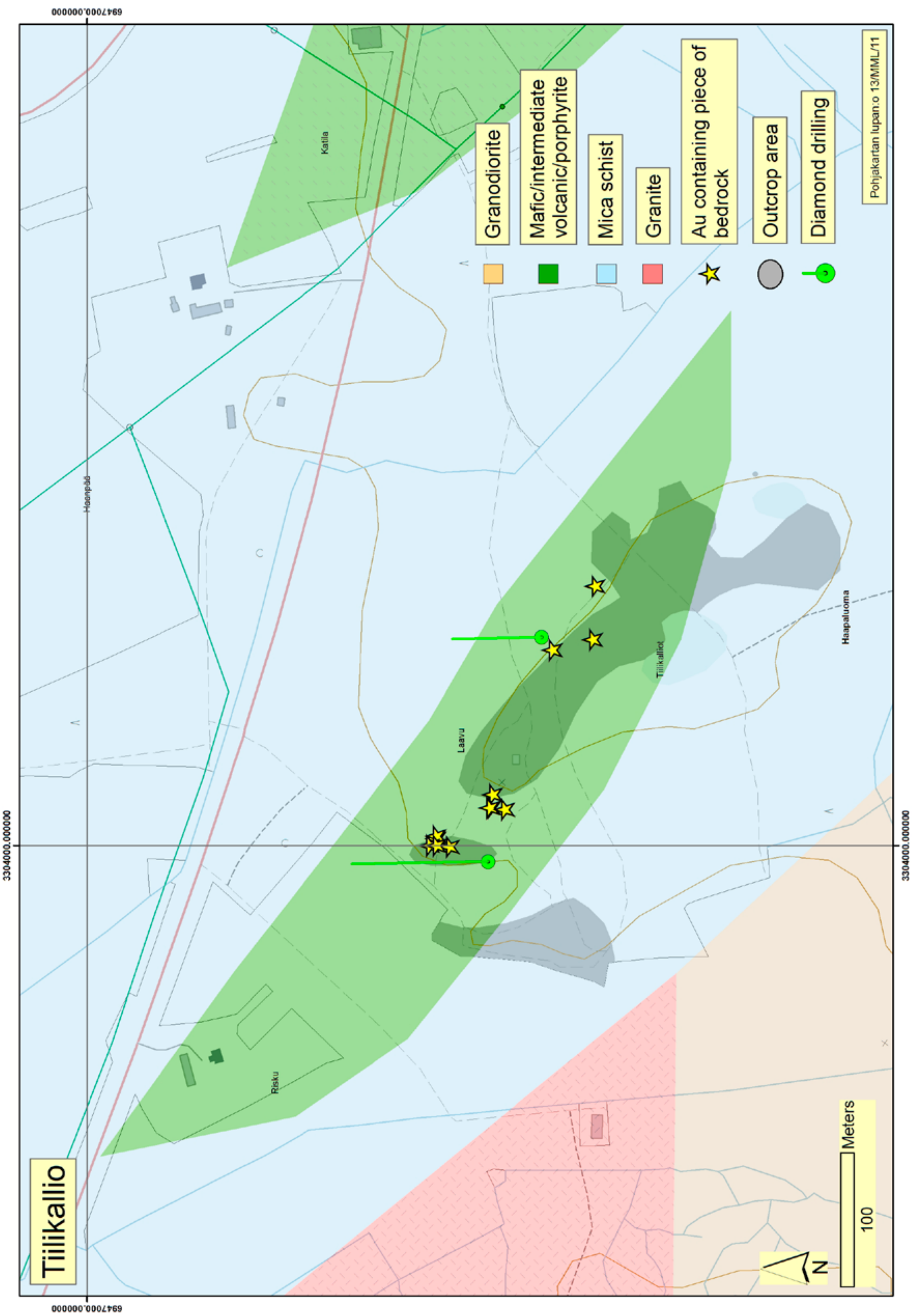

Figure 10. The bedrock of the Tiilikallio area according to Lahti and Mäkitie (1990), and the gold containing rock samples. Basemap © National Land Survey of Finland, licence no 13/MML/12.

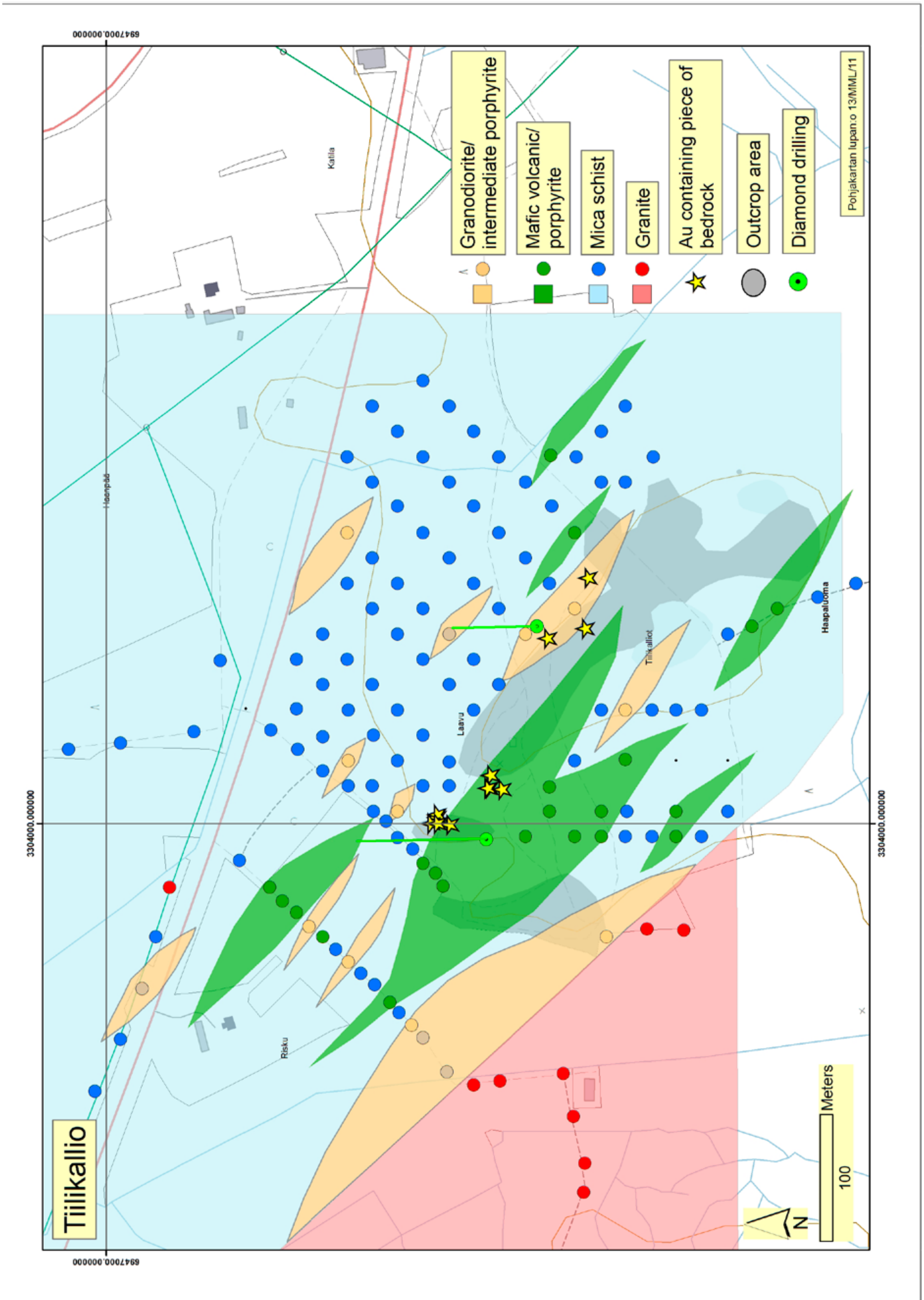

Figure 11. The bedrock of the Tiilikallio area according to soil geochemical sampling. Basemap © National Land Survey of Finland, licence no 13/MML/12.

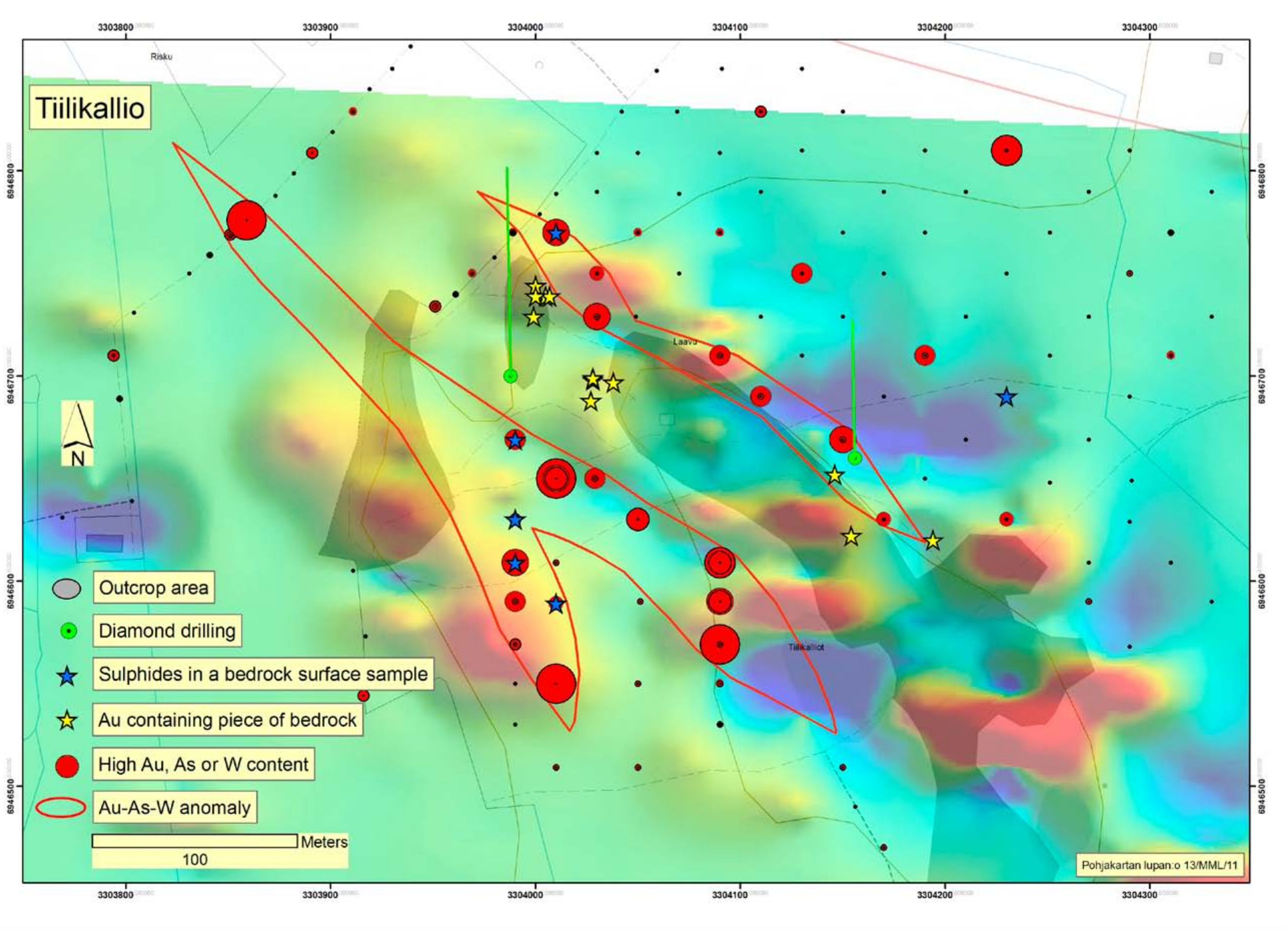

Figure 12. Gold, arsenic or tungsten content in combined till samples and samples taken from bedrock surface by hammer. Red lines delineate the highest contents of these elements. A map of magnetic field measurements is presented as background. Basemap © National Land Survey of Finland, licence no 13/MML/12.

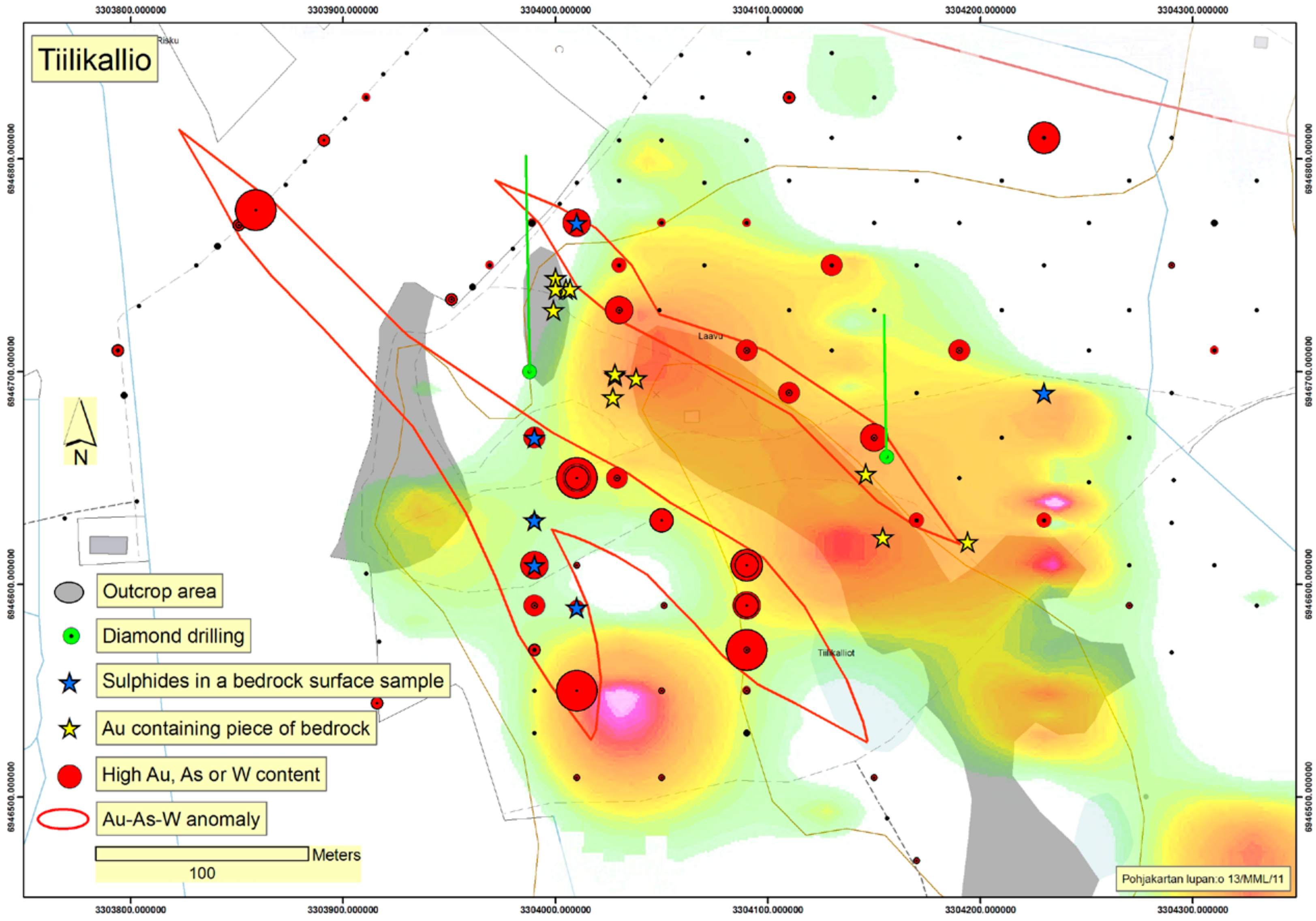

Figure 13. Gold, arsenic or tungsten content in combined till samples and samples taken from the bedrock surface by hammer. Red lines delineate the highest contents of these elements. A map of induced polarization measurements is presented as background. Basemap © National Land Survey of Finland, licence no 13/MML/12..

Table 7. Contents of selected soil geochemical samples from Tiilikallio, Seinäjoki. BD=sample of bedrock surface, BDTL=combined bedrock and till sample, WPTL=combined weathered bedrock and till sample, MAF=mafic volcanic rock, MC=mica schist, POR=intermediate porphyry. Analysed by ICP-MS. Au and Te as ppb, others as ppm.

	Kivilaji	As	Au	Bi	Sb	Te	W	Cu	S
BD	MAF	556	6	0.2	0.9	49	3	108	4200
BDTL	MC	5	6	3.0	1.1	156	0	63	136
BD	POR	700	7	0.9	6.3	678	0	158	25700
BDTL	MC	535	11	0.2	1.0	28	0	22	388
BDTL	POR	1520	11	0.4	3.2	26	0	46	1760
BDTL	POR	695	31	0.7	1.0	42	0	37	662
BDTL	MAF	670	37	0.6	0.7	28	68	32	1130
WPTL	MAF	2280	101	1.3	0.8	65	1	47	4500
BD	MC	3840	218	2.4	1.9	136	98	135	8640
BDTL	MAF	29	388	2.3	0.4	321	0	56	25

SUMMARY AND CONCLUSIONS

The project of the Geological Survey of Finland entitled “Evaluation of the ore reserves of Southern Finland”, led by Project Manager Niilo Kärkkäinen, began to investigate the gold potential of three tentatively studied gold targets in the Haapaluoma area of Seinäjoki in 2008. A part of the investigation involved sampling from the bottom of glacial till and from the bedrock surface more intensively and over a wider area than previously.

The thickness of the soil cover was on average four metres in the Haapaluoma area. The youngest ice movement direction was from north to south, boulder fans are also oriented in this direction

(Nenonen & Huhta 1981). The transportation distance of till is mostly short (Pääkkönen 1966, Nenonen & Hakala 1982). The influence of earlier glaciations is, of course, possible, and the so called complex transportation of till has no doubt occurred. However, there are only a small number of observations of older transportation (330°−340°) in Seinäjoki (Nenonen & Liippo 1984).

Karhukangas in Kauhajoki is situated about 60 km to southeast, where the soil thickness is up to 100 m. Even seven till beds separated by silt and sand layers have been observed in a soil profile (Pitkäranta 2009). During the soil geochemical studies, presented in this paper, older till than till than that of the Weichsel glaciations was probably met. At least very tight and consolidated till samples were collected in the Haapaluoma area.

Mica rich paragneiss dominates the Haapaluoma area. Depending, for instance, on the degree of metamorphosis, it can be referred to as mica gneiss, mica schist, metagreywacke or phyllite among others. Mafic, intermediate and acid volcanics occur less frequently. Hypabyssal dykes and uralite-plagioclase porphyrites cut schists and volcanics. Intermediate granitoids, tonalites, granodiorites and quartz diorites exist over wide areas. Diorite occurs as xenoliths in other granitoids. Granites as youngest granitoids also include xenoliths. Granite pegmatites occur as small intrusions and commonly as dykes in other rocks.

Two samples were taken at each sampling site with a Terri hydraulic percussion drill, the first from the bedrock surface and the other from till about a half a metre above the bedrock surface. Altogether, 2281 samples were collected. Local scale sampling was performed in a 100–200 m grid, and sampling at the target scale occurred along traverses. The soil type was verified and the colour and grain size of till samples was determined visually. The rock type was noted, as well as the colour, grain size and interesting minerals. If a sample contained ore minerals, both samples from the sampling site were analysed separately. Otherwise, samples from each site were combined and analysed at first by ICP-OES and GFAAS and later by ICP-MS.

The till samples were classified according to colour into three main groups. Greenish samples largely consisted of material from the mafic rocks situated on the proximal side of the sampling site. These samples were high in Ca, Fe and Mg. Fine sandy tills contained almost twice as much of the chalcophylic elements As, Cu, Fe and Te as coarse sandy tills. Ca and Mg, rich in mafic rocks, were also abundant in the fine sandy tills. One reason for this could be that rocks and minerals containing these elements are easy to comminute in glacial processes.

The sampling strategy was shown to be effective in delineating the gold potential at both local and target scales. According to the gold and arsenic contents of local-scale sampling, earlier known gold targets were wider than expected and new anomalies were also detected. Arsenic and tellurium proved to be excellent pathfinders for gold. On the other hand, it is evident that hydromorphic mobilization of sulphur, arsenic and tellurium has occurred during weathering and oxidation, while gold has remained immobile.

In target-scale studies at Pasto, two notable anomalies appeared. One of these was checked by diamond drillings. In the drill cores, arsenopyrite-containing quartz veins and patches existed in a several-metre-wide shear. Many 1-m drill core sections contained gold at the 1 ppm level, while the maximum content was 5 ppm/1 m.

According to the present studies, the gold mineralized zone observed in earlier diamond drillings at Timanttimaa (Kärkkäinen 1993b, c) continues in both directions. Besides the known gold horizon, a few parallel zones seem to exist at Timanttimaa.

At the Tiilikallio target, two longitudinal gold anomalies were also detected. They are probably related to shears in porphyrites.

ACKNOWLEDGEMENTS

The author wishes special thank to the Project Manager Niilo Kärkkäinen, who motivated to write this paper. The whole project could not be performed without the help of geologist Jorma Isomaa, foreman Viljo Bäck and assistants Mikko Pelkkala and Pauli Schroderus. I am grateful also to editorial board of Special Paper, especially to Roy Siddall, who translated my wrecked English to English.

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DISTRIBUTION OF GOLD IN TILL AT THE KALLIOJÄRVI GOLD OCCURRENCE IN THE PIRKANMAA MIGMATITE BELT

by
Thair Al-Ani and Niilo Kärkkäinen

Al-Ani, T. & Kärkkäinen, N. 2012. Distribution of Gold in Till at the Kalliojärvi Gold Occurrence in the Pirkanmaa Migmatite Belt. *Geological Survey of Finland, Special Paper 52*, 177–194, 13 figures, 7 tables and 1 appendix.

The till at Kalliojärvi is an unconsolidated mixture of clay, silt, sand and gravel deposited during the last glacial period in a ribbed moraine formation. A characteristic feature is the lack of maturity of till debris, indicating strong and multicyclic glacial erosion and short transport distances.

A 15-kg sample and a 1-kg subsample were taken from seven localities close to the unexposed Kalliojärvi gold deposit. In the heavy mineral concentrate (HMC), the most abundant minerals were magnetite and ilmenite (± chromite), pyrite, and chlorite. The HMC was concentrated in the coarse sand fraction (2–0.5 mm).

Altogether, more than 600 gold grains (nuggets) were recovered from these samples. The typical grain size of the gold varied from <0.004 to 0.5 mm. The form of the gold grains was rounded or subangular. The gold grains contained from 83 to 100 wt.% Au, 0–13 wt.% Ag, and traces of other elements (e.g., Fe, As, Te, Tc and Nb).

SEM analyses revealed that the surface topography of the gold grains was relatively irregular and vugs were common. There were diffuse imprints of the primary minerals. Diffuse and associated minerals consisted of iron oxide and clay coatings. A detailed study of the Kalliojärvi till samples demonstrated that close to the gold deposit, Au is enriched rather homogeneously in the till material under 2 mm. In the sample closest to the deposit, the Au content was higher in the coarse fraction (929 ppb, 0.5–2 mm) than in the finer fraction (599 ppb, <0.06 mm). Further from the deposit, the highest Au contents in chemical analyses were in the fine fraction (10–18 ppb, <0.06 mm). Mineralogical study revealed that the fine fraction may also contain an abundance of minute (10 µm) gold grains.

The pathfinder elements As, Cu, Zn, S and Te were observed to be enriched in the fine fraction of the till material, when comparing the Kalliojärvi till with the average level for the fine fraction of till (<0.06 mm) in Finland.

Keywords (GeoRef Thesaurus, AGI): gold ores, mineral exploration, till, grain size, geochemistry, gold, mineralogy, heavy minerals, Kalliojärvi, Lempäälä, Finland

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INTRODUCTION

Kalliojärvi is located 20 km south of Tampere, within the Pirkanmaa (Vammala) Migmatite Belt (Fig. 1). The Kalliojärvi gold mineralization was discovered during 1994 by GTK based on detailed heavy mineral and till geochemical studies (Rosenberg 2000). The Kalliojärvi deposit is covered by a 3–10m thick basal moraine that is composed of a single till bed. Since discovery it has been a test site for geochemical studies (Tarvainen et al. 2007) and further exploration (Lehto 2004, Kärkkänen et al. 2003).

In the nationwide till geochemical mapping by the Geological Survey of Finland at the beginning of the 1980s, only spiky gold anomalies were observed in the Pirkanmaa Belt. An interesting feature was a clear As anomaly zone orienting west from Nokia through the Pirkanmaa Belt southeast to the Hämeenlinna area. Later, a regional heavy mineral study and geochemical exploration indicated a prominent gold anomaly at least 400 m long in till around Kalliojärvi (Fig. 2), where a 250 m long and 50–60 m wide gold mineralization was found in a shear zone of greywacke domain bedrock (Rosenberg 2000, Lehto 2004). The MMI method was applied at Kalliojärvi and revealed that the gold deposit is also seen as a sharp but narrow MMI anomaly by sampling till from a line running through the mineralization (Tarvainen et al. 2007).

At Kalliojärvi, the bedrock is almost completely covered by till. The present study involved the examination and studying of different till samples from seven sites at Kalliojärvi. Samples were taken close to the soil surface, from a depth of 0.1–0.5 m below the organic material. One sample (Kallioj-6) was collected close to an outcrop consisting of mica gneiss with arsenopyrite-bearing quartz veins and was thus thought to represent a mixture of weathered bedrock and till. Other samples clearly comprised basal till, some of them partly washed during early postglacial processes.

The aim of this study was to assess the use of till as tool in gold exploration. The various grain-size fractions of the till matrix were investigated, especially the variation in heavy mineral concentrates and the chemical composition of these frac-

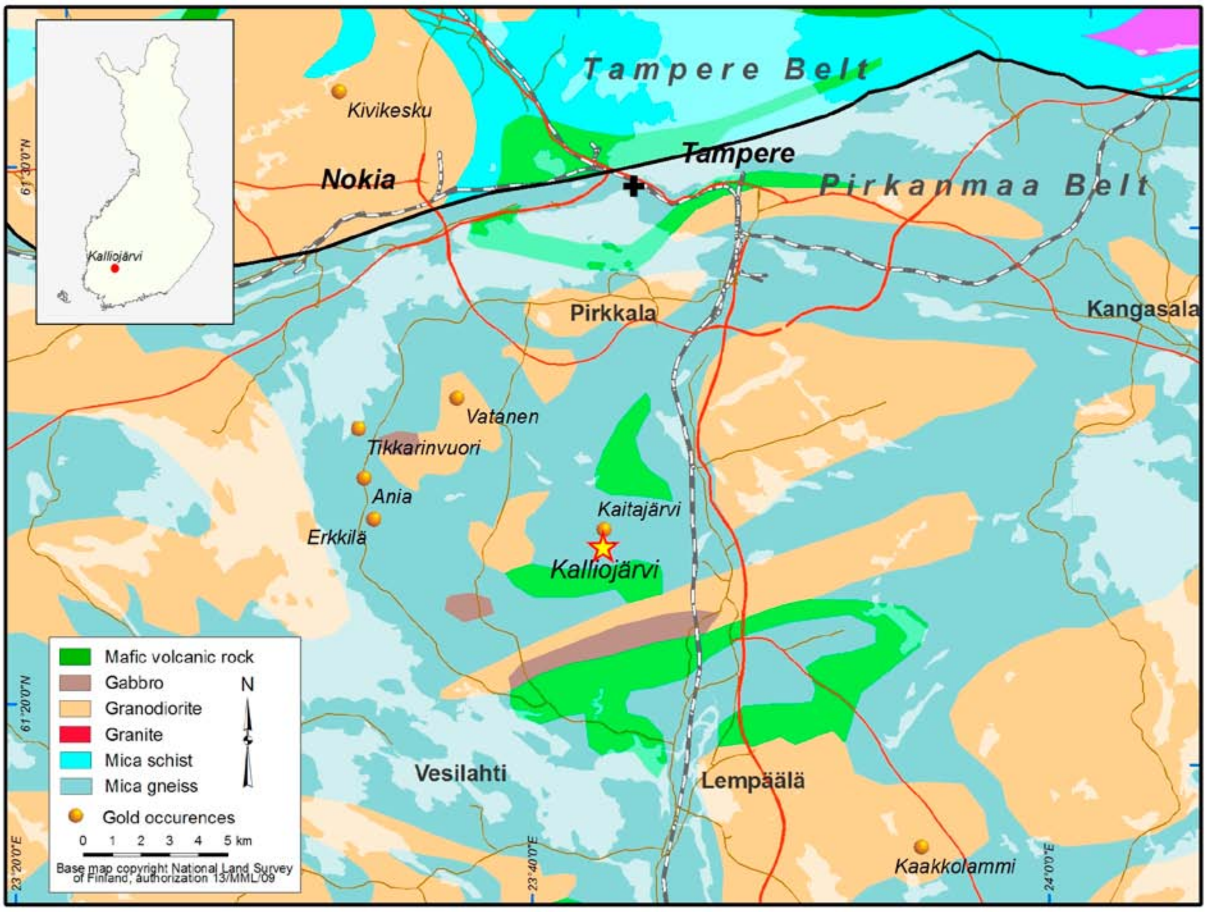


Figure 1. Location of Kalliojärvi on the bedrock map of Finland; other gold occurrences are marked as yellow labels. Basemap © National Land Survey of Finland, licence no 13/MML/12.

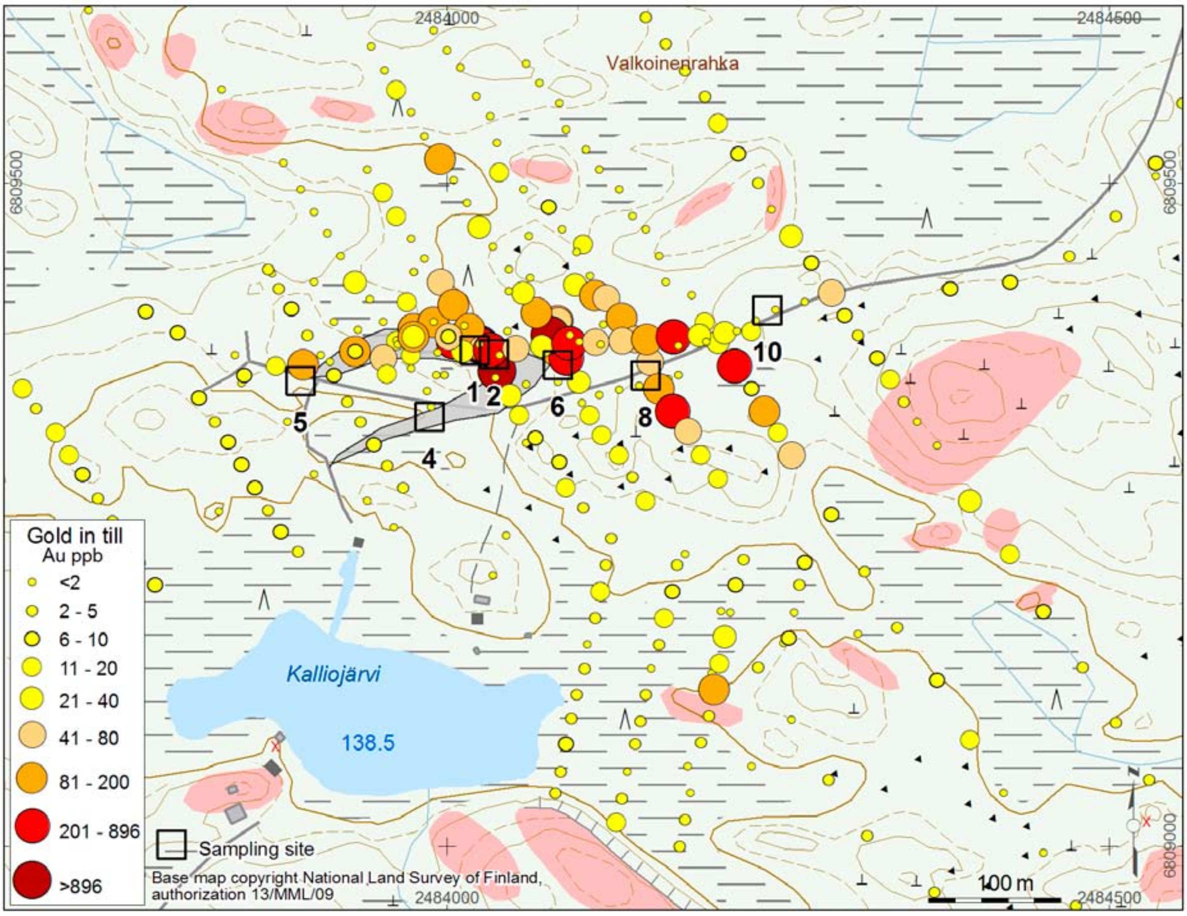


Figure 2. Sampling sites on a geochemical map of gold in the Kalliojärvi area; the outlined suboutcrop of the gold mineralization according to Rosenberg (2000). Basemap © National Land Survey of Finland, licence no 13/MML/12.

tions, and the quantity, composition and morphology of the gold grains. The possible regional variation in the features of the sampling area may be important in further exploration.

Most of the information contained in this article has been presented in GTK's report M19/*2123, 2734, 3721*/ (Al-Ani et al. 2008).

METHODS

Samples were taken by shovel from basal till close to the surface but just below the organic material, from a depth of 0.1–0.5 m (Fig. 3). Gravel-sized stones larger than 5 cm were removed from the sample in the field. Three samples were taken from seven locations close to the Kalliojärvi gold deposit (Table 1). One of the samples from each site was a 15-kg bulk sample and the two others were 1-kg subsamples.

Sample preparation

The 15-kg bulk samples from the Kalliojärvi target were transported whole for heavy mineral examination to the GTK's Southern Finland Office at Espoo. The sample processing is outlined in Figure 4 (Group b).

One series of 1-kg subsamples was used for detailed studies by Thair Al-Ani at the Espoo office. These studies included grain-size analysis, mineralogical investigations and chemical analysis of different grain-size fractions from each sample (Group a in Fig. 4).

The other 1-kg subsamples were sent to GTK's laboratory in Rovaniemi for total cyanide leach analysis.

a)

b)

c)

Figure 3. Sampling at Kalliojärvi: a) the landscape of the basal moraine area (Kallioj. -2); b) sampling depth (Kallioj.-2); c) the site close to an outcrop. The sample from this locality was assumed to represent till partly mixed with weathered bedrock (Kallioj.- 6).

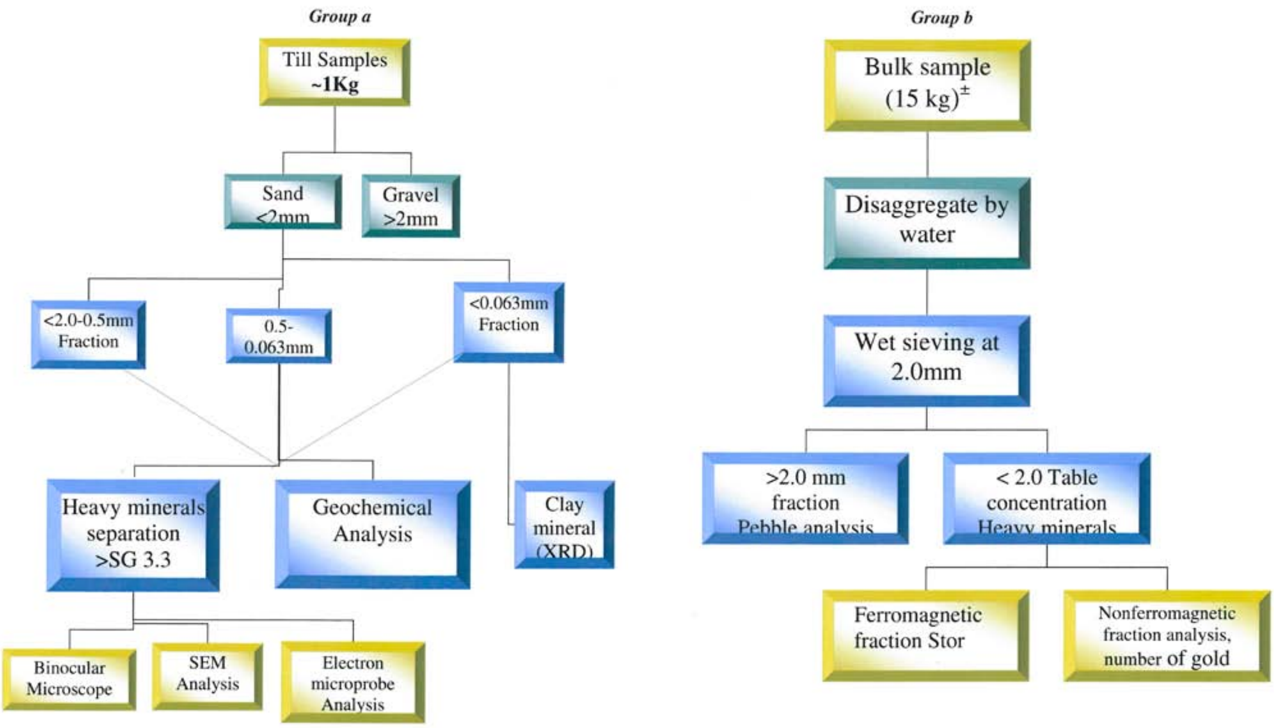


Figure 4. Sample processing flow chart for till sample preparation; Group a: preparation of different grain-size fractions for geochemical and mineralogical analyses. Au grains and heavy minerals were examined and counted from different fractions; Group b: preparation of heavy mineral concentrate for gold grain counting and indicator mineral applications.

Grain-size analysis

The analysis of the grain-size distributions in the till samples was started by dry-sieving the > 2 mm fraction from the bulk sample. The relative proportions of the < 2 mm fractions were determined by further dry-sieving by passed through a set of sieves with aperture sizes ranging from 2 to 0.063 mm (Table 1).

Mineralogical analysis

Mineralogical analyses were performed from each grain-size fraction. They were carried out by using X-ray diffraction (XRD) (Siemens Diffract Meter D5000) and scanning electron microscopy (SEM). The clay fraction of samples was studied for both powdered samples and oriented clay films. Oriented samples were used to obtain stronger basal reflections of the clay minerals in XRD. Heating techniques (550 °C), glycerol treatment (with Mg-saturated samples), and Ni-filtered CuKα radiation with a voltage of 40 kV and current of 40 mA were used in XRD.

Table 1. Locations and grain-size distribution of the studied till sub-samples (group b) from the Kalliojärvi area.

Sample No.			Sample locations		
	X(KKS coordinates)	y(KKS coordinates)	Sample material	Sample size(kg)	Depth(m)
Kallioj.- 1	6809374	2484021	Till	0.72	0.50
Kallioj.- 2	6809371	2484036	Till	0.98	0.30
Kallioj.- 4	6809324	2483987	Till	1.20	0.50
Kallioj.- 5	6809351	2483890	Till	1.20	0.50
Kallioj.- 6	6809363	2484084	Till	0.78	0.50
Kallioj.- 8	6809355	2484150	Till	0.71	0.50
Kallioj.- 10	6809404	2484242	Till	1.12	0.50

Examination of gold

The morphology and size of the gold grains were determined under an optical microscope and scanning electron microprobe (SEM). The SEM study was carried out in backscattered electron mode, using a Philips XL40 instrument fitted with an environmental sample chamber. This permitted examination of the samples without a conductive coating. Gold grains were analysed for Au, Ag, Cu, Fe, Si and Te. The chemical composition of the gold grains and the composition of neighbouring minerals were determined semi-quantitatively by using an energy dispersive detector (EDS). The precision was limited due to surface effects of the unpolished grains.

Chemical analysis

Three grain-size fractions (<0.06 mm, 0.06–0.5 mm, 0.5-2 mm) of the studied tills and the pulverized bulk till samples were chemically analysed (Appendix 1). The methods (and code numbers) are described in the Schedule of Methods of the Labtium chemical laboratory (http://www.labtium.fi/files/TESTING-AND-ASSAYING-2009.pdf).

The samples were first dried at 40 °C and then partially leached with aqua regia. Graphite furnace atomic absorption spectrometry (GFAAS, method 522U) was used to analyse Au, Pd and Pt, and inductively-coupled plasma atomic emission spectrometry (ICP-AES, 511P) for analysis of 31 other elements. The two coarser grain-size fractions (0.06–0.5 and >2 mm) were pulverized in a carbon steel bowl before leaching. Au was also analysed by using Pb fire assay flame absorption analysis (Method 705A, FAAS) and by flame absorption analysis from a cyanide leach of bulk sample (Method 236A, FAAS).

Heavy-mineral concentrate from till

Heavy mineral concentrates were recovered from each grain-size fraction and also from the 15-kg bulk till samples.

After sieving, each grain-size fraction (<0.063 mm, 0.25–0.5 mm and 0.5–2.0 mm fractions, each weighing 55–470 g) was further concentrated to a > 3.3 specific gravity, heavy-mineral concentrate (HMC) using density-dependent settling in ethylene iodide diluted with acetone. The ferromagnetic fraction containing magnetite was removed with a hand magnet or with an electrical magnet from the samples.

The heavy minerals fractions were examined under a binocular microscope. Gold and indicator minerals were picked from the samples during a visual scan. Gold and indicator minerals were counted and then examined to determine the nature of inclusions and textures using backscattering and in a scanning electron microprobe (SEM-EDS).

The heavy mineral study of a 15-kg bulk till sample is a standard method in mapping the gold potential in southern Finland by GTK. It is usually carried out when testing geochemical anomalies or the vicinity of gold-mineralized boulders. In this study, the heavy mineral analysis of bulk till samples was carried out for comparison of the number of gold grains in this standard-sized sample and the chemical analysis of gold from various grain-size fractions. The heavy mineral concentrate was prepared by using a spiral separator and by panning the overflowing material. The weight of these concentrates was about 200–600 g. Magnetite was removed with a hand-held magnet. The heavy mineral fractions were examined under a binocular microscope, and gold and indicator minerals were picked from the samples during a visual scan.

RESULTS

Grain-size distribution

Sieving revealed a polymodal particle-size distribution and an unsorted mixture of clay, silt, sand and gravel, with boulders up to 5 cm in diameter. Gravel percentages (>2 mm) range from 25% to nearly 42%, coarse sand from 15 to 31%, fine sand from 23 to 51% and the amount of fine-grained material <0.063 mm between 6 and 12%. (Table 2). The mode is in the size range of fine-medium sand (0.5–0.063 mm).

Mineralogy of the fine fraction

The clay minerals in the tills of the Kalliojärvi area are chlorite, kaolinite, illite and vermiculite. Mixed layers of illite and vermiculite also occur in these samples.

The main phyllosilicates were found to be a slightly weathered trioctahedral chlorite, rich in both Mg and Fe, together with dioctahedral mica and minor amounts of kaolinite, vermiculite and

Table 2. The grain-size distribution of till; 1-kg subsamples from Kalliojärvi.

Sample No.	Weight of subsamples(g)					Weight% of each fraction			
	>2mm	2-0.5mm	0.5-0.063mm	<0.063mm	Total	>2mm	2-0.5mm	0.5-0.063mm	<0.063mm
Kallioj.- 1	256.7	226	166.1	73	721.8	36 %	31 %	23 %	10 %
Kallioj.- 2	328.7	195.9	399	55	978.6	34 %	20 %	41 %	6 %
Kallioj.- 4	390.9	287.7	386.4	116.3	1181.3	33 %	24 %	33 %	10 %
Kallioj.- 5	314.3	285.7	474.6	133.2	1207.8	26 %	24 %	39 %	11 %
Kallioj.- 6	197.1	112.8	394.4	71.9	776.2	25 %	15 %	51 %	9 %
Kallioj.- 8	257.4	131.9	236	84.4	709.7	36 %	19 %	33 %	12 %
Kallioj.- 10	465.1	237.7	277.7	129.4	1109.9	42 %	21 %	25 %	12 %

mixed-layer minerals.

Clinochlore $(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8$ forms from the metamorphic and hydrothermal alterations of other iron and magnesium silicate minerals usually derived by alteration of primary Mg- and Fe-bearing minerals such as pyroxenes, amphiboles, biotite, and other ferromagnesian minerals (Nesse 2000).

Vermiculite and illite were the main secondary clay minerals found in the studied samples. Vermiculite can be identified by its typical 14–14.6 Å peak range (Brown & Brindley 1980) along with one at 3.36 Å. Illite (trioctahedral) can be identified by its 10 Å asymmetrical peak at low angles. Heating of a sample to 550 °C serves two important functions. It causes the collapse of vermiculite, which contains non-exchangeable interlayer Al complexes, and it destroys kaolin minerals. Vermiculite is confirmed by heat treatment through the disappearance of the 14 Å peak followed by an increase in the 10 Å peak. The mineralogy of the samples, particularly clay mineralogy, was determined to examine the degree of weathering in both types of samples: (i) moderate-high weathered till samples, and (ii) low weathered bedrock samples. In the study area, progressive weathering of the rocks has been marked by a high content of the fine fraction < 0.063 mm, comprising 10% or more for most of the studied samples (Table 2). The larger clay content of weathering profiles in the studied tills increases as a function of age, and kaolinite is the dominant clay mineral in till samples with a high content of the fine fraction.

Heavy-mineral analysis

The mass fraction of the heavy mineral concentrate (HMC) of each individual till grain-size fraction (Table 3) was calculated according to the method described in Luepke and Grosz (1986). Heavy minerals in each grain-size fraction were weighed and examined under a binocular microscope and then calculated as the total weight per 200 g of individual till particle fractions (Table 3).

The mode of the average HMC in each grain-size fraction falls in the coarse sand range (2–0.5 mm), while in the medium sand fraction (0.5–0.063mm) it is slightly lower and the average MHC of fine fractions (<0.063 mm) is only about 0.05 g (Fig. 5). The highest percentage of HMC was recorded in the sample Kallioj.-6, but no gold was found in the grain-size fractions. However, the HMC of the fine fraction of the sample Kallioj -2 contained the greatest number of gold particles (17 grains).

According to heavy mineral identifications (Table 4), the most abundant minerals are ilmenite and magnetite (totalling about 60% of each HMC), pyrite, and garnet and gold. Other minerals include hematite, goethite, chalcopyrite, epidote, pyroxene, amphibole, mica, apatite, zircon, and rutile, tourmaline, staurolite, apatite, limonite, anatase, sphene.

Table 3. Weight of heavy mineral concentrates (calculated for a 200 g sample size) and the number of free gold grains in concentrates of each grain-size fraction. Note that for concentrates weights are standardized according to the data in Table 2. The number in parentheses indicates the quantity of gold grains in each HMC fraction.

Fraction		Size of sample (200 gm)	
Size (mm)	2–0.5	0.5–0.06	<0.06
Kallioj. -1	0.44(7)	0.31(7)	0.006
Kallioj. -2	0.33(1)	0.16(2)	0.02(17)
Kallioj. -4	0.22(3)	0.27(1)	0.09
Kallioj. -5	0.34	0.37	0.19(2)
Kallioj. -6	0.80	0.16	0.005(1)
Kallioj. -7	0.39	0.31	0.01(2)
Kallioj. -8	0.30	0.11	0.01
Kallioj. -10	0.21	0.38	0.01(1)

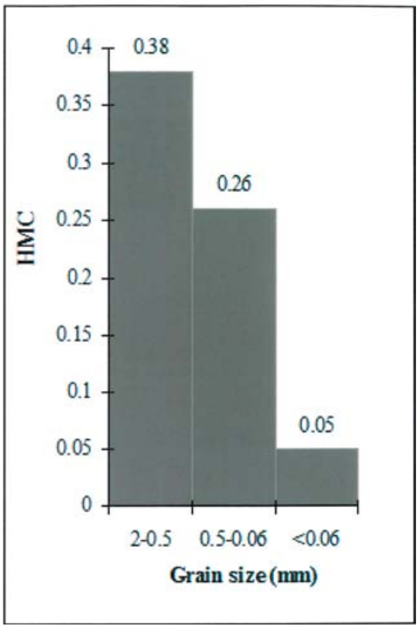


Figure 5. The averaged weights of the heavy mineral concentrates (HMC) of grain-size fractions of the Kalliojärvi till samples.

Table 4. Heavy-mineral analyses of various grains-size fractions of till from Kalliojärvi.

Size (mm)	2–0.5	0.5–0.063	<0.06
Kallioj.- 1	ilmenite, magnetite, pyrite, gold	garnet, pyrite, ilmenite, magnetite, gold, others	garnet, pyrite, ilmenite, magnetite, others
Kallioj.- 2	ilmenite, magnetite, garnet, mica, gold	garnet, ilmenite, pyrite, magnetite, gold, others	ilmenite, pyrite, magnetite
Kallioj.- 4	ilmenite, magnetite, pyrite, gold	garnet, ilmenite, magnetite, gold, pyrite, others	ilmenite, magnetite, rutile, pyrite,
Kallioj.- 5	garnet, ilmenite, mica	garnet, ilmenite, pyrite, rutile, others,	ilmenite, magnetite, garnet, rutile, gold, others
Kallioj- 6	ilmenite, magnetite, quartz, mica	garnet, ilmenite, pyrite, quartz, mica	ilmenite, rutile, garnet, gold
Kallioj.- 8	garnet, ilmenite, mica	garnet, ilmenite, magnetite, tourmaline	ilmenite, rutile, garnet, hematite, gold
Kallioj.- 9	ilmenite, quartz, mica, many light minerals	garnet, ilmenite, magnetite	ilmenite, rutile, garnet, hematite
Kallioj.- 10	garnet, ilmenite, tourmaline	garnet, ilmenite, rutile, tourmaline, magnetite	ilmenite, rutile, garnet, gold, others

Optical examination of gold grains

The gold occurred as microscopic and sub-microscopic particles and showed a wide range of sizes, shapes and colours. There were a large number of gold grains in some bulk-till samples from Kalliojärvi (Table 5 and Fig. 6). Highest number was 215 gold grains in the sample Kallioj.-1 and the smallest number in the 15-kg sample was 6 gold grains (Kallioj.-5 and Kallioj.-8).

Gold grains recovered from the studied samples varied in size between <10 µm and 1000 µm, and most gold grains were <20 µm (Fig. 7). The high proportion of small-sized grains may reflect the nature of the bedrock Au mineralization rather than the glacial transport history (Averill 2001), because the latter means the folding and crumpling of larger grains to form small ones, and this is not likely to occur with gold.

The gold from studied area showed a mixture of shapes and colours. Many grains were very yellow to deeper yellow in colour, and the shapes varied from sub-angular to sub-rounded or flat (Fig. 8). In some cases, angular grains had distinct negative crystal shapes indented in their surfaces and a few grains still contained interstitial quartz. A very small proportion of the grains were rounded, and some had Fe-oxide coatings seen in Figure 9.

The results of both sample types (15-kg bulk samples and 1-kg subsamples) indicated that the sample size fraction 0.5–0.063 mm contained the highest numbers of gold grains.

Table 5. The number of free gold grains in 15-kg bulk till samples from Kalliojärvi.

Sample	<10 µm	10-20 µm	20-30 µm	100-500 µm	1000 µm	Gold Particles
Kallioj.- 1	100	99	16	0	0	215
Kallioj.- 2	19	54	10	3	0	86
Kallioj.- 4	9	5	1	0	0	15
Kallioj.- 5	1	4	1	0	0	6
Kallioj.- 6	36	15	1	0	1	53
Kallioj.- 8	0	5	0	1	0	6
Kallioj.- 10	3	5	0	0	0	8
Total	168	187	29	4	1	389

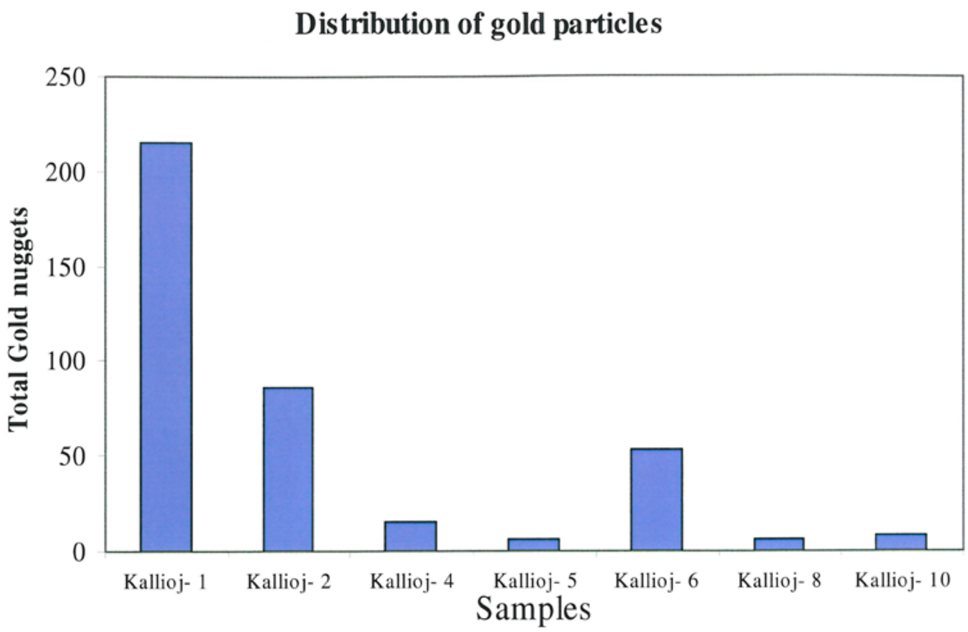


Figure 6. The number of gold grains in bulk till samples from the Kalliojärvi area.

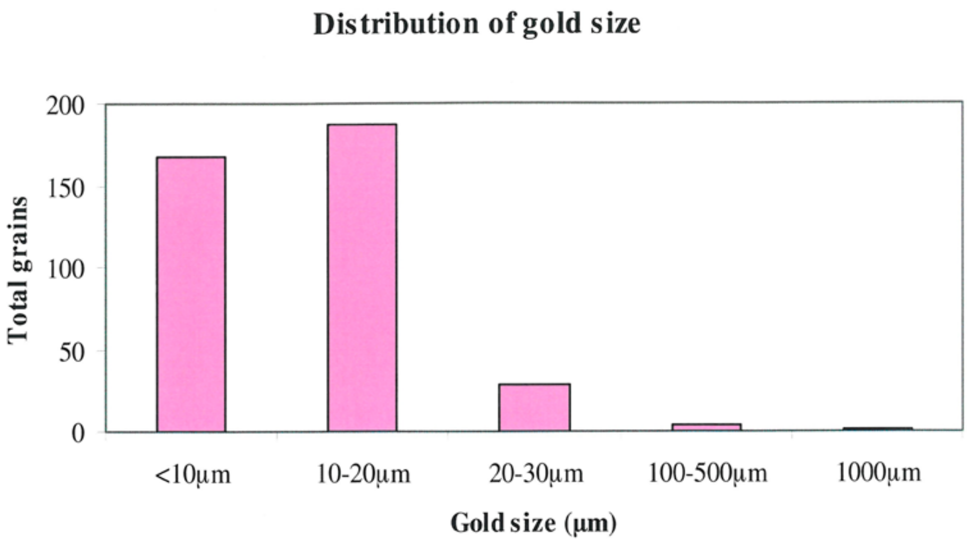


Figure 7. Size distribution of gold particles in the studied bulk till samples.

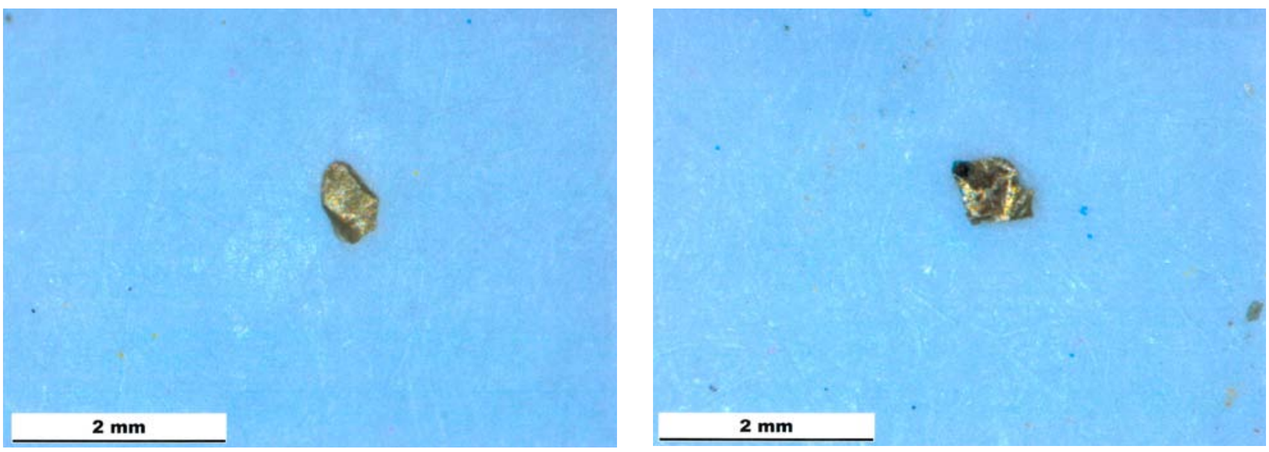


Figure 8. Microscopic images of sand-sized gold grains from Kallioj.-1.

SEM-EDS examination of gold grains

The gold from Kalliojärvi till predominantly consisted of small, rounded grains with etched, flaky and angular shapes (Figs. 9a and b) and a minor proportion were more or less crystalline gold grains (Figs. 8 and 9c). The SEM backscattered electrons images generally confirmed two types of gold with different physical appearances, and both of these types were found in every sample.

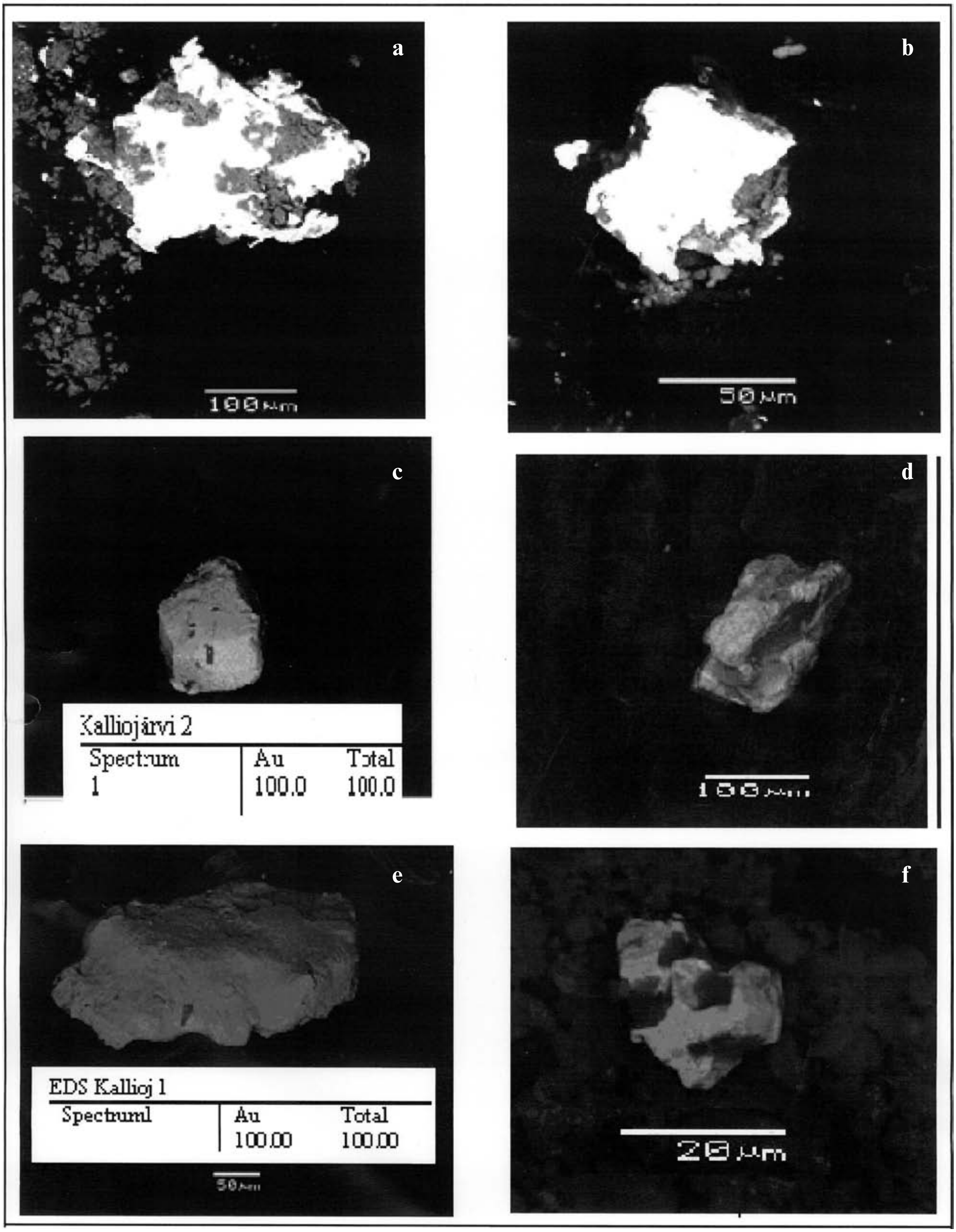


Figure 9. Backscatter image of micro-grained gold particles from Kalliojärvi samples.

One group consisted of grains with a rounded appearance and an effective size of more than 50 µm, and grains in the other group had etched, flaky, indefinite shapes and a smaller size (20 µm). Especially very small gold grains were often subangular and equant (Fig. 9d), rather than flat and occasionally intricate in shape (Fig. 9e). It is evident that the regular shapes of gold grains indicate a short distance of transport.

The chemical composition of gold grains analysed by EDS indicated that they were native gold or simple Au–Ag alloys. The core composition of the gold grains varied little with an average chemical composition of 83 to 100 wt.% Au and 0-13 wt.% Ag (Table 6). In the semi-quantitative analyses, traces of other elements such as Fe, As, Te, Nb) were detected (Table 6).

Table 6. EDS analysis results (wt%) of gold grains from studied samples.

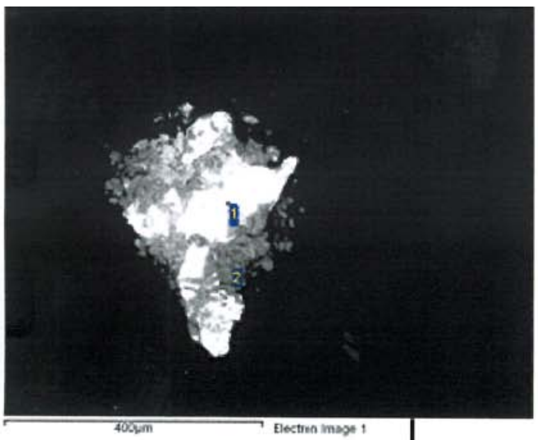
Sample		Au	Ag	Fe	Total
Kalliojärvi	1				
Spectrum	1	86.84	13.16		100
	2	90.26	9.74		100
	3	93.6	5.7	1.02	100
	4	100	0		100

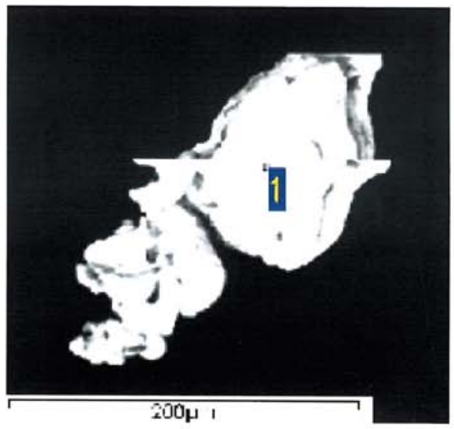
An interesting feature of the gold grains was minor zoning in the composition. The rim of each grain was generally richer in gold than the core, and the contact between rim and core was very sharp but irregular in shape and complex in texture (Figs. 9 and 10). Some of the gold grains contained inclusions of niobium minerals, as in sample Kallioj.-2, which contained karnasurtite as an inclusion in gold grains (Fig. 10).

Backscattered electron images revealed the surface of gold grains to be coated by iron oxides, manganese and other silicate material. These coatings on gold were formed either by supergene alteration of the deposit or introduced during the process of gold separation and recovery.

According to the EDS-SEM results, the observed elements in the gold grains can be grouped as follows:

- Gold particles with a low concentration of Ag; most common
- Specific native gold particles Au; chemically 100 wt.% Au
- Some gold grains with traces of Cu, Te, Tc, Nb and Fe.





EDS Kallioj 2

Spectrum	Ag	Au	Total
1	10,92	89,08	100,00

Gold contain inclusion of karnasurtite (Nb) at Kallioj.-2

Spectrum	O	Al	Si	Ag	Fe	Nb	Au	Total
1				5,70	1,02		93,6	100.0
2	54.02	3.05	39.92		0.94	2.07		100.0

Figure 10. Backscatter image and EDS of some gold grains from sample Kalliojärvi 1.

Geochemistry of the till

The three different grain-size fractions of till (<0.06, 0.06–0.5 and 0.0–2.0mm) were also chemically analysed (Table 7 and Fig. 11).

Elevated Au concentrations were determined to occur throughout the Kalliojärvi till. The lowest Au contents were 9.7 ppb and 10 ppb in the fine fractions of samples Kallioj.-4 and Kallioj.-5, which were both collected south of the mineralization. These till materials cannot have been transported from the mineralization, because the direction of the ice drift here is from the west.

There were four samples with an exceptionally high gold content in each grain-size fraction, from 69 to 929 ppb Au (samples Kallioj. - 1, 2, 6 and 8). The whole samples were analysed by cyanide leach of the pulverized sample (Method 236A, FAAS). It was also observed that these samples showed a high Au content (0.5, 0.4, 0.3 and 0.2 ppm for Kallioj.-1, -2, -6 and -8, respectively).

The coarse fraction of the samples Kallioj.4, 5 and 10 were relatively low (<10 ppb), but increased by a factor of many times in the fine fraction to

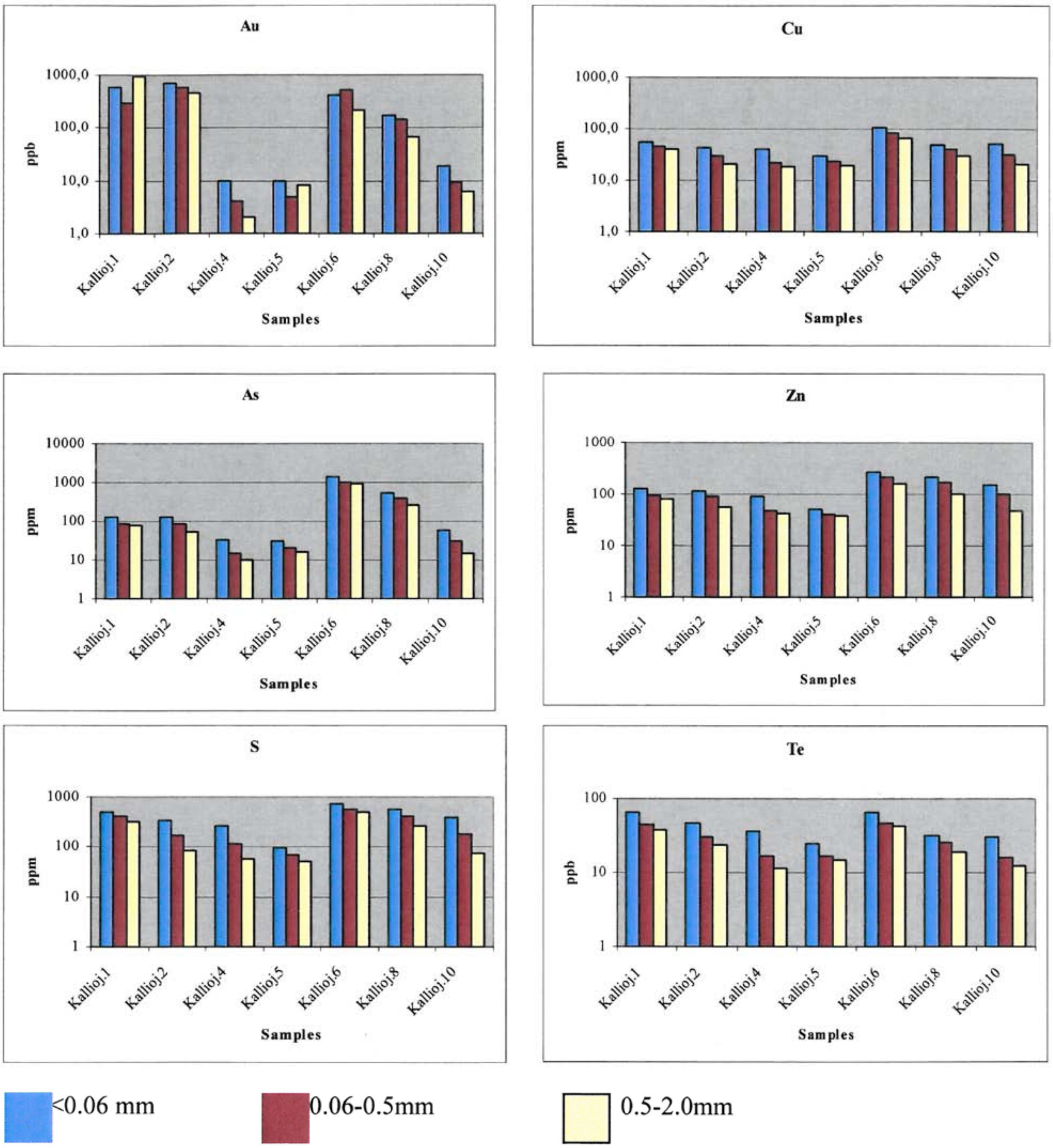


Figure 11. Distribution of Au, As, Cu, Zn, S and Te in each subfraction of Kalliojärvi samples.

Table 7. The contents of Au, Cu, As, Zn, S and Te in the fine (<0.06 mm), medium (0.06–0.5 mm) and coarse (0.5–2 mm) fraction of till samples from the Kalliojärvi area. Analyses were performed from aqua regia (partial) leach by ICP-AES (511P) and GFAAS (522U). The last column presents the gold contents in till determined with an FAAS technique from a total leach of till using cyanide (< 2 mm till fraction).

Elements chemical method	As mg/kg + 511P	Cu mg/kg+ + 511P	S mg/kg + 511P	Zn mg/kg + 511P	Te µg/kg + 522U	Au µg/kg + 522U	Au mg/kg 236A
Fine fractions <0.06mm							**<2mm fraction**
Kallioj.-1 <0.06mm	128	55.3	484	124	65	599	0.5
Kallioj.-2 <0.06mm	125	41.9	336	111	47	684	0.4
Kallioj.-4 <0.06mm	33	39.8	258	89	36	10	<0.1
Kallioj.-5 <0.06mm	31	30.4	96	51	24	10	<0.1
Kallioj.-6 <0.06mm	1390	108.0	729	270	66	412	0.3
Kallioj.-8 <0.06mm	516	49.7	555	213	32	174	0.2
Kallioj.-10 <0.06mm	57	52.4	396	149	30	18	<0.1
Fraction 0.06-0.5mm							
Kallioj.-1 0.06-0.5mm	88	45.2	412	94	45	300	
Kallioj.-2 0.06-0.5m	86	29.4	167	88	30	601	
Kallioj.-4 0.06-0.5m	15	22.3	115	48	17	4	
Kallioj.-5 0.06-0.5m	20	23.4	68	39	17	5	
Kallioj.-6 0.06-0.5m	1040	82.7	564	217	46	526	
Kallioj.-8 0.06-0.5m	382	40.8	399	167	26	149	
Kallioj.-10 0.06-0.5m	30	32.4	183	98	16	9	
Fraction 0.5-2.0mm							
Kallioj.-1 0.5-2mm	78	39.1	312	77	38	929	
Kallioj.-2 0.5-2mm	54	21.2	87	55	24	455	
Kallioj.-4 0.5-2m	10	18.3	57	41	11	2	
Kallioj.-5 0.5-2m	16	18.9	52	37	15	8	
Kallioj.-6 0.5-2m	913	65.7	504	161	43	220	
Kallioj.-8 0.5-2m	265	29.3	261	101	19	69	
Kallioj.-10 0.5-2m	15	20.8	72	47	13	6	

an Au content considerably greater than the average level in Finland. The pathfinder elements As, Cu, Zn, S and Te were also enriched in the fine fraction of the till material of each sample (Fig. 11). Arsenic was the best pathfinder element, although the other elements also correlated slightly with Au (Fig. 12). It is, however, noteworthy that when comparing each grain-size fraction of the various samples the relative variation between the samples was in the same order. Thus, the same results and Kalliojärvi-type anomalies could be observed by using any of the grain-size fractions or pulverized total samples.

Sulphur and arsenic concentrations were high in comparison to the average level in Finnish till (Salminen 1995). The concentrations were lowest in the coarse fraction (arithmetic mean 193 ppm S and 192 ppm As respectively), and increased by a factor of more than two in the fine fraction (arithmetic mean 327 ppm S and 408 ppm As).The high S and As contents, particularly in the fine fraction, suggest the presence of pyrite and arsenopyrite crystals in the till, which is supported by the observation of euhedral pyrite crystals in the heavy mineral samples.

Geographic distribution

There was a clear geographic variation of the quantity of gold grains (Fig. 13a) and the chemical concentration of gold in various grain-size fractions (Fig. 13b) within the Kalliojärvi area.

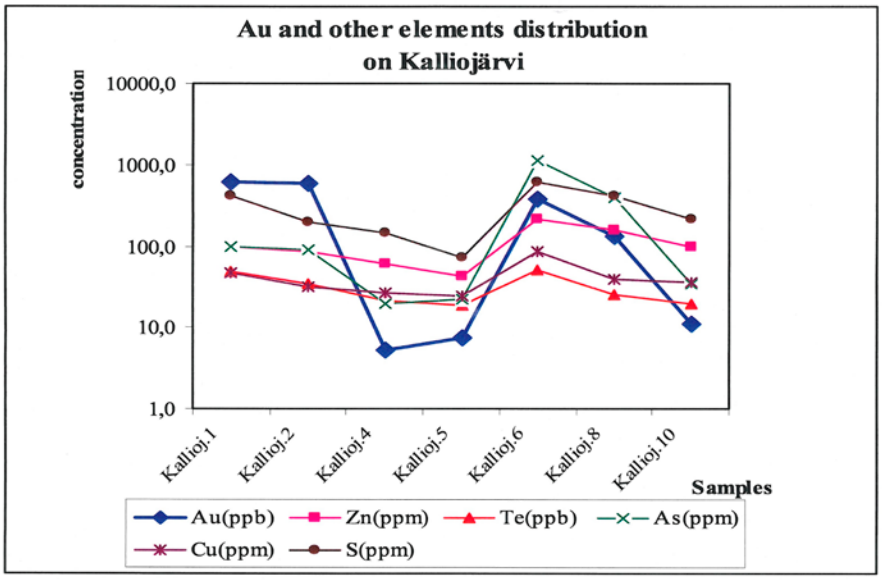


Figure 12. Geochemical anomalies of Au and pathfinder elements in studied samples from the Kalliojärvi area.

The correlations between the number of gold grains in heavy mineral fractions and geochemical anomalies of gold indicated a very close correlation between geochemical data and the gold nugget effect. In both gold particles and geochemical Au, anomalies were present in nearly every fraction of all samples of surface till collected directly over the mineralization zone. Strong anomalous values were also developed immediately adjacent to the mineralisation in surface till (site Kallioj.6). Au values were weakly anomalous to the background at sites Kallioj. 6, 8, and 10 in the southwest part of the Kalliojärvi area, downstream of the mineralisation. The ice low direction was from west to east here.

SUMMARY AND CONCLUSIONS

The goal of this study was to examine the distribution of gold in various grain-size fractions of till. In geochemical exploration for gold, the fine fraction (<0.06 mm) or some coarser sieved fraction (usually <1 mm) or pulverized total till sample are variably used as the analysed material. The most frequently used standard for heavy mineral gold is 10 litres of till. Kalliojärvi has previously been found to have prominent amounts of heavy mineral gold and a gold geochemical anomaly in the till, and is used as a test site for MMI and geochemical studies of the till fine fraction (Rosenberg 2000, Tarvainen et al. 2007).

A 15-kg sample and 1-kg subsamples were taken from seven localities close to the un-exposed Kalliojärvi gold deposit. Magnetite, ilmenite, hematite, chlorite, quartz, pyrite and amphibole were the most common minerals in the heavy mineral concentrates prepared from the Kalliojärvi till samples. There also abundant gold grains in some samples such as Kallioj.-1, Kallioj.-2, and Kallioj.-6, which contained 215, 86 and 52 gold grains, respectively. The presence of pyrite and arsenicpyrite in most of the studied samples suggests that Au is related to sulphide alteration.

X-ray diffraction analyses of the <0.063 mm size fraction of the till samples indicated that the major minerals of the clay fraction are chlorite, kaolinite, illite and vermiculite, with some mixed-layer clay minerals of chlorite and/or vermiculite. The composition of the clay minerals is related to the compositional variation of the underlying bedrock. Typically the till at Kalliojärvi is an unconsolidated mixture of clay, silt, sand, and gravel deposited during the last glacial period in a basal moraine formation. A characteristic feature is the lack of maturity of till debris, indicating strong and multicyclic glacial erosion and short transport distances.

A total of more than 600 Au grains were recovered from all the studied samples. The form of the gold grains was rounded or sub-angular. Chemically, the gold grains were rather pure, on average 92 wt.% Au (86–100 wt.% Au) and 8 wt.% Ag (0–13 wt.% Ag), and contained only traces of other elements (e.g., Fe, As, Te, Tc and Nb). The gold grains contained inclusions of quartz and other silicate minerals, hematite, pyrite, chalcopy-

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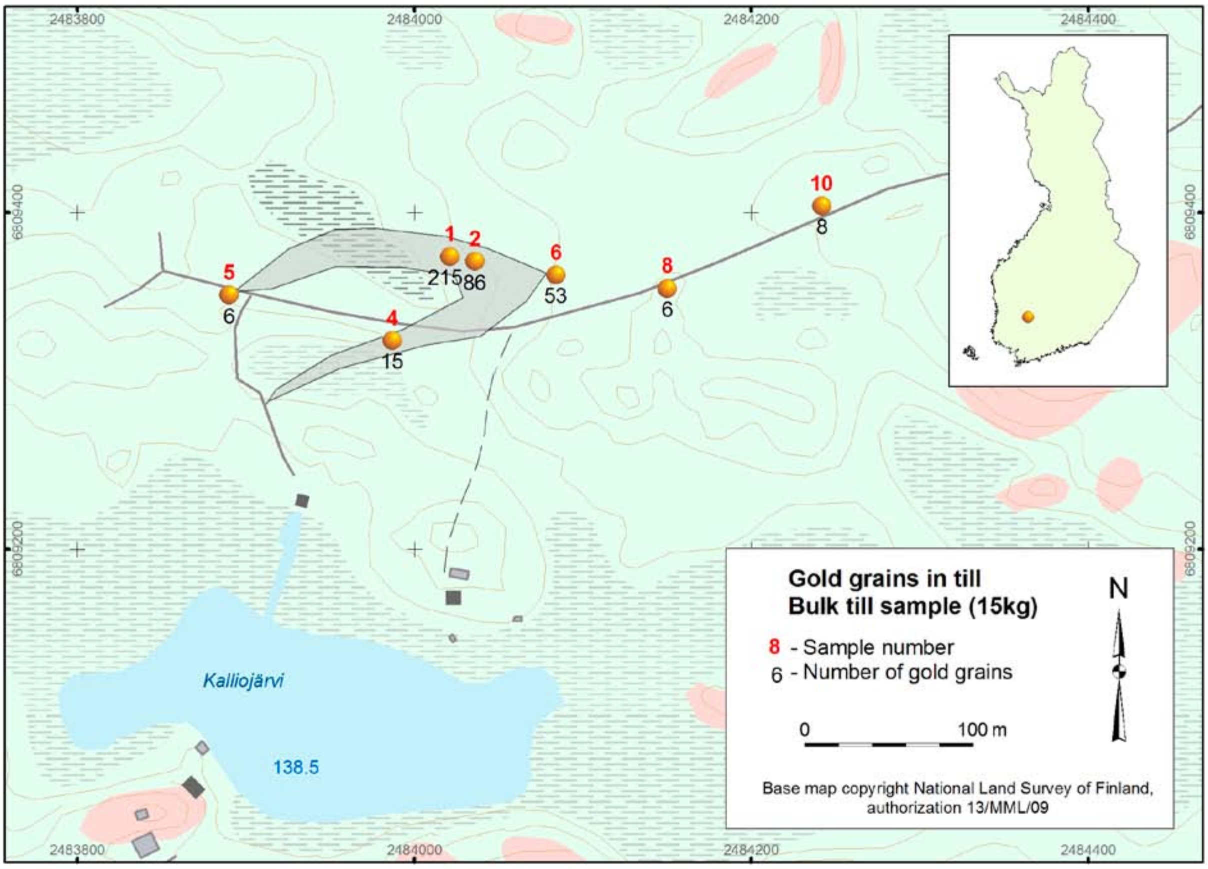

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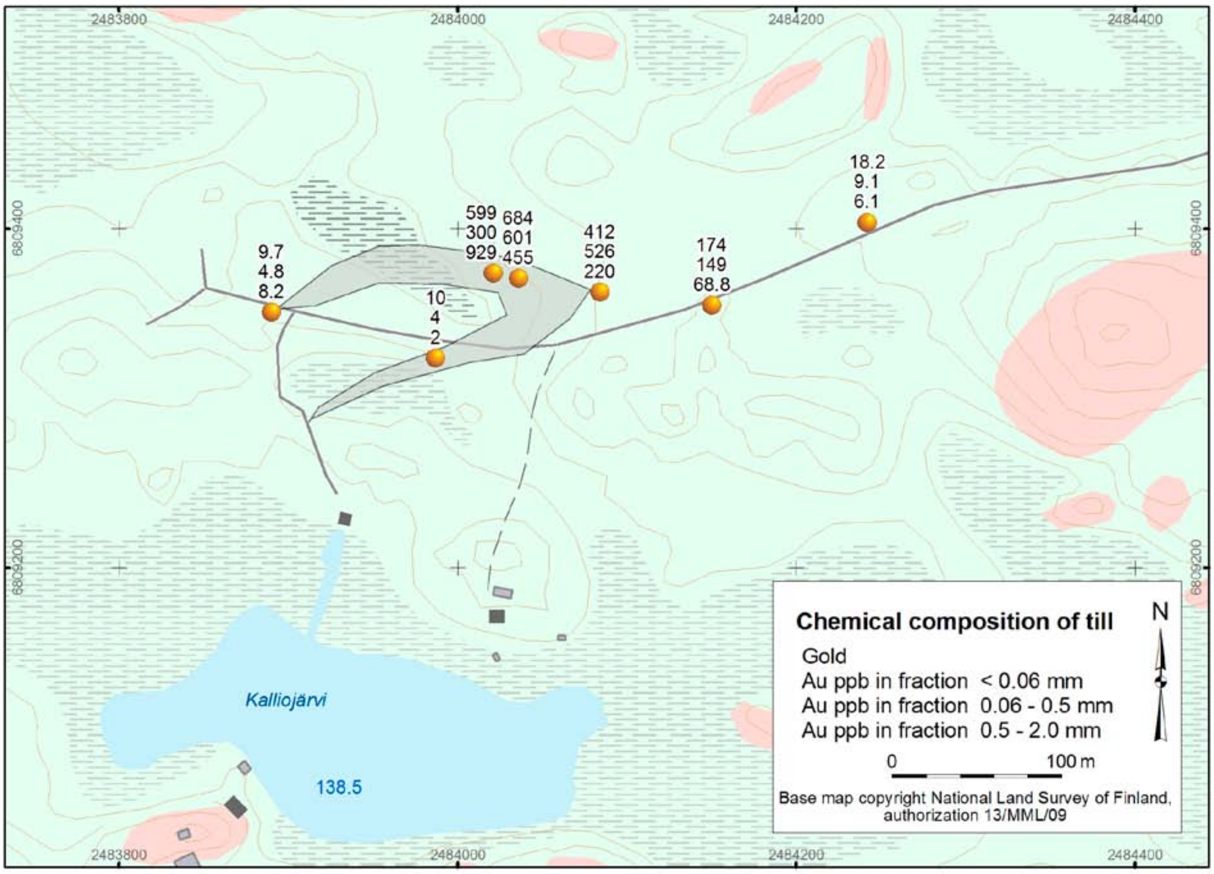

Figure 13. Gold distribution at Kalliojärvi according to (a) gold grains in till (sample size 15 kg) and (b) gold geochemistry of various grain-size fractions. The outlined area is a suboutcrop of the Kalliojärvi deposit according to Rosenberg (2000). Basemap © National Land Survey of Finland, licence no 13/MML/12.

rite, and arsenopyrite. Primary minerals imprints were diffuse and associated minerals consisted of iron oxide and clay coatings.

The size of the gold grains varied between <10 µm and 500 µm, and most of the gold grains were <20 µm size. The gold from the studied area showed a mixture of sizes, shapes and colours. Many grains were very yellow to deeper yellow, sub-angular to sub-rounded and flat grains. Some of the gold grains ranged in shape from rounded grains to folded leaf-like masses, flattened grains, to arbores cent grains. The surface topography was observed to be irregular and vugs were a common feature on grains in some cases. We found rounded grains of gold together with gold grains in a crystal form. In addition, there were also some rounded grains with an overgrown crystal of gold on gold to form a folded leaf-like appearance. This provides evidence that most of the gold grains were very malleable and were deformed rather than comminuted during glacial transport.

Detailed study of the samples from Kalliojärvi till revealed that gold is enriched in the fine fraction (<0.06 mm) of most of the studied samples. However, in one case (Kallioj. 1) the chemical Au contents were much higher in the coarse fraction (929 ppb) than in the fine fraction (599 ppb). This sample may contain abundant broken fragments or bolder from the mineralization zone. The pathfinder elements As, Cu, Zn, S and Te were also enriched in the fine fraction of the till material, when compared to the average level in the fine fraction of till (<0.06 mm) in Finland. Arsenic correlated best with gold.

The pathfinder elements (As, Cu, Zn, S and Te) were slightly enriched in the fine fraction of the till material, when compared to other grain-size fractions. However, each element showed similar order of concentrations in all grain-size fractions.

In exploration of the Kalliojärvi-type occurrence from this area (and probably also elsewhere), one could use any of these grain-size fractions or a powdered bulk till sample to observe the same anomalies as when using the fine (<0.06 mm) fraction.

ACKNOWLEDGEMENTS

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Appendix 1. Chemical analysis of till samples in different size fractions for Kalliojärvi.

Tilli samples in different fractions	Ag mg/kg + 511P	Al mg/kg + 511P	As mg/kg + 511P	B mg/kg + 511P	Ba mg/kg + 511P	Be mg/kg + 511P	Ca mg/kg + 511P	Cd mg/kg + 511P	Co mg/kg + 511P	Cr mg/kg + 511P	Cu mg/kg + 511P	Fe mg/kg + 511P	K mg/kg + 511P	La mg/kg + 511P	Li mg/kg + 511P	Mg mg/kg + 511P
Kallioj.1 <0.06mm	<1	38500	130	11	159	2.5	2310	<1	19.3	76.8	58.0	51000	6240	41	77	13400
Kallioj.1 <0.06mm	<1	37600	128	13	155	2.4	2270	<1	18.6	75.2	55.3	50100	6100	41	76	13100
Kallioj.2 <0.06mm	<1	41100	125	13	116	2.7	1670	<1	17.0	67.7	41.9	45800	3650	38	77	11500
Kallioj.4 <0.06mm	<1	32300	33	<5	104	1.5	1570	<1	13.1	71.2	39.8	37000	4180	47	42	11100
Kallioj.5 <0.06mm	<1	19300	31	<5	67	1.0	1580	<1	8.4	35.8	30.4	21800	2160	42	23	5740
Kallioj.6 <0.06mm	<1	44100	1390	<5	133	1.6	1420	<1	24.0	71.2	108.0	69200	1850	38	89	7640
Kallioj.8 <0.06mm	<1	39800	516	<5	96	1.5	1440	<1	14.6	63.0	49.7	46700	1530	39	63	6570
Kallioj.10 <0.06mm	<1	35200	57	<5	89	2.1	1670	<1	20.6	78.2	52.4	41700	1910	45	55	11000
Kallioj.1 0.06-0.5mm	<1	32300	88	15	144	1.9	1710	<1	13.9	62.7	45.2	41700	6430	25	68	10900
Kallioj.2 0.06-0.5m	<1	34600	86	13	89	2.3	1130	<1	13.2	53.8	29.4	37600	2970	23	65	9360
Kallioj.4 0.06-0.5m	<1	18500	15	<5	73	0.8	1250	<1	7.8	41.5	22.3	21100	2980	20	26	6550
Kallioj.5 0.06-0.5m	<1	15500	20	<5	67	0.8	1510	<1	6.4	29.0	23.4	17300	2290	18	19	4540
Kallioj.6 0.06-0.5m	<1	36800	1040	<5	133	1.4	1420	<1	18.7	64.0	82.7	56700	3000	28	74	7340
Kallioj.8 0.06-0.5m	<1	30600	382	9	87	1.1	1270	<1	11.4	52.9	40.8	36600	2050	26	52	5870
Kallioj.10 0.06-0.5m	<1	22600	30	7	66	1.2	1310	<1	12.7	52.7	32.4	26200	2060	26	40	7820
Kallioj.1 0.5-2mm	<1	26900	78	14	114	1.6	1550	<1	12.2	52.8	39.1	36400	5810	21	61	10500
Kallioj.1 0.5-2mm	<1	27400	81	14	116	1.5	1590	<1	12.4	53.8	40.7	37300	5890	23	63	10700
Kallioj.2 0.5-2mm	<1	21200	54	11	62	1.4	995	<1	9.2	36.7	21.2	26300	2970	17	46	7550
Kallioj.4 0.5-2m	<1	14900	<10	6	59	0.6	1670	<1	7.2	39.8	18.3	19700	3010	16	28	7130
Kallioj.5 0.5-2m	<1	13900	16	<5	62	0.6	2010	<1	6.2	29.2	18.9	18100	2880	16	22	5650
Kallioj.6 0.5-2m	<1	28300	913	<5	109	1.0	1290	<1	15.4	52.1	65.7	47000	2710	22	56	6260
Kallioj.8 0.5-2m	<1	21800	265	<5	71	0.8	1270	<1	10.4	37.8	29.3	27400	2220	20	37	4740
Kallioj.10 0.5-2m	<1	15900	15	5	61	0.7	1310	<1	9.4	41.1	20.8	21100	3180	19	33	7360

Appendix 1. (continued). Chemical analysis of till samples in different size fractions for Kalliojärvi.

Tilli samples in different fractions	Mn mg/kg + 511P	Mo mg/kg + 511P	Na mg/kg + 511P	Ni mg/kg + 511P	P mg/kg + 511P	Pb mg/kg + 511P	S mg/kg + 511P	Sb mg/kg + 511P	Sc mg/kg + 511P	Sr mg/kg + 511P	Ti mg/kg + 511P	V mg/kg + 511P	Y mg/kg + 511P	Zn mg/kg + 511P	Au µg/kg + 522U	Pd µg/kg + 522U	Te µg/kg + 522U
Kallioj.1 <0.06mm	557	<2	397	41.2	863	15	511	<20	9.6	18.8	2440	98.3	13.1	147	598.0	<2	66
Kallioj.1 <0.06mm	545	<2	398	40.6	843	15	484	<20	9.4	18.3	2380	96.4	12.8	124	598.0		
Kallioj.2 <0.06mm	413	<2	359	38.8	1140	11	336	<20	8.7	13.9	1890	79.9	11.6	111	684.0	<2	47
Kallioj.4 <0.06mm	361	<2	390	38.6	443	11	258	<20	9.8	10.6	2410	83.5	15.2	89	10.0	<2	36
Kallioj.5 <0.06mm	224	<2	366	24.1	621	<10	96	<20	5.0	11.3	1380	47.5	12.6	51	9.7	<2	24
Kallioj.6 <0.06mm	466	2.9	331	48.3	3190	17	729	<20	9.3	14.4	2870	107.0	10.1	270	412.0	<2	66
Kallioj.8 <0.06mm	318	<2	334	30.2	2330	15	555	<20	8.5	12.8	2370	87.5	10.6	213	174.0	<2	32
Kallioj.10 <0.06mm	360	<2	332	47.5	1890	15	396	<20	11.5	12.4	2370	84.9	13.5	149	18.2	<2	30
Kallioj.1 0.06-0.5mm	464	<2	625	30.2	590	11	412	<20	7.8	16.3	1810	78.8	8.6	94	300.0	<2	45
Kallioj.2 0.06-0.5m	321	<2	457	31.2	896	<10	167	<20	7.0	10.1	1380	59.7	7.5	88	601.0	<2	30
Kallioj.4 0.06-0.5m	232	<2	595	22.3	210	<10	115	<20	5.5	10.8	1280	46.8	7.2	48	4.0	<2	17
Kallioj.5 0.06-0.5m	194	<2	651	18.9	381	<10	68	<20	4.0	13.3	1000	36.4	6.8	39	4.8	<2	17
Kallioj.6 0.06-0.5m	424	2.4	532	37.6	2320	14	564	<20	8.2	14.6	2580	94.7	7.3	217	526.0	<2	46
Kallioj.8 0.06-0.5m	293	<2	452	25.2	1650	10	399	<20	7.2	11.1	1980	71.9	8.1	167	149.0	<2	26
Kallioj.10 0.06-0.5m	263	<2	491	30.6	911	<10	183	<20	7.4	10.2	1540	54.5	8.7	98	9.1	<2	16
Kallioj.1 0.5-2mm	440	<2	482	27.5	537	<10	312	<20	6.8	12.3	1560	66.6	8.1	77	929.0	<2	38
Kallioj.1 0.5-2mm	451	<2	486	27.9	552	<10	329	<20	7.1	12.6	1580	67.9	8.4	79	796.0	<2	37
Kallioj.2 0.5-2mm	264	<2	488	23.4	592	<10	87	<20	4.7	6.6	839	41.9	6.4	55	455.0	<2	24
Kallioj.4 0.5-2m	256	<2	622	21.1	253	<10	57	<20	5.0	11.8	1150	42.3	7.2	41	2.0	<2	11
Kallioj.5 0.5-2m	219	<2	678	17.7	306	<10	52	<20	4.1	15.9	985	37.5	6.8	37	8.2	<2	15
Kallioj.6 0.5-2m	462	<2	508	32.4	1950	13	504	<20	6.4	12.4	1950	79.7	6.6	161	220.0	<2	43
Kallioj.8 0.5-2m	428	<2	570	21.9	1200	<10	261	<20	4.9	10.9	1250	55.8	6.7	101	68.8	<2	19
Kallioj.10 0.5-2m	270	<2	625	25.6	478	<10	72	<20	5.2	9.5	985	44.4	7.7	47	6.1	<2	13

Gold in Southern Finland: Results of GTK studies 1998–2011
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PALAEOMAGNETIC AND AMS STUDIES ON SATULINMÄKI AND KOIJÄRVI FAULT AND SHEAR ZONES

by
Satu Mertanen and Fredrik Karell

Mertanen, S. & Karell, F. 2012. Palaeomagnetic and AMS studies on Satulinmäki and Koijärvi fault and shear zones. *Geological Survey of Finland, Special Paper 52*, 195–226, 21 figures and 2 tables.

Petrophysical, palaeomagnetic and anisotropy of magnetic susceptibility (AMS) studies have been carried out on two structurally controlled gold potential shear and fault zones in the late Svecofennian Häme Belt: the Satulinmäki formation in Somero and the Koijärvi formation in Forssa, where samples were studied from both outcrops and borehole cores. The main aim of the studies was to test the ability of combined palaeomagnetic and AMS methods to constrain the timing for the shearing event relative to the precipitation of ferromagnetic minerals and gold.

The magnetic mineralogy of the Satulinmäki and Koijärvi formations is dominated by monoclinic magnetic pyrrhotite, which is the carrier of remanent magnetization and is also mainly responsible for the AMS. The degree of AMS is strong in all formations and the AMS foliation plane typically follows the overall trend of tectonic structures. In some of the samples from Satulinmäki, the AMS is extremely high and may reflect an excess of tectonic stress and/or fluid activity compared to other sites. At Satulinmäki, the remanence directions are typically scattered, but the comparatively coherent mean remanence direction is aligned within the NE–SW trending magnetic foliation plane, defined by AMS, which coincides with the fault and shear structure. It is interpreted that at Satulinmäki the expected primary NW-pointing Svecofennian remanence direction was deflected and rotated from this direction during shearing and faulting, which must have taken place simultaneously with the hydrothermal event, in the very late stages of the Svecofennian orogeny.

The heavily sheared outcrops of the Koijärvi shear zone do not carry any stable remanence. The degree of AMS is strong. However, the fresh-looking outcrop outside the most heavily sheared area has retained its primary NW-pointing, ca. 1.84 Ga Svecofennian remanence direction. This site also shows the lowest degree of AMS, and the AMS direction is consistent with the directions from the shear zone proper. Consequently, the AMS and palaeomagnetic results imply that even the seemingly well-preserved host rocks experienced the same tectonic stress as the strongly sheared rocks. In the borehole cores of Koijärvi, the degree of AMS is also relatively low, and in these samples the primary NW-pointing Svecofennian remanence direction has been preserved. The preservation of primary remanence is either due to the location in deeper parts or to the survival of some well-preserved regions within the zones that are unaffected by shearing. Alternatively, it is also possible that the deeper parts experienced fracturing and post-tectonic fluid flow when new magnetic minerals were precipitated.

The present study demonstrated that a combination of palaeomagnetic and AMS studies on heavily deformed structures is usable, and can provide new

information on the timing of gold-forming hydrothermal processes relative to the structural processes.

Keywords (GeoRef Thesaurus, AGI): paleomagnetism, natural remanent magnetization, magnetic susceptibility, magnetic fabric, shear zones, fault zones, gold ores, petrophysics, magnetic minerals, Proterozoic, Satulinmäki, Koijärvi, Finland

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INTRODUCTION

The Geological Survey of Finland (GTK) has carried out gold prospecting in southern Finland in different structural zones that are delineated by distinctive aeromagnetic anomalies (e.g. Kärkkäinen & Lehto 2004, Kärkkäinen et al. 2006, Kärkkäinen 2007). The aeromagnetic anomalies coupled with other geophysical and geological surveys have demonstrated that ferromagnetic minerals such as magnetite and especially pyrrhotite form one characteristic feature of the gold-rich zones. Because magnetite and pyrrhotite are among the main carriers of remanent magnetization, palaeomagnetic studies have been carried out in two gold potential localities, in Somero and Forssa. The first palaeomagnetic test measurements from the Satulinmäki prospect in Somero have already revealed that the rocks are able to carry comparatively stable remanent magnetization (Mertanen 2006). This study was carried out in order to further test the ability of the palaeomagnetic method to provide some age constraints for the gold-forming processes, and to investigate the genesis of magnetic minerals that are related to gold. Because the gold-mineralized zones are characterized by strong shearing and faulting, studies on anisotropy of magnetic susceptibility (AMS) were carried out to define the deformed structures, in conjunction with palaeomagnetic studies.

The magnetization of rocks is composed of two factors: induced magnetization and remanent magnetization. Induced magnetization reflects the magnetization of the rocks in the present Earth's geomagnetic field. It is directly related to the quantities of ferromagnetic minerals in the rock and is generally the main cause of aeromagnetic anomalies. The remanent magnetization (remanence) of rocks reflects the past geomagnetic field that was blocked during the formation of the rock and is not dependent on the quantities of ferromagnetic minerals. It can consist of different components acquired in diverse geological processes. In hydrothermal systems, remanent magnetization is typically of secondary origin, either chemical (CRM) or thermochemical (TCRM), which is formed when new ferromagnetic minerals are either crystallized from fluids or recrystallized from pre-existing minerals. The acquisition mechanism of CRM or TCRM is different from thermal remanent magnetization (TRM), which is formed during the original cooling of the rock, and which is regarded as the primary remanent magnetization. In both remanence types, the direction of magnetization is blocked according to the geomagnetic field direction that prevailed during the rock formation process. Consequently, by measuring the remanence direction of a rock and by comparing the direction with the known remanence directions from isotopically dated rocks, it is possible to obtain the timing for the geological process in which the remanence was formed. Secondary chemical remanences can be formed at very low temperatures, below ca 300 °C, and they can therefore be used in tracing those geological processes that are accompanied by low-temperature hydrothermal systems. The most common ferromagnetic minerals in the Finnish bedrock are magnetite or titanomagnetite, pyrrhotite and hematite, which may all be formed in these systems.

In this study we have investigated the remanent magnetization of two structurally controlled gold potential formations, the Satulinmäki formation in Somero and the Koijärvi formation in Forssa, which represent hydrothermal systems. Several previous studies have shown that the main ferromagnetic mineral in the Satulinmäki formation is pyrrhotite, with possible minor amounts of magnetite (e.g. Kärkkäinen & Lehto 2004, Kärkkäinen et al. 2006, Kärkkäinen 2007, Perälä 2003). According to these studies, pyrrhotite occurs in a paragenesis with arsenopyrite, which is the other main sulphide mineral related to gold. The first palaeomagnetic measurements of this study from Satulinmäki showed that the direction of the remanent magnetization was not the one expected for Svecofennian rocks aged ca. 1.9–1.8 Ga, and it was therefore considered that the remanence had been deflected or rotated due to later tectonic events. Therefore, in order to identify investigate the structures that may have been responsible for the deflection, AMS studies have been carried out. AMS investigations can reveal the magnetic orientation of the ferro- and paramagnetic minerals formed during tectonic events such as shearing and faulting. When combined with knowledge of remanence directions, they can be used to determine the timing for the shearing event relative to precipitation of ferromagnetic minerals and gold. Consequently, the main purpose of this study has been to provide new independent information on the relative timing in the formation of the ferromagnetic minerals within the controlling structures. In order to confirm the occurrence of pyrrhotite and magnetite in different types of rocks, the magnetic mineralogy of the formations was studied using several rock magnetic methods. The primary aim of this article is to present the new results from the investigated locations. The other aim is to assess the methods used in the framework of future gold prospecting studies. In this sense, the methods are thoroughly described.

GEOLOGICAL SETTING

The Satulinmäki area forms part of the Paleoproterozoic Svecofennian island arc complex of southern Finland, and belongs to the Forssa Group in the western part of the Häme Belt, locating between the Pirkanmaa Belt in the north and Uusimaa Belt in the south (Fig. 1). The orientation of the bedding in the Häme Belt is SW–NE to WSW–ENE, and the dip of the units is typically steep. The gold mineralization and tectonic evolution of the Häme Belt has been thoroughly described by Saalmann et al. (2009). The Forssa Group is composed of volcanic and mainly pelitic sedimentary rocks. According to Saalmann et al. (2009), the age of the felsic volcanic rocks of the Forssa group is 1881 ± 3 Ma. The rocks were metamorphosed in amphibolite facies conditions at ca. 1.88–1.86 Ga, and the peak of metamorphism took place at 1.83 Ga, during the late Svecofennian metamorphic events (Saalmann et al. 2009). The volcanic rocks are strongly deformed, and at Satulinmäki they are strongly sheared and hydrothermally altered and brecciated by quartz veins and tourmaline (Kärkkäinen et al. 2006). The Satulinmäki deposit represents an orogenic-type gold mineralization that was formed during the late-Svecofennian events. Based on U-Pb zircon data, ^{39}Ar-^{40}Ar hornblende and biotite data and weighted $^{207}Pb/^{206}Pb$ data on pegmatitic dykes, shear zones and gold-bearing veins, Saalmann et al. (2009) have bracketed the age of mineraliza-

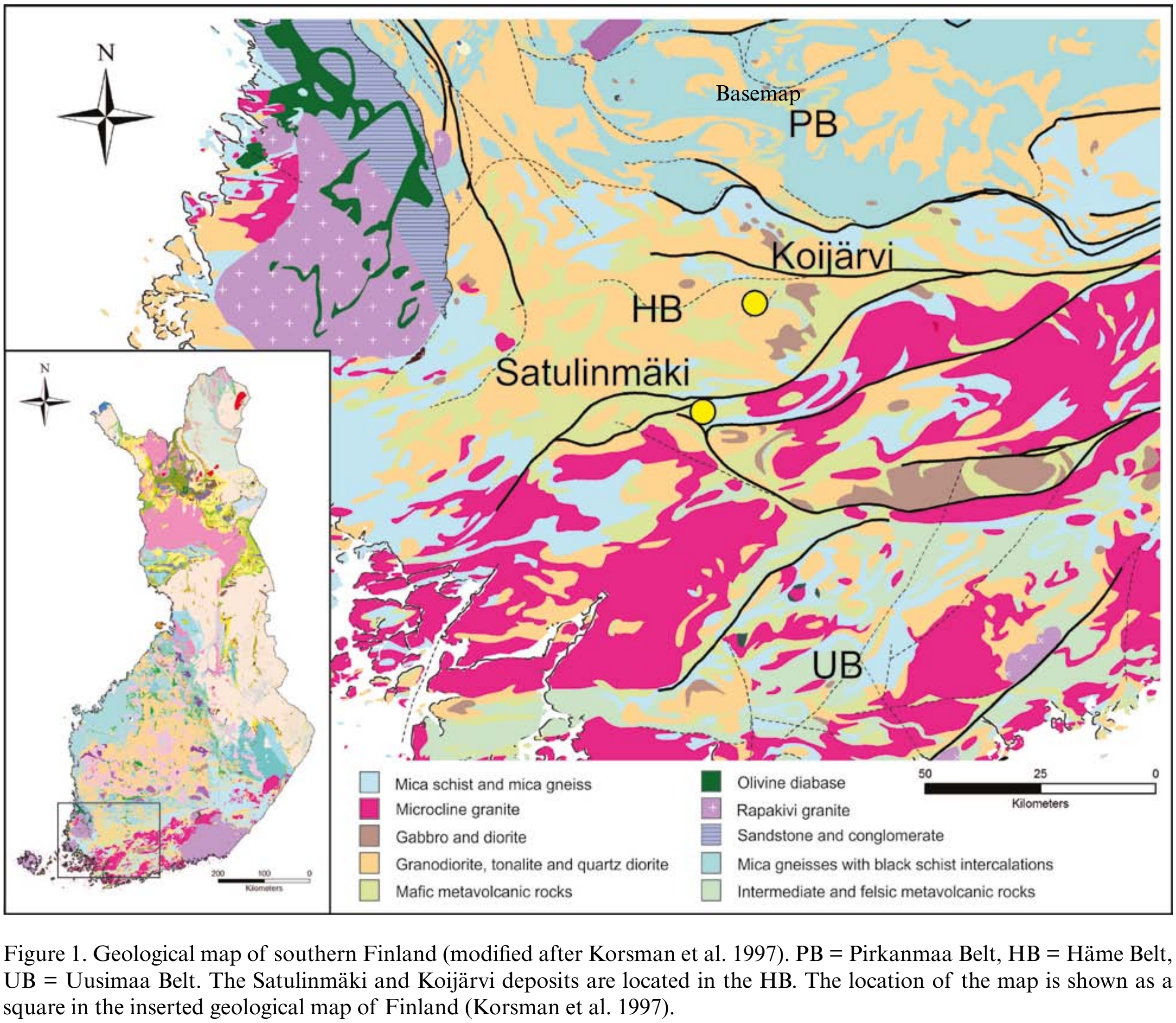

Figure 1. Geological map of southern Finland (modified after Korsman et al. 1997). PB = Pirkanmaa Belt, HB = Häme Belt, UB = Uusimaa Belt. The Satulinmäki and Koijärvi deposits are located in the HB. The location of the map is shown as a square in the inserted geological map of Finland (Korsman et al. 1997).

tion between ca. 1.82 Ga and 1.79 Ga. The gold mineralization is closely related to quartz veins and structurally controlled by WSW–ENE to SW–NE and NW–SE trending shear zones and faults, formed during prolonged dextral oblique contraction in the late stages of Svecofennian orogenic evolution (Saalmann et al. 2009).

The Koijärvi area is located in the northern part of the Häme belt (Fig. 1). The studied outcrop is situated on the western side of the steeply dipping NE–SW trending Koijärvi fault that branches from the major E–W trending subvertical Aulanko fault (Nironen et al. 2006). In the Koijärvi area the main rock type is metamorphosed basic and intermediate tuffite and amphibolite, surrounded by granodiorite and gneissose granite. The rocks are strongly sheared with NNE–SSW foliation.

SAMPLING

At Satulinmäki (Fig. 1), samples were taken from two outcrops, SO and SM (Fig. 2a), located in the western par Basemap t of Satulinmäki hill. All samples in the field were taken with a portable mini drill, the length of the cores typically being about 8–10 cm, thus allowing the preparation of approximately three 2.1 x 2.4 cm cylindrical specimens from each core. The Satulinmäki outcrops are located 50 m apart and may represent the continuation of the same structure. Site SM is located in trench M2 (Kärkkäinen et al. 2006) (Fig. 2b, 2c). The main rock type is intermediate volcanic tuff that is partly heavily oxidized on both sites, as seen by a dark brown rusty colour. Both sites show conspicuous NE–SW trending shearing. At site SO, two samples (SO1 and SO5) were taken from a lighter coloured 'host rock' that was thought to be more arsenic, but containing less pyrrhotite. Three samples (SO2–4) were taken from the dark brown oxidized zone, probably containing pyrrhotite. At site SM, five samples were taken from the rusty rock (SM1–4 and SM6) and three samples from the lighter-coloured rock (SM5 and SM7).

In the Koijärvi fault zone (Fig. 3a), the first samples were taken from four borehole cores in the Loppi drill core depot. Most samples from these cores were oriented, but some unoriented samples were also taken in order to examine their magnetic stability. The Loppi cores were prepared in the laboratory to standard cylindrical specimens. The uppermost sample was taken from core FO31 from the depth of 10.12 m, and the deepest sample from core FO29 from the depth of 82.50 m. Cores FO29, FO30, FO31 and FO32 were drilled from within an area of less than about 1 km^2 (Fig. 3b).

Field sampling from the Koijärvi fault was carried out at a heavily sheared outcrop with an area of ca. 80 x 100 m (Fig. 3b). The outcrop is situated close to the deep cores, core FO31 being closest. Altogether, 46 core samples were taken from three different sites that all show strong NNE–SSW shearing. At the southernmost site, FS, 20 samples were taken from an intermediate volcanite that shows variations in oxidation, veining and the occurrence of tourmaline, formed during hydrothermal alteration of the rock. At site FA (Fig. 3c), which is located along the strike to the south of site FS, 15 samples were taken from a more mafic volcanite that also shows variations in the oxidation state, and in some places contains quartz seams rimmed with tourmaline. Further to the south, at site FC, 11 samples were taken from a similar rock type as at site FA. Parts of the samples were deeply rusty. In addition to these sites, six samples were taken from outside the shear zone at site FB, where the rock type is a light-coloured intermediate metavolcanite without any clearly visible structures.

METHODOLOGY

Magnetic and density properties

Densities, magnetic susceptibilities, intensities of remanent magnetization and Königsberger ratios (Q, the ratio of remanent to induced magnetization) were measured for all specimens. Densities were defined based on Archimedes' principle. The volume susceptibility was measured with GTK's kappabridge (applied alternating field 130 A/m and frequency 1025 Hz, Puranen & Puranen 1977). Remanent magnetization was measured with a 2G-Enterprises superconducting SQUID

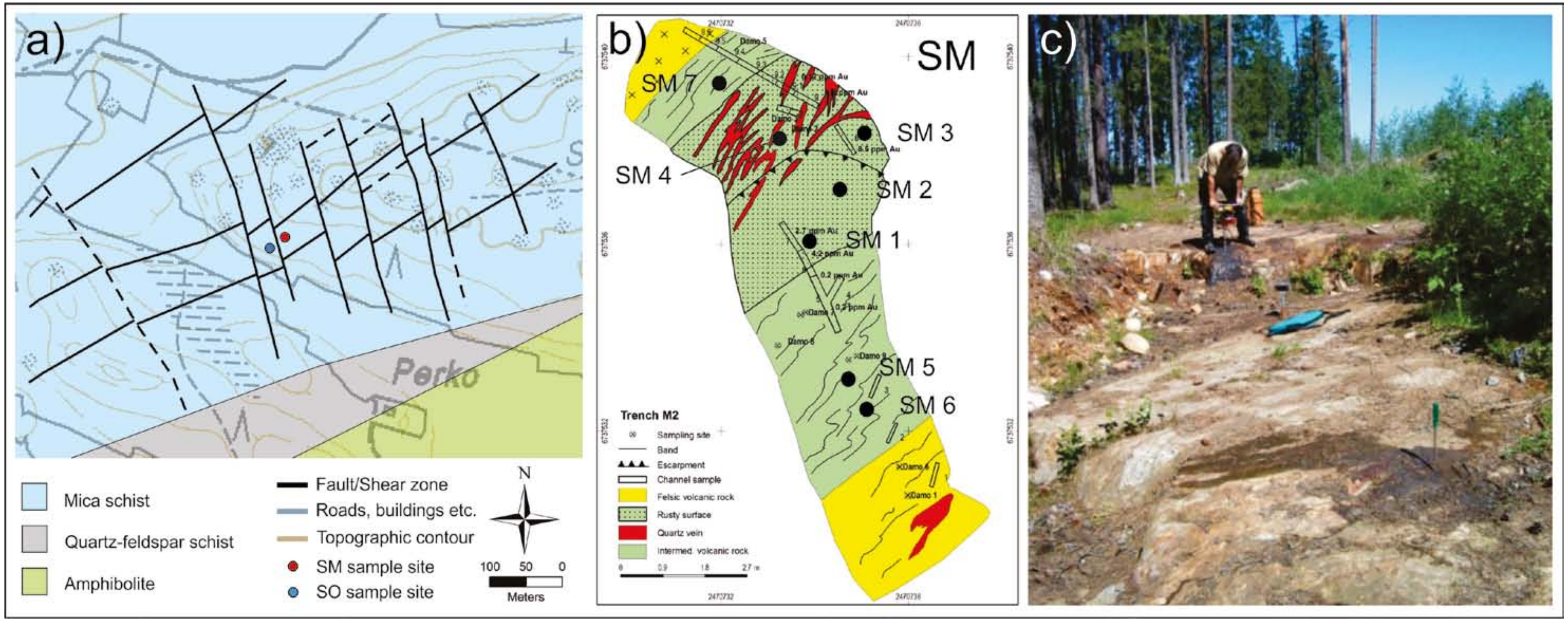

Figure 2. a) Geological map of Satulinmäki showing the major fault and shear zones (from Saalmann et al. 2009). Basemap © National Land Survey of Finland, licence no 13/MML/12. b) Detailed bedrock map of site SM (trench M2, Kärkkäinen 2006). Locations of samples SM1–7 are indicated. c) Photograph of site SM.

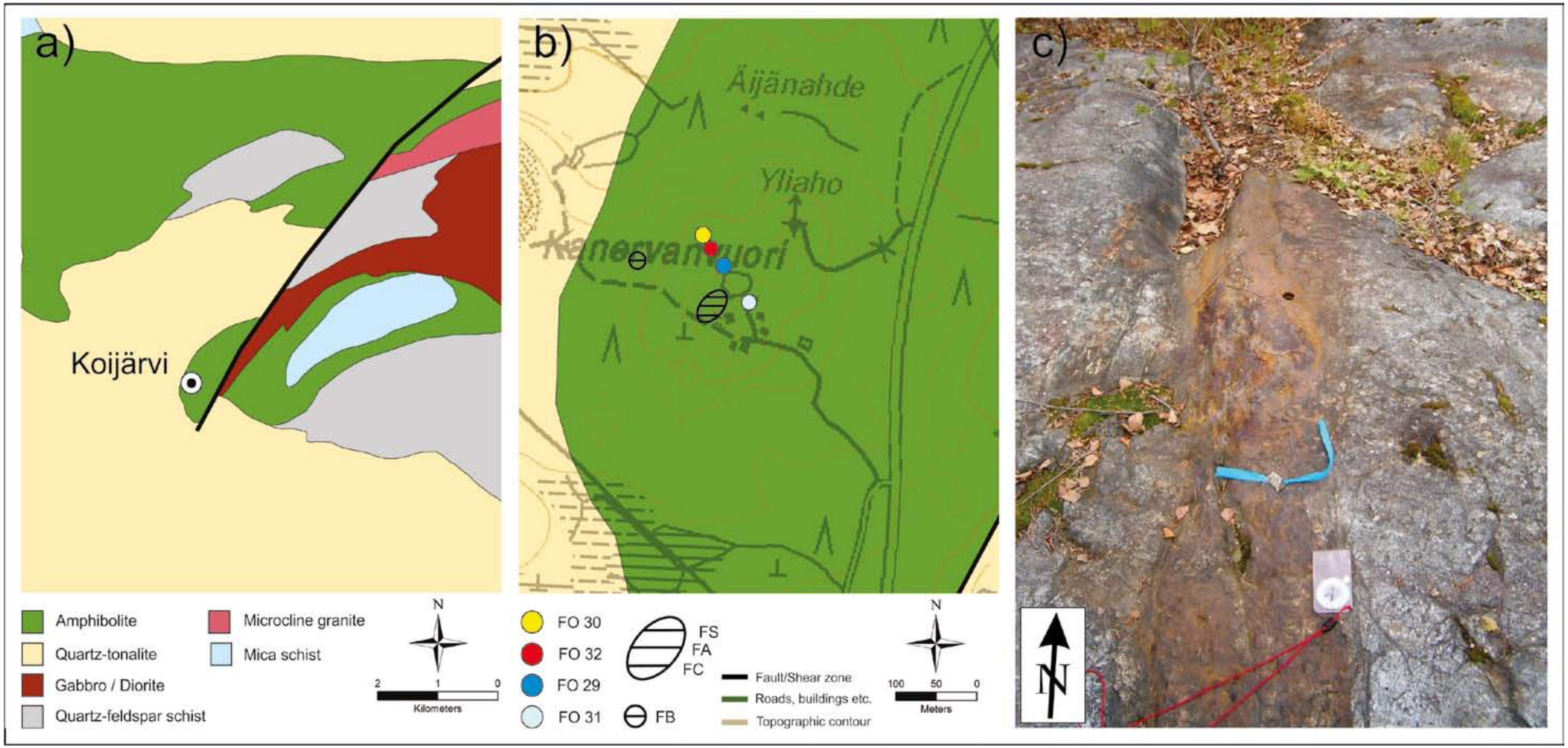

Figure 3. a) Geological map of Koijärvi. b) Bedrock map of Koijärvi. The location of sites FS, FA, FC and FB is shown as stripes in ellipsoids and the location of the drill core sites is shown as coloured circles. Basemap © National Land Survey of Finland, licence no 13/MLL/12. c) Photograph of site FA.

magnetometer. Petrophysical data are illustrated as scatter diagrams (Figs. 4–6). The scatter diagram of susceptibility versus density describes overall compositional variations, while susceptibility versus remanent magnetization and the Q ratio reflects the magnetic mineralogy and the grain size in magnetite-bearing rocks. Magnetite and pyrrhotite have distinct magnetic properties. Coarse-grained multi-domain (MD) magnetite typically has low Q ratios (<1) and high susceptibilities, whereas fine-grained single-domain (SD) magnetite has higher Q ratios (>1) with somewhat lower susceptibilities but high remanence. The magnetic susceptibility in magnetite-bearing rocks is generally higher than in pyrrhotite-bearing rocks. A general assumption is that if the magnetite content is greater than 1%, the magnetic susceptibility is of the order of 10 000 (μSI) or greater. Pyrrhotite-bearing samples have lower susceptibilities than magnetite-bearing rocks, but the remanent magnetization can be higher. Monoclinic magnetic pyrrhotite often has Q ratios above 10 (Puranen 1989). The variation in densities is dependent on the amount of mafic minerals and iron content of the rocks (Puranen 1989), and the densities have a tendency to increase with increasing sulphide (pyrite, pyrrhotite) concentration (Airo 2002).

Palaeomagnetism

Palaeomagnetic measurements were carried out using a SQUID magnetometer. The samples were gradually demagnetized either by stepwisely increasing the alternating field (AF) up to 160 mT or thermally up to the peak temperature of 600 ºC, but typically only up to 400 °C. One purpose of demagnetization was to reveal the most stable remanent magnetization components once the soft viscous or other unwanted spurious remanence had been removed. The other purpose of demagnetization was to isolate the remanence components that are formed in different geological processes so that the components are separated either due to their different coercivities (AF cleaning) or due to the different temperatures in which the remanence was acquired. In the current study, demagnetization was mainly carried out using an alternating field (AF). In the selected thermally demagnetized samples, mineralogical alterations were observed by monitoring magnetic susceptibility after each thermal step. Thermal demagnetization was not so favoured because the specimens were known to contain sulphides that can easily undergo chemical alterations during heating (Dekkers 1989, Bina & Daly 1994), as typically occurred. Remanence components were visually inspected from Zijderveld diagrams (Leino 1991, Zijderveld 1967) and the components were identified using principal component analysis (Kirschvink 1980). Mean remanence directions were calculated by using Fisher (1953) statistics. Examples of demagnetization behaviours are illustrated in Figures 10, 12 and 13, and mean directions in Figures 11 and 14.

Anisotropy of magnetic susceptibility (AMS)

Anisotropy of magnetic susceptibility (AMS) is a well-established petrophysical tool to investigate the magnetic fabric of rocks. AMS is mathematically described as a symmetric 2nd rank tensor, which can be visualized as an ellipsoid with three principal axes: the maximum (k_{max}), intermediate (k_{int}) and minimum (k_{min}) susceptibility axes. The maximum axis is normally referred to as the magnetic lineation and the minimum axis as the pole perpendicular to the magnetic foliation plane. When investigating the magnetic fabric, several parameters are used to describe it, two of them being most frequently used. The magnitude of the anisotropy is described by the corrected degree of anisotropy, P', which ranges from 1 (isotropic sphere) upwards. The shape of the ellipsoid is described by parameter T, where the shape ranges from prolate (T = -1) through neutral (T = 0) to oblate (T = 1) (Jelínek 1981). In the case of prolate (cigar-shaped) fabric, the linear parallel orientation (magnetic lineation) is developed more intensively than the planar orientation (magnetic foliation) defined by oblate (disc-shaped) shapes.

AMS analysis can confirm the general structural field measurements within the study area and provide some detailed information on the structure of the shear zone. Anisotropy of magnetic susceptibility measurements were employed on 42 specimens from the Satulinmäki formation and on 151 specimens from the Koijärvi outcrop. Twenty oriented specimens were measured at various depths from the four Koijärvi borehole cores. All measurements were carried out using the Kappabridge KLY-3S (300 A/m and 875 Hz) by Agico

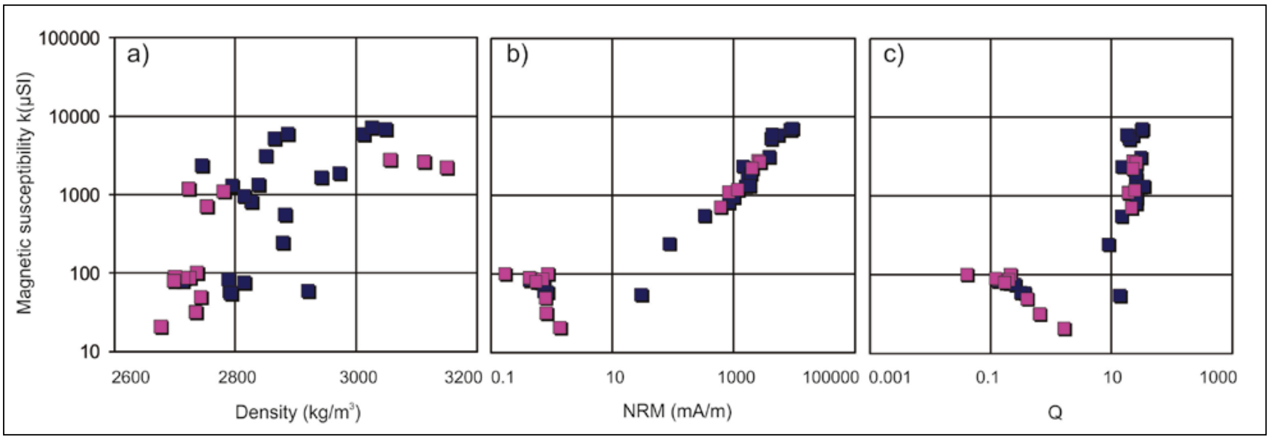

Figure 4. Petrophysical properties of the specimens from Satulinmäki, site SM = purple and SO = blue. a) Magnetic susceptibility (μSI) vs. density (kg/m³), b) Magnetic susceptibility (μSI) vs. intensity of natural remanent magnetization (NRM) (mA/m), c) Magnetic susceptibility (μSI) vs. Koenigsberger ratio (Q).

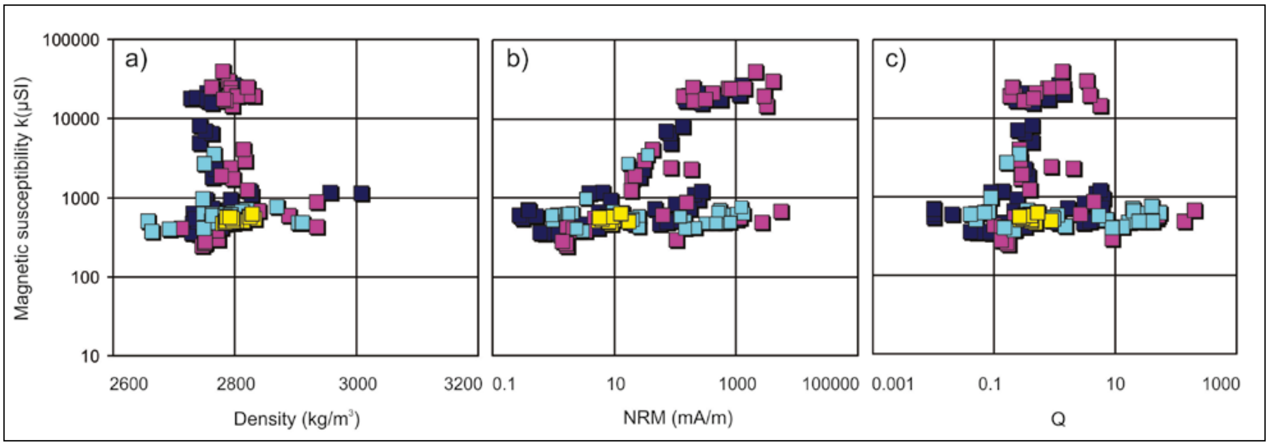

Figure 5. Petrophysical properties of the specimens from Koijärvi, site FS = dark blue, FA = purple, FC = light blue and FB = yellow. a) Magnetic susceptibility k (μSI) vs. density D (kg/m³), b) Magnetic susceptibility k (μSI) vs. intensity of natural remanent magnetization (NRM) (mA/m), c) Magnetic susceptibility k (μSI) vs. Koenigsberger ratio (Q).

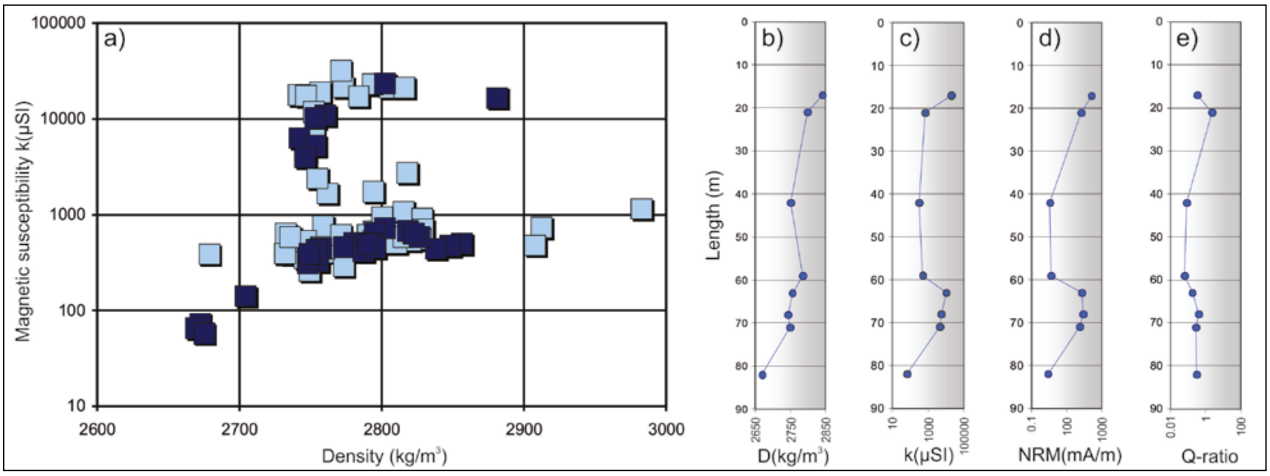

Figure 6. a) Magnetic susceptibility k (μSI) vs. density D (kg/m³) of samples from outcrops (light blue) and drill cores (dark blue). b–e) Koijärvi drill core FO29 showing depth vs. b) density D (kg/m³) c) magnetic susceptibility k (μSI) d) intensity of natural remanent magnetization (NRM) (mA/m) and e) Koenigsberger ratio (Q).

Inc. and the results were statistically evaluated using ANISOFT software (Jelínek 1978, www.agico.com). AMS results are presented in Figures 15–20. The initial intention of the AMS interpretation of the Satulinmäki and Koijärvi formations was to compare the orientations of the magnetic minerals derived from AMS measurements with the obtained palaeomagnetic directions. In addition, AMS data provide information on regional small-scale structural features linked to the shearing and eventually to the deformation mechanism, strain and stress of the shear zone. Tarling & Hrouda (1993) described four theoretical models in which the degree of anisotropy reflects the intensity of strain. The anisotropy of pyrrhotite has been investigated by Borradaile et al. (1992) and de Wall & Worm (1993), and referring to these studies, the field dependence and magnetic behaviour of pyrrhotite (sulphides) have to be taken into account, even in this interpretation (see also Karell et al. 2009). The field dependence, which is significant in the case of pyrrhotite, affects the intensity of the anisotropy (P'), but the shape (T) and the magnetic directions are not substantially affected (Pokorný et al. 2004). Each mineralogical component of the magnetic fabric has its own anisotropy, and the magnetic anisotropy of a rock is affected by all the magnetic minerals present (Tarling & Hrouda 1993). Shear zones typically show a complex magnetic mineralogy due to deformation mechanisms, recrystallization and fluid flow, which also affects the magnetic fabric (Borradaile & Jackson 2004). When defining strain with the AMS method, the normal procedure of analysing the shape versus degree of anisotropy can only be interpreted as relative strain values, but no absolute strain ratios can be expected due to the complexity of AMS in shear zones.

Thermomagnetic measurements

The variation in magnetic susceptibility with temperature (k-T curve) was examined in order to identify the magnetic minerals and to verify the petrophysical data, which provides the first estimation of magneto-mineralogy. In addition to defining the magnetic minerals, magnetic domain sizes of ferrimagnetic minerals can be identified. The domain size indicates how well the rock can preserve remanent magnetization. In k-T measurements, the susceptibility is continuously measured during heating from liquid nitrogen temperature (-192 ºC) to room temperature, from room temperature to a high temperature (up to 700 ºC), and during cooling back to room temperature. The minerals can be identified due to their characteristic Curie temperature points on the k-T curves. The measurements were carried out using a Kappabridge KLY-3S combined with the CS-3 apparatus (Agico Inc.). Crushed samples of ca. 0.7 g were used. The samples were heated in an argon environment to reduce the formation of secondary magnetite, which can form due to the oxidation of iron at suitable temperatures. Based on the bulk magnetic susceptibility and on thermal demagnetization, the upper temperature was selected to be 375 ºC, 600 ºC or 700 ºC. The temperature 375 ºC was typically used to avoid the oxidation of iron and formation of secondary magnetite due to heating (see Bina & Daly 1994). For some samples with low susceptibilities, thermomagnetic measurements were only performed above room temperature, because low temperature measurements are more suitable for ferrimagnetic minerals with high susceptibilities. The susceptibility data are presented as the total susceptibility and are not normalized for volume or mass. Three samples from Satulinmäki and six samples from the Koijärvi outcrop were measured. Two samples were measured from drill core FO31. Examples of thermomagnetic analyses are presented in Figure 7.

IRM acquisition curves

Isothermal remanent magnetization (IRM) acquisition curves were produced for three specimens (Fig. 8) in order to define the magnetic mineralogy and to obtain information on the coercivities of the remanence-carrying minerals (e.g. Dunlop & Özdemir 1997). IRM is the form of remanent magnetization that is left in the rock after subjecting it to very high magnetizing fields. For IRM measurements, the samples were first stepwise AF demagnetized in 15 steps up to the field of 160 mT. IRM was then produced along z axes by subjecting the specimens to 17 increasing magnetic fields, the highest field being 1.5 T. Magnetization was performed with a Molspin pulse magnetizer and the intensity of IRM was measured with a SQUID magnetometer between the magnetizing steps. Different ferromagnetic minerals produce characteristic IRM curves; the high coercivity minerals, such as pyrrhotite and hematite, show a gradual increase in magnetization and do not always reach the saturation IRM (SIRM) at 1.5 T, whereas low coercivity fractions such as magnetite already rapidly acquire magnetization in low magnetizing fields and are typically saturated below 0.3 T.

Lowrie tests

Three component IRM and subsequent thermal demagnetizations, the Lowrie tests (Lowrie 1990), were carried out for 12 specimens. In the Lowrie test the minerals are identified based on their coercivities and unblocking temperatures (e.g. the maximum unblocking temperature of magnetite is 580 °C and that of monoclinic pyrrhotite 325 °C, O'Reilly 1984). After demagnetization up to 160 mT, the IRM was first produced along the z axis in the highest magnetizing field of 1.5 T. After that, the IRM was produced along the y axis in a magnetizing field of 0.4 T and then in a magnetizing field of 0.12 T along the x axis. After the acquisition of IRM along the three orthogonal axes, the samples were thermally demagnetized in 16 steps at temperatures between 100 and 600 °C. Intensity curves for each axis were produced separately and the magnetic minerals were determined based on their maximum unblocking temperatures. Results of the Lowrie tests are presented in Figure 9.

RESULTS

Magnetic and density properties

Petrophysical properties for all studied samples are provided in Table 1 and Figures 4–6. In Table 2 the numerical data are presented for those samples that also provided stable palaeomagnetic results.

Satulinmäki

The samples from Satulinmäki are predominantly pyrrhotite-bearing, or their magnetic behaviour is dominated by paramagnetic mafic silicates. All samples from sites SM and SO have magnetic susceptibilities below 10 000 µSI. Two distinct populations are shown in the susceptibility-density plot (Fig. 4a): one population with low susceptibility values (~100 µSI), and another population with higher susceptibilities (~1 000–7 000 µSI). Densities vary, reflecting the variation in pyrrhotite content (increasing density with increasing content of sulphides). The grouping can be divided into samples that are dominated by pyrrhotite and those that are dominated by paramagnetic minerals. The greatest density variation can be seen in the pyrrhotite-bearing population. A similar grouping of samples can be seen in the susceptibility-remanence plot (Fig. 4b). Samples with higher magnetizations display a positive correlation between susceptibility and remanence, which demonstrates that at Satulinmäki the content of remanence-carrying minerals controls the intensity of remanence. The Q values are clearly higher (~20) for samples with higher susceptibilities and higher remanences (Fig. 4c).

Koijärvi

In the outcrop samples from Koijärvi, the density versus susceptibility plot in Figure 5a illustrates that the samples from sites FS and FA have two major populations. One population with high susceptibilities and modest variation in densities is regarded to be dominated by magnetite with only minor pyrrhotite. Another population with lower susceptibilities and more variable densities is regarded to contain purely pyrrhotite (see Clark 1997). At site FA, the highest susceptibilities occur in the quartz-tourmaline veins. Samples from site FC lack the high-susceptibility population and probably contain only pyrrhotite. The visibly non-sheared rocks from site FB have relatively low susceptibilities and show little variation in density.

Intensities of remanent magnetization range

Table 1. Petrophysical and AMS properties.

Sample	Petrophysics					AMS			
	n	k(µSI) (130 A/m)	D (kg/m3)	NRM (mA/m)	Q	n	k(µSI) (300 A/m)	P’	T
Satulinmäki									
SM1	3	1033	2706	1118.3	26.8	3	1368	2.484	-0.457
SM2	3	6655	2814	7635.8	28.5	2	8625	2.872	-0.493
SM3	3	4554	2716	3263.2	17.4	4	6660	3.497	-0.452
SM4	3	121	2731	29.3	3.2	4	142	1.205	-0.168
SM5	3	80	2686	0.6	0.2	3	89	1.088	0.086
SM6	3	1376	2766	1293.5	21.6	4	2454	1.761	-0.752
SM7	3	1516	2713	1880.5	25.9	4	1766	1.927	-0.125
SO1	3	97	2666	0.5	0.1	3	101	1.142	0.019
SO2	3	86	2652	0.6	0.2	4	91	1.116	-0.344
SO3	3	34	2659	1.0	0.9	4	509	1.097	-0.356
SO4	3	2561	2853	2392.3	23.4	3	3507	1.633	-0.492
SO5	3	1007	2676	861.2	21.4	3	1264	1.714	-0.554
Koijärvi									
FS1-3	7	629	2773	4.8	0.2	5	635	1.160	0.536
FS4-6	6	18197	2748	205.9	0.3	6	18433	1.184	0.803
FS7-9	9	9361	2754	356.0	0.5	6	9966	1.155	0.495
FS10	2	1156	2983	5.1	0.1	3	1237	1.018	0.046
FS11-13	7	4744	2773	77.6	0.3	9	5485	1.245	0.341
FS14-16	9	775	2777	135.6	4.0	11	819	1.373	0.436
FS17-20	12	439	2760	240.7	11.3	15	468	1.154	0.312
FA1-2	6	22241	2800	2036.3	2.5	6	24000	1.293	0.339
FA4-6	7	23514	2790	721.7	0.6	9	21500	1.265	0.178
FA7-9	9	1815	2804	44.7	0.6	10	2440	1.138	0.299
FA10-12	6	536	2832	1093.9	47.3	6	736	1.102	0.232
FA13-15	8	522	2770	4.4	0.2	9	597	1.070	0.360
FC1-2	5	490	2707	2.1	0.1	8	585	1.117	0.741
FC3-5	8	547	2783	373.9	15.4	7	642	1.106	0.433
FC6-8	9	544	2832	545.1	24.3	10	700	1.120	0.356
FC9	3	616	2771	1.5	0.1	3	987	1.215	0.691
FC10-11	6	1212	2774	22.2	0.7	7	1640	1.138	0.320
FB1-6	18	538	2808	8.8	0.4	21	631	1.034	-0.458
Drill cores									
FO29 17m	2	20027	2842	257.6	0.3	2	23050	1.202	0.044
FO29 21m	2	691	2799	67.1	2.4	4	705.5	1.188	0.338
FO29 42m	2	318	2752	1.1	0.1				
FO29 59m	2	509	2786	1.2	0.1				
FO29 63m	2	10612	2757	73.2	0.2				
FO 29 68m	2	5548	2744	86.3	0.4				
FO29 71m	2	4644	2750	54.1	0.3				
FO 29 82m	2	70	2671	0.8	0.3				
FO 30 14m	3	462	2774	4.3	0.2	2	534	1.025	-0.531
FO 30 38m	3	474	2847	7.7	0.4	1	556	1.012	-0.028
FO 31 10m	3	395	2753	2.8	0.2	2	436	1.074	0.331
FO31 24m	2	414	2752	1.0	0.1	1	492	1.101	0.253
FO31 41m	1	58	2675	0.3	0.2				
FO31 80m	1	142	2704	0.4	0.1	1	172	1.049	0.089
FO32 24m	2	614	2824	1.1	0.0	1	751	1.090	0.815
FO32 42m	3	451	2792	1.0	0.1	1	484	1.089	0.456
FO32 69m	3	605	2810	25.8	1.1	1	576	1.009	-0.658

Note: n is the number of specimens; k is magnetic susceptibility (µSI) measured with an applied field of 130 A/m and 300 A/m for the GTK and KLY device, respectively; D is density (kg/m3) and NRM natural remanent magnetization (mA/m); Q is the dependence between remanent/induced magnetization: P’ is the anisotropy degree and T is the shape parameter.

widely, but a positive correlation between higher susceptibilities and higher remanences can be observed in the FA and FS samples (Fig. 5b). The FC samples show relatively little variation in susceptibility, but the intensities of remanent magnetization vary greatly. The FB samples are homogeneous and show hardly any variation in either remanence or susceptibility. In the susceptibility/Q ratio plot (Fig. 5c), the magnetite-bearing samples from site FS have Q values ranging from 0.23–1.14. The magnetite-bearing samples from FA show somewhat larger variation in Q values, ranging from 0.20–4.25. When susceptibilities are below 10 000 µSI, the variation in Q ratios is greater. The FB samples are also homogeneous with respect to the Q ratio.

In the petrophysical properties of the borehole cores from Koijärvi, the depth of the samples was taken into account. In the density-susceptibility plot (Fig. 6a), the samples can be divided into high and low susceptibility groups for samples from both the drill cores and outcrops. The samples from core FO29 were taken from the depths of 17, 21, 42, 59, 63, 68, 71 and 82 metres. The depth aspect shows that at 17 m both the density (Fig. 6b) and susceptibility (Fig. 6c) are high, whereas from 21 to 59 m the susceptibility is lower. From 63 to 71 m the susceptibility values are higher and at the depth of 81 m the susceptibility drops to under 100 (µSI). The densities are more or less constant, except for samples from a depth of 82 m, which have low densities, and one sample from 17 m, which shows a higher density. In other cores there are no systematic differences with respect to depth, and in general the variations in susceptibilities and densities therefore probably reflect the differences in lithology and amounts of Fe-bearing minerals.

The remanent magnetizations of core FO29 (Fig. 6d) show that samples with higher susceptibilities also carry higher remanent magnetization (~40–250 mA/m). An exception is for specimens from 21 m, which show higher remanence values (30–100 mA/m) but have low susceptibilities.

Borehole cores FO30 and FO31 have remanent magnetizations less than 10 mA/m at all depths, and core FO32 has remanent magnetizations up to 30 mA/m. Table 1 shows that the greatest variation in magnetic properties is in borehole core FO29, while the other cores (with fewer samples) are more coherently grouped with fairly constant susceptibilities and remanent magnetizations.

The Q ratios of all samples from core FO29 are below 1 (Fig. 6e), except for samples from the depth of 21 m. Core FO30 has Q values of 0.2–0.5 and FO31 has values of 0.06–0.25. Core FO32 has Q values of 0.04–0.07, except for samples from 69 m, which have slightly higher Q values (0.85–1.19). The low Q values show that the magnetization of the borehole cores is dominated by induced magnetization, while the contribution of remanence is smaller.

Thermomagnetic analysis

In the Satulinmäki samples the k-T curves (Fig. 7) indicate that ferrimagnetic monocline pyrrhotite is the main magnetic mineral. Small amounts of hexagonal non-magnetic pyrrhotite are also present in some of the samples. In samples heated to 700 °C, secondary magnetite was formed during heating (Fig. 7a), typical for the alteration of pyrrhotite to magnetite (Bina & Daly 1994). Sample SM7 was only heated to 375 °C to avoid such alteration and no secondary magnetite was formed (Fig. 7b).

At the Koijärvi sites FS and FA, magnetite is the main magnetic mineral (sample FS5-1A, Fig. 7c). The k-T curves display a Verwey transition point at ca. -155 °C, which is typical for MD or PSD magnetite, originating from changes in the structure of the crystal lattice. The samples clearly show the magnetite Curie temperature of 580 °C, where the sample loses its magnetization. The samples from site FC indicate the presence of pyrrhotite (see Lowrie tests below). The weakly magnetized sample FB6-1A (Fig. 7d) from site FB shows a drop in susceptibility near the Curie temperature of magnetite, indicating that magnetite is responsible for the magnetic susceptibility in this sample.

IRM acquisition curves

The IRM acquisition curve (Fig. 8) for sample SO3-1A from Satulinmäki indicates a hard coercivity mineral that saturates above 1 T, suggesting that the sample contains pyrrhotite, in agreement with other rock magnetic measurements. Sample FO32-42 from the borehole core of Koijärvi is dominated by hard coercivity pyrrhotite, but also contains magnetite, as shown by a rapid increase

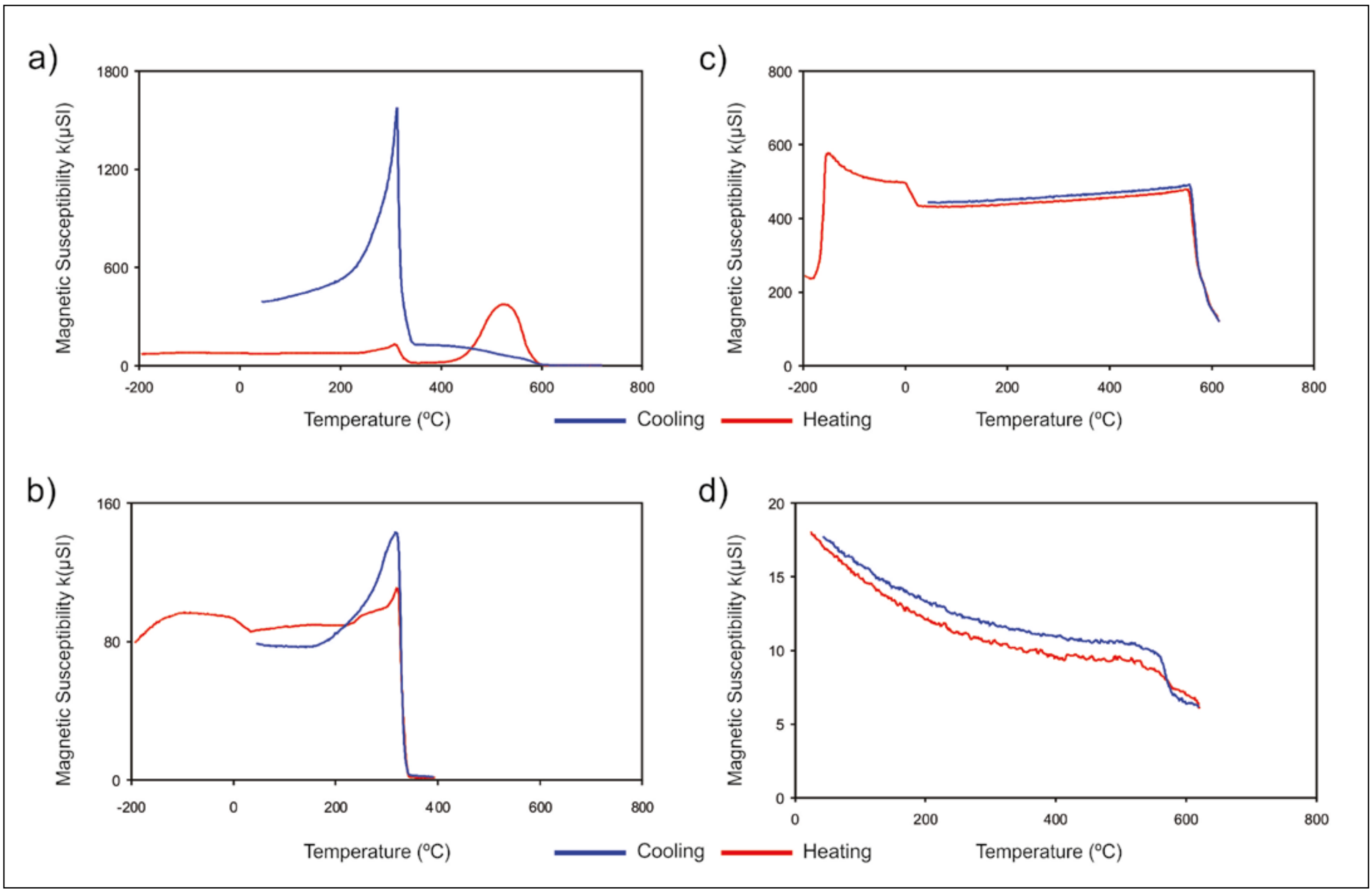

Figure 7. Thermomagnetic (k-T) curves from Satulinmäki, a) site SO 4, b) site SM 7 c) site FS 5, d) site FB 6.

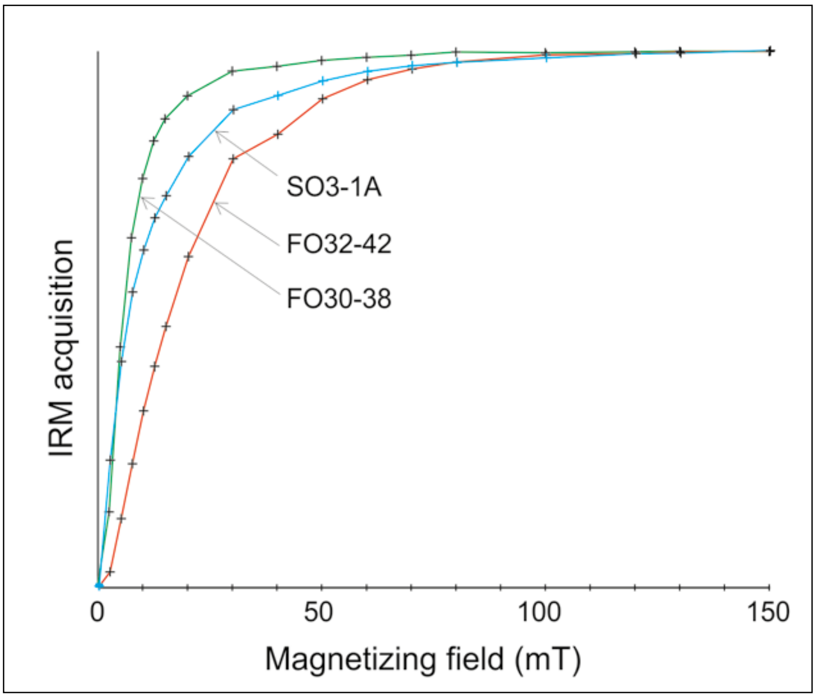

Figure 8. Normalized IRM acquisition curves for sample SO3-1A from Satulinmäki and for borehole cores FO32-42 and FO30-38 from Koijärvi.

in intensity in the lowest fields. Sample FO30-38 displays a rapid increase in magnetization in the low fields below 50 mT and saturation at about 50 mT, suggesting that in this sample the dominant ferromagnetic mineral is magnetite.

Lowrie tests

The samples from Satulinmäki (sample SM4-1A as an example, Fig. 9a) are characterized by magnetic, monoclinic pyrrhotite that unblocks at 300–350 °C, seen in all components x, y and z. The Lowrie tests thus verify the results obtained from thermomagnetic measurements. The Lowrie tests demonstrate that the Satulinmäki samples also contain very small amounts of soft MD titanomagnetite, which unblocks at 540 °C. Because the titanomagnetite only occurs in the softest x-fraction, it probably does not carry any remanence, and due to its small quantity, it probably does not contribute to the aeromagnetic anomaly of the area (see Kärkkäinen et al. 2006).

Petrophysical properties of samples from the Koijärvi outcrops indicate the presence of magnetite and pyrrhotite dominated populations, although the thermomagnetic analyses only demonstrate the dominance of magnetite. Sample FA9-1A (Fig. 9b) carries both magnetite and pyrrhotite, but sample FS11-1A (Fig. 9c) consists almost entirely of pyrrhotite with only minor amounts of magnetite. Similar behaviour is seen at site FC. Based on these results, the samples dominated by MD magnetite also contain finer-grained SD/PSD magnetite and pyrrhotite, the latter being able to carry remanent magnetization.

Sample FB3-1A (Fig. 9d) from the visibly unsheared host volcanic rock at site FB contains magnetite as the main magnetic mineral, seen as a drop in intensity at ca. 580 °C for all fractions. The sample is dominated by the softest x-component, suggesting MD magnetic grain sizes, but a very slight drop in intensity at ca. 300–320 °C suggests that the sample may also contain a small amount of monoclinic pyrrhotite.

The borehole cores from Koijärvi clearly differ from the samples taken from the outcrops. In all studied samples (Fig. 9e–f) the magnetic mineral is magnetite/ titanomagnetite, seen in all fractions

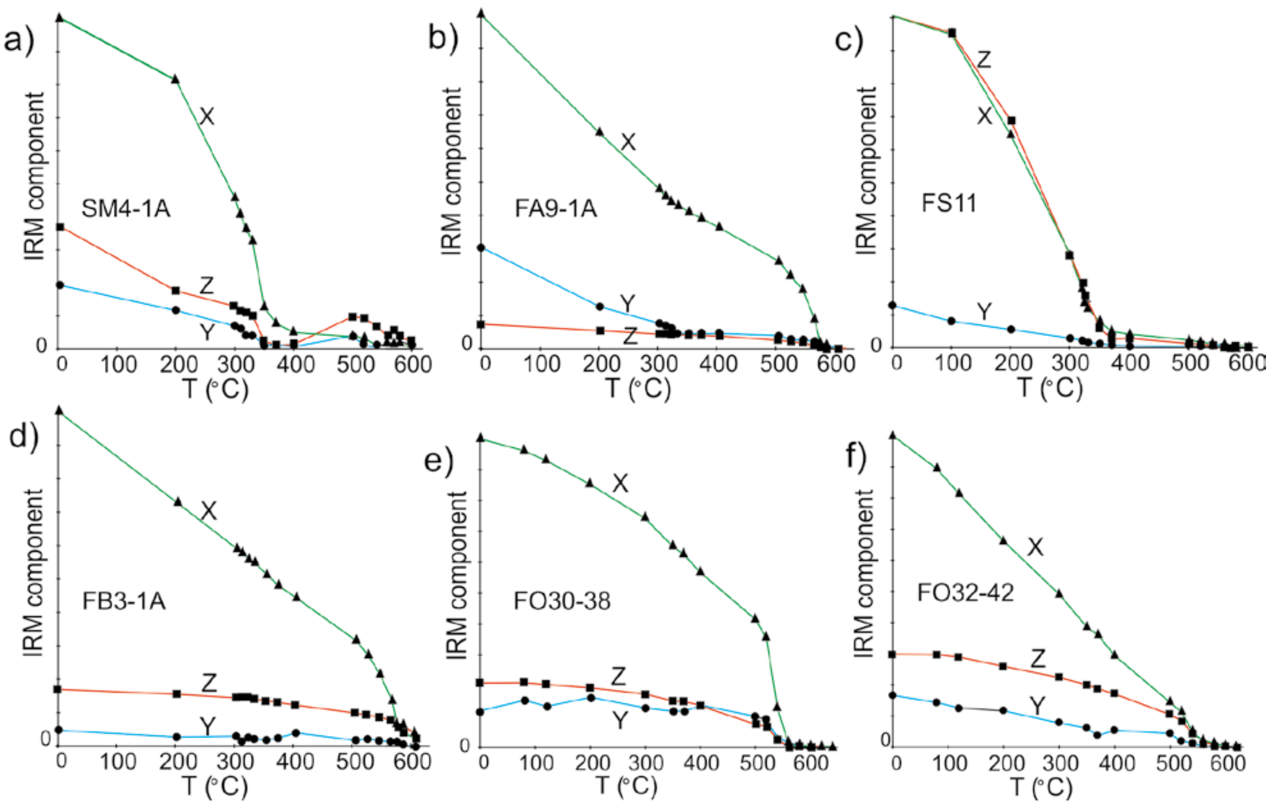

Figure 9. Three-axis IRM measurements. Thermal demagnetizations after IRM acquisition along three orthogonal directions with fields of 1.4, 0.4 and 0.12 T to define the hard (>0.4 T, z), intermediate (0.12-0.4 T, y) and soft (<0.12 T, x) coercivity fractions. a) Satulinmäki, b–d) Koijärvi outcrops, e–f) Koijärvi borehole cores.

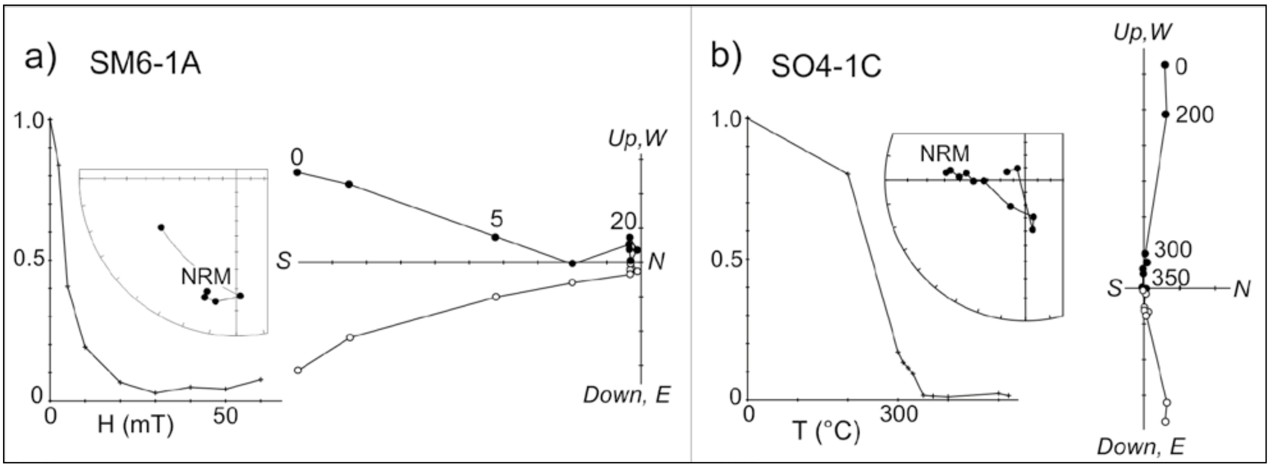

Figure 10. Examples of demagnetization behaviour from specimens in Satulinmäki. a) AF demagnetization, site SM, b) thermal demagnetization, site SO. The diagram on the left shows the decay of remanence intensity during demagnetization in increasing AF fields or temperatures. The central stereoplot shows the movement of NRM directions during demagnetization. The Zijderveld diagram on the right shows the component analyses where closed (open) circles denote projections onto horizontal (vertical) planes. The numbers refer to mA/m (in a) or °C (in b).

x, y and z. The dominating magnetite phase is carried by MD grain sizes, but the samples also contain considerable amounts of PSD/SD grain sizes with hard and intermediate coercivities, which are able to carry stable remanence. In sample FO32-42A (Fig. 9f), pyrrhotite is seen in the intermediate y component, consistent with the AF and thermal demagnetization data, which imply that the remanence is carried by both magnetite and pyrrhotite.

Palaeomagnetism

In general, the remanence directions are scattered in both Satulinmäki and Koijärvi localities. This may be due to very weak remanence intensities in some cases, but in most cases it is implied that the scatter reflects later tectonic movements, which has randomized the remanence directions. In the Satulinmäki samples the average NRM direction has a SW-pointing declination and a moderate positive inclination (Fig. 10). This direction makes a large angle with the present Earth's field-induced magnetization direction, which should be taken into account with regard to magnetic modelling (see Clark & Tonkin 1994). However, as the data were obtained from a very limited number of samples, the palaeomagnetic results can only be taken as preliminary. In the following the demagnetization results are briefly discussed from each locality. The results for each palaeomagnetically stable sample are shown in Table 2. Examples of demagnetization behaviours are presented in Figures 10, 12 and 13 and the mean directions in Figures 11 (Satulinmäki) and 14 (Koijärvi).

Satulinmäki

Six samples at site SM and five samples at site SO yielded comparatively stable palaeomagnetic results (Table 2). Those samples that have high remanence intensities and magnetic susceptibilities also carry the most stable remanence directions. The sample locations of site SM are illustrated in Figure 2. Samples were taken from both a visibly oxidized, rusty rock type and from a lighter-coloured rock. The error angle used in principal component analysis was less than 6° for most specimens, but in two specimens the angles were as high as 11°. The characteristic remanent magnetization (ChRM) component was typically isolated in AF fields above 20–70 mT, but in some samples (e.g. specimen SM6-1A, Fig. 10a) in fields of 0–20 mT (Table 2). In thermally demagnetized specimens, a corresponding remanence direction was typically isolated in a temperature range of 200–350 °C (e.g. specimen SO4-1C, Fig. 10b), verifying pyrrhotite as the remanence carrier. Unlike most Satulinmäki samples, samples SM3 and SM7 carry a NE-pointing moderate to low

Table 2. Palaeomagnetic results for samples from Satulinmäki (Lat = 60.75°N, Long = 23.46°E) and Koijärvi borehole cores and site FB (Lat = 60.95°N, Long = 23.66°E).

Sample	AF (mT)	Th (°C)	D (°)	I (°)	Dens. (kg/m³)	J (mA/m)	K (x10-6 SI)	Q
Somero, Satulinmäki								
SM1	2.5-20	-	119.8	60.4				
SM2	20-160	-	79.6	77.3				
SM3	-	200-310	229.5	39.1				
SM4	-	200-320	285.6	43.8				
SM5		-	-	-				
SM6	0-10	200-330	256.5	23.6				
SM7	0-10	0-330	217.7	10.1				
SO1	-	200-310	249.9	51.6				
SO2	50-70	-	136.5	67.4				
SO3	-	200-310	250.2	50.9				
SO4	-	200-320	278.4	31.2				
SO5	0-10	0-330	221.2	7.1				
Mean	N = 11/17		238.0	52.1	a95 = 24.7°, k = 4.4			
		VGP: Plat = 20.1, Plong = 341.1°, dp/ dm = 23.2°/ 33.8°, A95 = 32.3°, K = 3.0						
Koijärvi, borehole cores								
FO29-21	10-30	-	359.0	45.6	2799	67.1	691	2.4
FO29-59	70-160	300-340	357.3	47.5	2786	1.2	509	0.2
FO30-14	120-160	300-340	358.9	35.7	2774	4.3	462	0.2
FO31-10	90-160	320-500	323.2	57.3	2753	2.8	395	0.2
FO31-41	90-160	-	329.4	48.2	2675	0.3	58	0.2
FO32-24	140-160	0-560	331.4	49.5	2824	1.1	614	0.1
FO32-42	20-160	320-540	342.1	47.5	2792	1.0	451	0.1
FO32-69	140-160	-	339.5	40.7	2810	25.8	605	1.1
Mean	N = 8/15		343.2	47.2	a95 = 7.8°, k = 51.7			
		VGP: Plat = 55.7°, Plong = 231.4°, dp/ dm = 6.5°/10.1°, A95 = 9.1°, K = 37.8						
Koijärvi, site FB, high								
FB1	120-160	-	333.4	42.7	2824	9.0	562	0.4
FB2	140-160	-	331.3	46.4	2815	7.3	527	0.4
FB3	30-160	-	335.9	47.2	2803	5.5	509	0.3
FB4	50-160	-	340.3	46.2	2785	17.4	503	0.9
FB5	120-160	-	335.0	40.7	2796	6.3	535	0.3
FB6	120-160	-	328.1	45.4	2829	12.9	623	0.5
Mean	N = 6/12		334.0	44.8	a95 = 3.2°, k = 439.6			
		VGP: Plat = 51.2°, Plong = 242.5°, dp/ dm = 2.6°/4.0°, A95 = 3.5°, K = 366.9						
Koijärvi, site FB, intermediate								
FB1	50-120	-	351.3	-2.4				
FB2	60-140	-	341.8	5.7				
FB5	70-120	-	353.1	3.8				
FB6	50-120	-	340.7	12.0				
Mean	N = 4/6		346.8	4.8	a95 = 9.9°, k = 87.2			
		VGP: Plat = 30.6°, Plong = 219.1°, dp/ dm = 5.0°/9.9°, A95 = 8.0°, K = 132.0						

Note: AF (Th) denotes the range of AF (Th) demagnetization; D and I are the mean declination and inclination, respectively; N/n is number of samples/ specimens; α95 is the radius of the circle of 95% confidence; k is the Fisher's (1953) precision parameter; Plat and Plong are the palaeolatitude and palaeolongitude for the virtual geomagnetic poles (VGPs); dp and dm are the semi-axes of the oval of 95% confidence; A95 is the radius of the circle of 95% confidence of the mean pole.

negative inclination component isolated in AF fields of 0–20 mT (SM7) and at temperatures of 200–310 °C. This direction is antipodal to that of other samples. When the polarity is reversed, the remanence directions plot among the other samples. The occurrence of the ChRM component is not directly related to the intensity of magnetization, because the samples with very low magnetizations, due to very small amounts of pyrrhotite, also give corresponding remanence directions to the highly magnetic samples. The samples taken from the less rusty rock type carry a corresponding remanence direction to the more rusty rocks.

Because the remanence directions from both sites SM and SO overlap, a common mean remanence direction was calculated for all samples (Table 2, Fig. 11). The mean direction has D = 238.0°, I = 52.1° (α = 24.7°, n = 11/17 samples/specimens, Table 2). Although the mean remanence direction has a high scatter, it is clear that it deviates from the known 1.9–1.8 Ga Svecofennian remanence direction, which points to the northwest (e.g. Pesonen et al. 2003). The southwest-pointing direction parallels the mean magnetic foliation plane defined by AMS studies, as well as with the geologically defined structures of the region. Therefore, it is interpreted that the remanence directions at Satulinmäki have been affected by the shearing process, as will be discussed later.

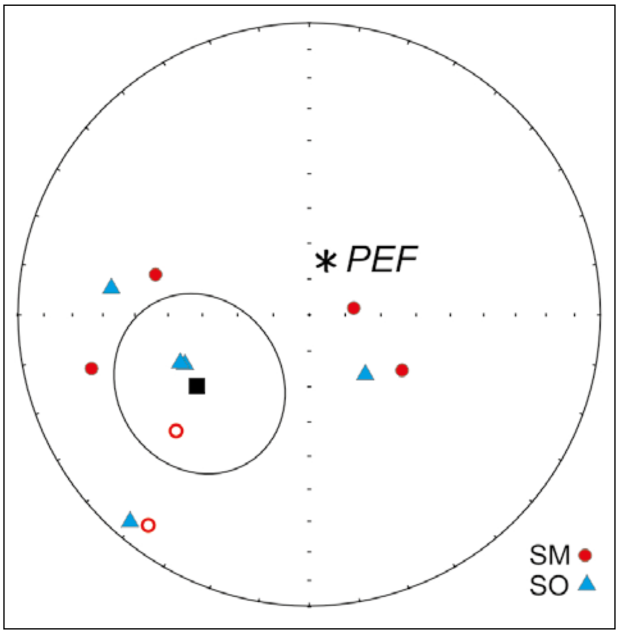

Figure 11. Mean palaeomagnetic directions of samples from sites SO and SM of Satulinmäki. The circle shows the cone of α95 confidence about the mean direction. PEF denotes direction the present Earth's field of the site.

Koijärvi outcrops

Site FS covers the whole width of the outcrop that is revealed along a length of about 70 m. Samples were taken from six locations along an E–W profile that transects the shear zone. Most of the rocks are intermediate volcanites, which in some places appear homogeneous and in others are more clearly sheared. The remanence is unstable and the remanence directions are scattered between different locations. Therefore, no mean remanence direction could be calculated. At site FA, thermal demagnetizations indicate that the rocks contain both magnetite and pyrrhotite, consistent with the Lowrie tests (specimen FA7-1C, Fig. 12a). As at site FS, the palaeomagnetic directions are all scattered and no consistent mean remanence direction could be calculated (Fig. 14a). The magnetic behaviour of site FC corresponds to that of sites FS and FA in that the remanence directions are highly scattered (Fig. 14b). AF and thermal demagnetizations give similar results. According to thermal demagnetizations and rock magnetic studies, the dominant magnetic mineral at site FC is pyrrhotite. The lack of magnetite in the studied samples may simply reflect the sampling, which was concentrated on the clearly rusty rock types, while less rusty samples were not collected. Samples FC1 and FC2, which were taken from dark, narrow (less than 1 cm) veins, have remanence directions corresponding to the Svecofennian direction. The direction may be accidental, or it may indicate that the veins represent the latest Svecofennian event at this location, unaffected by any later deformation or metamorphic events. As will be shown later, this interpretation conflicts the AMS results, which indicate that these samples also have a characteristic SW–NE trending magnetic foliation plane like the other samples of the outcrop. Samples FC3 and FC4 (specimen FC4-1A, Fig. 12b) carry a hard coercivity remanence component that has a NW declination and low inclination. In sample FC5 from the same site, the direction is antipodal. The most notable result from sites FS, FA and FC is that none of them carries the typical Svecofennian remanence direction.

Site FB is located about 100 m from the previous sites and represents a homogeneous rock type that is visibly not deformed or sheared. The magnetization behaviour is clearly different. The main magnetic mineral is magnetite, but according to thermal demagnetization and Lowrie tests, a small pyrrhotite component also exists. Thermally demagnetized samples were not used at all for mean calculations, as marked mineralogical changes took place at temperatures above 500 °C, typical for the occurrence of pyrrhotite. All six AF demagnetized samples give consistent remanence directions (Table 2, Fig. 12). Because the samples are from a single small outcrop, the secular variation in the Earth's magnetic field has not been averaged and the remanence may represent a local geomagnetic field direction. The hard, small ChRM component was revealed in high AF fields of 120–160 mT, and in some cases in 50–160 mT. The remanence has a NW-pointing declination and intermediate inclination, typical for Svecofennian aged rocks. It is considered to be primary in origin. In most cases, the demagnetization trajectories do not pass through the origin, as the specimens cannot be fully demagnetized (specimen FB3-1B, Fig. 12c.). In addition to the ChRM component, a NW-pointing remanence with very low inclination was isolated in intermediate AF fields of 50–120 mT in four samples (Table 2, Fig. 14c). A third, steep inclination component close to the present Earth's field direction was isolated in low coercivities in all samples. It is possible that in the AF demagnetized samples the high and low coercivity components overlap, producing the third low inclination component. This is seen as curved zijderweld diagrams in most specimens. On the other hand, a similar low inclination component can be seen in thermally demagnetized specimens at magnetite unblocking temperatures (specimen FB2-1C, Fig. 12d). As shown before, at site FC a similar NW-pointing low inclination component was isolated in three samples, although there the remanence resides in pyrrhotite. It is possible that the component has some real geological importance, although its origin is so far unknown. The NW-pointing component corresponds to the known Svecofennian direction. It is noteworthy that the core samples FO29-FO31 (four cores) taken between locations FB and FC carry the same Svecofennian direction, as will be shown below.

Koijärvi, borehole cores

At Koijärvi, altogether 12 oriented samples from four borehole cores were studied. Stable, coherent results were obtained from 8/15 samples/specimens (Table 2, Fig. 14d), even though the samples are weakly magnetized. The ChRM component has a NW-directed moderate inclination direction, typically isolated in high AF fields of 70–160 mT (10–30 mT in one specimen) (Fig. 13a). Thermal demagnetization results and the Lowrie tests of cores FO29 and FO30 suggest that the

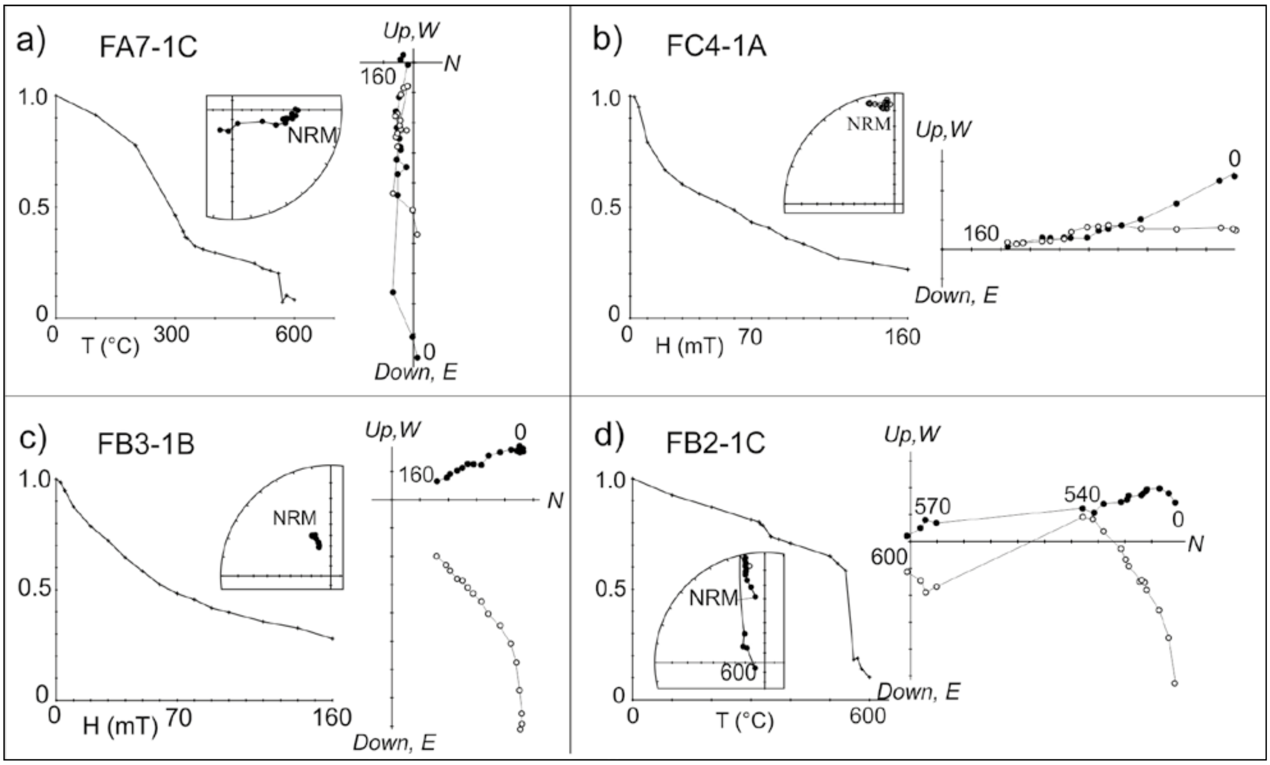

Figure 12. Examples of demagnetization behaviour of specimens from Koijärvi outcrops. For explanations, see Fig. 10.

ChRM component resides in pyrrhotite, although the dominant magnetic mineral is magnetite. Apparently, the magnetite has MD grain sizes, unable to carry ancient remanent magnetization. On the other hand, in cores FO31 (Fig. 13b) and FO32 the NW-pointing remanence component resides in both pyrrhotite and magnetite that has smaller magnetic grain sizes than in cores FO29

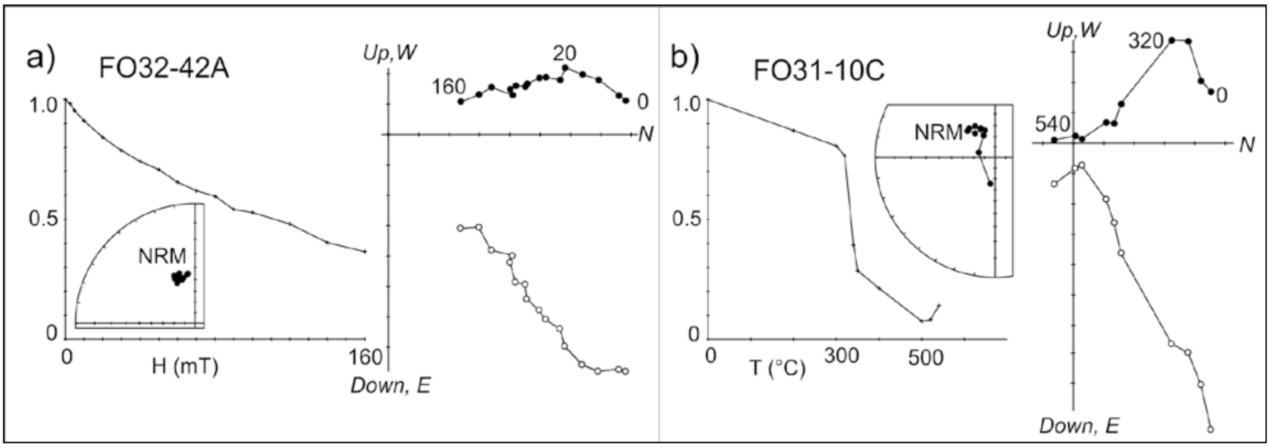

Figure 13. Examples of demagnetization behaviour of specimens from the Koijärvi borehole cores. For explanations, see Fig. 10.

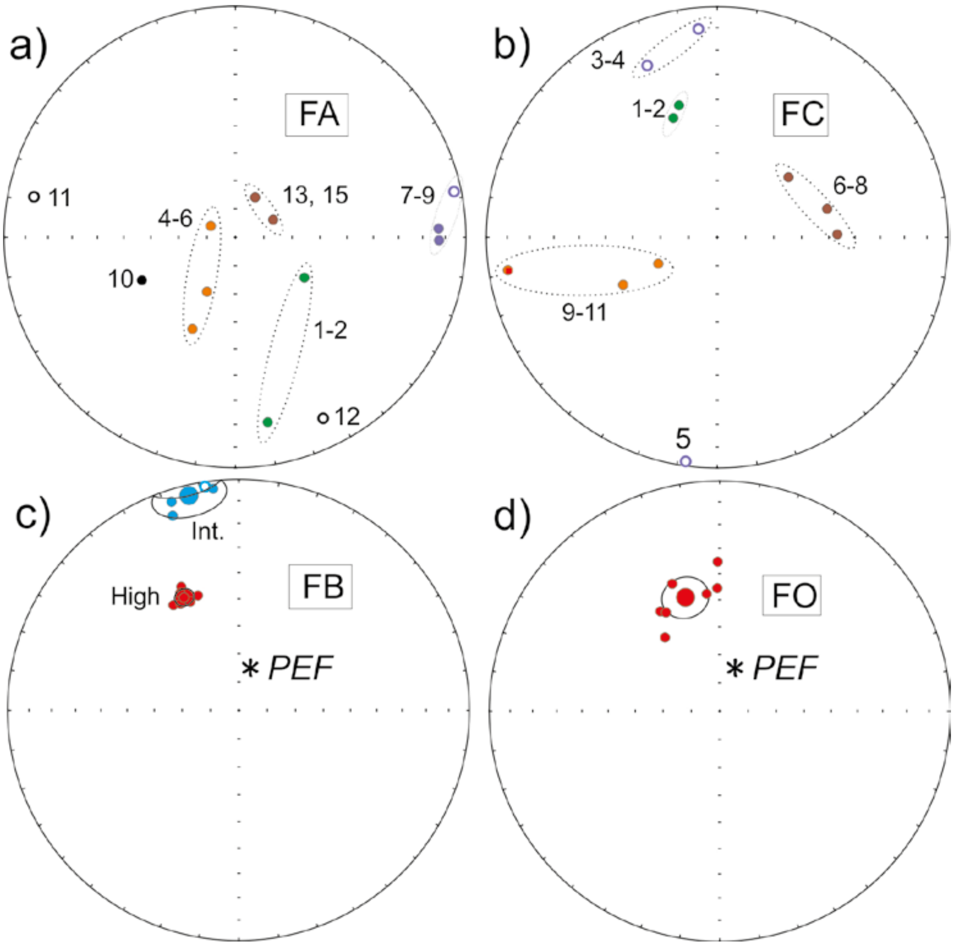

Figure 14. Site mean palaeomagnetic directions for a) site FA, b) site FC and c) site FB of Koijärvi outcrops and f) FO from the borehole cores of Koijärvi. Small symbols display the sample mean directions and large symbols the site mean (FB) or core mean (FO) directions. In a) and b) the grouping of sample directions according to sites is shown as dashed lines. In c) and d) the circles indicate the cones of α95 confidence about the site/core mean directions. In c) the High (Int.) denote the components isolated in high (intermediate) coercivities. PEF denotes the direction of the present Earth's field of the site.

and FO30. Since the remanence components were only isolated in a few samples per core, the results must be treated with caution.

A mean direction was calculated for the NW-pointing remanence component (Table 2, Fig. 14d). The data are slightly streaked, which may be due to the presence of some uncleaned viscous component. However, compared to the very scattered remanence directions from the Koijärvi outcrops FS, FA and FC, the borehole cores are comparatively well clustered. The mean remanence direction is in accordance with that of site FB. The NW-pointing remanence corresponds with the remanence direction typically obtained in Svecofennian ca 1.88–1.84 Ga rocks. As will be discussed later, it is implied that in these deeper cores, as well as at outcrop FB outside the actual shear zone, the Svecofennian age remanence direction has been preserved, and has not been affected by later tectonic events.

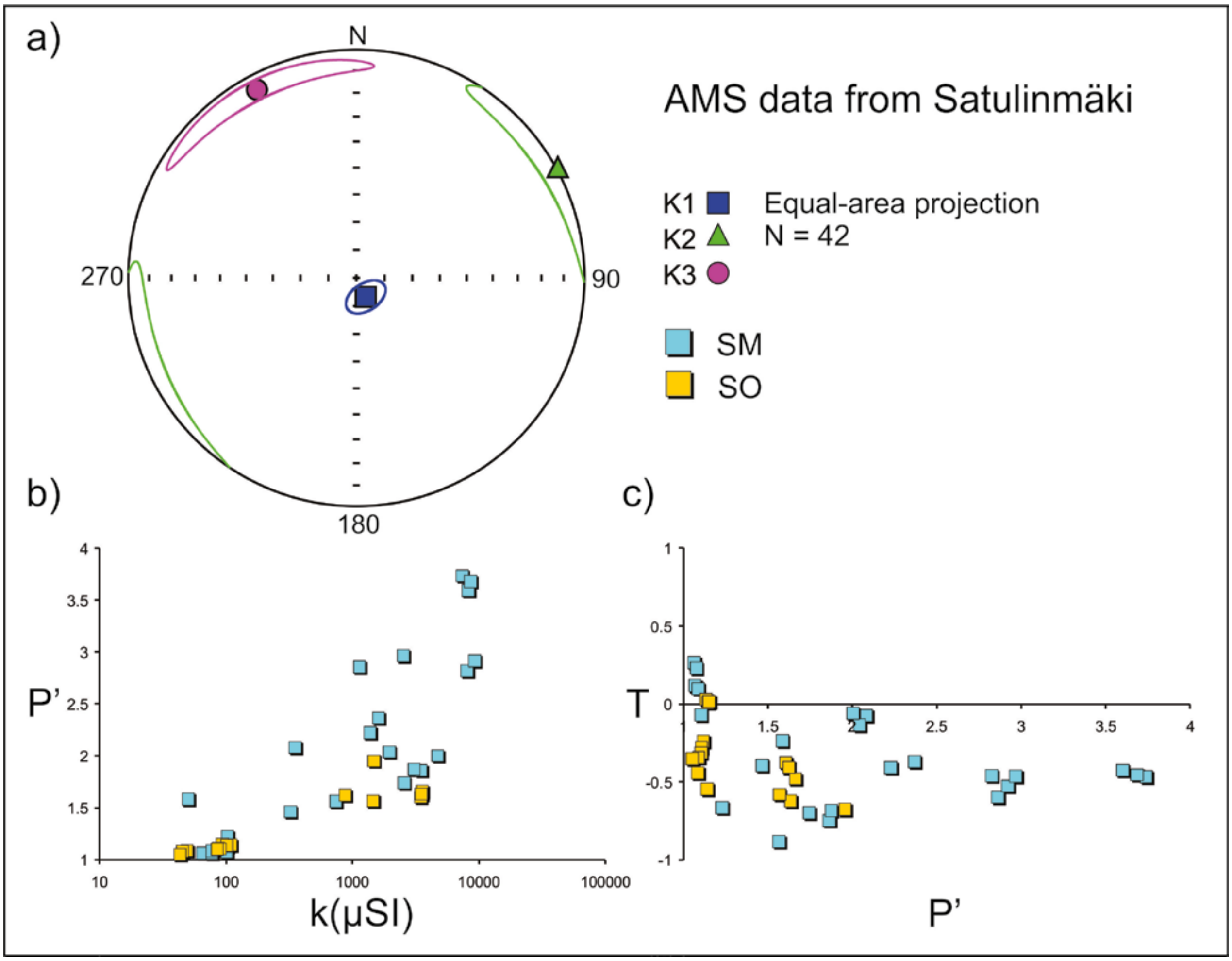

Figure 15. a) AMS mean directions and confidence ellipses projected on an equal-area lower hemisphere of sites SM and SO. Squares are maximum susceptibilities representing the magnetic lineation, intermediate susceptibilities are plotted as triangles and minimum susceptibilities are plotted as circles, referred as the pole to the foliation plane. b) The left diagram shows the degree of anisotropy (P') plotted against the bulk susceptibility, k(μSI). c) The right diagram shows the Jelínek plot (Jelínek 1981), where the shape (T) is plotted against the degree of anisotropy (P'). In case of negative T-values, the shapes are prolate (cigar). Positive T-values represent oblate shapes (disc). The light blue colour denotes SM samples and yellow denotes SO samples.

Anisotropy of magnetic susceptibility (AMS)

Satulinmäki

AMS measurements of all (SM and SO) samples from Satulinmäki show that the directional data are well clustered and variations between the samples are very small. The magnetic lineations are tightly clustered and the plunge is almost vertical. The mean magnetic foliation of all samples strike NE–SW almost vertically along the general shear structure (Fig. 15a). However, two major directions of the magnetic foliation plane are observed from site SM (Fig. 16): one that is parallel to the NE–SW shearing (Fig. 16b) and another that slightly cuts the first in the E–W direction (SM1-4). The E–W directions (Fig. 16c) lie within the heavily oxidised zone.

The anisotropy degree P’ in some of samples of the more altered rocks is exceptionally high, with an average of about 3, corresponding to a 200% degree of anisotropy. In slightly less altered rocks the P’ values are also high, ranging from ~1.5 to ~2.2 (Fig. 15 b). The weakly magnetized samples SM 4–5 have lower P’ values of 1.15 (15%). Thus, a positive correlation between the degree of anisotropy and magnetic susceptibility can be observed in the samples from site SM. Conversely to SM, the P′ value as well as the susceptibility of samples from the SO site is lower in the altered heavily rusty zone. Samples SO1, SO2 and SO3 have an average P’ value of about 11%, whereas samples SO4 and SO5 have higher P’ values (Table 1).

The shapes of the AMS ellipsoids of both SM and SO samples are generally prolate (Fig. 15c), except for samples SM4 and SM5, which show both prolate (cigar-shaped) and oblate shapes (disc-shaped). Samples SM4 and SM5 also differ from other samples in that they have low susceptibilities and low intensities of remanent magnetization, and they do not carry a stable remanent

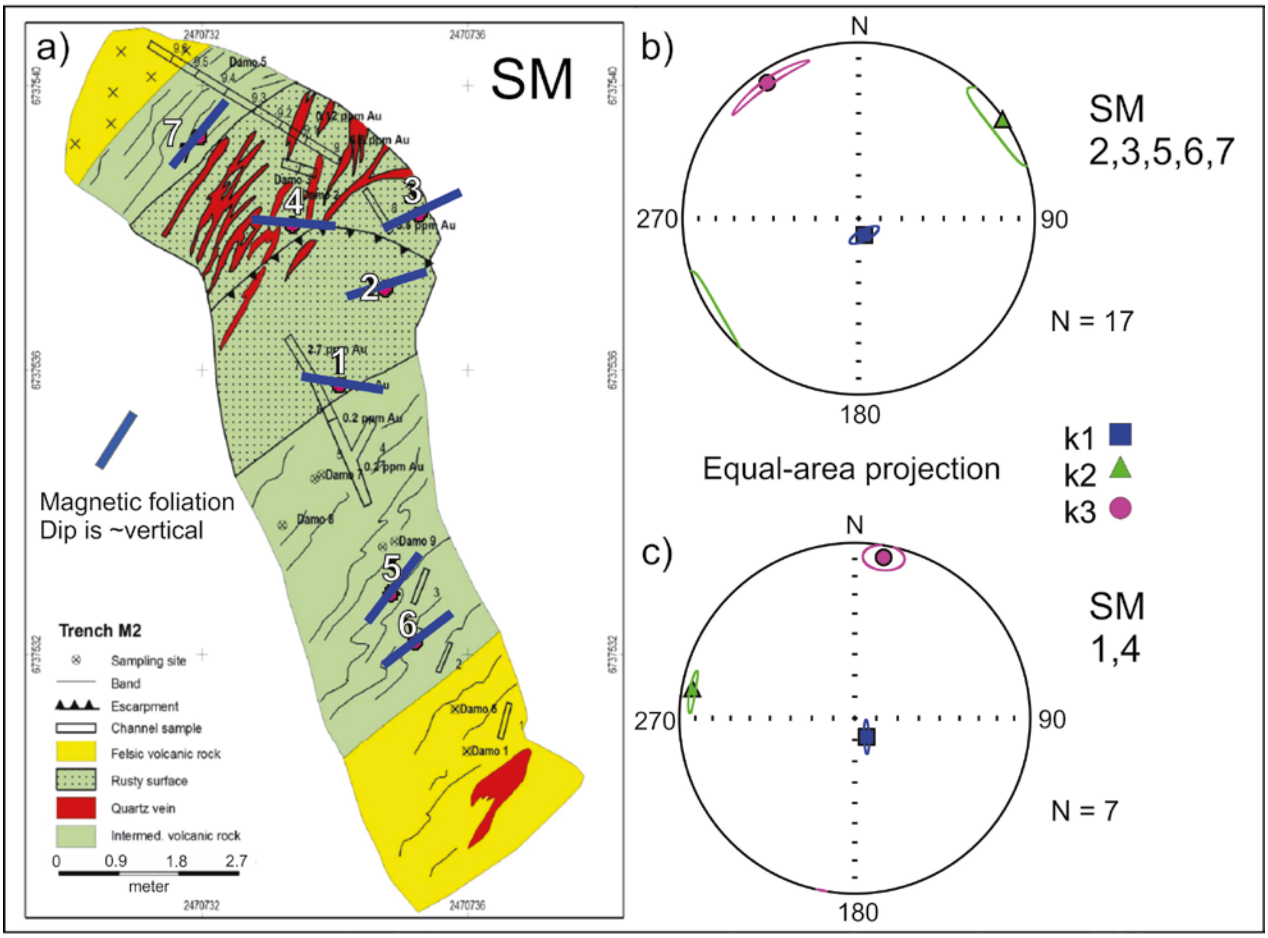

Figure 16. a) Detailed bedrock map of site SM (trench M2, Kärkkäinen, 2006). Strikes of magnetic foliation planes are shown at sample locations SM 1–7. b) Magnetic foliation of samples SM2, 3, 5, 6 and 7 is parallel to the NE–SW shearing and c) in samples SM1 and 4 the magnetic foliation planes strike E–W. Sites SM1 and 4 lie within the heavily oxidised zone.

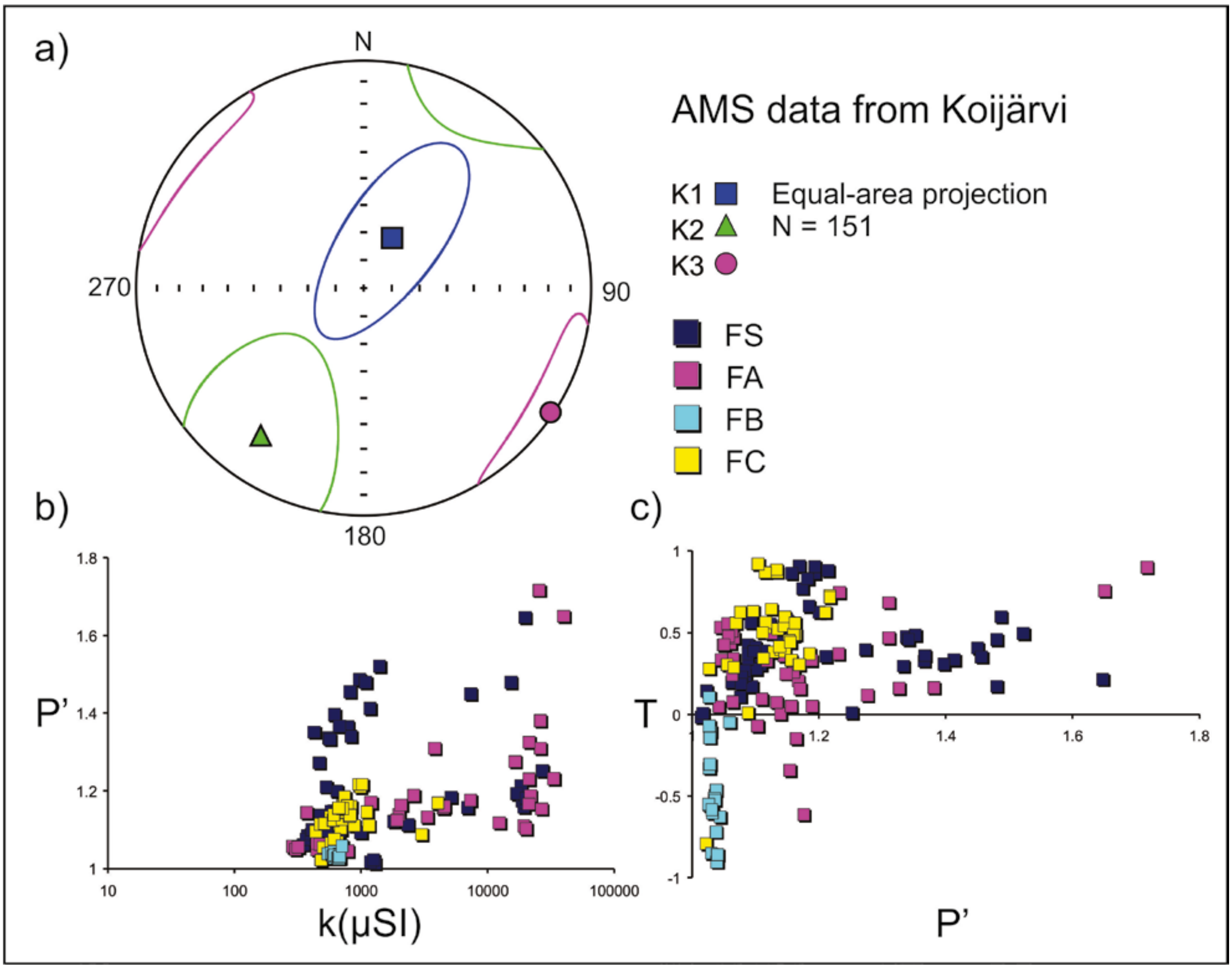

Figure 17. a) AMS mean directions and confidence ellipses projected on an equal-area lower hemisphere of sites FS, FA, FB and FC. b) Degree of anisotropy, P' vs. magnetic susceptibility k(μSI) diagram. c) AMS shape, T vs. anisotropy degree, P' plot. For explanations, see Fig. 15.

magnetization direction. Samples SO1, SO2 and SO3 are also similar to samples SM4 and SM5, with a low remanence intensity and susceptibility (Table 1).

Koijärvi outcrops

Directional AMS data of all specimens from the Koijärvi outcrops FS, FA, FB and FC demonstrate that the mean directions follow the same trend in all locations (Fig. 17a). The AMS scalar data of the Koijärvi samples are presented in Figures 17b and 17c. The average anisotropy degree of the FS samples is about 18%, but varies strongly even within a single location, most likely due to variation in the magnetic mineralogy. Approximately the same P' values (~17%) are obtained within site FA as in FS. The FS samples are dominantly oblate and no obvious trend between shape and the degree of anisotropy can be observed. The FA site shows predominantly oblate shapes and a positive trend of increasing P' values with increasing susceptibilities. The FC samples show an average P' value of ca. 14%, and they predominantly have oblate shapes as at sites FS and FA. Compared to the previous Koijärvi sites, at site FB the degree of anisotropy is significantly lower, the average P' value being 3%. An increasing prolateness with increasing P' values can be observed. The shapes of the AMS ellipsoids of the FB samples are predominantly prolate, in contrast to the other sites at Koijärvi.

At site FS (Fig. 18a), the mean (eigenvector) magnetic lineation plunges moderately (47°) to the NE and the magnetic foliation is almost vertical and strikes SW–NE. The magnetic foliation of samples FS4-6 and FS11-13 strikes WSW–ENE

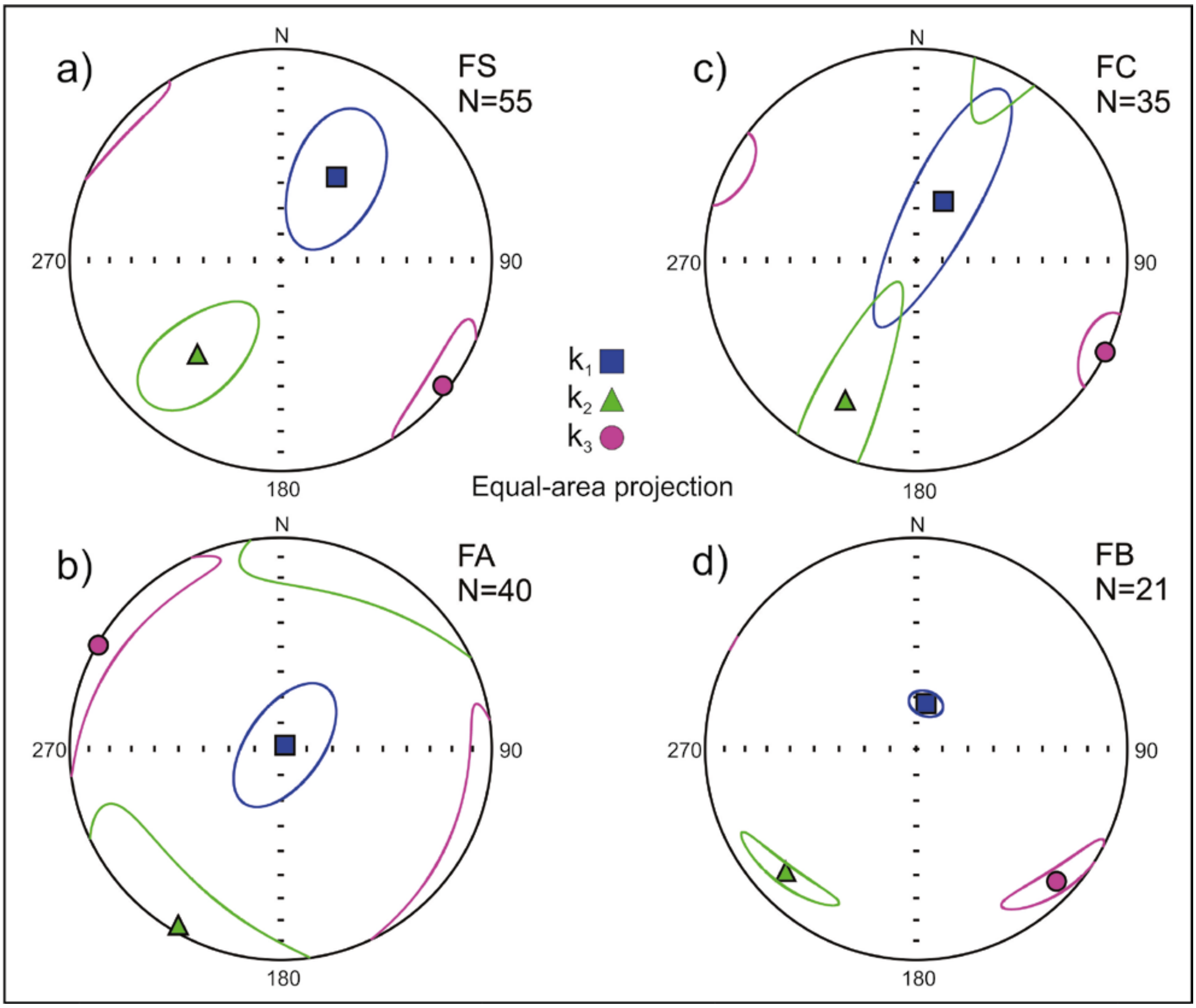

Figure 18. AMS mean directions and confidence ellipses projected on an equal-area lower hemisphere of sites a) FS b) FA c) FC and d) FB from Koijärvi outcrops. For explanations, see Fig. 16.

(Fig. 19). Rock magnetic studies demonstrate that in these samples magnetite makes a major contribution to the magnetic fabric. It is therefore possible that magnetite follows an older, more WSW–ENE striking foliation trend, whereas the pyrrhotite-dominated samples of younger age follow a SW–NE trend. The magnetic lineation at site FA is almost vertical. The magnetic foliation is steep and follows similar SW–NE directions (Fig. 18b), except for samples FA10–12, which show a N–S striking foliation (Fig. 19). These samples also differ from the rest of the FA locations in having a rusty oxidized surface. The FC samples (Fig. 18c) have generally lower susceptibilities, but their magnetic foliations concur with the previous sites. The magnetic foliation has a SW–NE strike. The magnetic lineations are more scattered, although individual locations are well-clustered. The average magnetic lineation plunges 70° to the NNE and the magnetic foliation plane dips vertically in an ESE direction. The magnetic susceptibility of rocks within the FB site is constant, ca. 550 (µSI). Even though at macroscopic scale the rock appears rather homogeneous, the AMS results clearly show that the rock follows the same general foliation trend as the previous sites. The mean magnetic foliation plane is in the SW–NE direction and a steep lineation plunges to the N (Fig. 18d).

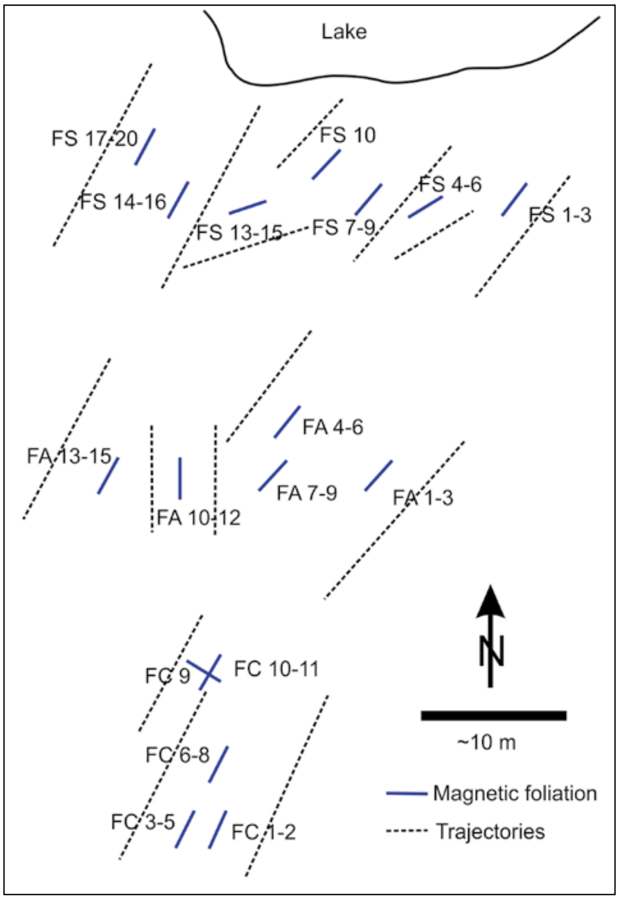

Figure 19. Strikes of the magnetic foliation (blue lines) for all Koijärvi samples. Dotted lines are trajectory lines for the magnetic foliations. The dips of the foliations are ~vertical.

Koijärvi, borehole cores

The AMS analyses for borehole cores shown in Table 1 and in Figure 20 were carried out from various depths. The AMS reflects the orientation of all minerals, but as was shown by rock magnetic studies and thermal demagnetization, the dominant magnetic mineral in the cores is magnetite. Therefore, it is possible that magnetite dominates the AMS while the contribution of pyrrhotite to the total AMS is probably smaller. The AMS parameters of the borehole cores differ from those of the outcrops. The mean magnetic foliation of all FO samples strikes N–S and dips almost vertically. The mean magnetic lineations are aligned horizontally in the N–S direction (Fig. 20a).

The P' diagram (Fig. 20b) of all cores shows a small decrease in the degree of anisotropy as a function of depth. All borehole cores except for FO29 have relatively low P' values below 1.10. In core FO29 the majority of the P' values exceed 1.10, but decrease downwards. The AMS shapes (Fig. 20c) show greater variation with depth than the degree of anisotropy. FO31 is more or less constant, while FO30 is prolate at ca. 15 m and then neutral at ca. 38 m. Cores FO29 and FO32 show both oblate shapes in the upper part of the core and prolate shapes further down.

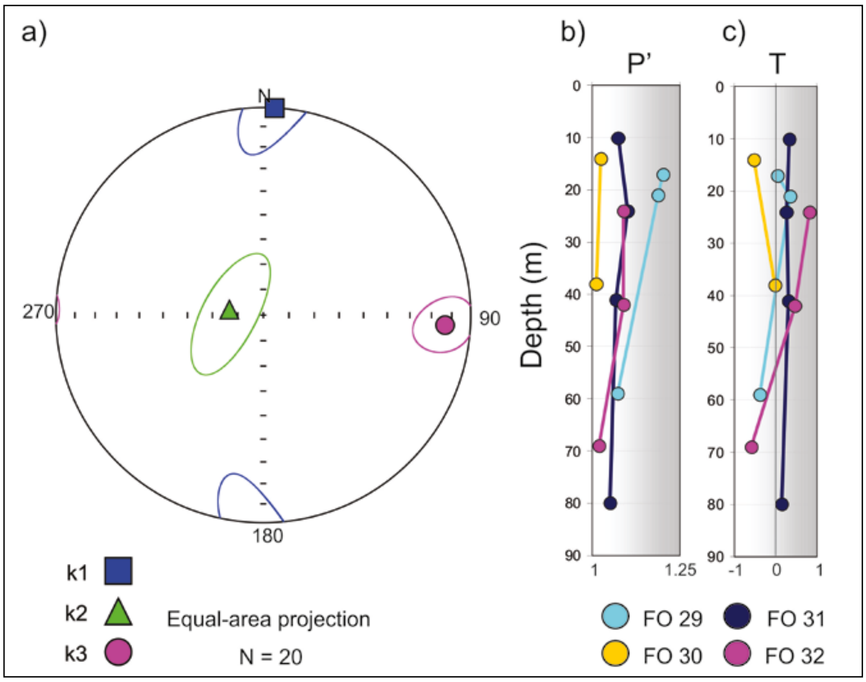

Figure 20. a) AMS mean directions and confidence ellipses projected on an equal-area lower hemisphere from Koijärvi drill cores FO 29, FO 30, FO 31 and FO 32. Squares are maximum susceptibilities and represent the magnetic lineation, intermediate susceptibilities are plotted as triangles and minimum susceptibilities are plotted as circles, referred as the pole to the foliation plane. b) The anisotropy degree (P') vs. the depth of drill cores. c) The AMS shape (T) vs. the depth of drill cores. Light blue circle = FO29, yellow = FO 30, dark blue = FO 31 and purple = FO 32.

DISCUSSION

Magnetic mineralogy

The present study on the Satulinmäki formation indicates that although the magnetization (both magnetic susceptibility and remanence intensity) may be very low, it is mainly carried by magnetic, monoclinic pyrrhotite. All thermally demagnetized specimens from Satulinmäki demonstrate that the remanence resides in pyrrhotite with unblocking temperatures of ca 320–350 °C. The Lowrie tests and thermomagnetic analyses from Satulinmäki support this observation. In the thermomagnetic curve of specimen SM7-1D, a slight increase in intensity can be seen at about 200 °C, which probably indicates the inversion of hexagonal non-magnetic pyrrhotite to monoclinic pyrrhotite. As the increase is minimal, the amount of hexagonal pyrrhotite is probably very small. In natural pyrrhotites it is typical that both phases occur simultaneously (e.g. Dunlop & Özdemir 1997). The study at Satulinmäki was carried out in an area where the magnetic anomaly and IP anomaly overlap (Kärkkäinen et al. 2006). It was suggested that the anomalies are associated with magnetic pyrrhotite. Further to the east these anomalies separate, and it is implied that the strong IP anomaly with a low magnetic field is related to non-magnetic pyrrhotite and arsenopyrite, coupled with the occurrence of gold. Previous studies have also demonstrated that the pyrrhotite in the Satulinmäki volcanites mostly occurs in its nonmagnetic, hexagonal crystal structure that cannot, for instance, cause the observed magnetic anomaly (Vanhala 2006, Kärkkäinen et al. 2006). High susceptibility values were also measured from cores and were related to monoclinic pyrrhotite. Based on rock magnetic data and thermal demagnetization, the present study confirms that the main source of the magnetic anomaly in the western part of Satulinmäki hill is magnetic, monoclinic pyrrhotite. In these western sites, pyrrhotite with very low magnetization values is predominantly also of the monoclinic, magnetic phase. No rock magnetic studies were carried out in the eastern sites to confirm the occurrence of hexagonal pyrrhotite.

The samples from the Koijärvi outcrop are characterized by both pyrrhotite and magnetite. Based on rock magnetic analysis, the less rusty rocks are dominated by magnetite, which most likely represents the primary ferromagnetic mineral. Pyrrhotite is presumably related to the secondary hydrothermal event. The occurrence of pyrrhotite is most clearly seen in the rusty rock types, but those rocks that are less rusty also contain pyrrhotite. This is seen especially when comparing the sheared rocks from sites FS, FA and FC with the least sheared, fresh-looking rocks of site FB. The dominant magnetic mineral of site FB is magnetite, but it also contains small amounts of pyrrhotite. It is suggested that magnetite represents the primary magnetic mineral and pyrrhotite was formed in a later hydrothermal event, most likely related to the fluid activity of the same event that is seen at the other Koijärvi outcrops.

The main magnetic minerals in the four studied borehole cores of Koijärvi are magnetite and pyrrhotite. Pyrrhotite carries stable remanent magnetization in two of the cores and both pyrrhotite and magnetite in two other cores. In general, most samples from the cores are weakly magnetized, except for some of the samples from core FO29. Those samples with the highest magnetization values do not carry stable remanent magnetization, most likely due to the coarse MD grain sizes of magnetite.

AMS versus remanent magnetization

Rock magnetic tests and thermal demagnetization verified that the dominant magnetic mineral at Satulinmäki is monoclinic pyrrhotite. The magnetic foliation plane defined by AMS reflects the orientation of these pyrrhotite grains. The AMS fabric parallels the rock fabric, indicating that the magnetic fabric is a deformationally induced phenomenon (see e.g. Goldstein & Brown 1988) and reflects the general strong SW–NE shearing of the Satulinmäki area (Saalmann 2007, Saalmann et al. 2009). The preferred orientation of the pyrrhotite grains in the magnetic foliation plane suggests their pre-or syndeformational formation (see Clark & Tonkin 1994). In addition, the remanent magnetization resides in pyrrhotite, and the overall SW-pointing palaeomagnetic direction coincides with the magnetic foliation plane and rock fabric. In the following, the degree of magnetic anisotropy is discussed, and its impact on the direction of remanent magnetization is evaluated.

The degree of anisotropy in the Satulinmäki rocks is high, with P’ typically exceeding 1.15

(Table 1). In the most anisotropic sample the P' value is extremely high, over 3, which means 200% anisotropy. The overall magnetic fabric at Satulinmäki can be interpreted to be as expected for deformed rocks, regarding the strain field and complexity of magnetic fabrics in shear zones. However, in the most pyrrhotite-bearing zone of site SM, the degree of anisotropy is extraordinarily high, coupled with the prolate shapes. The magnetic fabric in this zone is much stronger than at site SO and also when compared to the Koijärvi sites. There may be several explanations for this unusual behaviour:

1. Stronger P' values are due to higher susceptibilities. This is obvious, but it cannot fully explain the extremely high P' values. Also the field dependency of pyrrhotite increase the P' values.
2. The tectonic impact on site SM has been greater.
3. The hydrothermal activity together with the tectonic shear have affected the magnetic minerals and have given extremely high P' values.
4. The P' value is not the best way to describe strain, and the results possibly do not represent the strain in the sense of describing the changes within the shear zone.

In comparison, the magnetic fabric at sites SO has not been so strongly affected by the factors described above, but there the major contributor to the magnetic fabric is the tectonic impact. The tectonic effect is also the main cause of the high AMS at site SM, but additional factors are also required. It is implied that tectonic effects as a whole at the Satulinmäki sites are linked to the regional shear zones on a broader scale, while the most severely sheared zone with extremely high P' values at site SM seems to be a local phenomenon restricted to certain parts of the zone.

AMS and remanent magnetization are related. If the degree of AMS is more than 10% (P' > 1.10), it is possible that the direction of remanent magnetization is deflected and does not correctly reflect the ambient geomagnetic field (e.g. McElhinny & McFadden 2000). At Satulinmäki the P' values are high (Table 1), and it is thus evident that the remanence directions are deflected. The effect of deflection can be significant in strongly foliated rocks. Hargraves (1959) has shown that the remanence vector migrates towards the magnetic foliation plane during deflection. According to Raposo et al. (2003), the amount of deflection depends on the angle between the ambient field direction and the AMS foliation plane. At Satulinmäki, the angle between the expected NW direction of remanence and the SW–NE-directed AMS foliation plane is about 90°. Consequently, substantial deflection of remanence due to AMS is evident and the direction of remanence is not therefore aligned along the geomagnetic field prevailing during the Svecofennian orogeny.

One additional important factor at Satulinmäki is that the magnetization (both induced and remanence) resides in pyrrhotite, which has strong intrinsic magnetocrystalline anisotropy due to its lattice structure (Dunlop & Özdemir 1997). The most severe effect of this anisotropy is to deflect the remanent magnetization from the ambient geomagnetic field direction so that the remanence direction is controlled by the geological structures. The effect of intrinsic anisotropy is to rotate the remanence away from the ambient field direction towards the direction of the cleavage or fault structure that forms the easy plane of magnetization (see Thomson et al. 1991).

As a result, both AMS and intrinsic anisotropy of pyrrhotite in the strongly sheared rock point to the deflection of remanence from the ambient geomagnetic field. The remanence directions show notable scatter at both site SM and SO. When compared with the general SW–NE trending magnetic foliation plane, defined by AMS, it is most likely that the remanence directions are controlled by these structures. However, due to similarity in the directions of the rock fabric, magnetic fabric and remanence, coupled with the extremely high P' values in some of the samples from Satulinmäki, it is implied that in addition to the anisotropy effects, another major cause of the observed remanence directions is either the deformation that has rotated the already blocked remanence directions, or the simultaneous acquisition of remanence during the strong shearing event. This will be discussed later.

In the Koijärvi outcrops, no coherent single remanence direction could be defined. As no NW-pointing Svecofennian remanence has been preserved at Koijärvi, the dispersion of remanence vectors in this location is also most likely due to the NNE–SSW shearing along with deflection due to anisotropy effects. Naturally, the overall weak magnetization is also one reason for the scatter in directions. The P' values from sites FS, FA, and FC are comparatively high, generally well above 1.10. Both the AMS and remanence directions show good grouping in a single locality, but are more scattered between different localities, demonstrating that the remanences in the Koijärvi outcrops are affected by shearing.

In the borehole cores of Koijärvi, where the P' values range from 0.009 (0.9%) to as high as 1.202

(20%) (see Table 1), the angle between the N–S trending AMS direction and the NW ambient field direction is ca. 5–10°. Therefore, if the conclusion of Raposo et al. (2003) is valid (see above), the degree of anisotropy (P') of even more than 10% will not significantly affect the remanence direction. Furthermore, as was shown by rock magnetic studies and thermal demagnetization, the remanence and AMS probably reside in different minerals. In the Koijärvi borehole cores, the remanence was shown to reside in both pyrrhotite and magnetite, although more often in pyrrhotite, whereas AMS is dominated by magnetite. Therefore, the remanence carried by pyrrhotite may have a different direction from AMS carried by magnetite, and the two minerals and their NRM/AMS directions may be unrelated. Consequently, despite high P' values in some samples, it is possible that the remanence in the borehole cores correctly represents the ambient direction of the magnetic field in the Svecofennian age.

Site FB at Koijärvi is located at a distance of about 100 m from the sheared outcrops and from the borehole cores. At this site the degree of AMS is the lowest. Accordingly, AMS has not affected the remanent magnetization. The magnetic mineralogy and AMS behaviours correspond to those of the borehole cores, and the remanent magnetization reflects the ambient geomagnetic field during the Svecofennian time.

In general, regarding all studied areas, there is a clear correlation between the direction of remanence and degree of AMS. In those samples where the degree of anisotropy is very high, the remanence directions are deflected, whereas in those samples where the degree of anisotropy is low, the expected remanence direction has been preserved and reflects the ambient direction of the geomagnetic field.

Timing of remanence versus shearing

According to Saalmann (2007), at Satulinmäki the hydrothermal events responsible for the orogenic gold mineralizations took place in several stages. The gold mineralization has a clear structural control and it is regarded to post-date the peak metamorphism, being related to late-tectonic events of the Svecofennian orogeny (Saalmann et al. 2009). New U-Pb zircon and titanite ages and ^{39}Ar-^{40}Ar amphibole and biotite cooling ages of the gold-bearing quartz vein and shear zone range between 1.84 and 1.74 Ga, and the age of gold mineralization is estimated at 1.82–1.79 Ga (Saalmann et al. 2008, 2009). Although there have most likely been several generations of pyrrhotite formation in different tectonic stages, it is assumed that pyrrhotite was formed simultaneously with gold. Accordingly, the remanent magnetization residing in pyrrhotite should have been acquired during cooling of the last hydrothermal event in the area at ca. 1.82–1.79 Ga, during the sulphide and gold remobilization. The remanence in pyrrhotite represents the last remanent magnetization event in the rocks and indicates that since its blocking, the temperature has not exceeded 320 °C, the Curie temperature of pyrrhotite. Consequently, if the remanence was originally blocked in the hydrothermal event at ca. 1.82–1.79 Ga, the expected remanence direction would be directed to the NW, which is the remanence direction formerly known from isotopically dated undeformed late-Svecofennian age rocks (e.g. Buchan et al. 2000, Pesonen et al. 2003). As the measured remanence direction differs distinctly from this direction, it is implied that the remanence was rotated due to the deformation that is responsible for the overall shear and fault structures. In addition, as shown before, the deflection of remanence due to anisotropy effects is one controlling factor. If only tectonic rotation is considered, the remanence to its present SW direction should have taken place along with the hydrothermal event or before that, at temperatures below 320 °C. As it is unlikely that significant deformation has taken place at such low temperatures, it is implied that the remanence was deflected and rotated when the transition from ductile to brittle deformation was ongoing, while the temperature was still above 325 ºC. This deformation occurred concurrently with the emplacement of hydrothermal fluids. According to Saalmann (pers. comm. 2008), it is indeed probable that the tectonic and hydrothermal events were quite simultaneous. Based on ^{39}Ar-^{40}Ar datings of amphibole (Ar closure temperature ca. 550–500 ºC) and biotite (Ar closure temperature ca. 300 ºC) at 1807.7 Ma and 1791.4 Ma, respectively, it is possible that the remanence was blocked during that time, with the final blocking of remanence (in pyrrhotite with a Curie temperature of ca. 325 ºC) taking place near to the biotite closure temperature at about 1.79 Ga.

As one geological scenario, Saalmann (2007) suggested that the fluid flow responsible for the formation of sulphides and gold could *post-date* shearing, at least in some places at Satulinmäki (see also Kärkkäinen et al. 2006), so that the pre-existing shear zones would have acted as pathways for fluids. This assumption does not fit so well with the present study, because in such a case it is expected that the remanence would point to the Svecofennian NW direction instead of the SW direction observed in this study. The present study is in agreement with the later interpretation of Saalmann et al. (2009) of the prolonged deformation of shear zones and fluid flow. However, as discussed earlier, the anisotropy effects may form a significant contribution to the deflection of remanence from the ambient geomagnetic field direction, and hence there is the possibility that the hydrothermal fluids were indeed emplaced into pre-existing structures, which preferably controlled the remanence direction. Nonetheless, as already stated, based on the extremely high degree of anisotropy of AMS and the similarity in the remanence direction of AMS and structural fabrics, it is assumed that simultaneous post-fluid deformation plays a significant role, and the observed remanence direction principally originates from the deformation.

The Koijärvi outcrops FS, FA and FC show only very scattered remanence directions. This is probably partly due to weak intensities and the magnetic properties of the minerals, which do not favour the preservation of ancient remanent magnetizations, and partly due to later deformation and the anisotropy factor. Consequently, the palaeomagnetic results from the Koijärvi outcrops FS, FA and FC are not suitable for any palaeomagnetic dating purposes. The better-preserved site FB at a distance from the shear zone proper shows a typical Svecofennian remanence direction that has been preserved following later tectonic events. Palaeomagnetic poles from the high coercivity remanence component (pole FB_H) and intermediate coercivity component (pole FB_I) are plotted in Figure 21, showing that pole FB_H is close to the known Svecofennian 1.88 Ga and 1.84 Ga key poles (Buchan et al. 2000), thus confirming its preservation from major tectonic events.

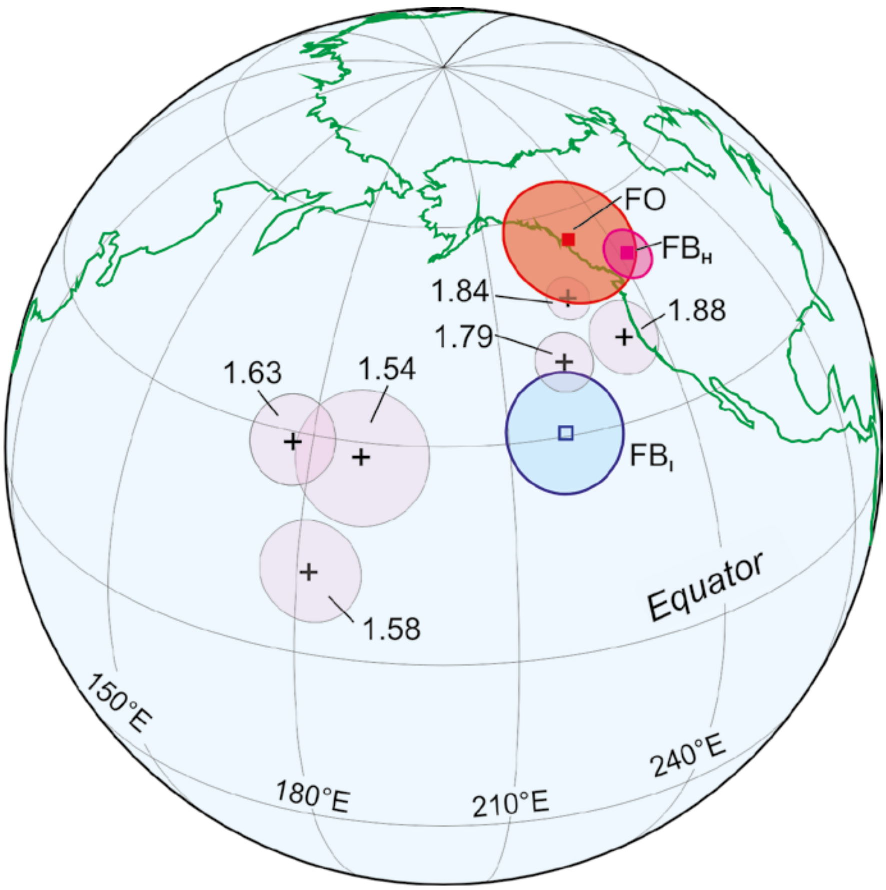

Figure 21). Mean virtual geomagnetic poles (VGP's) for components isolated from the borehole cores FO and from site FB at Koijärvi. Pole FB_H (FB_I) denotes the poles of high (intermediate) coercivity components. The A95 confidence circles are shown around the mean poles. Closed (open) symbols denote normal (reversed) polarity. The crosses with shaded A95 circles denote the 'key poles', the ages of which are indicated (see Buchan et al. 2000, Pesonen et al. 2003, Mertanen & Pesonen 2005). The close match of poles FO and FB_H with the 1.84 Ga key pole implies that the remanences were acquired in the late stages of the Svecofennian orogeny. The age of pole FB_I is undetermined.

Pole FB_I is close to the 1.79 Ga pole, which may be related to a later hydrothermal event of that age. However, as this result only comes from one outcrop, its origin is not discussed any further. The main result from the outcrops is that the most striking tectonic effect of the Koijärvi shear zone is limited to the severely sheared rocks. The AMS results nevertheless demonstrate that the FB site has the same general magnetic foliation trend as the other Koijärvi outcrops, which is evidence that the shearing has also influenced site FB. The influence is weak, shown as a low degree of anisotropy, but still undoubtedly detectable.

Palaeomagnetic results from the borehole cores FO29–FO32 of Koijärvi differ from the results of the outcrops of the shear zone. These samples carry only the typical Svecofennian remanence direction (in addition to some viscous magnetizations). As the Svecofennian remanence has been preserved in pyrrhotite, the temperature has not exceeded 320 °C since the remanence was acquired. Likewise, because the remanence has a typical Svecofennian direction, the rocks were not involved in later tectonic events. Figure 21 presents the pole FO from the borehole cores (see Table 2), and is close to the Svecofennian 1.84 Ma key pole, which defines its approximate age. There is therefore a possibility that the rocks have retained their original Svecofennian remanence either due to their deeper location (stable palaeomagnetic results were obtained from borehole cores between 10–69 m), or there may have been some well-preserved regions within the zones that were unaffected by shearing. It is also possible that in the upper outcrops the fluid flow and shearing event took place place later than in the deeper parts, where the primary remanence has been preserved. Alternatively, it is possible that the deeper parts have experienced later fracturing and the fluids were able to move and precipitate freely without shear stress. This is supported by the AMS results, which show that the degree of anisotropy of the borehole cores generally decreases as a function of depth. This possibly indicates that shearing and hydrothermal activity has been stronger at rather shallow depths, but has been minor in deeper parts.

CONCLUSIONS

1. The magnetic mineralogy of the Satulinmäki and Koijärvi shear and fault zones is dominated by monoclinic magnetic pyrrhotite, which is the carrier of remanent magnetization and is also mainly responsible for the anisotropy of magnetic susceptibility (AMS). At Koijärvi, the other magnetic mineral is magnetite. In many samples, magnetite has multi-domain (MD) grain sizes that do not carry remanent magnetization but do contribute to the AMS. Magnetite most likely represents the primary magnetic mineral of the rocks. Pyrrhotite is implied to be related to the late hydrothermal events and to have precipitated simultaneously with gold.
2. The degree of AMS is strong in all formations, and the AMS foliation plane follows the overall trend of tectonic structures. In some of the samples from Satulinmäki the AMS is extremely high and may reflect excess tectonic stress and/or fluid activity compared to other sites. In general, the magnetic anisotropy (P' value) is lowest in the borehole cores of Koijärvi, although the most clearly foliated rocks of the cores also show higher P' values. The P' values decrease as a function of depth.
3. At Satulinmäki, the remanence directions are typically scattered, but the comparatively coherent mean remanence direction is aligned within the NE–SW trending magnetic foliation plane, defined by AMS, which coincides with the fault and shear structures. Based on alignment of the remanence direction along the magnetic and structural fabrics, it is interpreted that the primary NW-pointing Svecofennian remanence was deflected and rotated in the tectonic events that took place simultaneously with the acquisition of remanence. Although pyrrhotite has a strong intrinsic magnetocrystalline anisotropy that may align the remanence in the direction of the pre-existing fault structure, it is implied that the main reason for the deviation of remanence from the ambient field direction is shearing and faulting that took place during the hydrothermal event in the very late stages of the Svecofennian orogeny.
4. The heavily sheared outcrops of the Koijärvi shear zone do not carry a stable remanence. However, the fresh-looking outcrop outside the most heavily sheared area in Koijärvi has retained its primary ca. 1.84 Ga Svecofennian remanence direction. This site also shows the lowest degree of AMS. The AMS direction is in agreement with those from the shear zone.

5. In the borehole cores of Koijärvi, the degree of anisotropy of AMS is relatively low and the rocks have retained their primary NW-pointing Svecofennian remanence direction. The preservation of primary remanence is either due to the location in deeper parts (stable palaeomagnetic results were obtained from borehole cores between 10–69 m) or to the survival of some well-preserved regions within the zones that have been unaffected by shearing. Alternatively, it is also possible that the deeper parts have experienced later fracturing and fluid flow.
6. The present study has demonstrated that a combination of palaeomagnetic and AMS studies on heavily deformed structures is usable, and can provide new information on the timing of the gold-forming hydrothermal processes relative to the structural processes.

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Gold in Southern Finland: Results of GTK studies 1998–2011
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GEOPHYSICAL STRUCTURES WITH GOLD POTENTIAL IN SOUTHERN FINLAND

by
Meri-Liisa Airo and Hanna Leväniemi

Airo, M.-L. & Leväniemi, H. 2012. Geophysical structures with gold potential in southern Finland. *Geological Survey of Finland, Special Paper 52*, 227–244, 5 figures.

Analysis of the geophysical provinces and structure of the western part of the Pirkanmaa belt in southern Finland reveals a complex fault and shear zone pattern with multiply reactivated weakness zones. The known gold occurrences are commonly located along the boundaries of the geophysical provinces, indicated by magnetic or gravity gradients. Lineament analysis to examine the association of known Au deposits with controlling lineament systems was based on processed aeromagnetic data using total magnetic intensity (TMI), tilt derivatives, upward-continuation and classification. The geophysical provinces were characterised on the basis of airborne magnetic, radiometric and electromagnetic (EM) in-phase and quadrature component data. The geophysical provinces can be attributed to different lithological units and the interpretation result thus represents a 'lithogeophysical' map.

Keywords (GeoRef Thesaurus, AGI): gold ores, geophysical methods, geophysical maps, bedrock, lineaments, structural controls, Pirkanmaa Belt, Pirkanmaa, Kanta-Häme, Finland

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INTRODUCTION

The geophysical characteristics of prospective gold regions in southern Finland have been examined during several projects aiming at either structural or ore potential investigations. This article summarises the results of these earlier studies and presents some new results concerning lineament analysis performed over the Häme and Pirkanmaa belts (Fig. 1a). The definition of the geological areas is based on Nironen et al. (2002). The geophysical data sets used consist of airborne geophysical (magnetic, electromagnetic and radiometric), regional gravity and petrophysical data. The proposed lineament analysis over southern Finland is compared with regional geophysical lineament trends over the northern Fennoscandian shield. The basic principle of this study is that the geophysical properties and the characteristics of the main geological provinces in the study area differ from each other and thus the geophysical signatures attributed to Au deposits obey different controlling factors.

Recently, airborne geophysical and petrophysical data were used to describe mafic intrusions hosting gold occurrences in southern Finland, and the first Self-Organizing Map (SOM) test over Huittinen in the Häme area was included (Huuskonen 2009). Furthermore, SOM analysis of airborne geophysical, gravity and petrophysical data in the area of Vammala and its surroundings was presented by Airo (2009) and Airo & Leväniemi (2009). These studies suggest that the areas of Häme and Pirkanmaa can be divided into structural sub-provinces. The geophysical characteristics of the so-called Häme dolerite dyke set were earlier compared with other mafic/ultrabasic dyke sets representing different age groups in Finland (Airo 1999a). The linear structures related to the dyke swarm crosscut over the whole of southern Finland. The geophysical characteristics of graphite-bearing metamorphosed schists (black schists) in the Pirkanmaa belt have been examined as part of studies on black schists in Finland (Arkimaa et al. 2000, Airo & Hyvönen 2008). Black schists with various contents of electrically conductive minerals, graphite and sulphides, are the main reason for the electrically conductive strong anomalies within the migmatitic Pirkanmaa belt.

Geophysical signatures and regional- and local-scale geophysical lineaments of the bedrock in southern Finland have been the target of many urban geological research and mapping projects at GTK, starting with investigations in the area of Pori, western Finland (Pajunen et al. 2001), and in the Helsinki Region of southern Finland (Pajunen et al. 2008, Wennerström et al. 2008). New analysis methods have been developed during these projects in order to intensify and rationalize the geological observation procedure. These projects have aimed at improving knowledge of the basement structure and bedrock weakness zones by mapping the distribution of fracture zones and by describing their geological and geophysical characteristics. The procedure for structural interpretation based on GTK's airborne geophysical data was developed during these projects. It emphasizes the close correlation between aerogeophysical and geological information. Advanced, detailed studies have been carried out on the overlapping directions of fracture zone orientations in bedrock and the orientations of magnetic trends (Wennerström et al. 2008). Systematic trends in subtle, near-surface aeromagnetic signatures were found to be related to jointing structures. We verified this method in a test area in the Helsinki Region for predicting possible weakness zones where fractures and jointing tend to develop, and carried out field tests on outcrops in order to determine which magnetic or other properties control the relationship between the interpreted magnetic trend lines and jointing (Airo & Wennerström 2010).

Fractured bedrock is commonly marked by reduced magnetization. Linear, negative magnetic anomalies mark faults and shear zones. The systematic nature of parallel magnetic lineaments indicates that they are attributed to one tectonic, crust-deforming episode. These systematic trends can easily be mapped by detecting aeromagnetic data, in particular from filtered derivative data. By inspecting aeromagnetic maps it can be observed that fracturing and jointing orientations on a detailed scale largely follow regional tectonic trends.

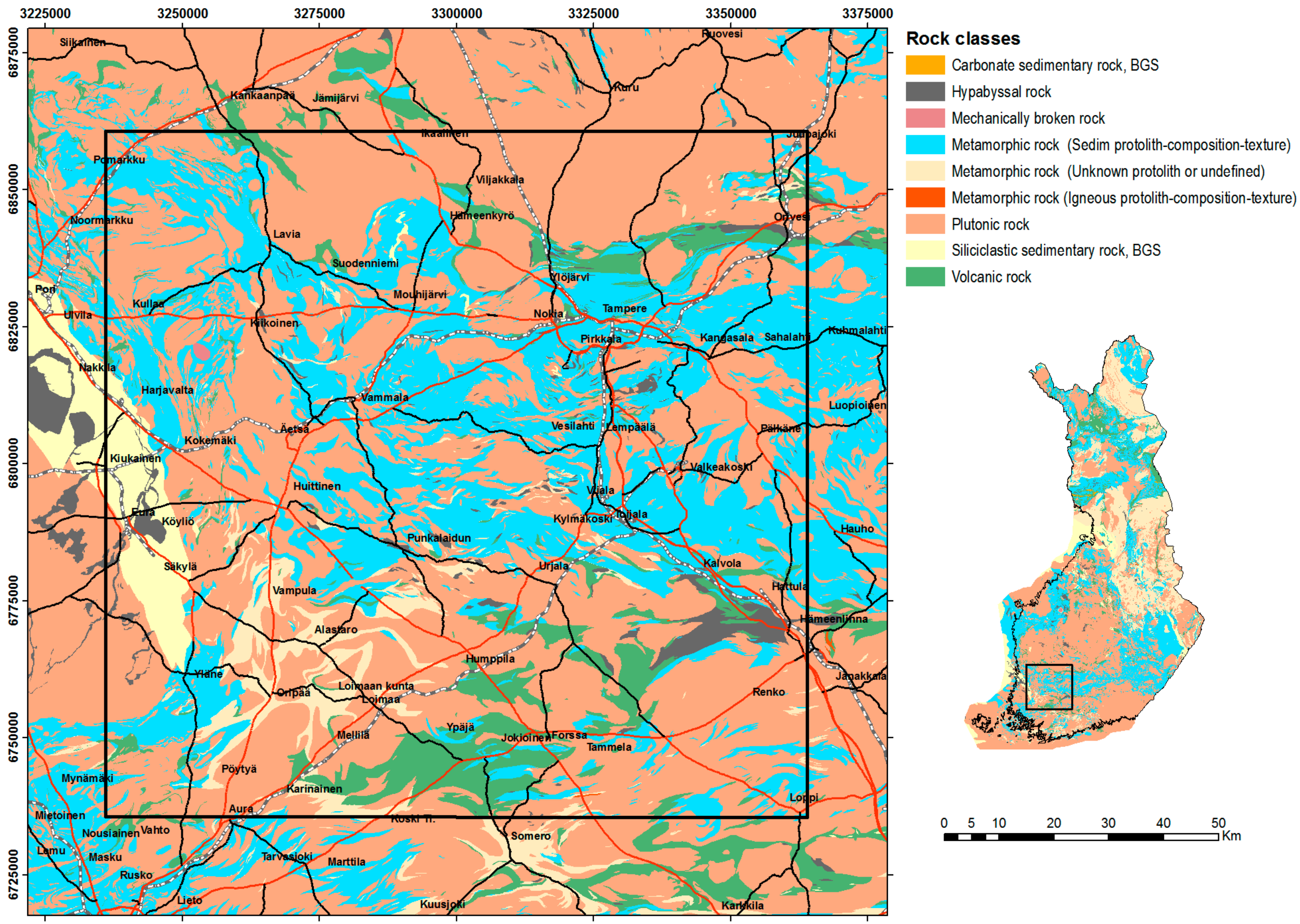
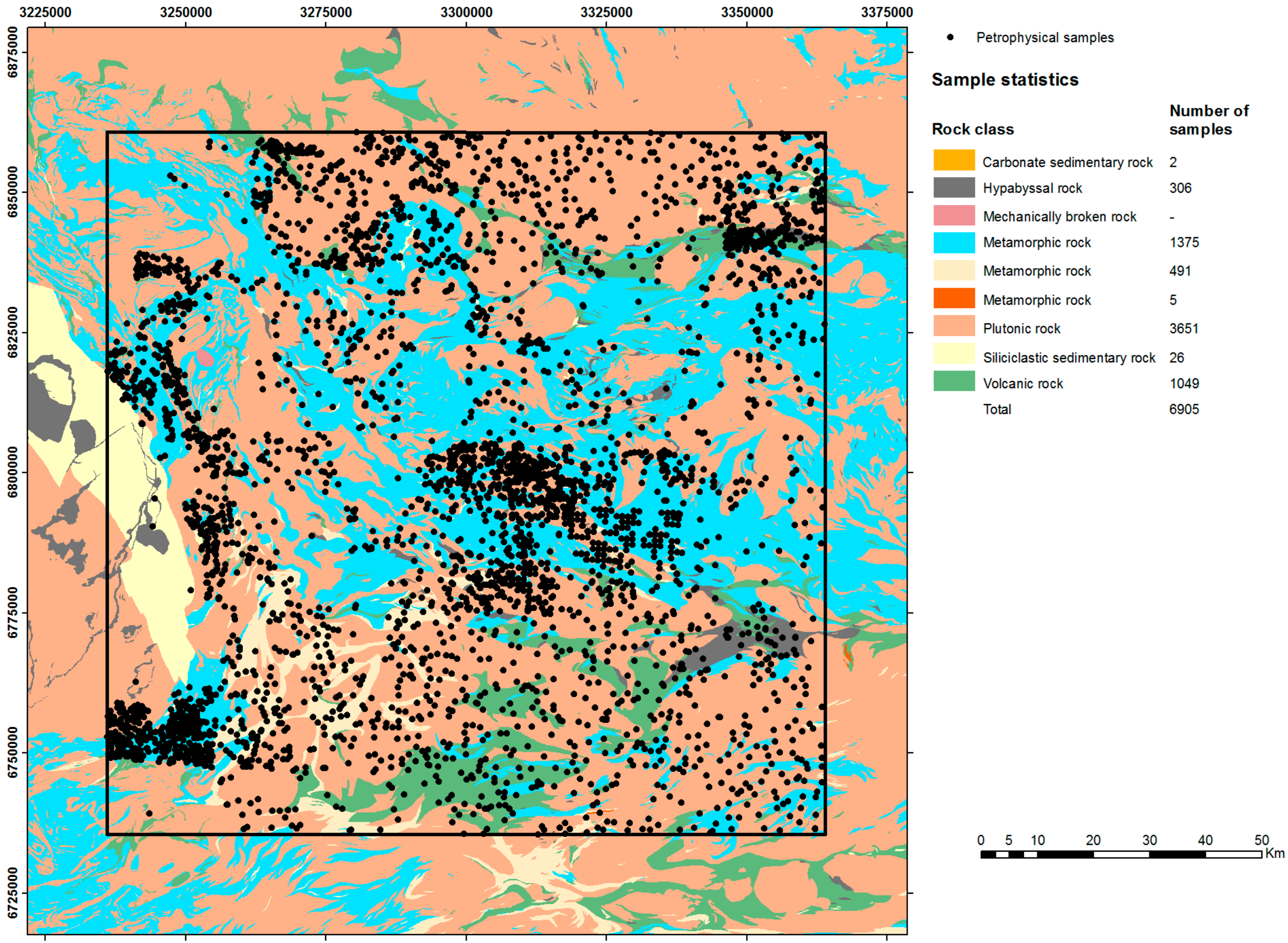
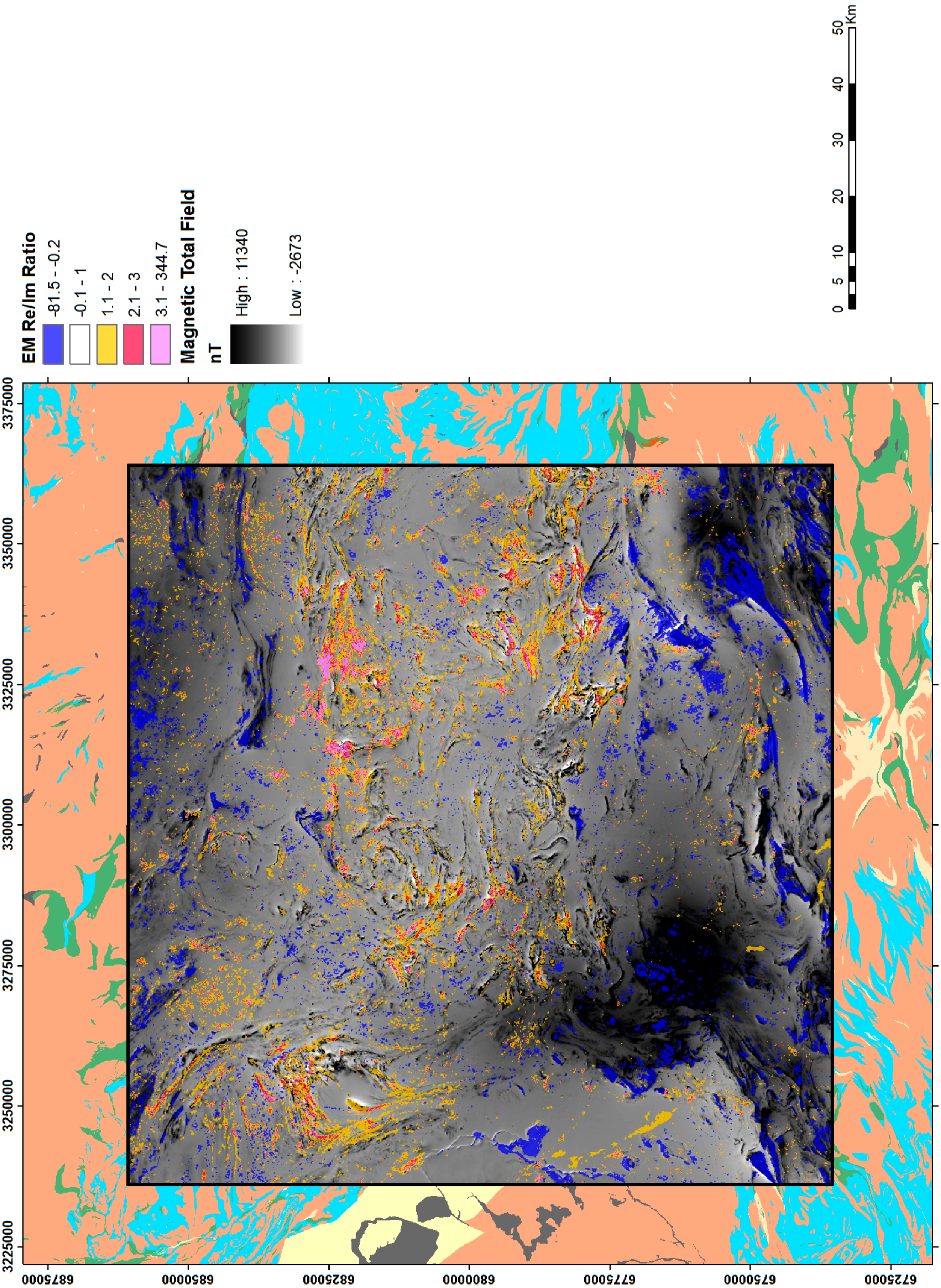


Figure 1. The study area in southern Finland and lithogeophysical maps based on the classification of airborne geophysical data.

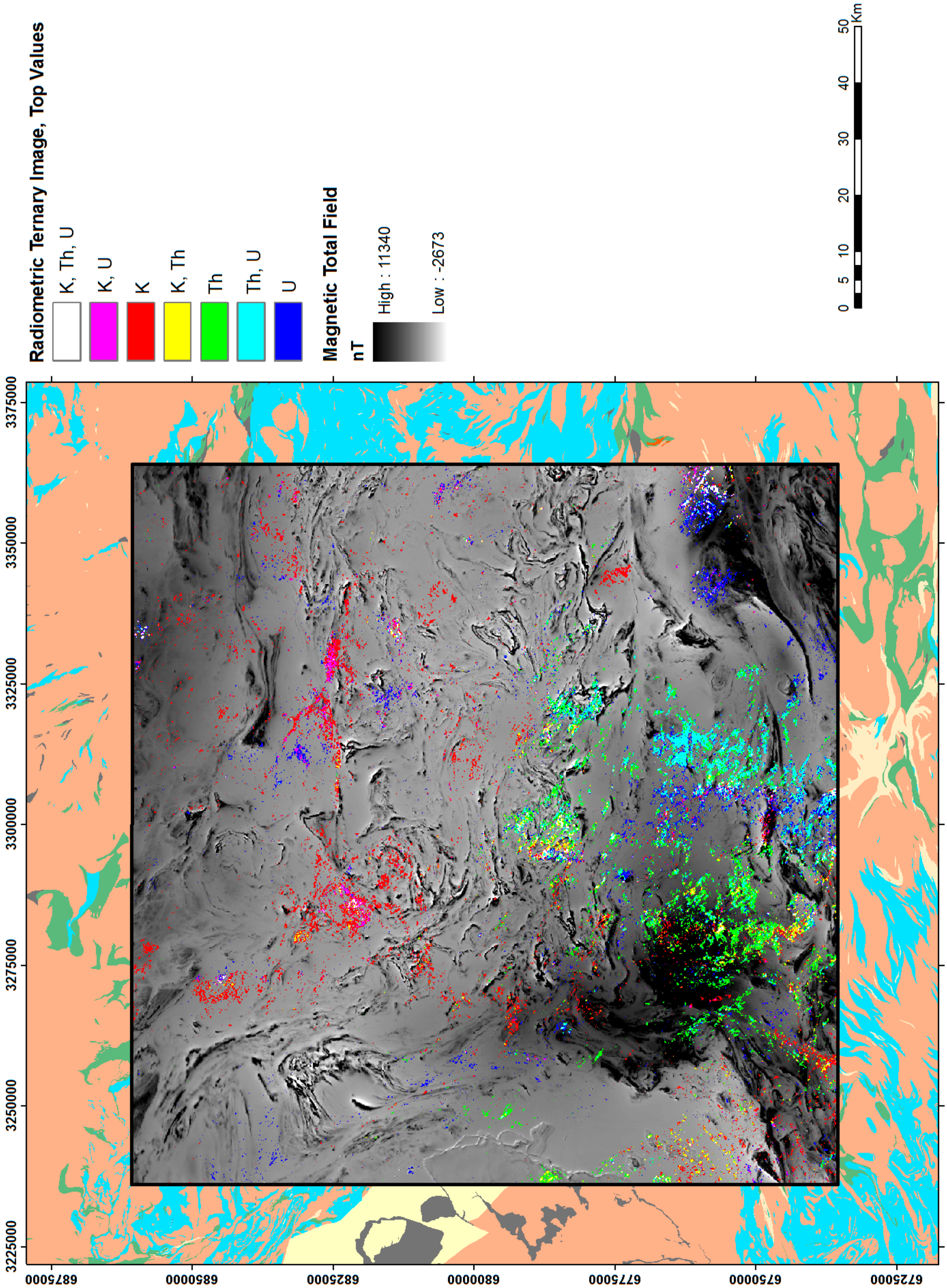
a) Rock class map. The names of rock classes are based on the Bedrock of Finland – DigiKP. Digital map database. Espoo: Geological Survey of Finland. The rock class map is used as background for the lithogeophysical maps to help in connecting geophysical anomalies with the lithology. Basemap © National Land Survey of Finland, licence no 13/MML/12 and Logica Suomi Oy.



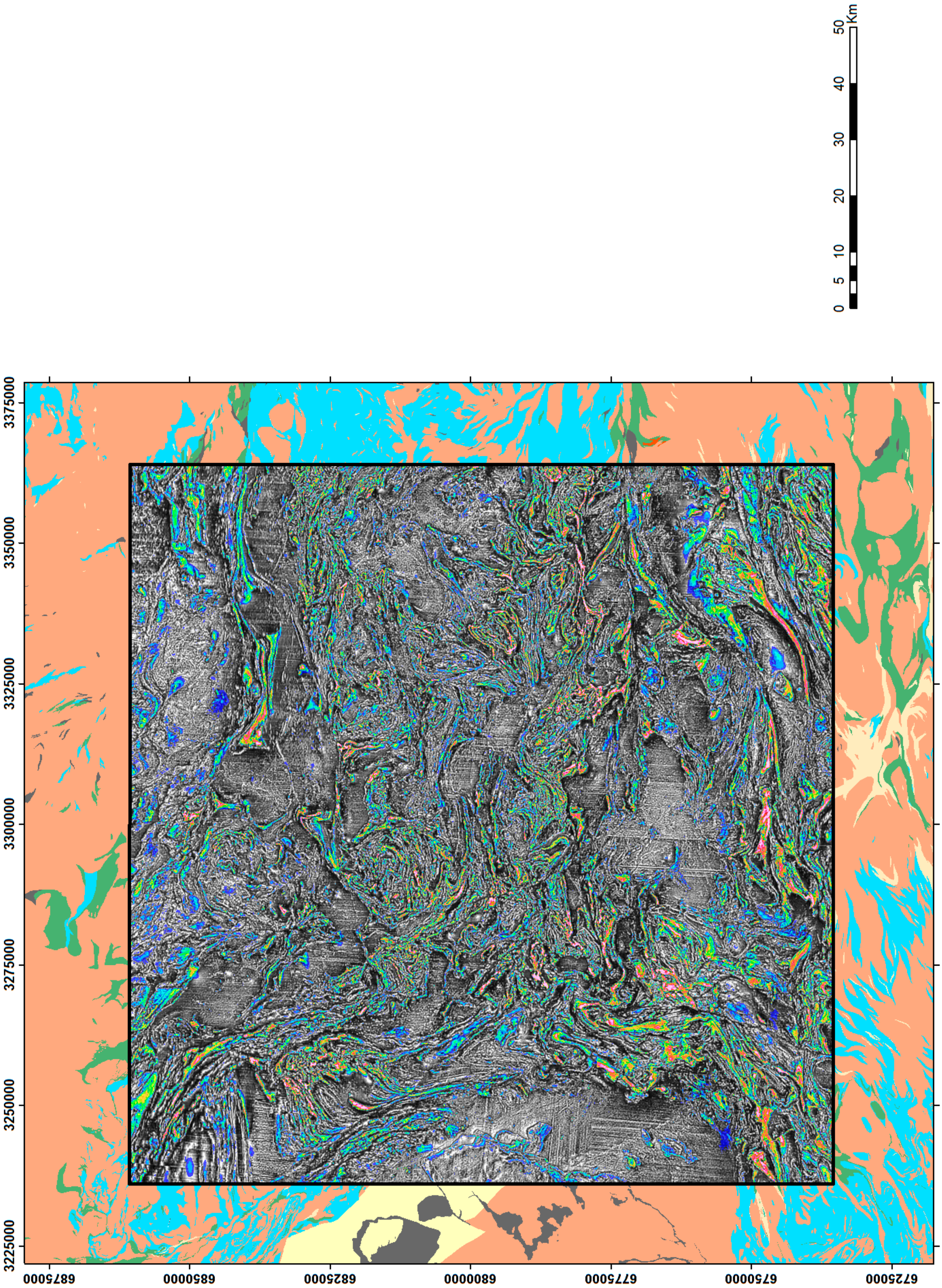
b) Petrophysical sampling sites (from the petrophysical database of GTK) superimposed on the rock class map.



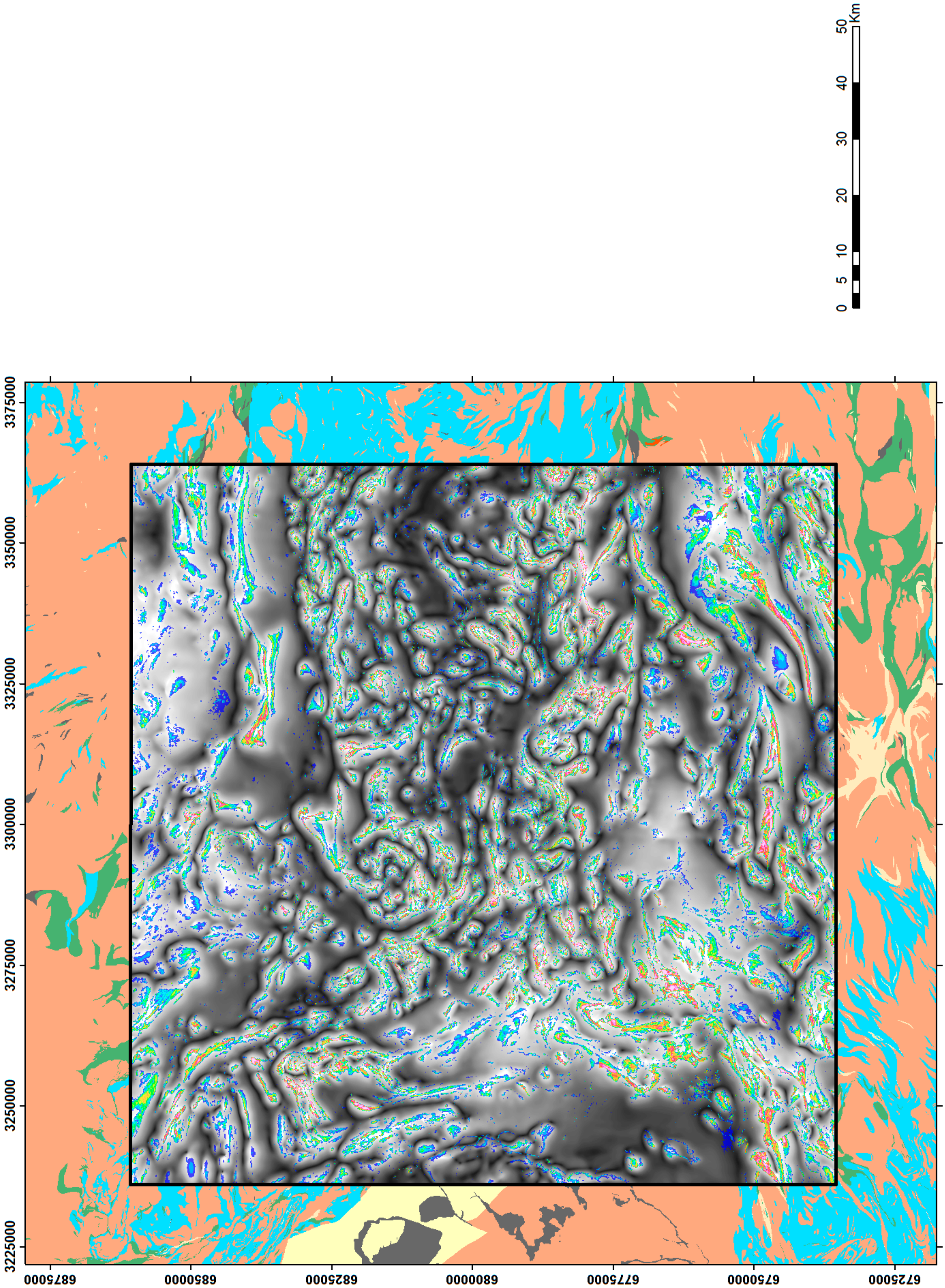
c) Electromagnetic Re/Im ratio (the ratio of the real and imaginary components) indicating the distribution of ground conductivity. Magnetite-bearing units were interpreted (shown in blue).



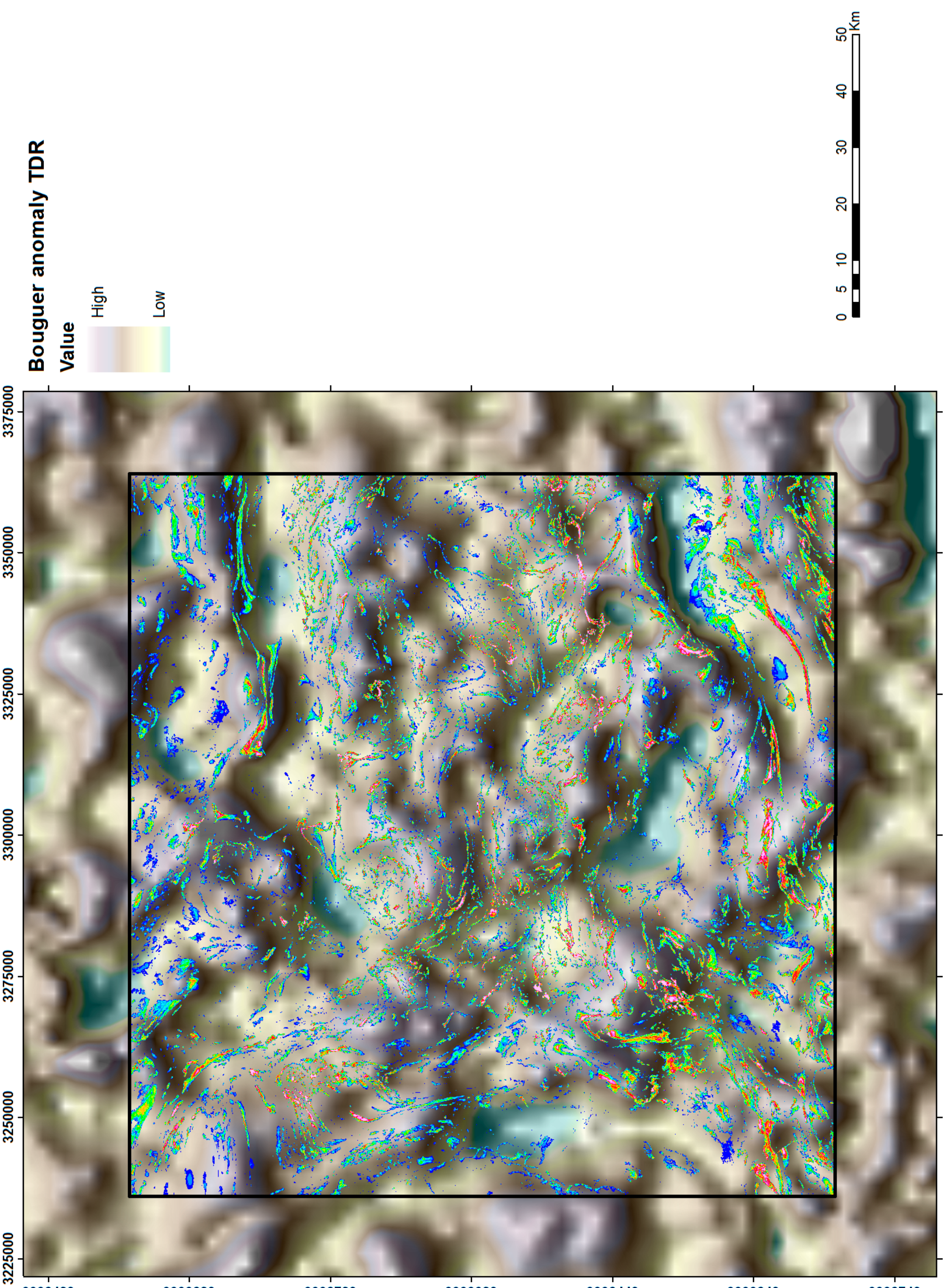
d) Top values of radiometric window data.



e) Top values of magnetic total field data (on a blue-red colour scale) and tilt derivative (in greyscale) indicating local structures.



f) Top values of magnetic total field data (on a blue-red colour scale) and tilt derivative of the upward continued field (in greyscale) indicating regional structures.



g) Top values of magnetic total field data (on a blue-red colour scale) and tilt derivative of gravity data indicating regional major structures (on a green-purple colour scale).

GEOPHYSICAL DATA ANALYSIS

Geophysical data sets

Airborne geophysics

GTK's airborne geophysical database comprises the results of a low-altitude mapping survey programme carried out during 1975–2007. The systematic three-component (magnetic, radiometric, electromagnetic) measurements cover the whole country at 200 m line spacing and a 30 m nominal terrain clearance. The extensive datasets contain magnetic total field intensity, radiometric K, U and Th window components and frequency-domain (3 kHz) EM data (Hautaniemi et al. 2005). Airborne data can be utilized in several ways in regional studies. In particular, magnetic data and the derivatives provide an insight into bedrock lineaments and structures at different scales.

Gravity

A gravity database has been compiled by GTK and the Finnish Geodetic Institute. The station spacing for the data is ca. 5 km and the data have further been interpolated to a 2-km cell-sized grid (Elo 1997). Gravity data interpretation has proven an extremely useful tool for interpreting regional structural features, such as basement block boundaries. For example, the tilt derivative of gravity data reveals strong gradients that can be interpreted to represent block boundaries from ancient tectonic episodes.

Petrophysics

Petrophysical data extracted from the national petrophysical database comprise ca. 6900 samples from the study area (Fig. 1b). The measured petrophysical parameters are density, magnetic susceptibility and the intensity of the remanent magnetization. Magnetic susceptibility is a function of ferromagnetic minerals content (magnetite and monoclinic pyrrhotite in rocks) and it affects the induced magnetization of rocks. Rocks bearing fine-grained magnetite have a high intensity of remanent magnetization. The ratio of remanent / induced magnetization (Königsberger ratio Q) can be used in estimating the abundance of magnetic carriers in rocks. For example, the ratio is typically high for rocks containing monoclinic pyrrhotite (Airo 1999b, 2005).

Lithogeophysical maps

Various airborne geophysical data sets are available as such or slightly processed via GTK's ArcGIS system. There are numerous ways of processing and representing aerogeophysical data. Sometimes, merely simple, basic classification of the data sets may help in understanding the extensive and diverse geological information they contain. We present easily-read thematic maps to aid in geological mapping and interpretation (Fig. 1). The geophysical classification of the study area is based on the geophysical characteristics of different provinces. We have classified magnetic, EM and radiometric data to describe:

- Magnetic anomaly amplitudes
- Regional and local structural magnetic signatures
- Bedrock conductivity
- Geological bodies bearing magnetite
- K, U and Th radiation (Top values)

The bedrock geology and petrophysical sampling sites are displayed in Figures 1a and 1b. Variation in the electrical conductivity of the ground is presented in Figure 1c. Enhanced electrical conductivity (in warm colours) combined with local magnetic anomalies is typical of the migmatitic Pirkanmaa belt, as can be seen in the middle of the study area. The surrounding volcanic belts are characterized by wide, intensive magnetic anomalies caused by magnetite (in blue), as indicated by EM data. The top values of radiometric data (Fig. 1d) are only locally attributed to exposed bedrock, such as the high uranium radiation (in blue) of granitoids in the southeastern corner of the map area (Tammela-Renko area – see Fig. 1a). The combination of uranium (blue) and thorium (green) radiation is largely related to the overburden and marks the clayish fields in the central southern part of the map (Loimaa, Forssa and Urjala – see Fig. 1a). A high potassium content (in red) indicates regions of infrastructure (Tampere), but also is attributed to outcropping granitoid areas in Lavia, Karkku and in the Pirkanmaa belt. The deviating mineral composition of different granitoids in the study area is reflected by their prevalent potassium or uranium radiation.

In interpreting structural controls and lineaments we processed magnetic data to separate local and regional structures (Figs. 1e and 1f). The tilt derivative practically reveals both the magnetic continuity and discontinuity and it enhances even the weak, subtle magnetic features. Upward continuation of magnetic data helps to outline the main structural features that control the more local structures. The highest magnetic intensity anomalies are enhanced and categorized by colours to observe the details within anomalous zones. The gravity gradient zones are displayed by using the TDR of gravity data (Fig. 1g). The top values of local magnetic anomalies enhance the gradient zones and the highest magnetic anomalies are located along the gradient edges.

An example and detail of lithogeophysical maps in Figure 2 compares two regions within the Pirkanmaa belt: Vammala and Pirkkala (see locations in Fig. 1a). The Vammala area includes several Ni deposits, whereas the Pirkkala area is occupied by several Au deposits about 30 km to the east of Vammala. High K (red) is related to biotite paragneiss in the Vammala area, but high U (blue) typifies the Pirkkala Au province. The difference must indicate some variation in the mineral composition of the paragneiss. Conductivity anomalies are more frequent in the Au province. The complicated, folded structure is enhanced by magnetic form lines.

The lithogeophysical characteristics of the study area can be summarized as follows:

Pirkanmaa migmatite suite
- Occasionally high U radiation; different migmatite provinces may be outlined on the basis of the variation in lacking or enhanced U radiation
- Conductivity caused by graphite and/or sulphide-bearing rock units
- K is high in the granodiorites and porphyritic granites of the Pirkanmaa intrusive suite, but magnetically they are weak

Häme and Forssa volcanic suites
- Magnetite-bearing granitoids and metavolcanic rocks
- High U and Th

Southern Finland granite suite
- U radiation and magnetic intensity (due to magnetite) are high

Volcanic rocks of the Tampere group
- Magnetite causes broad magnetic anomalies

Central Finland Granitoid Complex
- Enhanced K radiation

LINEAMENT ANALYSIS

Local lineaments

We used the magnetic tilt derivative (TDR) data to draw local lineaments in the study area. This type of processing is an ideal tool for a first-pass magnetic lineament interpretation and it enhances both the continuous folded structure (magnetic form lines) and the fractures crosscutting and disrupting them (Fig. 3). Straight lines and linear structures with magnetic reduction are generally attributed to magnetic lineaments. The parallel orientation of several lineaments refers to formation in the same tectonic or deformation event. The "Häme lineaments" in Figure 3 represent local lineaments in the area and they may represent faults or systematic fracturing. The known mineral deposits are located in structurally complex areas and there is a connection between magnetic lineaments and known mineral deposits. To understand this connection, we aimed to examine how the local trends are related to regional tectonics and inspected the Fennoscandian shield magnetic and gravity maps (trends A-B-C-D in Fig. 3 and in Fig. 4). The local lineament pattern in the study area strongly reflects the pattern of regional lineaments that can be followed across Finland, and over the entire northeastern Fennoscandian shield. The regional trends either break the basement into blocks or they control the shape and order of the magnetic anomalies within the blocks. Which of these structures control mineralisation is difficult to specify in detail.

Comparison with regional lineament trends

The larger tectonic picture for northern Fennoscandia has been described by Kukkonen & Lauri (2009) and Elming et al. (2010), among others. The most prominent geophysical crustal scale features are related to the large tectonic events. By investigating the general geophysical trends in magnetic

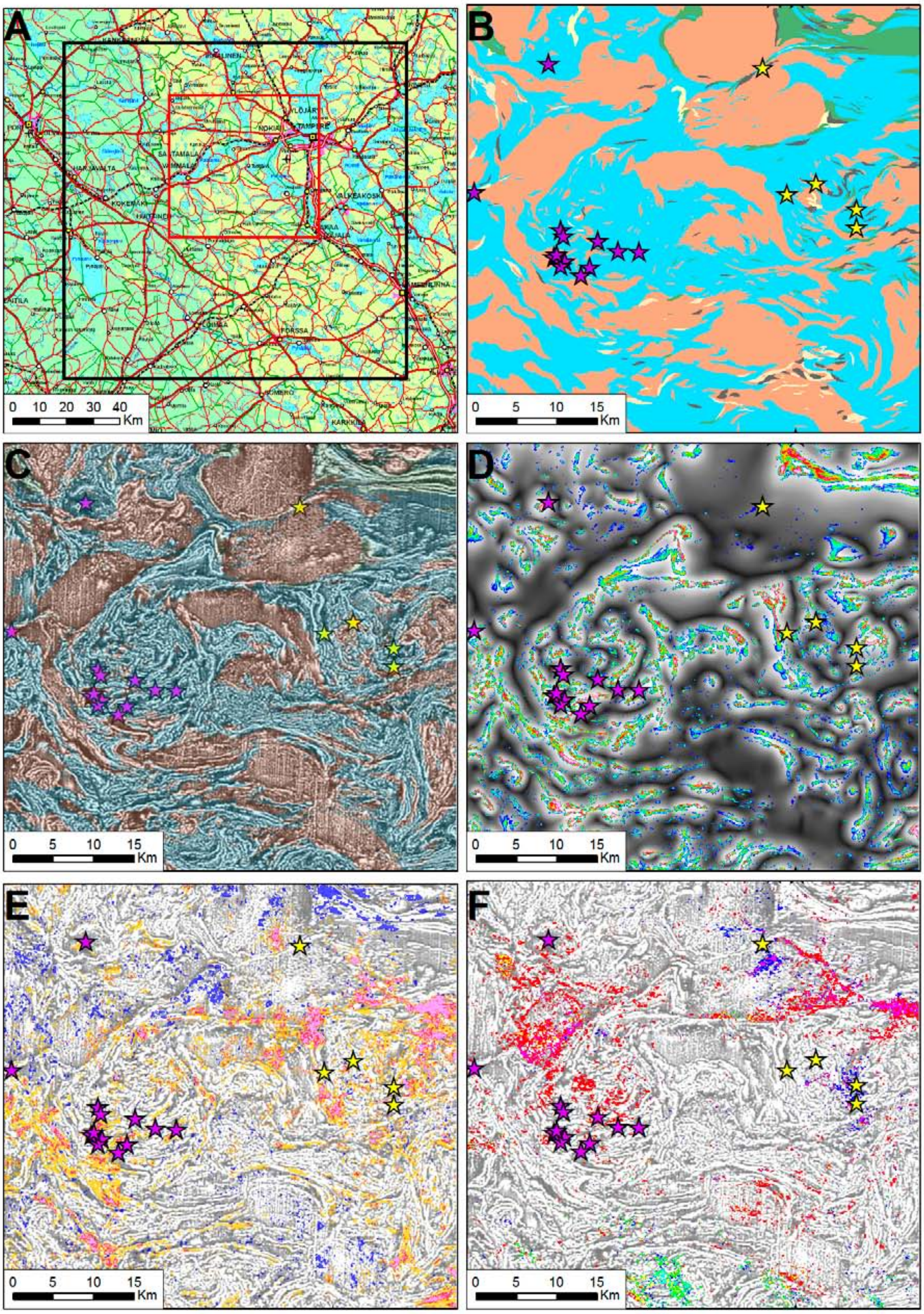


Figure 2. Detailed example of lithogeophysical maps from the Pirkkala area. Basemap © National Land Survey of Finland, licence no 13/MML/12 and Logica Suomi Oy.

a) Example area (outlined in red) in reference to the study area (outlined in black).
b) Rock classes of the example area along with the known Ni and Au deposits (in purple and yellow, respectively).
c) Rock classes (on a blue-red colour scale) superimposed on the magnetic tilt derivative indicating local structures (in greyscale).
d) Top values of magnetic total field data (on a blue-red colour scale) superimposed on the magnetic tilt derivative of the upward continued field, indicating regional structures and outlining the Ni and Au provinces (in greyscale).
e) AEM conductivity anomalies (same colour scale asin Fig. 1d.) superimposed on the magnetic tilt derivative (in greyscale).
f) Top values of radiometric window data (in colour) superimposed on the magnetic tilt derivative (in greyscale).

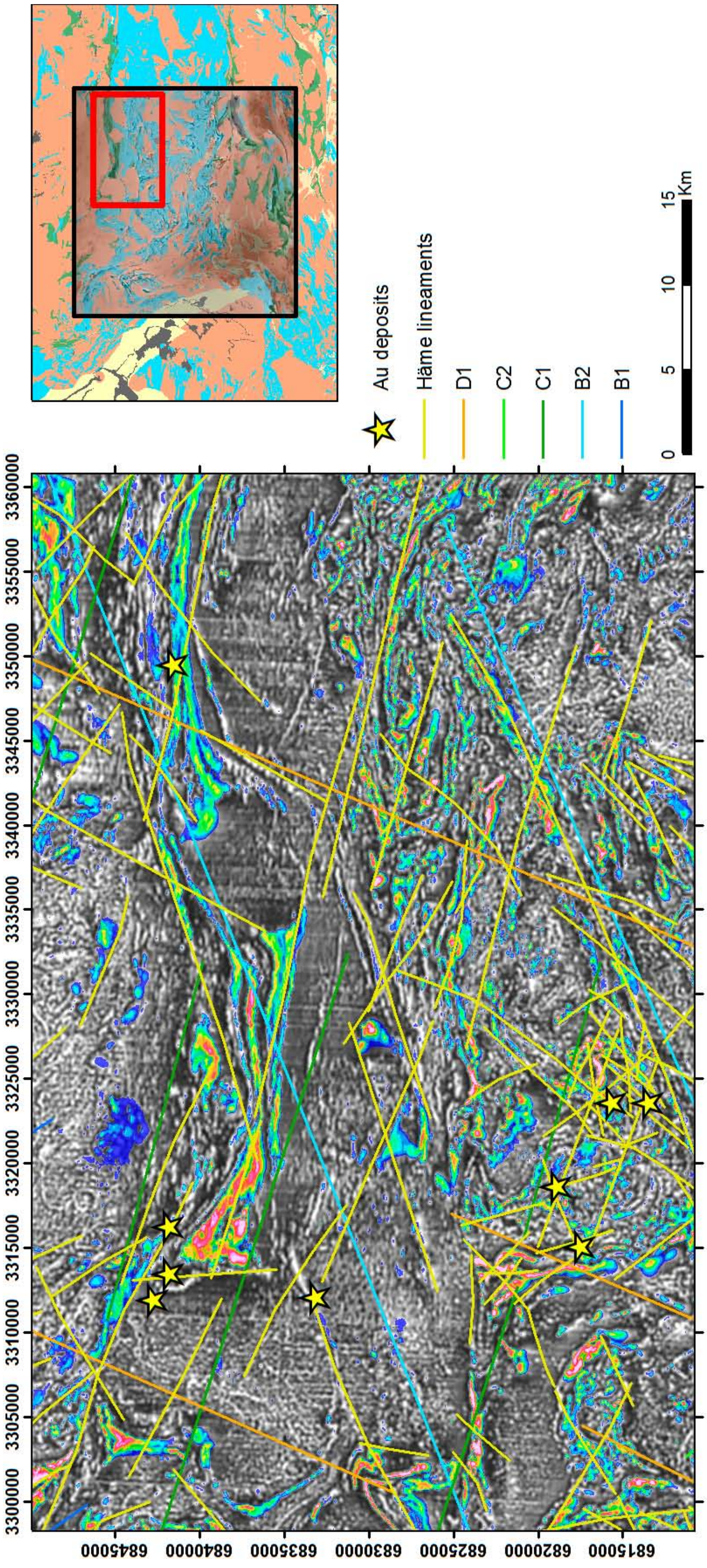


Figure 3. Detail of the lineament patterns superimposed on the magnetic field top values (on a blue-red colour scale) and magnetic tilt derivative (in greyscale). Lines A-D represent different orientations of lineament trends and are further explained in the text.

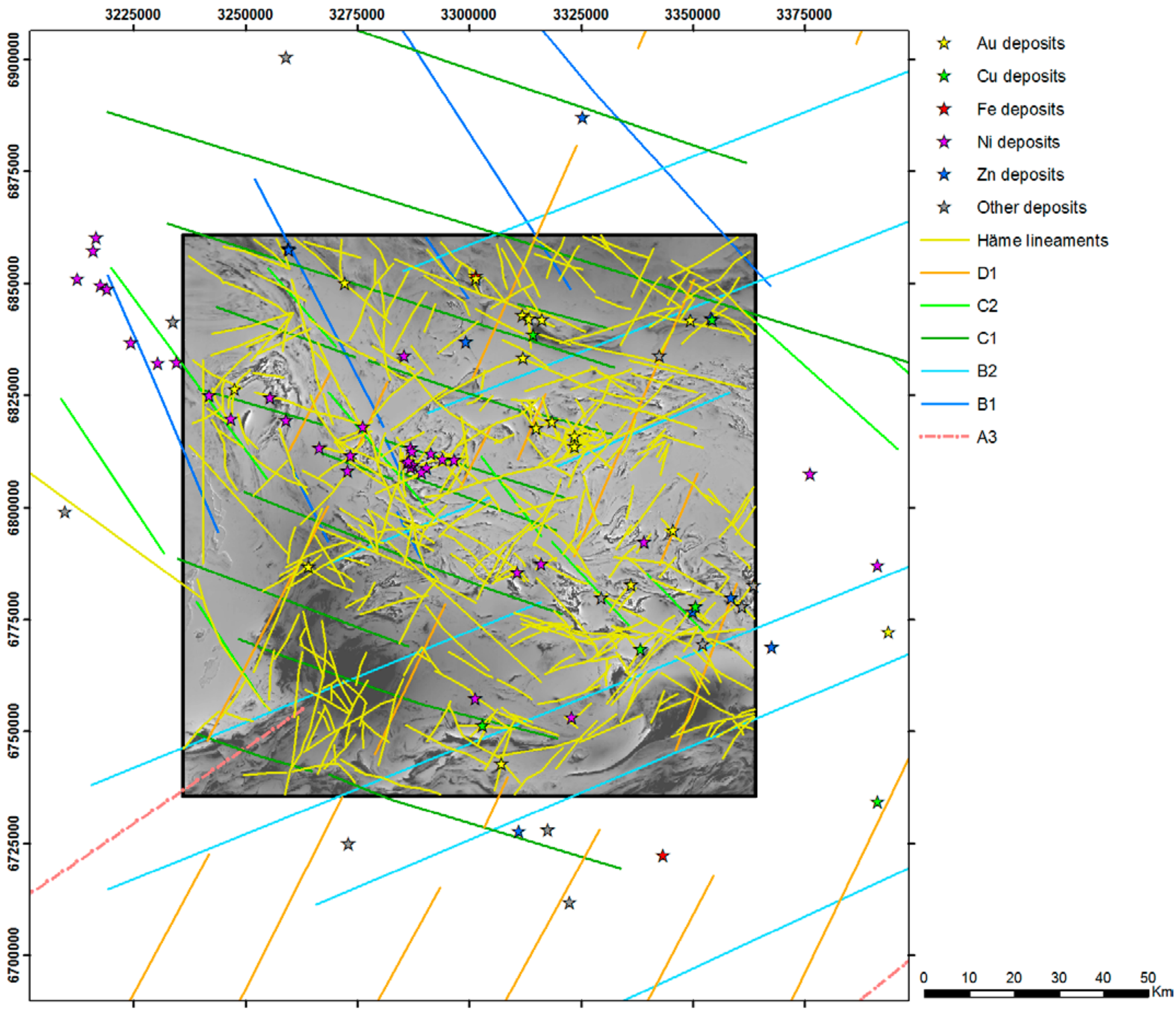


Figure 4. Lineament interpretation of the study area superimposed on the total magnetic field data. Lines A-D represent different orientations of lineament trends and are further explained in the text.

and Bouguer-anomaly data, it is evident that the orientations of local structures mirror the trends and orientations of extensive regional structures. Figure 5 outlines some regional trend directions in the Fennoscandian shield gravity and aeromagnetic data (Korhonen et al. 2002a, Korhonen et al. 2002b). These trend lines, which are connected to extensive regional gravity and magnetic minima, are tens to hundreds of kilometres long, and they control geological province boundaries. They are often indicated by several repeated parallel lineaments. Their great length also indicates their extension deep into the crust, and this is why these lineaments are almost straight lines. It is surprising that the same lineament directions can be observed over the Archaean and the Svecofennian crust. This must mean that the orientation of the early crustal weakness zones in the Archaean has been repeatedly guiding the formation of the later tectonic signature. Throughout tectonic history, the same trends are apparent several times, which means reactivation of the major earlier trends has occurred.

The main magnetic signature and the present picture of magnetic anomalies in southern Finland were formed during the Svecofennian orogeny, when the ferrimagnetic minerals magnetite and pyrrhotite crystallised and the rocks acquired their remanent magnetisation. Magnetic anomalies were created under the prevailing stress field,

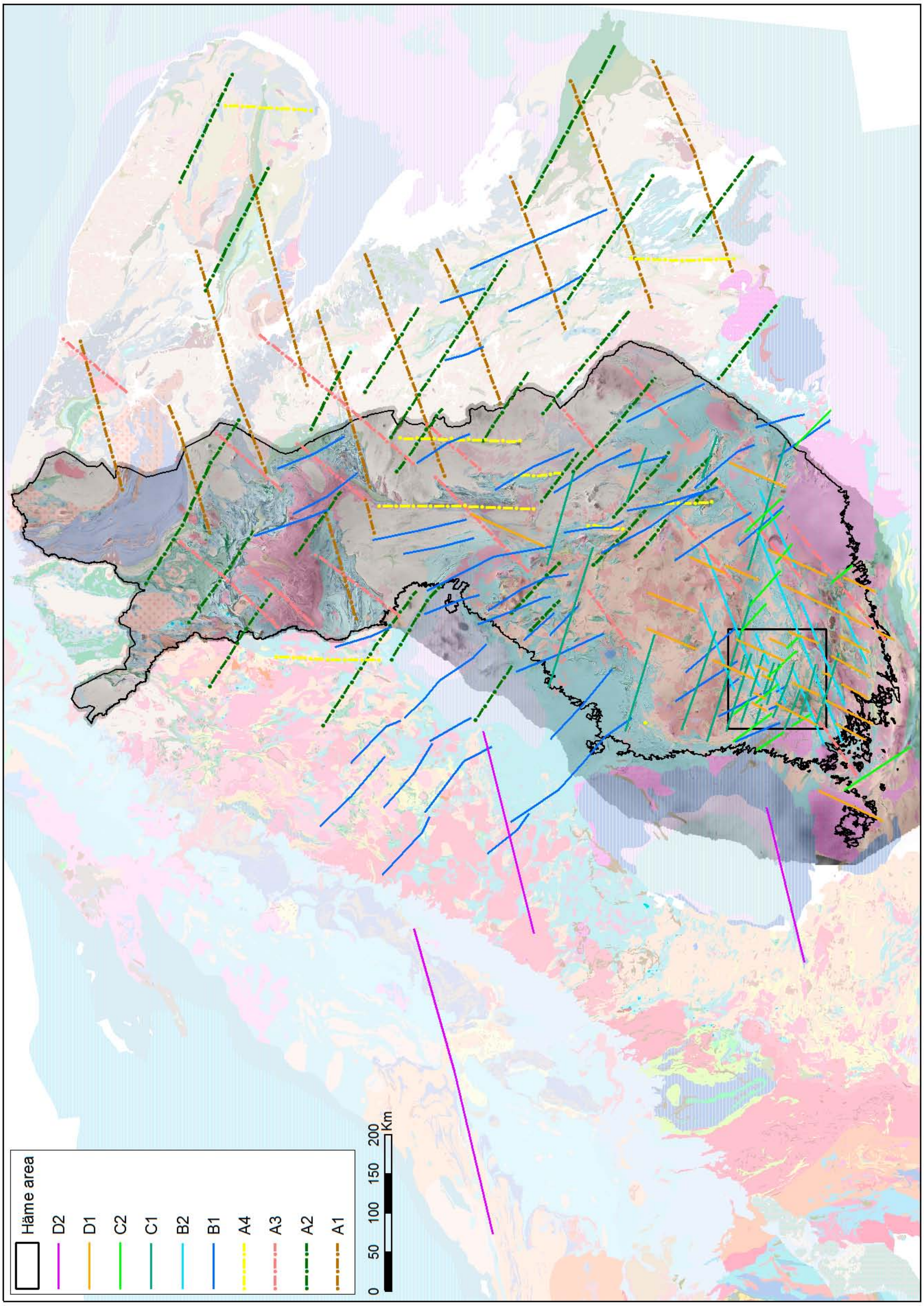


Figure 5. Interpreted regional geophysical trends that can be connected to various tectonic episodes. Lines A-D represent different orientations of lineament trends and are further explained in the text. Basemap adapted from Koistinen et al. 2001.

and thus the shape of magnetic form lines within different bedrock blocks is controlled by the block boundary framework. Since the Svecofennian orogeny, several tectonic periods have affected the crust in southern Finland, reforming the magnetic signatures. This has meant the disruption of patterns, fragmentation and magnetic intensity reduction due to tectonic deformation, chemical alteration and weathering.

The regional magnetic and gravity trends in Figure 5 are classified by their orientation into the following groups:

- A1 Same orientation as the 2.5–2.4 Ga layered intrusions in Central Finland and Russian Karelia;
- A2 Same orientation as the 2.1–1.9 Ga eastern Finland dykes; controls the structural framework of greenstone belts in Russian Karelia and Kola; controls the shape of the Muhos formation; controls the structure of the Central Lapland Greenstone Belt;
- A3 Orthogonal direction connected to A2;
- A4 N-S trend; orientation repeated in formations of different ages: the Urals, Pajala and Hirvaskoski shear zones, N–S orientation in the Pudasjärvi block; younger formations such as the Lake Päijänne fracture zone;
- B1 Mirrors the Raahe-Laatokka zone and the 1.9–1.8 Ga Svecofennian collision; found in Karelia, outlining the greenstone belts;
- B2 Orthogonal to B1; controls the northern boundary of the 1.8–1.7 Ga South Finland granites;
- C1 Outlines the 1.6 Ga Jotnian basins for Satakunta sandstone and Lake Laatokka;
- C2 Orientation of the 1.6–1.5 Ga dolerite dykes in southern Finland; controls the emplacement rapakivi granites;
- D1 This trend is observed in southern Finland; it is parallel to the structural trends of the 1.4 Ga Caledonian tectonism;
- D2 Orientation of the 1.2 Ga dykes in Sweden.

In addition to these major trends detected in regional geophysical data sets, for example an E-W direction is attributed to dykes and regional fracture zones particularly in eastern Finland and the Pudasjärvi block, as well as the Vittinki structure close to Vaasa.

The orientations typical of both the Svecofennian and the Jotnian tectonism control the geophysical signature of the Häme–Pirkanmaa study area, either as crosscutting fracture and fault zones or as directional trends related to fold axes weakness zones. The outlines of southern Finland granitoids seem to follow B2, but there is also (possibly) an earlier trend A3. The tectonic trends A1, A2 and A3 predominate in the fragmentation of the crust in eastern Finland. A4 is the north-south trend observed in the Archaean side (Karelia), but it has also been active during the formation of, for example, the Pajala shear zone in Sweden and its parallel, the Hirvaskoski shear zone in central Finland (Airo 1999a). The north-south trending fracture of Lake Päijänne is possibly younger, but its position seems to be controlled by the earlier north-south trending fragmentation of the crust when N–S trending weakness zones have been formed. An effective period for geophysical signatures in southern Finland was 1.6–1.4 Ga ago, when the crust was strongly fractured and mafic / ultrabasic dyke swarms and intrusions intruded and rapakivi plutons were emplaced. The same weakness zones were repeatedly used in the Jotnian period, when the Svecofennian crust was strongly fractured and pathways for mafic dyke intrusion were created (C1, C2). Orthogonal to C1 and C2, there is a crosscutting trend that fragments the Pirkanmaa belt in the middle (D1).

SUMMARY

Geophysical indications of Au deposits in southern Finland depend on their host rock association and the mineralisation type. Thus, the Au deposits cannot be characterised by only one or two geophysical properties. Common geophysical indicators include:

- reduced magnetisation intensity and a weakened or broken anomaly signature (in the case of magnetite loss in hydrothermally altered mafic/ultramafic host rocks),
- locally increased electrical conductivity (because of sulphide growth),
- in some cases changes in radioelement contents (due to chemical alteration)
- structural controls revealed by gradients in magnetic or gravity data.

The Au deposits in our focus area are divided into two groups by their locality: those in the province characterised by electrical conductors and

local magnetic anomalies (Pirkanmaa belt) and those in the province characterised by geophysical signatures caused by magnetite-bearing rocks (Tampere and Häme / Forssa metavolcanic belts). There seems to be some connection of enhanced uranium contents with the regions where Au deposits are located. The high U contents are attributed to granodiorites, particularly where there are indications of granitisation. The Pirkanmaa migmatitic rocks display enhanced U radiation.

The known mineral deposits are located in structurally complex areas. Known Au deposits are located along local fractures or jointing related to large-scale structural trends. They may be situated along a lineament or more precisely where a lineament cuts the fractured fold structure. Lineament analysis seems to link the Au mineralisation to regional structures that were formed after the Svecofennian and before the Jotnian. Known Ni and Cu deposits follow the inferred Jotnian trends and are located within the area of conductivity anomalies.

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LOCAL- AND REGIONAL-SCALE GEOPHYSICAL CHARACTERISTICS OF THE HAVERI MINE

by
Tapio Ruotoistenmäki

Ruotoistenmäki, T. 2012. Local- and regional-scale geophysical characteristics of the Haveri mine. *Geological Survey of Finland, Special Paper 52*, 245–254, 9 figures.

The Haveri Au-Cu deposit is located in southern Finland on the northern edge of the continental island arc-type, volcano-sedimentary Tampere Schist Belt. On the magnetic map, the Haveri area is located in the contact zone of a northern, magnetite rich granitoid block and a southern, pyrrhotite-dominated migmatite zone. Moreover, the contact zone is characterized by deep, crustal-scale northward dipping and shallower southward dipping seismic reflectors. On the local scale, the Au-Cu-bearing association can be interpreted to represent an overturned synform-antiform pair consisting of folded magnetite-rich mafic metavolcanic rocks below overlying pyrrhotite-rich, banded metavolcanic or metasedimentary rocks. It can also be concluded that magnetite to pyrrhotite alteration occurred before the layers were overturned. While gold is assumed to be connected with alteration processes in the bedrock, the targets for future gold exploration should be selected close to zones where both magnetite and pyrrhotite are present, and where more altered pyrrhotite-rich rocks dominate. The available magnetic susceptibility data from drill holes are sparse and no definite conclusions on petrophysical parameters or gold contents can be drawn.

Keywords (GeoRef Thesaurus, AGI): gold ores, copper ores, schist belts, Tampere Belt, geophysical methods, petrophysics, tectonics, Paleoproterozoic, Haveri, Finland

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INTRODUCTION

The Haveri Au-Cu deposit is located in southern Finland about 175 km north of Helsinki. It occurs on the northern edge of the continental island arc-type, volcano-sedimentary Tampere Schist Belt (TSB) within the Palaeoproterozoic Svecofennian Domain (2.0–1.75 Ga) of the Fennoscandian Shield. Locally, the Haveri gold mine area represents a rather exotic part in the seam of the southern Finland migmatite belt and the Central Finland Granite Complex (SMB and CFG), whose Pb isotope whole rock age of ca. 1990 ± 25 Ma (Vaasjoki et al. 1987) appears to be much older than those of surrounding blocks at ca 1880–1900 Ma. Ruotoistenmäki (1996) interpreted the Haveri area to represent a seamount squeezed between the SMB and CFG. This is supported by the MORB affinity volcanics in the lower sections of the Haveri Formation, while arc magmas dominate in the upper parts (Kähkönen & Nironen 1994). The Haveri Formation consists of metavolcanic pillow lavas and breccias passing upwards into intercalated metatuffs and metatuffites. The Au-Cu deposit at Haveri is chiefly hosted by mafic metavolcanic rocks that are tholeiitic in composition, and to a smaller extent by mafic to intermediate tuffs and tuffites (Strauss 2004, Eilu et al. 2004). For a more detailed geological summary of the Haveri area, see Eilu (2012, this volume).

This paper summarises the geophysical studies in the Haveri mine area based on reports by Eilu et al. (2004) and Ruotoistenmäki (2004). The geophysical maps used here have been processed from low-altitude aeromagnetic data by the Geological Survey of Finland (e.g. Hautaniemi et al. 2004) and Fugro Airborne Surveys (1996). The petrophysical data were recorded by the Northern Lion Company.

GEOPHYSICAL CHARACTERISTICS OF THE STUDY AREA

Figure 1 presents a regional-scale aeromagnetic map of the Haveri area connected with selected tectonic features. In the map, some of the major lineaments have been marked by dashed white lines. Some significant intrusions cross-cutting older structures and anomalies have been marked by ‘I’. The S-shaped anomalies in blocks B1, B2 and B3, emphasized with black and white curves, give indications of the relative motions in the area. From their curvature, the direction of faulting between blocks B1–B4 can be interpreted to be dextral (right-lateral), resulting in clockwise rotation inside blocks B1–B3.

The directions of faulting derived from Figure 1 indicate that blocks B1–B4 have all been moving southeast relative to block B0. The increasing length of the SE-pointing arrows in the blocks indicates the relative amount of displacement that must increase towards the northeast to explain the relative shifts in the faults. The large grey arrows on the N and S edges of the map indicate the main compressional regional forces to explain these fault directions. The SE-trending I bars give estimates of relative horizontal movement for each block, interpreted from the discontinuities of the anomalies to be ca 6.4–6.7 km to the SE.

The relative amplitude of the regional magnetic anomalies decreases from the granitoid block in the north to the migmatite-dominated block in the south (red → yellow → green → blue), indicating a regional dip of anomaly sources from north to south. However, in the seismic reflection profile Fire1–Fire2 in Figure 2 (Kukkonen et al. 2006) crossing the eastern part of the area in Figure 1, the dip of the deep reflectors is towards the north, although shallower, southwards-dipping structures can also be detected. Thus, there seem to have been roughly simultaneous over- and underthrusting processes in the area (‘crocodile tectonics’).

Figure 3a depicts the local-scale magnetic anomaly map of the Haveri area recorded by Fugro Airborne Surveys (1996), and Figure 3b a NE-trending 2.5D model profile interpreted across the main anomalies in the area. The dips of the model sources suggest a synform-antiform fold system across the area from SW to NE.

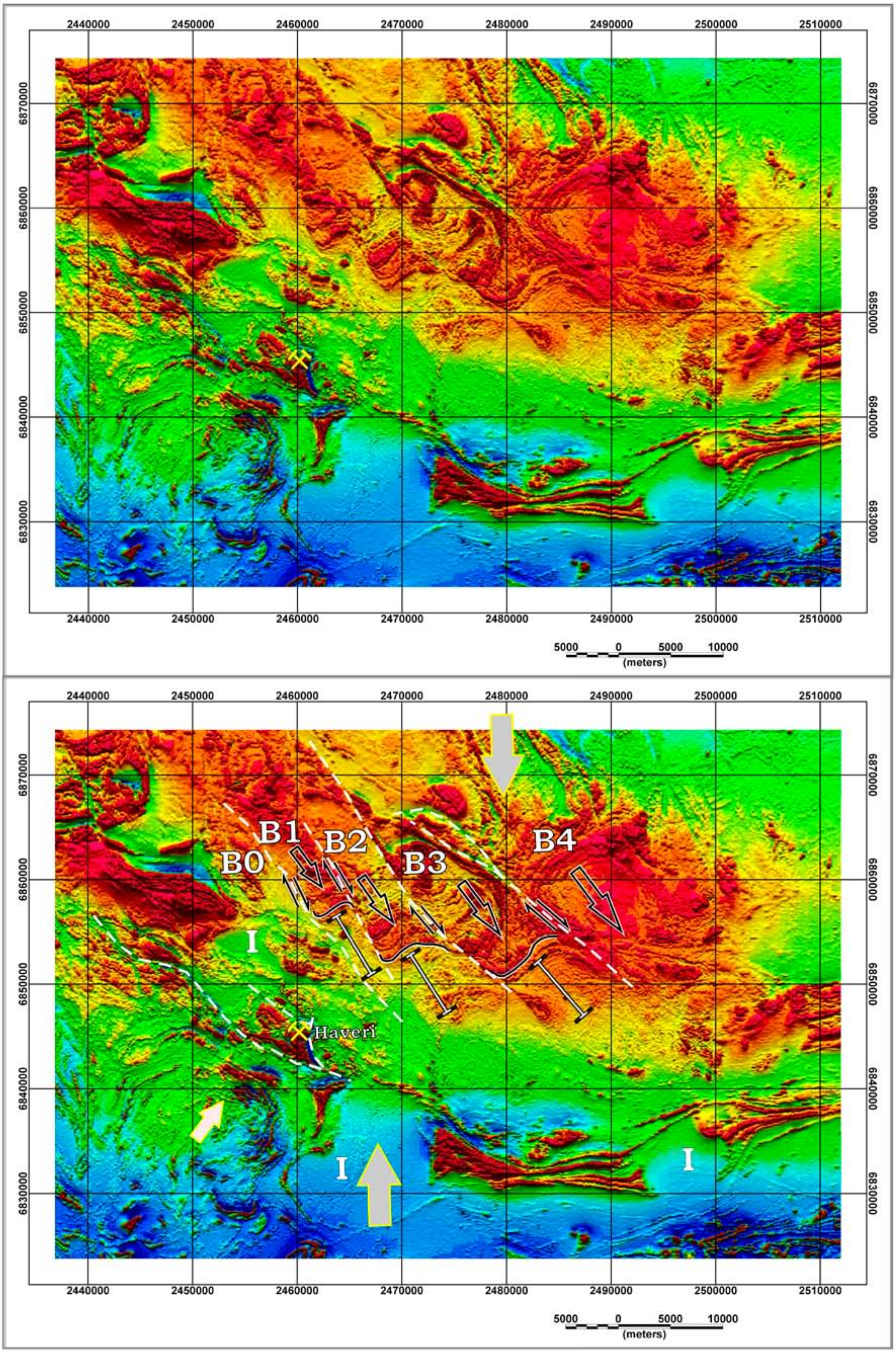


Figure 1. A regional-scale aeromagnetic map of the Haveri region. The location of the mine site is indicated by crossed hammers. Major tectonic features are indicated on the lower map version. The anomaly level decreases from red → yellow → green → blue. Symbols B0–B4 refer to fault-bounded blocks. I: Anomalies indicating cross-cutting intrusions. Grey arrows refer to interpreted major thrust directions. The data were recorded and processed by the Geological Survey of Finland (Hautaniemi et al. 2004).

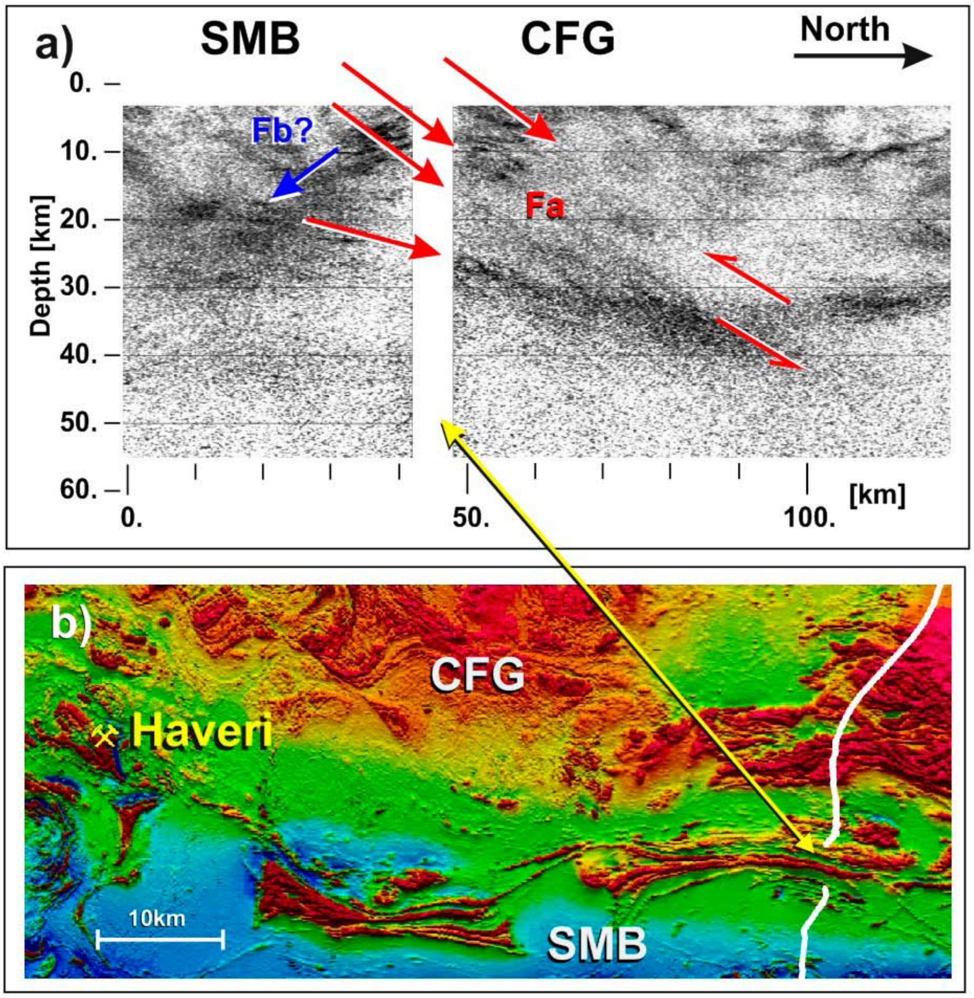


Figure 2. a) A section of the seismic reflection profile Fire1–Fire2 (Kukkonen et al. 2006). CFG: Central Finland Granitoid complex; SMB: Southern Finland Migmatite Belt. The white line in the magnetic anomaly map (b) shows the course of the profile. The yellow double arrow indicates the location of the discontinuity in the profile. Fa: Thrust faults dipping to the north. Fb: Southwards-dipping, shallower, less distinct structures shown as a regional green → blue magnetic anomaly gradient from CFG to SMB. Haveri is located in the westward continuation of the SMB-CFG 'seam' of the profile.

The characteristics of the sources for the magnetic and electromagnetic anomalies are examined in more detail in Figure 4. Using these maps, one can separate pyrrhotite-bearing electrically conductive schists (high magnetic and EM in-phase anomalies = P1 and P2 in the maps) from magnetite-bearing poorly conductive rocks (high magnetic and low EM in-phase anomalies = M1–M4 in the maps). For the principles underlying this method, see e.g. Peltoniemi (1982 and references therein). Strauss (2004) noted that in Haveri there is a general progression from early magnetite through pyrrhotite to pyrite, indicating an increasing degree of sulphidation over time. Gold is typically found as free gold within quartz veins and within zones of intense amphibolitisation. Considerable gold is also found in the cataclastite ore type, either as invisible gold within the sulphides and/or as free gold within breccia fragments.

In the schematic lithological map by Kähkönen and Nironen (1994, in Figure 5), the magnetite-rich rocks (anomalies M1, M2 and M4) can be connected with mafic metavolcanic rocks, and the overlying pyrrhotite rich rocks (anomalies P1 and P2) with banded metavolcanic or metasedimentary rocks.

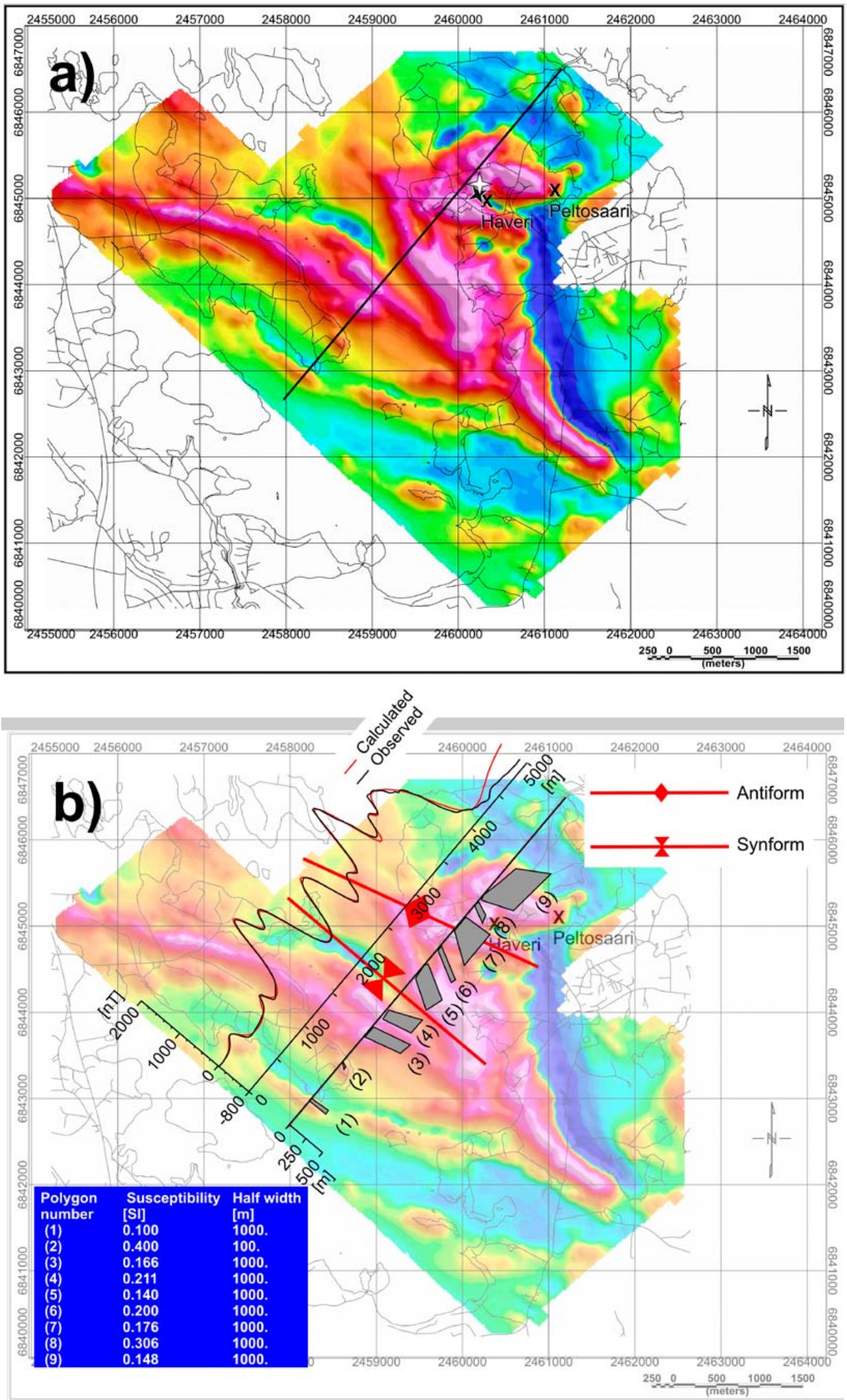


Figure 3 (a). A local-scale aeromagnetic map of the Haveri area recorded by Fugro (1996). The location of the Haveri mine and Peltosaari mineralisation are marked by crosses. The black line depicts the location of the magnetic anomaly profile interpreted in (b) using 2.5D models (grey polygons). The blue inset gives the susceptibilities and half widths of the polygons. No remanence data were available. In (a) the stars show the location of drill holes HN-03 (white star) and SZ-05 (black star) described below.

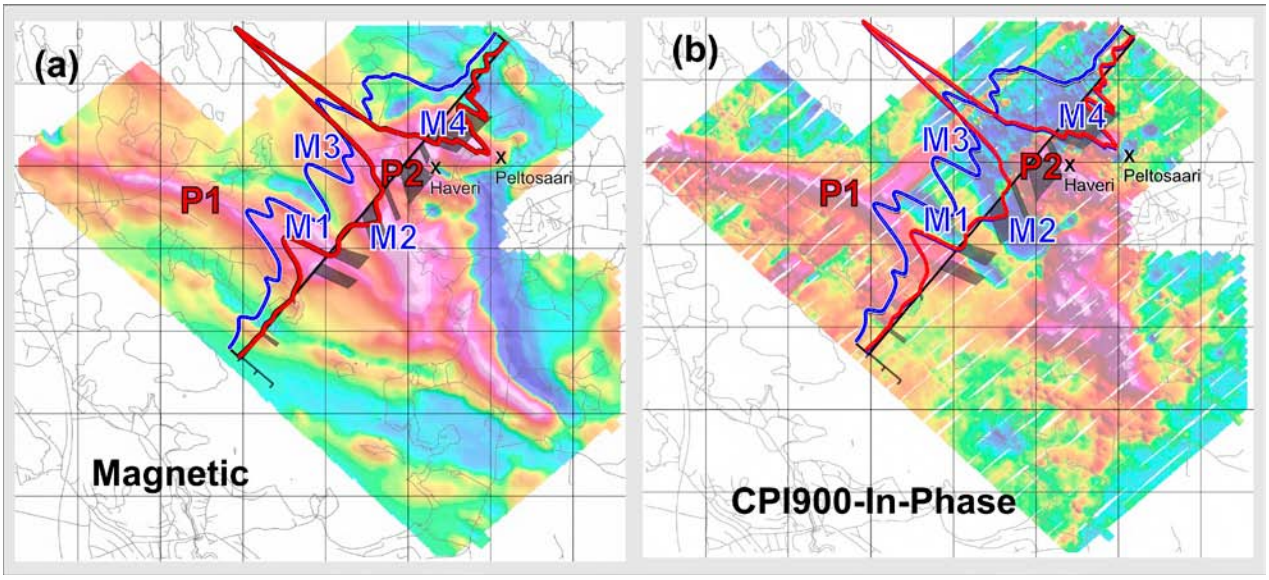


Figure 4. a) A magnetic map of the Haveri area (Fugro 1996). The blue profile is the magnetic anomaly interpolated from the map grid. The grey polygons depict the 2.5D models interpreted from the profile. The red profile gives the corresponding electromagnetic in-phase anomaly. b) The corresponding electromagnetic in-phase map (Fugro 1996).

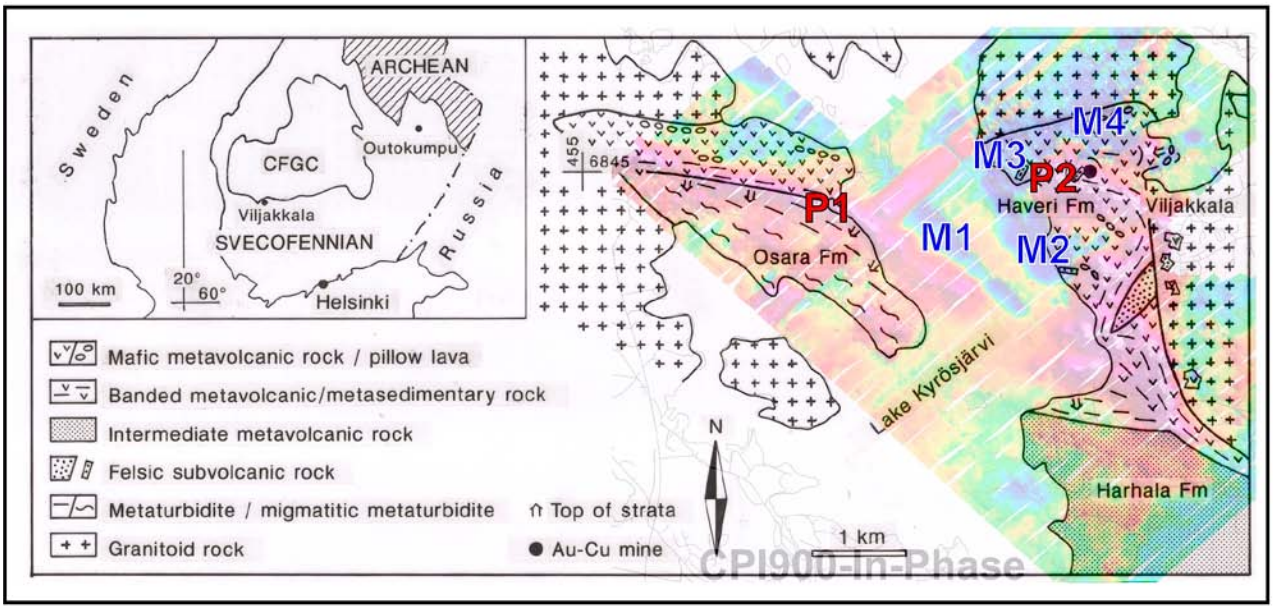


Figure 5. Schematic lithology by Kähkönen and Nironen (1994) connected with the in-phase electromagnetic CPI900 anomaly (Fugro 1996).

Figure 6 illustrates two possible fold structures fitted to the magnetic model interpretation given in Figures 3–4 connected with a stratigraphic top interpretation adopted from Kähkönen and Nironen (1994; Fig. 5). They interpreted the direction of younging of the stratigraphy in the SW flank of the 'synform' to be towards the SW. From the figures it can be seen that the synform-antiform fold model in Figure 6a provides a much better fit to the interpreted magnetic profile model compared to the antiform-synform fold model in Figure 6b. The discrepancy between the geophysical model and the geological field observations in Figure 6a can be explained by an overturned fold tectonic model schematically illustrated in Figure 7.

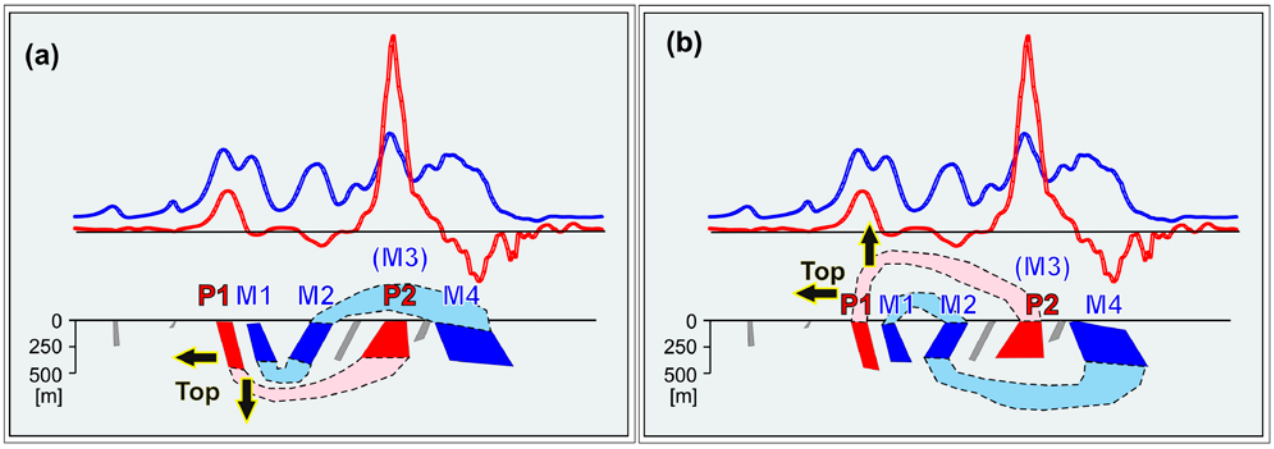


Figure 6. Schematic fold models fitted to interpreted magnetic profile models of Figure 3 and Figure 4. Blue profile: magnetic anomaly. Red profile: Electromagnetic in-phase anomaly. Red polygons: Magnetic and conductive pyrrhotite-rich. Blue polygons: Magnetic and resistive magnetite-rich. The black arrows depict the direction of the stratigraphic 'top' interpreted by Kähkönen and Nironen (1994; Fig. 5). In (a) the interpreted magnetic anomaly sources are connected in a synform-antiform pair, while in (b) the folds are in the opposite antiform-synform direction.

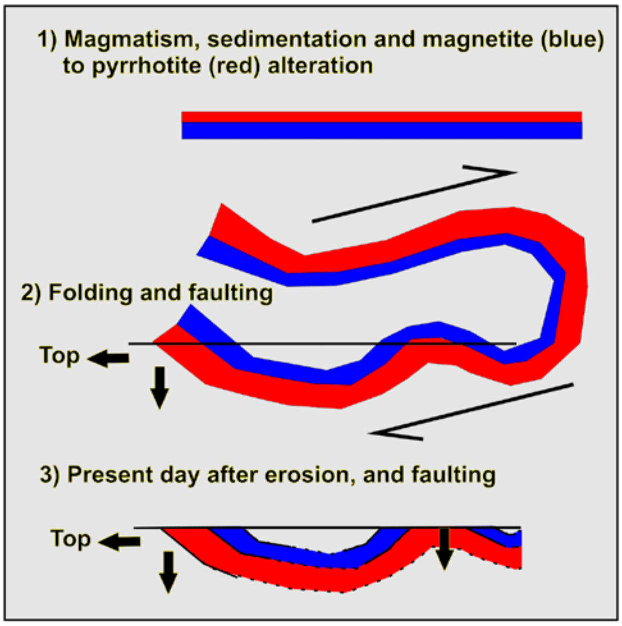
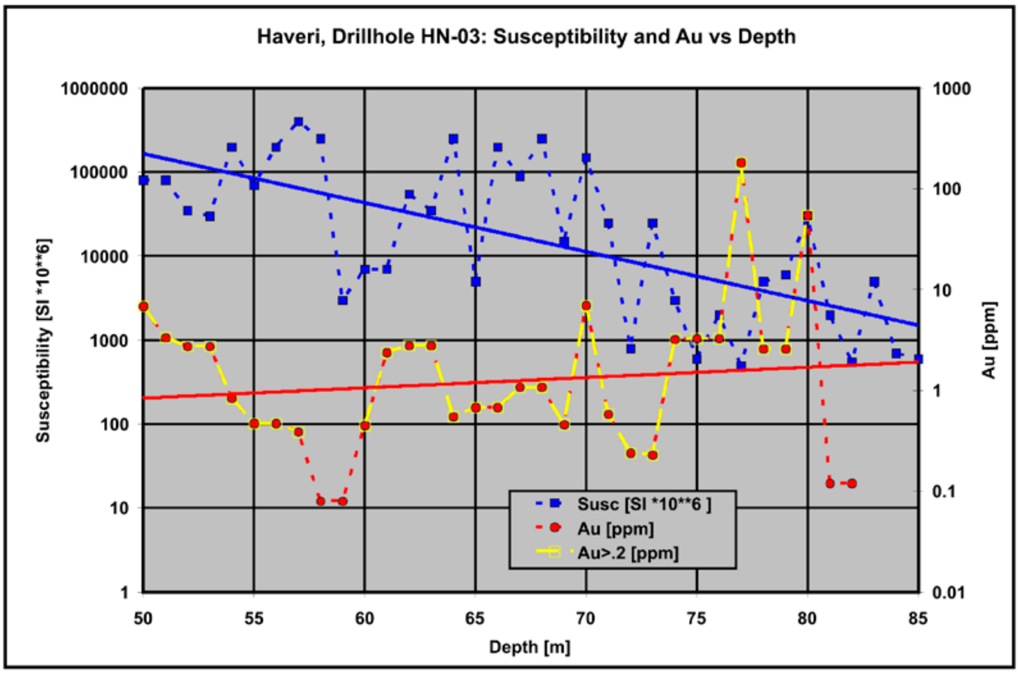


Figure 7. A schematic model of an overturned fold to explain the model in Figure 3b and in Figure 6a.

PETROPHYSICS

The petrophysics of the Haveri area was investigated from samples of two drill cores:
HN-03: E2460240, N6845200, azimuth 90, dip 65, length 395.9 m, 36 samples, and
SZ-05: E 2460230, N6845040, azimuth 90, dip 60, length 262.4 m, 27 samples.
The locations of the drill hole collars are indicated in Figure 3a. The susceptibility of the samples was measured manually with a Jalander JH-8 susceptibility meter at approximately one-metre intervals. Moreover, in the GTK petrophysics laboratory, susceptibility, remanence and density were measured from 16 + 14 samples. Here, the correlations of the petrophysical parameters with each other and with the Au content analysed from the cores are considered.

Figure 8 illustrates the correlations between susceptibility (measured manually) and Au content as a function of depth in the drill holes. In these diagrams the yellow boxes and lines refer to



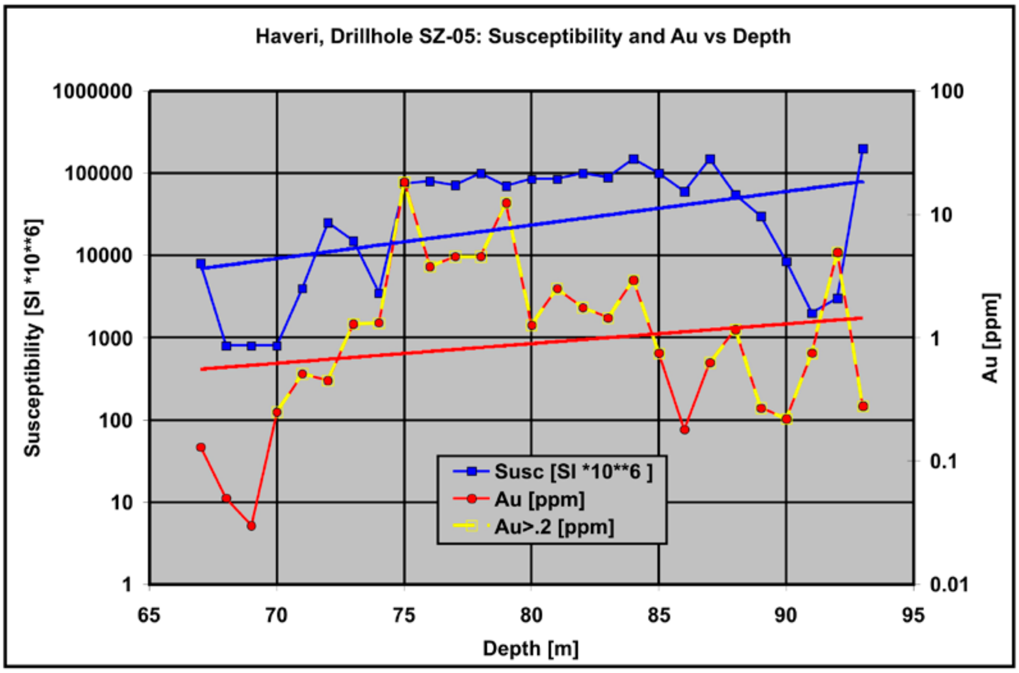


Figure 8. Susceptibility and Au content vs. depth in drill holes HN-03 and SZ-05. Note the logarithmic scale of the vertical axis. Dots: measured values. The yellow dashed line refers to values where Au > 0.2 ppm. Solid lines: Regression lines.

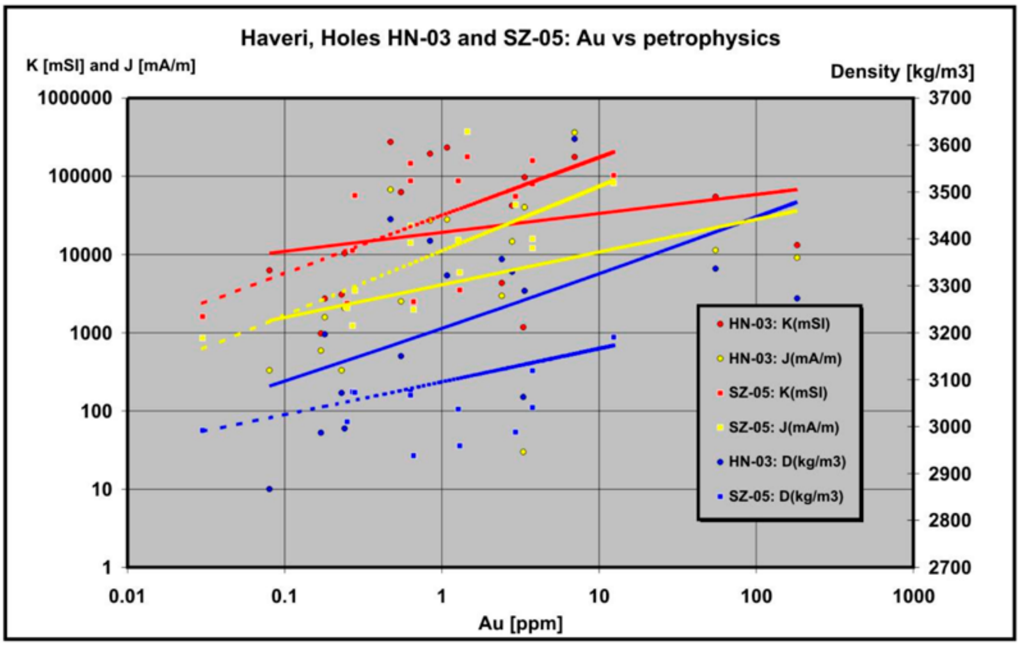


Figure 9. Drill holes HN-03 and SZ-05: Laboratory measurement values of susceptibility (K), remanence (J) and density (D) vs Au-content. Dots: measured values. The dashed trend lines refer to SZ-05 (the dashes disappear at higher values due to the logarithmic scale of the horizontal axis).

Au values above 0.2 ppm. The diagrams demonstrate that there is no significant correlation between gold and susceptibility. However, the results of laboratory measurements in Figure 9 suggest that there could be a weak positive correlation between susceptibility, remanence, density and Au content.

Thus, it can be concluded that there may be correlations between petrophysical parameters and the Au content, but much more data and careful laboratory measurements are needed to verify the results. In particular, more regional-scale tests should be performed in magnetite- and pyrrhotite-rich areas to determine whether the alteration of magnetic minerals (magnetite → pyrrhotite) could indicate bedrock alteration, and possibly an increasing gold potential.

CONCLUSIONS - WHERE TO EXPLORE FOR GOLD IN THE REGION?

Geophysical interpretation indicates that the Haveri area ‘block’ forms a synform-antiform pair, whose stratigraphy is upside down. Moreover, when combining magnetic and electromagnetic data, it can be seen that the flanks of the folds consist of magnetite- and pyrrhotite-rich ‘layers’. The magnetite-rich layer consisting of mafic metavolcanic rocks appears to represent the stratigraphically lowermost unit below the pyrrhotite-rich layer, which consists of banded metavolcanic or metasedimentary rocks. Moreover, pyrrhotite has been interpreted to represent an alteration product of magnetite.

The fact that magnetite- and pyrrhotite-rich layers occur very symmetrically in the folds and they appear to be upside down indicates that the magnetite to pyrrhotite alteration took place before the layers were overturned. Thus, if gold is assumed to be connected with alteration processes in the bedrock, the targets for future gold exploration should be selected close to zones where both magnetite and pyrrhotite are present and where more altered pyrrhotite-rich rocks dominate. These zones can be defined using the magnetic and electromagnetic in-phase maps presented above.

ACKNOWLEDGEMETS

In this context I would like to thank the Northern Lion Company for permission to publish the results and data from our studies on the Haveri mine area.

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THE HAVERI COPPER-GOLD DEPOSIT: GENETIC CONSIDERATIONS

by
Pasi Eilu

Eilu, P. 2012. The Haveri copper-gold deposit: genetic considerations. *Geological Survey of Finland, Special Paper 52*, 255–266, 3 figures.

The Haveri copper-gold deposit is located in the western part of the Palaeoproterozoic Tampere schist belt in SW Finland. The deposit is chiefly hosted by mafic tholeiitic metavolcanic rocks. Lithological, structural, and primary and alteration geochemical and mineralogical evidence mostly support mineralisation in a VMS-like setting, and that the deposit was significantly affected by regional deformation and metamorphism. There appears to be no support for IOCG mineralisation, and only a little support for any significant orogenic gold overprint on a Cu-only VMS mineralisation. A number unanswered questions still remain for Haveri, such as the extent of primary geochemical haloes and their timing, chemical changes during alteration, the relationship between gold and biotite alteration, the exact siting of gold in its various mineralogical settings, and fluid, metal and heat sources during mineralisation.

Keywords (GeoRef Thesaurus, AGI): copper ores, gold ores, massive sulfide deposits, metavolcanic rocks, mineral deposits, genesis, alteration, Paleoproterozoic, Haveri, Finland

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INTRODUCTION

The Haveri region (Fig. 1) has seen a long history of mining and exploration since the first attempt to exploit magnetite in 1737 (Stigzelius 1944). In 1935, Vuoksenniska Oy went to Haveri on the basis of reports that copper and gold was detected in the old magnetite pits. The deposit was mined by Vuoksenniska from 1942 to 1962. During that time, 1.559 Mt of ore was mined at the grades of 2.85 g/t Au and 0.39% Cu (Puustinen 2003). During the 1970s and since the early 1990s, the deposit and its surroundings have been under exploration by several mining and exploration companies (Pehkonen 1979, Karvinen 1997, 2003, Fraser 2005). At present, the area is held by Lappland Goldminers AB. Recent exploration has indicated that Haveri has an inferred resource of 24.7 Mt at 0.89 g/t Au, as calculated with a cut-off grade of 0.5 g/t Au (Lappland Goldminers 2008). In 2004, geoscientists from the Geological Survey of Finland (GTK) visited the deposit and briefly worked on the data and a drill core made available by Northern Lion Gold Corp. What is presented below is based on investigations by previous researchers and on our work on the deposit (Eilu et al. 2004).

GEOLOGICAL SETTING

The Haveri Au-Cu deposit is located in the westernmost part of the Tampere schist belt (TSB), southern Finland, and hosted by the Haveri Formation of the Tampere belt (Figs. 1 and 2). The regional and local geology at Haveri has been described by Stigzelius (1944), Mäkelä (1980), Kähkönen and Nironen (1994), Nironen (1994, 2005), Strauss (2004), Kähkönen (2005) and Forss (2006). The description below is based on these reports, unless otherwise is indicated.

Most of the supracrustal rocks of the TSB were deposited during about 1904–1889 Ma. The whole belt underwent a major stage of deformation, with intrusion of synorogenic granitoids, at ca. 1880 Ma. The Haveri Formation is the oldest unit in the Haveri region, and obviously also the oldest stratigraphic unit in the whole TSB; it clearly predates the oldest well-dated, 1904 ± 4 Ma, units of the TSB. Whole-rock and ore-mineral Pb-Pb data from the Haveri Fm are ambiguous but indicate deposition between 2000 and 1900 Ma (Vaasjoki & Huhma 1999). Most of the geological descriptions from the area suggest that the Haveri Fm rocks were formed only briefly before 1904 Ma. Chemical composition and isotope data indicate that the Haveri Fm volcanic rocks represent a discrete, compositionally distinct domain within the TSB, with a marginal basin affinity. Therefore, it is possible that the Haveri Fm is exotic with respect to the other units of the TSB, unless the former represent the depositional substrate to the overlying volcanic arc sequences of the belt.

The Au-Cu deposit at Haveri is chiefly hosted by mafic metavolcanic rocks that are tholeiitic in composition, and to a minor extent by mafic to intermediate tuffs and tuffites. Away from the Haveri mine site, the latter appear to grade into volcanogenic to epiclastic metasedimentary units of the Osara Formation lying immediately above the Haveri Fm, suggesting that the Haveri Fm is not an exotic terrain unrelated to the rest of the TSB. Most of the lava flows in the Haveri Fm have a massive structure, but pillows and fracturing have also been detected across the formation (Fig. 3a). In addition, hyaloclastic units from one centimetre to one metre thick commonly occur between the lavas (Figs. 3a and 3b). The hosting sequence is intruded by felsic and intermediate porphyry dykes and sills, and by rare granitic pegmatites, nearly all of which cut across sulphide mineralisation. Just a few of the porphyry dykes are locally weakly mineralised. Some reports state that felsic volcanic rocks form a significant host to ore at Haveri (Karvinen 1997, Northern Lion Gold Corp. 2006; Fig. 3). However, we have not been able to confirm the latter observations, nor did we see any felsic rock to host the ore.

STRUCTURAL SETTING

The interpretation of the structural setting of the gold-copper mineralisation presented below is based on previous work by Kähkönen and Nironen (1994), Eilu et al. (2004), and Strauss

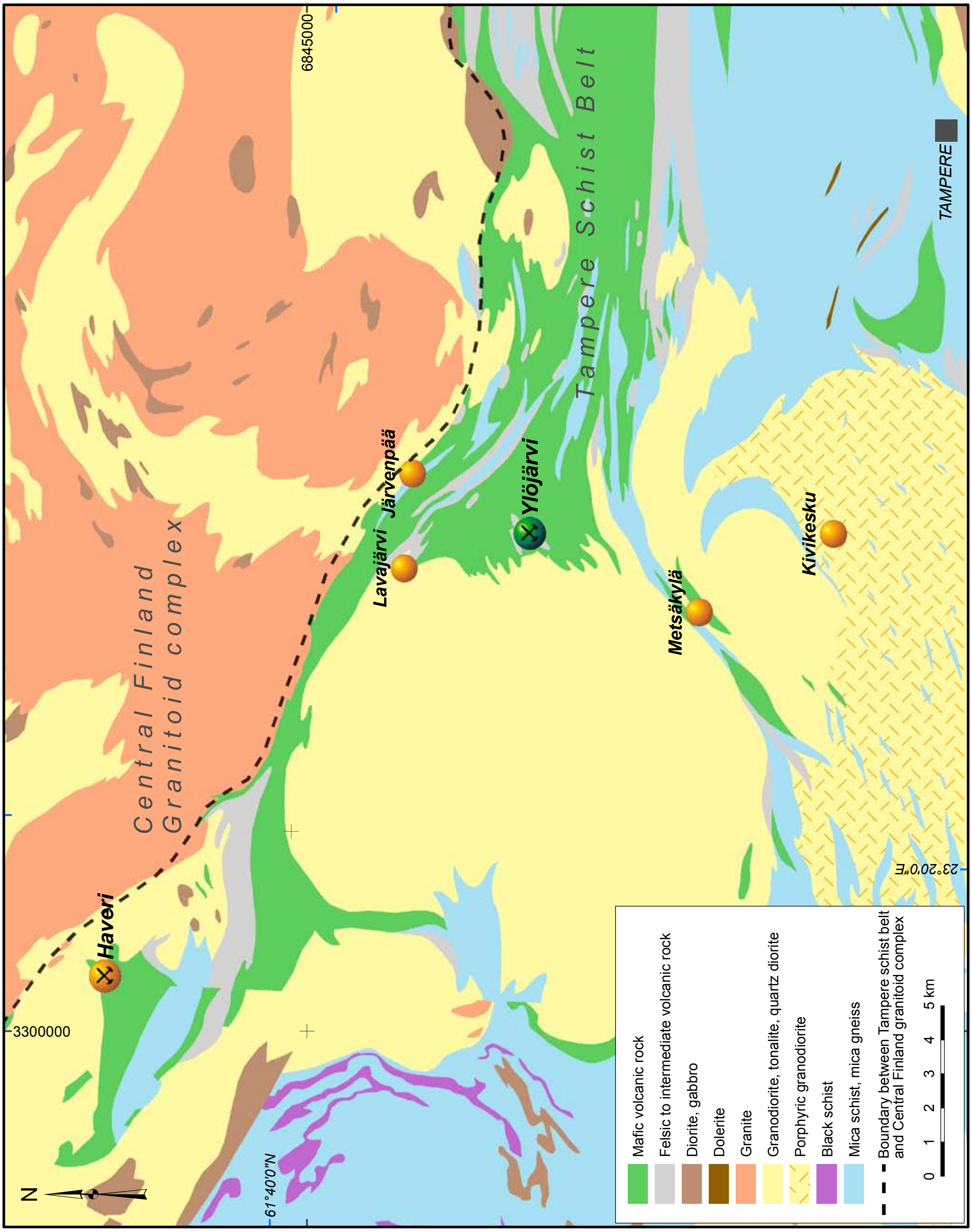

Figure 1. Gold occurrences and mines in the western part of the Tampere schist belt. Dot colours: orange, Au ± Cu; green, Cu-W-As-Au. Geology after GTK internal bedrock database (Bedrock of Finland – DigiKP), gold deposits from the FINGOLD database (Eilu & Pankka 2009).

(2004), and on a historical mine plan and section maps. The earliest structures visible are primary layering (S_0) defined by pillow lavas, compositional banding in tuff and boudins, and a schistosity (the main foliation in the area, S_1) parallel or subparallel to layering. Most sulphide bands, veins and fractures are subparallel to foliation. The old mine maps also suggest that the dominating ore orientation is subparallel to the foliation. The orientations and density of sulphides in old mine maps (available on request) suggest that intersections of the faults are an important control of ore shoots. As the main foliation (S_1) is the strongest control on mineralisation, the dominant ore body or shoot plunge orientation is likely to be in this plane (about 60° towards 280°). From the historical cross and long sections, the interpreted ore envelope plunges moderately to the SW. This is broadly the same orientation as for the F_2 fold axis and S_1 and S_2 intersection lineation (which would be the same as D_2 shear and S_1 intersection lineation).

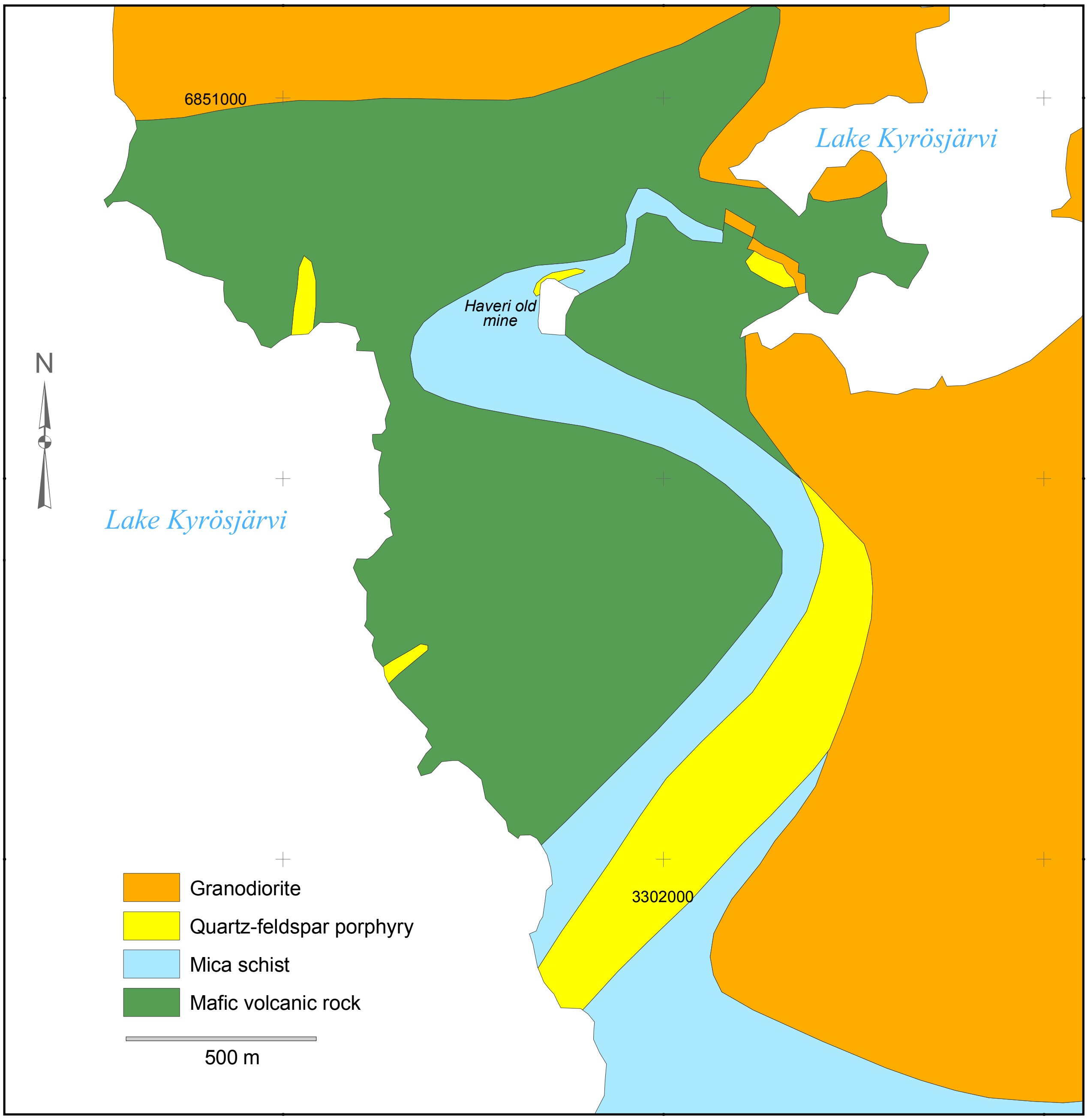

Figure 2. Haveri and its immediate surroundings according to Strauss (2004). Most of what is marked as mica schist in this map may in fact be spilitised mafic volcanic rock, especially within the area <500 m from the old mine. Coordinates according to the Finnish National ykj grid.

ALTERATION

Two major styles of alteration were detected in drill core at Haveri: an earlier synvolcanic submarine spilitisation and a later biotitisation. In the past, iron oxide-copper-gold (IOCG) (Strauss 2004) and orogenic gold-style mineralisation has also been suggested for Haveri. In our investigations, no obvious indications of alteration of either of the two latter styles were detected.

The formation of amphibole, albite and magnetite characterises many IOCG systems (e.g., Pollard 2001), but the albite and magnetite appear to be very early at Haveri, and so too are the structures controlling albite and amphibole. In addition, the amphibole is probably a result of metamorphic replacement of early chlorite. There is no evidence of disoriented foliated clasts within brecciated zones, or of albitic alteration replacing a foliated texture. Moreover, the recognition of weakly strained amygdales and pillow core to rim transitions in the drill core indicates that even the primary textures may be well preserved at Haveri.

Biotitisation characterises proximal alteration in orogenic gold systems at upper-greenschist to amphibolite facies and calcic amphibole at amphibolite facies (e.g., Eilu et al. 1999). However, significant facts speak against orogenic gold-related alteration at Haveri: 1) There are no indications of systematic and consistent biotitisation of the host rock proximal to gold mineralisation or around auriferous quartz veins (although some biotitisation may be syndeformational, as suggested by Fig. 3f). 2) There are no consistent amphibole-rich selvages or proximal rims on auriferous quartz veins (or around any quartz veins) or sulphide-bearing shear zones.

Synvolcanic alteration

The synvolcanic, spilitic alteration can be detected throughout in the mafic volcanic rocks at Haveri. It is characterised by variably bleached, albitised, angular fragments of mafic lava and tuff, albitised pillow margins, dark-green, amphibolite-rich material that forms the matrix between the variably albitised fragments and the lava pillows (Figs. 3a–3d). There also are locally abundant, up to 2 cm wide, amphibole-rich veins and medium-green (amphibole ± diopside?) veins with a very dark amphibole and pale-grey albitised selvages (Figs. 3a and 3c). The amphibolite-rich material commonly contains variable amounts of pyrrhotite and chalcopyrite (Fig. 3d). In places, the latter grade into stringer, and semimassive to massive sulphide zones (Figs. 3g and 3h). In addition, silicification has locally taken place in fragmented lava in areas of sulphidation.

The amphibole-rich domains (matrices, veins, hyaloclastites) are probably areas with a high fluid/rock ratio in a spilitised system, where originally abundant chlorite was formed with variable volumes of quartz and minor titanite and calcite (e.g., Reed 1983, Petersen et al. 2000, Teagle & Alt 2004). During the regional metamorphism under lower amphibolite-facies conditions at Haveri, all of this chlorite would have been replaced by amphibole. Precipitation of iron and base-metal sulphides, with variable amounts of gold, is typical in such a spilitic alteration environment, as well as the albitisation of lavas, which tends to form under somewhat lower fluid/rock ratios than chloritisation (Reed 1983, Shau & Peacor 1992, Petersen et al. 2000).

The dark-green veins and matrices at Haveri are all well-healed. They also show a penetrative foliation, anywhere where there are signs of foliation in the rock. The relationship between these alteration and veining features and deformation indicates that albitisation, the formation of the presently amphibole-rich matrices and veins, and the possible silicification predate all regional plastic deformation (Figs. 3e and 3f).

Biotitisation

Biotitised zones one centimetre to one metre wide occur in most of the sulphide-rich domains at Haveri. These zones are characterised by a distinct medium-brown colour and they may contain deformed remains of quartz veins (Figs. 3c, 3e and 3f). The extent and intensity of biotitisation throughout the deposit and its surroundings remains unclear. However, the extent of biotitisation in a single ore zone clearly varies and generally appears to be minor. Strauss (2004) reported that biotitisation becomes more common towards the south of the Haveri mine. This suggests that biotitisation is more common upwards in the stratigraphic sequence, if the interpretation of the stratigraphic younging to the south is correct.

Biotitisation postdates spilitisation, as biotite replaces amphibole or its precursor chlorite. There also are distinct biotitisation fronts across the previously altered amphibole-rich rock, and biotitisation seems to envelop narrow (1–2 mm wide) intensely deformed quartz(?) veins (Fig. 3f). Biotitisation either predates or is contemporaneous with the dominant regional deformation, as the dominant foliation is always discernible in the biotitised zones (Figs. 3e and 3f). Biotitisation can, hence, be syn- or epigenetic at Haveri. If the former, it took place during the late stages of the evolution of the local submarine hydrothermal system. In such a system, potassium can be extracted from sea water, as suggested by Shau and Peacor (1992) for a recent system, or K can be derived from synvolcanic, hypabyssal, felsic to intermediate intrusions. Huston (1993) has also described a case of synvolcanic biotitisation during the formation of a VHMS deposit in a terrain metamorphosed after biotitisation. Even if the biotitisation was epigenetic, it did not postdate the peak deformation (Fig. 3e). Furthermore, it predates the peak of the regional metamorphism, as porphyroblastic amphibole can be seen replacing the biotite in the drill core.

MINERALISATION

The main ore type at Haveri comprises sulphide veins from a few millimetres to tens of centimetres wide to semi-massive zones 10 m thick and 50 m long. The ore chiefly comprises pyrrhotite-chalcopyrite and magnetite patches, and pyrrhotite-chalcopyrite veins and vein networks. The dominant gangue is dark-green hornblende. The massive to semi-massive type grades into a disseminated type with no obvious change in the mineral assemblage, except for the decrease in the relative volume of ore minerals and amphibole.

Both the massive and disseminated ore types contain significant gold. Gold occurs at Haveri in three major sitings (Strauss 2004): 1) invisible in and free native gold closely associated with pyrrhotite and chalcopyrite, 2) free gold in quartz veins and their immediate wallrock, and 3) free, locally very high-grade gold in the amphibole gangue (Fig. 3i). There is no information on whether the invisible gold (siting 1) occurs in-sulphide lattice or as submicroscopic inclusions. There appears to be no linear correlation between Au and Cu concentrations. These observations are in line with the earlier work on the deposit by Stigzelius (1944) and Mäkelä (1980).

A multitude of hypotheses have been presented for the genesis of the sulphide and gold mineralisation, from completely syngenetic to entirely epigenetic and several combinations of these. From the previous work (Stigzelius 1944, Mäkelä 1980, Kähkönen & Nironen 1994, Nironen 1994, Strauss 2004), and also supported by our observations, a combination of syn- and epigenetic mineralisation processes seems likely. Re-evaluation of the Pb-Pb data by Vaasjoki and Huhma (1999) suggests two sulphide mineralisation stages for Haveri: 1) a primary, major, process involved lead that is cogenetic with basalts and is similar to that at Outokumpu, and 2) a second, minor process, that introduced radiogenic upper crustal lead from the adjacent sedimentary rocks. This can be further interpreted as follows:

1. Simultaneously with the extrusion of the Haveri Fm basalts into the sea floor, a submarine hydrothermal system was in action. This resulted in albitisation of lava pillows and massive lava fragments (low fluid/rock ratio regime) and chloritisation of hyaloclastic material (high fluid/rock ratio regime). In addition, Fe and Cu sulphides with a significant Au content were precipitated in the fractures forming vein and vein network zones cutting across the basalt and hyaloclastite layers, also forming sulphide dissemination in hyaloclastite-rich zones and layers, and possibly forming conformable sulphidic layers on the sea floor. Ore mineral assemblages described in the literature for Haveri (e.g., Mäkelä 1980, Strauss 2004) suggest that the locally very abundant magnetite was also formed in this stage, either in the more oxidising or in the sulphur-deficient parts (or both) of the mineralising system.

   The cross-cutting relationship between the amphibole- and sulphide-rich zones and the layering of the host rocks may well also be a primary feature. It can be explained by most of the sulphide mineralisation representing a sub-seafloor stringer-style mineralisation zone(s). Such sulphidised upflow zones, with the formation of Fe- or Mg-rich chlorite as one of typical forms of alteration, are common in

Figure 3a. Brecciated mafic volcanic rock (lava). The brecciated fragments are partially albitised, and hence bleached. The dark-green matrix between the fragments comprises amphibole; no tourmaline has been detected in the matrix. Diamond-drill core 5 cm across. Parts of the drill hole MW07 in the range 189.5–192.8 m down-hole depth (dhd). Photo: Tapio Ruotoistenmäki, GTK.

Figure 3b. Hyaloclastic tuff: pale-grey albitised lava fragments and dark-green amphibole-rich hyaloclastic matrix. Stripped area west to the open pit at Haveri. Pen length 14 cm.

Figure 3c. Amphibolite-rich veins and inter-pillow-matrix, albitised vein selvages. Locally biotitised mafic lava. Diamond-drill core 5 cm across. Drill hole MW07, 239 m dhd.

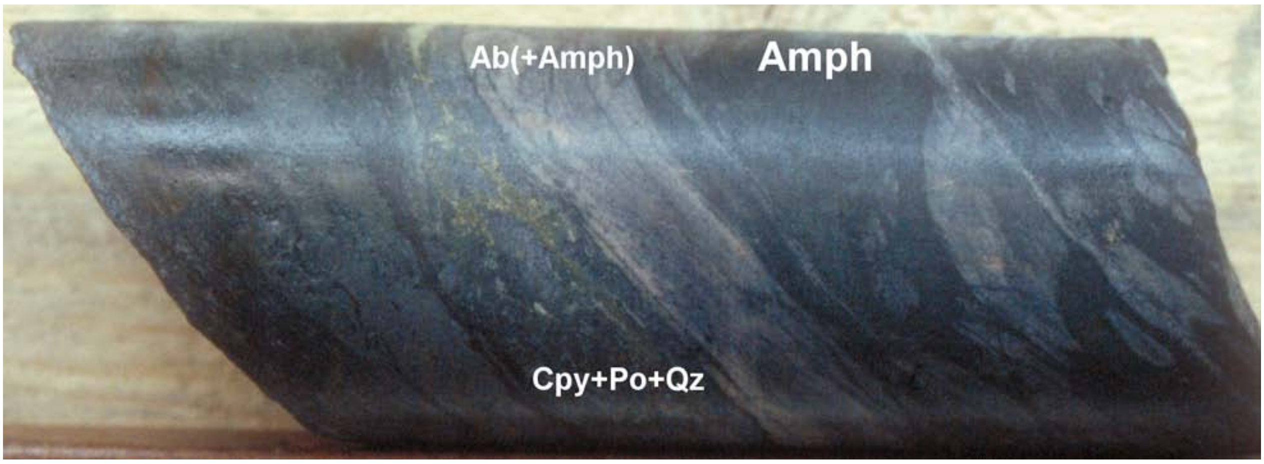

Figure 3d. Albitised lava fragments, abundant hyaloclastic material (now chiefly amphibole) and remobilised pyrrhotite and chalcopyrite with quartz subparallel to foliation. Diamond-drill core 5 cm across. Drill hole MW07, 239.40 m dhd.

Figure 3e. An intensely biotitised mafic volcanic rock, characterised by a distinct medium-brown colour, containing remains of amphibolite-rich material. Note that the dominant foliation is also clearly discernible in the biotitised zone. Diamond-drill core 5 cm across. Drill hole MW07, 216.3 m dhd.

Figure 3f. A narrow biotitised zone possibly with the remains of a quartz vein. Note how the biotitisation cuts across albitised lava fragments and amphibole-filled fractures, and how the dominant foliation has affected all domains of the rock postdating all alteration. Diamond-drill core 5 cm across. Drill hole MW07, 227.0 m dhd.

Figure 3g. Sulphide dissemination and vein networks grading into massive or semimassive sulphide zones. Diamond-drill core 5 cm across. Drill hole HN03. Photo: Tapio Ruotoistenmäki, GTK.

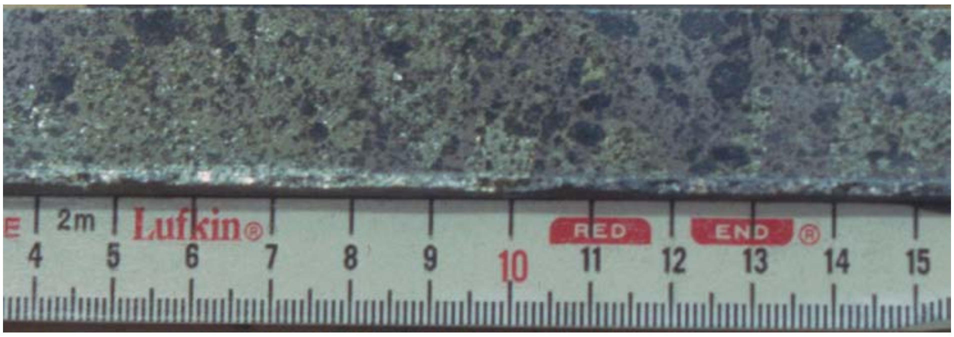

Figure 3h. Massive pyrrhotite-chalcopyrite with dark-green amphibole fragments (hyaloclasts?). Drill hole SZ05, 78.6 m dhd.

Figure 3i. Abundant visible gold in ore at Haveri; all yellow material is gold. Field of view 10 cm. Photo: Jari Väätäinen, GTK.

the lower parts of VHMS-style deposits of all ages (e.g., Mottl 1983, Poulsen & Hannington 1996, Petersen et al. 2000, Schardt et al. 2001). This would also explain the generally stratiform nature of mineralisation on a large scale at Haveri, that the mineralisation took place at a certain depth interval, perhaps immediately below the sea floor (stringer zone in lava and earliest hyaloclastic tuffs), and on the seafloor (dissemination and conformable bands within hyaloclastic tuffs).

Potassic alteration (now biotite) followed in certain high fluid/rock ratio domains where sea water- or intrusion-derived K-rich fluids deposited potassium. This took place after the chloritisation and sulphide mineralisation stage.

2. If biotitisation was not related to the early, submarine stage of alteration described above, intrusion-derived K-rich fluids may have caused biotitisation in high fluid-rock ratio domains during early deformation, before the peak of regional metamorphism.

   In any case, the main effects of deformation and regional metamorphism were: 1) recrystallisation and deformation of the silicate mineral assemblages formed in the syngenetic stages, 2) deformation and partial remobilisation of sulphides and, 3) significant remobilisation of gold into the locally active shear and fracture zones. This resulted in all hyaloclastic and other chlorite-rich domains becoming amphibole-dominated and gold enriched into the amphibole-rich zones, into some of the syndeformational quartz veins, and into the immediate wallrock of the veins.

   The gold mineralisation is limited, on a broad scale, to the domain of sulphide mineralisation. Despite extensive recent drilling, there appears to be no indication of significant gold-only mineralisation, as the sulphides (pyrrhotite and chalcopyrite) always seem to occur at least somewhere within a few metres, if not within a few millimetres or centimetres, from any gold. This is a strong indication that all or almost all of the gold was derived from the sulphide mineralisation, not from external sources during deformation. The local remobilisation of gold also explains the lack of a linear correlation between gold and copper concentrations on a sample scale. The Pb-Pb data also suggest only a small external sulphide contribution during deformation at Haveri (Vaasjoki & Huhma 1999); this could have been taken place, for example, in relation to the 'slight remobilisation during D_2' of Nironen (1994).

The interpretation above further suggests that regardless of the genesis of the ore, the controls of the geometry of the Cu-Au mineralisation at Haveri are stratigraphy and deformation. On a large scale (from kilometres down to perhaps a hundred metres), the stratigraphic setting of the known mineralisation and the major fold structures would control the location of potential ore. These regional scale structural controls are, according to Nironen (1994), the F_1 and F_2 fold closures. On a local scale (from less than perhaps hundreds of metres down to millimetres), the control would be the primary and remobilised sulphidic zones, boudin necks, the late shear and fault zones, their intersections and quartz veins.

CONCLUSIONS

The main results of the present review are summarised below. Additional research may change the views presented here. From the available data it is concluded that:

1. The Haveri Cu-Au deposit is hosted by tholeiitic mafic lavas and hyaloclastic tuffs. No felsic volcanic rock seems to host to ore.
2. The siting of gold is as: a) invisibly in and freely native with the sulphides, b) free gold in quartz veins and their immediate wallrock, and c) free, locally very high-grade gold with the amphibole gangue.
3. Two styles of alteration were detected in the drill core: an earlier synvolcanic submarine spilitisation and a later biotitisation. At least the spilitisation predates all regional deformation.
4. Most, perhaps nearly all, of the sulphides, as well as magnetite, are related to an early, spilitic, submarine hydrothermal system.
5. Spilitic alteration produced albitisation in massive parts of the volcanic rocks and chloritisation in hyaloclastites.
6. Most, if not all, of the gold appears to be genetically related to the syngenetic sulphide mineralisation.
7. The timing of biotitisation is later than albitisation and chloritisation, but pre-dates the

peak regional metamorphism.

8. All of the inferred early chlorite was replaced by amphibole during regional metamorphism.
10. At the deposit scale (from kilometres down to perhaps a hundred metres), the stratigraphic setting of the known mineralisation and the major fold structures seem to be the most important controls on the potential location of ore.
11. At a smaller scale (from less than perhaps 100 m down to millimetres), the controls on ore are the primary and remobilised sulphidic zones. The ore envelope plunges moderately SW. This is the same as the S_1 and S_2 shear intersection orientation and probably the most common ore shoot plunge direction.

A number of matters still remain unanswered at Haveri. These include:

- What is the exact siting of gold with sulphides. This would also provide important information for planning ore processing, to potentially increase the recovery of gold.
- What exactly is the correlation between metals enriched with different types or styles of ore; this might also provide geochemical vectors to ore. A sympathetic correlation of depletion and enrichment patterns between Cu, Au and S, and possibly with other elements, would provide evidence for Au enrichment during primary submarine hydrothermal processes.
- Whether there is a relationship between gold distribution and Na and K enrichment or depletion. This would test the possible association of gold with biotite alteration and whether the mechanical behaviour of albitised rock had an influence on patterns of fluid flow.
- Whether there could have been enough gold with the sulphides to account for all the gold at Haveri (is all gold present indeed remobilised from a VMS-style Cu-Au deposit). SIMS Pb isotope studies could be used to attempt to define whether different sulphide generations can be identified and linked to the distribution and enrichment of gold. This would help address the issue of how much gold was originally present with the sulphides.
- Which elements were enriched and which depleted during different stages of alteration and mineralisation. Investigations using robust mass-balance calculation methods have so far not been carried out at Haveri
- The relationship between the local intrusions, structure and mineralisation, and whether any of the local intrusions have acted as the heat engine for the submarine hydrothermal system.
- The relationship between biotitisation, structure and mineralisation.
- Fluid sources during different stages of alteration and mineralisation could be investigated with fluid inclusion and stable isotope studies.

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WEAK EXTRACTION OF SURFACE SOIL SAMPLES IN NICKEL PROSPECTING IN SE-FINLAND

by
Aimo Hartikainen

Hartikainen, A. 2012. Weak extraction of surface soil samples in nickel prospecting in SE-Finland. *Geological Survey of Finland, Special Paper 52,* 267–276, 7 figures and 2 tables.

To locate a nickel deposit in a mafic-ultramafic intrusion close to the rapakivi granite area in south-eastern Finland, 131 samples were collected at three separate targets. A weak extraction method was applied to analyse the ions weakly bound to the surfaces of grains. The till samples were collected at a depth of 20–40 cm from pits made by spade and extracted in ammonium acetate at pH 4.5. The determinations were performed by ICP-OES and ICP-MS in the laboratory of Labtium plc in Espoo.

When applying the weak extraction method, the concentrations were naturally low, but the differences between the lowest and the highest contents of several elements were many-fold, indicating the theoretical functionality of the method.

At the Mustapää target in Savitaipale, samples were collected along two traverses on the northwest side of a nickel-rich boulder. In these samples, nickel contents were very low, but as expected the REEs were highly anomalous in the rapakivi area. Thorium and uranium contents were also high at the same sampling sites. Highly anomalous Pb-Zn-Ag values were recorded on both sides of the contact zone between the rapakivi granite and mica gneiss, but airborne geophysical measurements did not support a more detailed follow-up survey.

The nickel contents at the Ahokkala target in Taipalsaari were mostly at a low level, but in the vicinity of a small known nickel mineralization, contents were very anomalous and the Ni x Ni/Ce ratio was particularly high. The nickel mineralization at the Kuurmanpohja target in Lappeenranta was indicated by extremely high Ni x Ni/Ce values, being 92 times greater than the mean.

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

Keywords (GeoRef Thesaurus, AGI): nickel ores, mineral exploration, geochemical methods, till, weak extraction, chemical composition, metals, Mustapää, Savitaipale, Ahokkala, Taipalsaari, Kuurmanpohja, Lappeenranta, Finland

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INTRODUCTION

The objective of this small-scale study was to rapidly and in a cost-effective way investigate three nickel potential targets comparable to the Telkkälä mine occurring within the study area. The Telkkälä nickel ore (Fig. 1) was small and mined during two periods, 1969–1970 and 1988–1992 (Säilä & Grahn 1990, Isomäki 1994). The ore and its gabbro-peridotite host could be easily delineated by geophysical measurements due their high magnetic properties compared to the surrounding rocks. There are several known nickel-bearing boulders in the surroundings of Lappeenranta, but the location of their sources is complicated because of wide lakes and thick glaciofluvial deposits, dominated by II Salpausselkä.

Good but somewhat contradictory results have been achieved using the weak extraction method in Finland (Sarala et al. 2008, Sarala et al. 2011). It has been suggested that the method works especially well in areas, that are typified by intense capillary action and evaporation. Capillary action can be impressive: in a semiarid area in the USA, about 2/3 of water has been found to evaporate into the atmosphere, while 1/3 flows to the sea (De Wiest 1965). In northern areas the ratio is reversed (De Wiest 1965). On the other hand, the method has also worked in rainy areas such as in Scotland and Venezuela (Mann et al. 1998). One reason for the rise of ions to the surface could be the oxidation of the ore, which produces warming and the convection of ions beneath the ground-water table (Mann et al. 2005). It has been suspected that the mobilization of ions from mineralized bedrock to the surface can also occur via different gaseous hydrocarbon components (Malmqvist & Kristiansson 1984), electrochemically or because of changes in air pressure (Sarala et al. 2008). In the most successful cases, an anomaly exists in the surface part of the soil directly above the ore. An example of this is the Golden Web gold deposit in Western Australia, which was found using the weak extraction method, despite a thick overburden (Mann et al. 1997). In Finland, the theoretically most suitable soil types for the method are probably clay, silt and till with at least moderate clay and silt contents.

Figure 1. The three weak extraction sampling targets at Mustapää, Ahokkala and Kuurmanpohja around Lappeenranta, SE-Finland, selected on the basis of known nickel mineralizations and nickel-bearing boulders. Basemap © National Land Survey of Finland, licence no 13/MML/12.

The two most important advantages of the weak extraction method compared to conventional geochemical exploration methods (total analysis or partial analysis) are that: a) mineralization is reflected vertically in the soil surface, where samples can be easily collected, and b) the contrast between anomalous and background contents is high, the differences being even higher when using element ratios (Mann et al. 1998).

The target areas at Mustapää in Savitaipale, Ahokkala in Taipalsaari and Kuurmanpohja in Lappeenranta were selected due to the presence of aeromagnetic anomalies, nickel-bearing boulders or previously known mineralizations (Fig. 1). There are several outcrops in Kuurmanpohja, but the other targets are weakly exposed.

The Mustapää target is situated at the contact zone between rapakivi granite and mica gneiss, the others being related to the mica gneiss area. The bedrock of the targets mainly consists of mica schist/mica gneiss intruded by granodiorites and diorite-gabbros. All these are commonly cut by 0.2–10-m-thick pegmatitic granite veins (Simonen & Tyrväinen 1965, 1981).

The soil type at all targets consisted of till. The topography was almost flat at Ahokkala, slightly sloping at Mustapää, while the Kuurmanpohja target was almost entirely on the western slope of a quite high hill. The A horizon was not perfectly developed at any of the targets.

Geologist Aimo Hartikainen and assistant Tuomo Stranius, collected the samples in August 2009 as a part of the Geological Survey of Finland (GTK) project “Evaluation of the nickel potential of South and Mid-Finland”. The results were reported during the project “Evaluation of the mineral potential of East Finland” in 2011.

SAMPLING AND ANALYSES

Samples were collected along traverses using 10–m intervals and following the MMI sampling guide (Mobile Metal Ion Technology 2004, Mann et al. 1995, 2005). The samples, having a weight of

Table 1. Average parameters of sampling at the three targets in SE-Finland, n=number of samples.

	Organic matter (range)	**Roots from the surface (cm)**
Mustapää	8.3 (5–20 cm)	23 (16–25 cm)
Ahokkala	7.0 (3–50 cm)	25 (15–40 cm)
Kuurmanpohja	12.9 (8–25 cm)	25 (20–28 cm)
	Top depth of the sample (cm)	**Podsol layer (n)**
Mustapää	25.4 (20–30 cm)	A 14, A+B 18, B 19
Ahokkala	26.2 (20–50 cm)	A 8, A+B 22, B 33, Org 1
Kuurmanpohja	25.3 (25–30 cm)	B 17
	Colour	**Soil type (n)**
Mustapää	middle-light brown, grey	till 51
Ahokkala	middle-light brown, grey	till 63
Kuurmanpohja	middle brown	till 17
	Matrix of till (n)	Wetness (n)
Mustapää	sand 41, fine sand 10	dry 51
Ahokkala	sand 53, fine sand 10	dry 63, wet 1
Kuurmanpohja	sand 17	dry 17
	Leaking pit (n)	**Gradient (n)**
Mustapää	none 51	even 37, gently sloping 14
Ahokkala	dry 63, seeping 1	even 42, gently sloping 22
Kuurmanpohja	none 17	even 2, gently sloping 15
	Country type (n)	**Contamination (n)**
Mustapää	coniferous forest 11, mixed forest 40	none 47, sandy road 4
Ahokkala	coniferous forest 32, mixed forest 32	none 35, sandy road 25, electrical power line 4
Kuurmanpohja	mixed forest 17	none 13, sandy road 1, electrical power line 3

250–300 g, were taken by spade 10–30 cm beneath the organic matter, the real depth being approximately 20–40 cm. Before placing each sample in a plastic bag, the roots and fragments larger than 0.5 cm were removed. All the parameters concerning the sample and the sampling site were recorded (Table 1). During four days, two men collected 131 samples. The weather had been dry before sampling for several days and during sampling it was also rainless, except for one minor thundershower.

Homogenized samples weighing 15 g were extracted in 1 M ammonium acetate solution at pH 4.5, following shaking of the samples for two hours before analysis. The determinations were performed using ICP-OES and ICP-MS in the laboratory of Labtium plc in Espoo (Labtium method codes 002P and 002M). Elements determined by ICP-OES were: Al, As, Ca, Fe, K, Mg, Mn, Na, P, S and Si. By ICP-MS the elements were: Au, Ba, Be, Bi, Cr, Cd, Ce, Co, Cr, Cu, Dy, Er, Eu, Gd, Hf, Ho, La, Li, Lu, Mo, Nb, Nd, Ni, Pb, Pd, Pr, Rb, Sb, Sc, Se, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn and Zr. Several of the elements displayed no variation in their contents, while the concentrations of REEs, for instance, varied considerably. Due to the relatively small number of samples, the statistical analysis was performed on pooled data from the three target areas.

THE TARGETS

The element concentrations of the samples collected from the three exploration targets are presented in Table 2 including the number of samples, minimum and maximum contents, and the mean and standard deviation. For several elements the maximum content was more than ten times higher than the mean content. Of these, 14 were REEs, three were main elements and 14 were other elements such as Cu, Ni, Pb, Pd, Zn and S. A high nickel content is typically related to min-

Table 2. Element contents of the samples at the three exploration targets. 002P=ICP-OES, 002M=ICP-MS, NH_4Ac extraction. Pd and Te presented as ppb, others as ppm.

	N	Minimum	Maximum	Mean	Standard deviation
Ca_002P	131	1.570	907	58.09	113.0
Ce_002M	131	0.015	13.47	0.594	1.651
Cu_002M	131	0.025	4.372	0.239	0.556
Dy_002M	131	0.001	2.572	0.062	0.241
Er_002M	131	0.001	1.499	0.032	0.138
Eu_002M	131	0.001	0.267	0.016	0.320
Fe_002P	131	9.980	1200	77.97	158.4
Gd_002M	131	0.002	2.883	0.077	0.276
Ho_002M	131	0.000	0.523	0.012	0.484
La_002M	131	0.006	7.770	0.328	0.839
Li_002M	131	0.000	0.398	0.023	0.042
Lu_002M	131	0.000	0.162	0.003	0.149
Mg_002P	131	0.934	279.0	14.00	32.19
Nd_002M	131	0.011	11.40	0.367	1.158
Ni_002M	131	0.037	7.109	0.297	0.714
Pb_002M	131	0.021	5.000	0.293	0.465
Pd_002M	131	0.010	18.96	0.411	1.739
Pr_002M	131	0.002	2.292	0.087	0.250
S_002P	131	0.500	458.0	42.28	64.24
Sm_002M	131	0.003	2.613	0.077	0.258
Sr_002M	131	0.041	10.65	0.900	1.389
Tb_002M	131	0.000	0.454	0.012	0.043
Te_002M	131	0.001	2.811	0.249	0.332
Th_002M	131	0.002	0.681	0.053	0.075
Tm_002M	131	0.000	0.186	0.004	0.017
U_002M	131	0.005	9.456	0.156	0.839
V_002M	131	0.005	12.49	0.179	1.094
W_002M	131	0.003	0.069	0.004	0.006
Y_002M	131	0.010	3.666	0.158	0.400
Yb_002M	131	0.000	13.00	0.185	1.134
Zn_002M	131	0.025	3.561	0.333	0.675

eralized mafic and ultramafic rocks, while cerium occurs at high concentrations in felsic intrusive rocks. Both of these elements can be reliably analysed by ICP-MS. Like nickel, cerium, despite belonging to the rare earth elements, is also quite a common element in the earth's crust, the average content being 46 ppm. As both are also relatively mobile elements, the Ni/Ce ratio theoretically emphasises the reflection of the mineralization in the surface part the soil cover, improving the contrast between mineralized and barren areas, as stated in the SMS technical guidebook (MMI Geochemistry for Nickel Exploration). The Ni x Ni/Ce ratio was found to be the most useful index in this study to delineate the areas with nickel potential.

Mustapää

In order to locate the source of two nickel-bearing boulders, 51 samples were collected at 10–m intervals along two sampling traverses (Fig. 2). The third boulder found in the area was related to the large end moraine, II Salpausselkä. These boulders have originated from the island of Leipäsaari in lake Kuolimonjärvi or its surroundings, as interpreted by Kurki (1975) and Lindmark (1980). This is also indicated by the ice flow striations in the direction 330º–340º (Rainio 1980). However, the nickel content in the sulphidic parts of the gabbro outcrop in Leipäsaari is lower than that recorded in the boulders. This study aimed to verify whether the source of the boulders could be closer than previously expected.

All the analysed soil samples at the Mustapää target were very poor in nickel (less than 0.4 ppm), and there was no indication that the source of the boulders could be close to the sampling location. Nevertheless, the magnesium content was relatively high, which may indicate the existence of a mafic xenolith in rapakivi granite. Palladium, thorium and uranium contents were high compared to background values immediately on the northwest side of the nickel-bearing boulder and thus closely resembled the REE anomalies. Five successive samples were highly anomalous in zinc, lead and silver on both sides of the contact zone

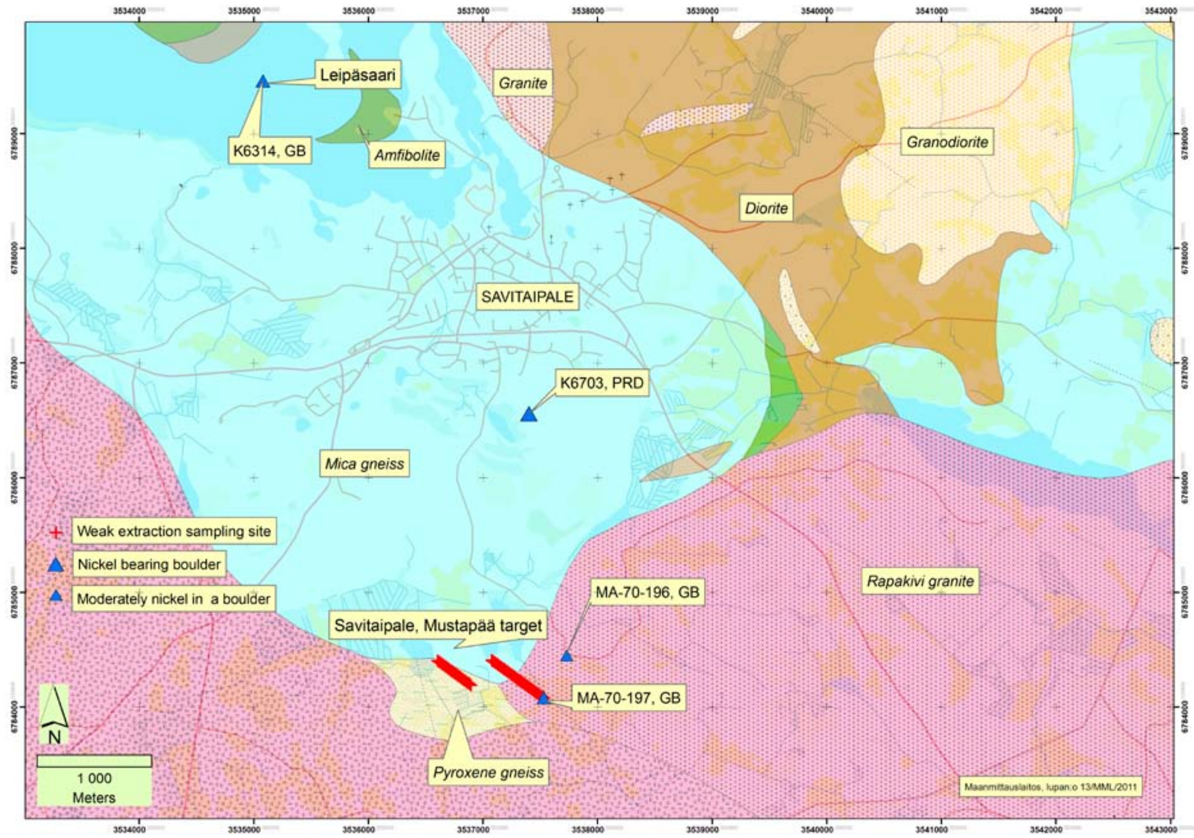

Figure 2. Nickel-bearing boulders and their rock types (GB=gabbro, PRD=peridotite), sampling profiles and the bedrock around the parish of Savitaipale (Bedrock of Finland – DigiKP). Basemap © National Land Survey of Finland, licence no 13/MML/12.

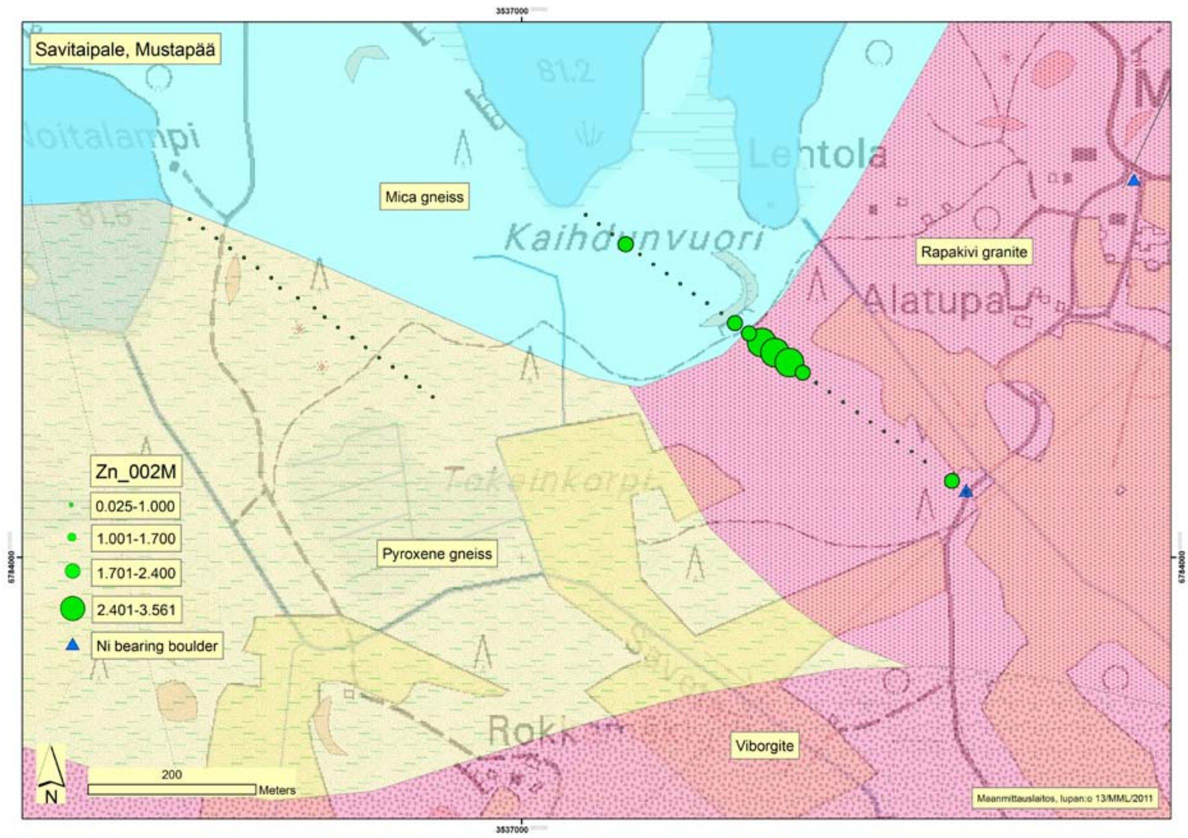

Figure 3. Zinc content in till samples analysed by the weak extraction method (ammonium acetate, ICP-MS) in Mustapää, Savitaipale. Basemap © National Land Survey of Finland, licence no 13/MML/12.

between rapakivi granite and mica gneiss (Fig. 3), indicating that these elements are enriched in the bedrock under the sampling sites. Airborne geophysical measurements in the area did not support the existence of sulphidization in the area. Ground geophysical measurements could provide more information on possible mineralization.

Figure 4 presents the content of cerium in the samples collected at Mustapää. As could be expected the REE contents are greater in the rapakivi area than in the pyroxene gneiss or mica gneiss area. According to the REE contents, the contact of rapakivi and mica gneiss could be 100 m to the southeast of the contact zone shown on the geological map. In any case, the high contents of cerium and other REEs in the rapakivi area indicate that the weak extraction method is applicable under favourable circumstances.

Ahokkala

About 100 years ago, the Geological Commission of Finland studied the small ore mineralization that is situated in a diorite-gabbro intrusion in Ahokkala, Taipalsaari. Vuoksenniska Oy drilled four holes in the immediate surroundings in the 1930's (the exact sites of the drill holes are not known). Outokumpu Oy made an inventory of the mineralization, which proved to be seven metres long and five metres wide, from which narrow sulphide-bearing veinlets truncate to norite (Kujanpää 1959). The nickel content is 0.9–1.6%, with lower copper, zinc, arsenic and cobalt values. Close to the mineralization, the norite does not have sulphides, but further away it contains uniform pyrrhotite dissemination. GTK has drilled three holes in the surroundings (Fig. 5) without discovering any noteworthy sulphidization (Halkoaho et al. in prep).

At Ahokkala, 64 surface soil samples were collected above gabbroic rock. Most of the samples were poor in nickel, also having low Ni x Ni/Ce values. Around the small mineralization (Kujanpää 1959), the nickel content and the abovementioned ratio were high and the mineralization would have been easy to locate using the weak extraction method (Fig. 5). In the samples with

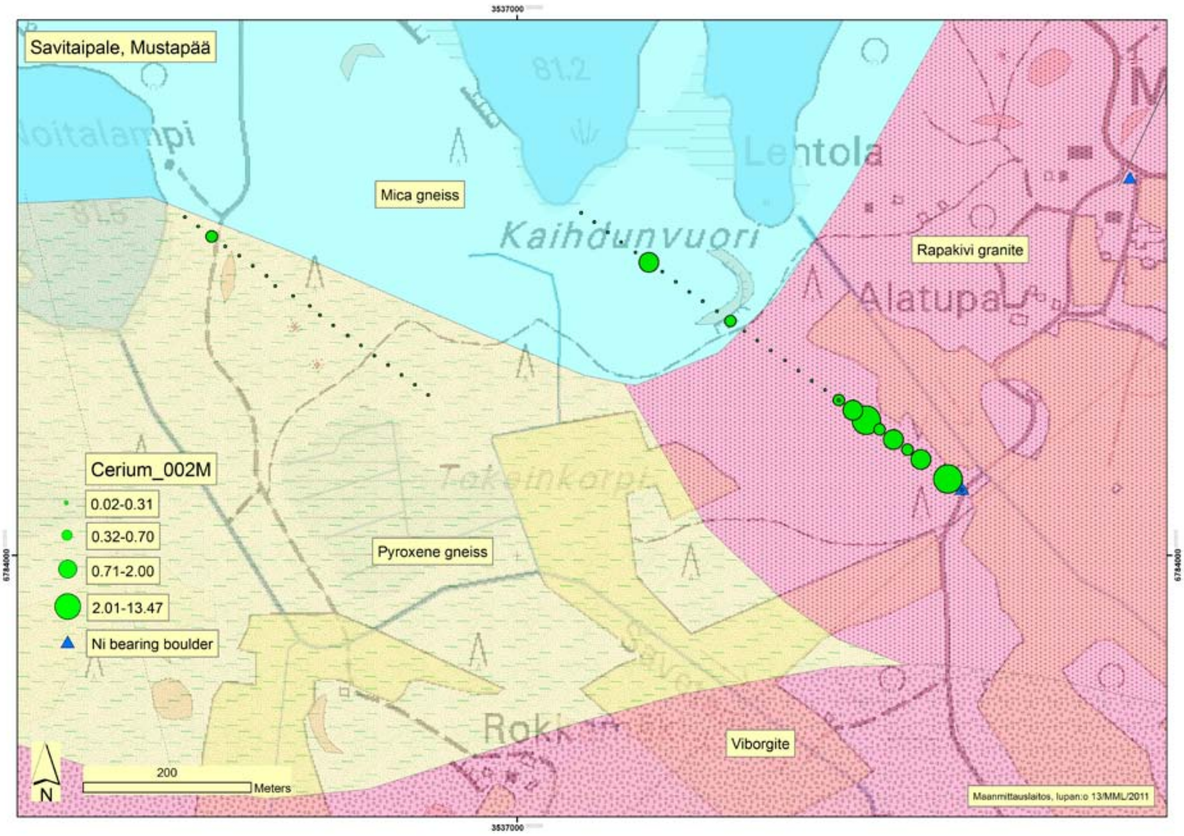

Figure 4. Cerium content in till samples analysed by the weak extraction method at Mustapää, Savitaipale. Basemap © National Land Survey of Finland, licence no 13/MML/12.

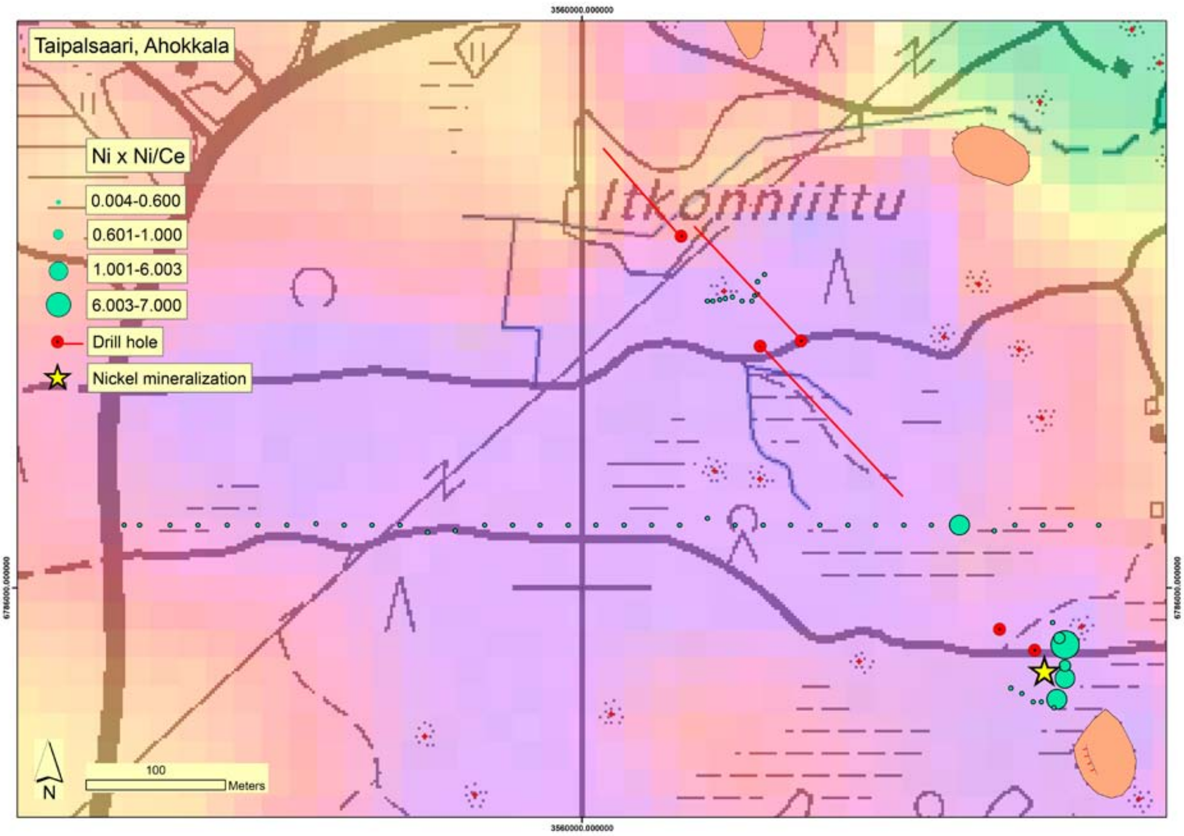

Figure 5. Ni x Ni/Ce values in till samples analysed by the weak extraction method at Ahokkala, Taipalsaari. Samples were collected along an E−W-trending profile and also close to the known nickel mineralization. A ground magnetic map is displayed as background. Basemap © National Land Survey of Finland, licence no 13/MML/12.

a high nickel content, the iron value was also 10 to 30 times higher than the mean content, and sulphur and chrome contents were additionally anomalous. Close to the mineralization, cobalt and copper were in some cases anomalous. No new nickel mineralization was discovered, but according to the high Ni x Ni/Ce value another occurrence could exist to the north-west of the known mineralization in the eastern part of the long, E–W-trending sampling line (Fig. 5). No anomalous values were detected in the northernmost sampling traverse, which is in accordance with the low nickel contents in drill cores.

Kuurmanpohja

At Kuurmanpohja in Lappeenranta, 17 samples were collected for weak extraction analysis. There are several outcrops in the area. GTK drilled five holes along two profiles in 2009–2010, so the geology of the area is well known. There were two reasons for the drilling: the presence of a 100 x 100 m – airborne magnetic anomaly, and a sulphide-containing gabbro outcrop located by an amateur geologist, Raimo Ronkainen (Halkoaho et al. in prep).

The highest nickel contents and Ni x Ni/Ce values of the three weak extraction targets in SE-Finland were at Kuurmanpohja (Fig. 6). According to the drillings, a 100–m–wide, E–W-trending mafic dyke in the area consists a nickel mineralization and several sulphidizations, all of which are against the longitudinal direction of the dyke (Halkoaho et al. in prep). By far the highest Ni x Ni/Ce value was recorded in till just above the mineralization located by diamond drillings. The value was about 92 times greater than the mean value, the mineralization would have been easy to locate by this method. Nevertheless, the sampling site occurs almost at the lowest site of the hill (Fig. 6), and it is possible that ions had percolated to a lower level, where they had been enriched.

Several samples were high in cobalt, copper, arsenic and zinc, including the sample above the mineralization. Visually, the sampling pit and till did not essentially differ from the other sites, except for the slightly darker colour of the till (Fig. 7).

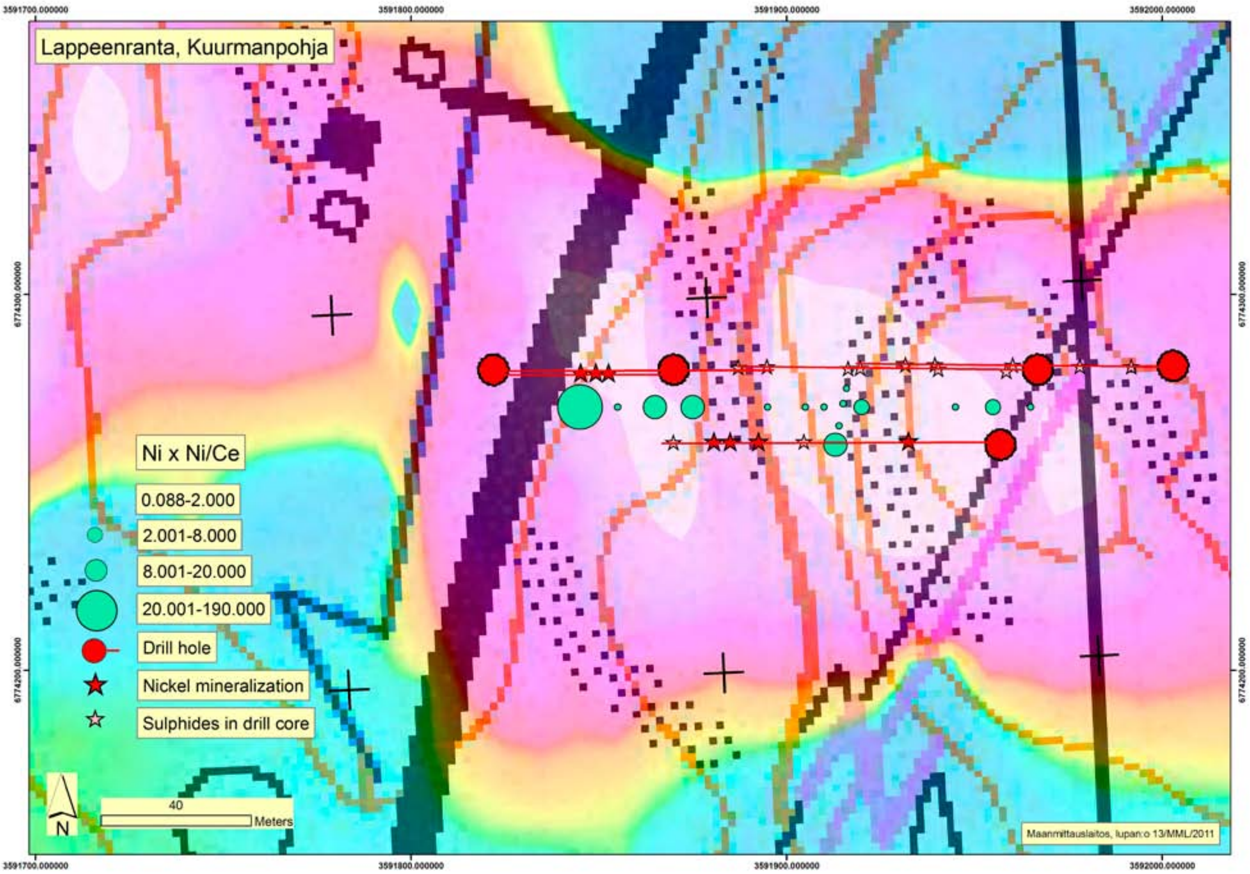

Figure 6. Diamond drill holes made by GTK, nickel mineralizations, sulphides in diamond drillings and the Ni x Ni/Ce ratio in till samples analysed by the weak extraction method. The ground magnetic map shows the lateral extensions of the Kuurmanpohja gabbro. Basemap © National Land Survey of Finland, licence no 13/MML/12.

Figure 7. The pit in till from which the sample rich in Ni and with an especially high Ni x Ni/Ce value was collected.

SUMMARY AND CONCLUSIONS

Altogether, 131 soil samples from the three targets were collected in SE-Finland. For sampling. a 40–50-cm-deep pit was made by spade, unnecessary matter was removed, and the rest was put into a plastic bag and transported to the laboratory, where the sample was dried, homogenized and analysed by a weak extraction method (ammonium acetate, pH 4.5) using the ICP-MS.

Because of the weak extraction, the contents were low, but the differences between the lowest and the highest contents for many elements were significant, indicating the theoretical functionality of the method.

The samples at the Mustapää target were collected from the northwest side of the nickel-bearing boulders, against the direction of ice movement. Nickel contents were low, but zinc, lead and silver contents, when compared with background values, were very high at the contact zone between the rapakivi granite and mica gneiss. As is typical to rapakivi granite, REE contents were anomalous. According to the cerium contents, the contact between the rapakivi granite and mica gneiss could be some 100 m further southeast from the zone indicated on the geological map.

Most of the samples in Ahokkala had a low nickel content, but samples close to the known, small nickel mineralization were rich in nickel with high Ni x Ni/Ce ratios. Copper and cobalt contents were also anomalous. An indication of another mineralization was revealed in the neighbourhood.

The nickel mineralization at Kuurmanpohja was reflected into the soil samples analysed by the weak extraction method. A till sample, highly anomalous in nickel was collected just above the mineralization, with a Ni x Ni/Ce ratio 92 times greater than the mean value. A minor chance exists that nickel ions percolated down the hill slope and enriched above the mineralization.

The weak extraction method was very effective at all three targets. By correctly using the differences between anomalous contents and background values, it is possible to locally determine the rock contacts. In the author's opinion, the main precondition for a good outcome from the sampling surveys is dry and warm weather before and during sampling, when the capillary action has been effective and the ions are 'stable' close to the surface of the soil cover.

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This Special Paper introduces the results of gold exploration and research in southern Finland carried out by the Geological Survey of Finland (GTK) in two projects that were active during 1998–2002 and 2003–2007, and the recently active follow-up projects. The publication contains sixteen articles that fall under three themes. The first articles concern regional surveys and updated data on Au occurrences in southern Finland. The second theme describes selected case studies on recently reported discoveries. The third theme comprises articles presenting recent research on geophysics and geochemistry.

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