Geological Survey of Finland
Current Research 1995–1996

edited by Sini Autio
Cover: The ratios from airborne gamma-ray data (blue dots), and the two main groups of the ratios indicating the known gold occurrences (red and green dots) in the Kuusamo schist belt. The yellow dots indicate the ratios of Juomasuo deposit. The figure is from the article Hilkka Arkima: The fingerprints of known gold occurrences in the Kuusamo schist belt as shown by airborne gamma-ray spectrometric data.
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The publication contains 22 articles outlining current research at the Geological Survey of Finland (GSF). The articles are separated into five categories. At the end of the publication there is a list of publications by GSF staff in 1995 and 1996.

The article on Economic geology and mineral exploration have been studied at the Vihanti zinc deposit and Kälviä ilmenite occurrence in western Finland. The Kutemajärvi gold deposit in southern Finland has been target for isotopic studies. Airborne gamma-ray spectrometric data have been discussed for a known gold occurrence in northern Finland. Large gold nuggets from Finnish Lapland, and carbonate rock units in Uusimaa are investigated. The history of mining activity in Finland is also reviewed.

Jointing and fracturing of drill cores have been described in one article.

Most numerous articles fall under subheading Quaternary geology and related studies, dealing with large scale topics as like Glacial and late-glacial development in northern Finland, to descriptions and development of Quaternary deposits, articles on wind-blown silt deposits, and sediment covered potholes in Helsinki. Impact crater rocks and minerals in Quaternary deposits are described as well as Quaternary deposits overlying sandstones in western Finland. A preliminary study on combining Quaternary geological databases and a digital elevation model is presented. Palaeontological studies include an article on Palaeozoic acritarchs, and a study on indications of prehistoric activity in western Finland is also presented.

Articles on chemical composition of clays and techniques on the leachability of elements in tills are included. Causes of mortality related to coronary heart disease have been discussed with respect to the influence of geochemical environmental factors.

Also information concerning petrophysical studies in the Crustal Model Program of Finland is included. New apparatus for electric conductivity and temperature logging are described. New maps are represented by a digitized geological map of Finland, while geophysical maps of central and northern Fennoscandia of Mid-Norden Project are presented. At the end of the publication there is Presentation of on line reference data bases and information concerning publication activity at the GSF.

Key words (GeoRef Thesaurus, AGI): Geological Survey of Finland, current research, projects, bibliography

Sini Autio
Geological Survey of Finland, P. O. Box 96, FIN-02151 ESPOO, FINLAND
E-mail: sini.autio@gsf.fi

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## CONTENTS

### Economic geology and mineral exploration

- Geochemical comparison of metamorphosed black shales associated with the Vihanti zinc deposit and prospects in western Finland, *Kirsti Loukola-Ruskeeniemi, Urpo Kuronen and Hilka Arkimaa* .......... 5

- Ilmenite exploration in western Finland, and the mineral resources of the Kälviä deposit, *Niall Kärkkäinen, Olli Sarapää, Matti Huuskonen, Esko Koistinen and Jukka Lehtimäki* ......................... 15

- The fingerprints of known gold occurrences in the Kuusamo schist belt as shown by airborne gamma-ray spectrometric data, *Hilka Arkimaa* .................................................................................................................. 25

- Nondestructive analysis of morphology, chemical composition and physical properties of large gold nuggets from Finnish Lapland, *Kari A. Kinnunen, Bo Johanson, Mauri Terho and Risto Puranen* 29

- Carbonate rock units in the Svecofennian Uusimaa Belt, SW Finland, *Jukko Reinikainen* .......................... 37

- Mining in Finland during the period 1530—1995, *Kauko Puustinen* ................................................................. 43

- Isotopic studies on the Kutemajärvi gold deposit, Orivesi, southern Finland, *Irmeli Mänttäri, Ari Luukkonen and Pentti Grönholm* ................................................................. 55

### Quaternary geology and related studies

- Glacial and late-glacial development in NE Kittilä, northern Finland, *Peter Johansson, Raimo Kujansuu and Kalevi Mäkinen* ................................................................. 59

- Wind-blown silt: a loss-like deposit in Finland. An example of aeolian activity and deposits associated with deglaciation near the centre of a glaciated area, *Heikki Rainio* ......................... 67

- Two till-covered potholes at Pihlajamäki, Helsinki, southern Finland, *Heikki Hirvas and Pekka Huhta* .................................................................................................................. 73

- Lappajärvi impact crater rocks and minerals in Quaternary sediments, *Marjatta Koivist and Juha V. Korhonen* .................................................................................................................. 79

- Almost 100 m of Quaternary deposits on sandstone at Karhunkangas, Kauhajoki, western Finland, *Pekka Huhta* .................................................................................................................. 89

- Palaeozoic acritarchs in till-covered sand deposits at Kauhajoki, western Finland, *Raimo Kujansuu and Anneli Uutela* .................................................................................................................. 93

- Indication of prehistoric human activity in an area rich in cairns in Ostrobothnia, western Finland, *Irmeli Vuorela* ........................................................................................................ 99

- Combining Quaternary geological and digital elevation model, *Jukka-Pekka Palmu* ........................................ 109
Geochemical and environmental studies

Chemical composition of clays in southwestern Finland, Reijo Salminen, Marjatta Kukkonen, Tarja Paukola and Seppo Töllikkö ................................................................. 117
Effects of pretreatment and partial decomposition techniques on the leachability of elements in podzolized tills, Lea Hämäläinen, Marja Liisa Räisänen and Olli Lehto .................................................. 127
Geochemical environment in areas of low and high coronary heart disease mortality, Anne Kousa and Maria Nikkarinen ........................................................................................................... 137

Geophysical studies and technical developments

A new apparatus for electric conductivity and temperature logging of soft sediments, R. Puranen, M. Mäkilä, K. Sulkonen and A. Grundström .............................................................. 149
Petrophysics in the Crustal Model Program of Finland, Juha V. Korhonen, Heikki Säävuori and Liisa Kivekäs ................................................................. 157
Defining jointing and fracturing from photographs of drill cores, Esko Koistinen and Niilo Kärkkäinen ........................................................................................................... 175

Mapping and information technology

Digitized geological maps of Finland, Boris Saltikoff, Markku Tiainen, Mikko Tontti, Matti Lehtonen and Esko Koistinen ........................................................................................................... 181
Mid-Norden Project, Geophysical Sub-Project: Introduction to combined geophysical maps of central and northern Fennoscandia, T. Ruotoistenmäki, S. Elo, S. Aaro, E. Kauniskangas, C. Kortman, J. Skilbrei and T. Tervo ........................................................................................................... 185
Internet online data bases produced by the Geological Survey of Finland, Caj Kortman ............... 193

Appendix 1. Papers published by Geological Survey of Finland staff in 1995
Appendix 2. Papers published by Geological Survey of Finland staff in 1996
Appended map 1. Gravity anomaly map of Northern and Central Fennoscandia.
Appended map 2. Aeromagnetic anomaly map of Northern and Central Fennoscandia.
GEOCHEMICAL COMPARISON OF METAMORPHOSED BLACK SHALES ASSOCIATED WITH THE VIHANTI ZINC DEPOSIT AND PROSPECTS IN WESTERN FINLAND

by

Kirsti Loukola-Ruskeeniemi\(^1\), Urpo Kuronen\(^2\) and Hilkka Arkimaa\(^1\)

\(^1\)Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
\(^2\)Outokumpu mining Australia PTY LTD, 1. Floor, Burswood Court, 141 Burswood Road, Burswood, WESTERN AUSTRALIA 6100
e-mail: kirsti.l-r@gsf.fi

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Introduction

From the point of view of economic geology, the most interesting occurrence in the Vihanti area is the Vihanti (Lampinsaari) zinc ore deposit. A total of 1,406,496 tons of zinc, 128,475 tons of copper, 98,489 tons of lead, 190,395 kg of silver, and 3,083 kg of gold were mined by the Outokumpu Company during 1954—1992. The deposit was discovered by the Geological Survey of Finland after local citizens had sent samples of mineralized glacial erratics to the Survey. A magnetic and electric anomaly was encountered in the presumed source area of the boulder train and diamond drilling revealed several parallel mineralized zones. Further exploration has been carried out in the area ever since, but it has not yet proven successful. The terrain is covered by extensive swamps, and outcrops are rare. Geophysical survey, the search for anomalous boulders and till geochemistry are therefore key methods in exploration, and based on this information, several prospects have been drilled during the past decades, mainly by the Outokumpu Company. Occurrences have been found, but none of them have been of economic grade.

The aim of the present research is to compare chemical and textural characteristics of graphite-bearing rocks encountered in the Vihanti zinc mine with those at the prospects; graphite-bearing rocks might constitute a useful exploration tool in poorly exposed areas such as Vihanti because they can be located and even classified by geophysical measurements (Airo and Loukola-Ruskeeniemi 1991). The research is a joint work where the main responsibilities are divided as follows: K.L-R., geochemistry and textures of black schists; U.K., geology and stratigraphy of the prospects; and H.A., geophysics.

Regional geology and geophysics

The bedrock of the Vihanti area consists mainly of gneisses and granitic, granodioritic and gabbroic rocks. The host rock association of the Vihanti Lampinsaari Zn is enveloped by mica gneisses and consists of dolomite, calc-silicate rocks, metavolcanics, graphite-bearing schists and cordierite gneisses. Rock associations resembling that of the Lampinsaari deposit have been encountered in several prospects. Rocks in the Vihanti area are Early Proterozoic in age, and have undergone several phases of deformation. Age determinations on whole rock samples from the U- and P-rich rocks of the Lampinsaari rock association indicate that the rocks underwent amphibolite facies metamorphism about 1880 Ma ago (Rehtijärvi et al. 1979). The rocks in the Pattijoki prospect represent a more sediment-dominated environment than rocks in the Vihanti area, and black shales constitute thicker beds that are not as intensely deformed as in the Vihanti area.
Fig. 1. Hill-shaded magnetic map covering the study area. Red colour indicates Re/Im values bigger than two. The original data are from low-altitude geophysical survey flown with an average terrain clearance of 30—40 m and line spacing of 200 m. For image processing purposes grids with cell size of 50m * 50m were interpolated.
Maps of airborne geophysical data were compiled and processed for qualitative interpretation. In the south and west the study area is characterized by strong magnetic anomalies mainly caused by mafic intrusions. The susceptibility of these rocks is due to magnetite and causes negative electromagnetic in-phase anomalies. The narrow schist belts also contain rather high magnetic anomalies that typically correlate with high positive electromagnetic anomalies. The conductive overburden and bedrock structures are shown well by the electromagnetic out-of-phase component.

Geophysical properties of metamorphosed black shales have previously been studied elsewhere in Finland, especially in the Kainuu schist belt (Tervo 1980, Airo and Loukola-Ruskeeniemi 1991) and during graphite exploration projects (Kukkonen 1984, Niskanen et al. 1992). In the Kainuu schist belt the black shale-hosted Ni-Cu-Zn mineralization can be distinguished from the other black shales with lower electrical resistivities (Tervo 1980). The aeromagnetic anomalies related to the black shale-hosted Ni-Cu-Zn mineralization have been found to be strong with irregular highs having high induced and remanent magnetization (Airo and Loukola-Ruskeeniemi 1991).

The main characteristics related to graphite bearing rocks in the highly metamorphosed and tectonized Vihanti area is that they appear both as magnetic and electromagnetic anomalies on the airborne geophysical maps. Magnetic anomalies appear as strong anomaly peaks varying between 500—3000 nT in studied formations. Electromagnetic in-phase anomalies in these formations vary between 1000—4500 ppm and out-of-phase anomalies between 500—2500 ppm.

The ratio values between electromagnetic in-phase and out-of-phase components, which indicate differences in conductivity, were determined. Re/Im values bigger than two, typically for very good conductors, characterize five of the seven studied prospects: Pattijoki, Lukkaroinen, Lampinsaari, Vilminko and Isokangas (Fig. 1). Nevasaari and Kuuhkamo, both located under thick conductive overburden, have lower ratio values (Re/Im<1). Studies based on geophysical ground survey and petrophysical measurements, which were not available for this study, are needed to achieve more detailed geophysical interpretation from the graphite bearing metasediments in the area.

In Figure 1, only the most conductive parts of the graphite-bearing layers are shown in red, and therefore it is not possible to follow the narrow and less conductive graphite-bearing layers on this geo-

physical anomaly map. Layers of graphite-bearing rocks occur in several prospects in the Vihanti area in the immediate vicinity of the hydrothermally altered rocks (Fig 2). In the Lampinsaari ore complex, graphite-bearing schists occur in close association with quartz rocks and dolomites (Rouhunkoski, 1968). Some of the graphite-bearing schists in the Lampinsaari deposit have been interpreted to show tuffitic features.

Zinc deposit and prospects

Studies of the geology of the Lampinsaari mine include, for example, those by Mikkola (1963), Rouhunkoski (1968), Wennervirta and Rouhunkoski (1970) and Rehtijärvi et al. (1979). Because of the lack of outcrops, observations are based on underground studies. The Lampinsaari association, favourable to the occurrence of ore, is enveloped by intensely metamorphosed mica gneiss with amphibolite intercalations. Lithological units at Lampinsaari are disrupted by numerous faults with displacements characteristically of the order of 5 m. Faults are commonly occupied by mafic and granitic dykes. The total thickness of the mineralized sequence is about 2 km, with a maximum width of 0.5 km and extensions to a depth of 700 m. Above the 400 m-level, the sequence becomes thicker, which is attributed to monoclinal folding.

The main rock type within the Lampinsaari association is a felsic metavolcanic which is in places homogenous quartz porphyry, in places tuff or tuffite. Other rocks include dolomite, calc-silicate rocks, cordierite gneiss and metamorphosed black shales. The same rock association is encountered at the Kuuhkamo, Vilminko and Isokangas prospects (Fig. 2).

Vihanti ore deposit consists of zinc ore bodies, pyrite ore bodies, disseminated copper ore bodies and uraninite-apatite occurrences. Graphite-bearing tuff is present in the same horizon with zinc ore bodies, which are hosted either by calc-silicate rocks and dolomites or by felsic volcanics. The Zn concentration of the zinc ores ranged from 5—14%, Cu concentration 0.4—1% and Pb concentration 0.3—0.7%. Trace element concentrations were on average: Au 0.4 g/t, Ag 26—30 g/t, Se 0.004 %, Sb 0.02%, As 0.01—0.05%, Co 0.005%, Ni 0.01%, Mo 0.005—0.02%, Cd 0.03%. Main ore minerals were sphalerite, chalcopyrite, galena, pyrrhotite and pyrite. Accessory minerals included cubanite, vallerite, gudmundite, tetrahedrite and tennantite as well as metallic gold. Massive, brecciated and disseminated ores were encountered. Pyrite ore
Fig. 2. Geology and stratigraphy of the Vihanti Lampinsaari Zn deposit and the Kuuhkamo, Vilminko, Isokangas and Nevasaari prospects.
Geochemical comparison of metamorphosed black shales ...

VILMINKO
y=567.000 (A - B)

VILMINKO
Prof. C - D

R1714 (Prof. K=40.40)
L=61.060

R1715 (Prof. K=40.80)
L=61.220

ISOKANGAS
bodies consisted mainly of pyrite, although the marginal parts of the ore bodies contained abundant pyrrhotite. The host rocks to the pyrite ores are felsic volcanics. Sulphur concentrations ranged from 20—35% and average Cu and Zn concentrations from 0.2—0.4%. Disseminated copper ore bodies are hosted by felsic volcanics. The main ore minerals are pyrite and pyrrhotite with chalcopyrite and sphalerite. Average concentrations were 0.5% Cu, 0.1—0.5% Zn and 10—15% S. Enrichments in U and P are hosted by dolomite and quartz feldspar porphyry (originally acid tuff), with average concentrations of 0.03% U and 3—5% P₂O₅. The sulphide ores have been considered as syngenerative and ore forming processes related to felsic volcanic activity (e.g. Rauhamäki et al. 1978).

Metamorphosed black shales are encountered in the Vihanti deposit in several profiles. Intense deformation has obscured the picture, but one interpretation is that a black shale bed with thickness exceeding 20 m originally occurred above the ore horizon, and a less than 3-m-thick S-rich layer containing around 1% organic C occurred below the ore horizon. Near zinc ore bodies the metamorphosed black shales contain abundant sulphide-rich veins.

**Geochemistry of metamorphosed black shales**

Concentrations of graphitic carbon and sulphur. Geochemistry of metamorphosed black shales from the Vihanti Lampinsaari deposit was studied with 45 samples, each representing a 30-cm-long unweathered section in drill core. Median value of graphitic C is 3.9%, a lower value compared with the median values of black shales in the Kuuhkamo and Pattijoki prospects (Figs. 1 and 2), as well as compared with those in the Kaustinen and Luopioinen prospects south of the Vihanti area. The median sulphur concentration of 9%, however, is high compared with the median S concentrations of black shales at the Kuuhkamo and Kaustinen prospects (Table 1).

In the Vihanti deposit, two different groups can be distinguished according to the ratio between the concentrations of graphitic carbon and sulphur. These groups do not occur as separate layers but rather tend to be mixed (at least at present). One group resembles the Cgraf and S concentration ranges of the Kainuu-Outokumpu serpentinite-related metamorphosed black shales where these values point to hydrothermal input to seawater during deposition of the organic-rich mud (Loukola-Ruskeeniemi 1992). In the black shales of the Vihanti Zn deposit, Cgraf concentrations range from some 3% to 9% and sulphur from 6% to 12%, in the Kainuu-Outokumpu black shales the median values for both Cgraf and S are commonly around 7%. The other group in the Vihanti deposit, in contrast, contains 0.1—3% Cgraf but S concentration ranges linearly from practically zero to almost 20%.

In Table 1, these groups have not been separated from each other, and therefore the median values of Cgraf (4%) and S (9%) represent all samples with both Cgraf and S values exceeding 1%. In Figure 3, the fields are separated according to the number of samples (diagonal hachured area contains most of the samples and shaded area only some samples), not according to these groups. Metamorphosed black shales from the Vilminko, Lukkaroinen and Pattijoki prospects show corresponding Cgraf and S values with the Vihanti Zn deposit black shales, but those of the Kuuhkamo prospect differ in their high Cgraf concentration (median value is as high as 15.5%). This might be due to enrichment of graphite during intense tectonic processes.

Calcium concentrations of the Vihanti black shales range from some 1% to some 6% with a median concentration of 3.2%. A calcium concentration of 3.5% separated black calc-silicate rocks from black shales at the Talvivaara black shale-hosted Ni-Cu-Zn occurrence in eastern Finland, with the former also showing differences in other element abundances, such as elevated Mg, F, P, and Ag concentrations compared with the low Ni-Mn and Ni-rich black shales (Loukola-Ruskeeniemi and Heino 1996). The black calc-silicate rock layers at Talvivaara exhibit rare earth element values typical of Mn-rich seawater near recent hydrothermal sites and heavy δ²⁵⁴S values (from -3.8‰ to +20.8‰) for pyrrhotite and -7.1‰ to +20.8‰ for pyrite). In the Vihanti deposit black shales, Ca values exceeding 3.5% do not form a distinct group, but Ca values gradually increase, just as in the black shales associated with the Outokumpu Cu-Co-Zn deposits at Outokumpu in eastern Finland (Loukola-Ruskeeniemi 1992). This suggests a gradually increasing enrichment of Ca in the vicinity of the Ca-rich rocks such as the present dolomites and calc-silicate rocks. Calcium concentrations in the Vilminko, Lukkaroinen and Kuuhkamo prospect black shales resemble those at the Vihanti deposit. Manganese concentrations are especially high at the Pattijoki prospect, with a median value of 0.6% Mn. At Pattijoki, alabandite (MnS) has also been found (Törnroos 1982). Mn-rich horizons containing alabandite are also characteristic of the Talvivaara occurrence (Loukola-Ruskeeniemi...
Table 1. Median values of selected elements in graphite-bearing metasediments (C > 1% and S > 1%) associated with the Vihanti Lamminsaari Zn mine and the Kuuhkamo and Pattijoki prospects (Figs. 1 and 2), Kaustinen prospect in Ostrobotnia, some 150 km south of Vihanti and the Luopioinen graphite occurrence, some 350 km south of Vihanti. Values from the low Ni-Mn metamorphosed black shales (Ni < 0.1% and Mn < 0.8%) at Talvivaara, eastern Finland, are shown for comparison. Carbon and sulphur concentrations were analysed by LECO analysers and the other elements by ICP-AAS at the Geological Survey of Finland except for Hg, which was analysed by cold vapour AAS at X-Ray Assay Laboratories in Canada. n = number of samples, n.d. = not determined.

<table>
<thead>
<tr>
<th>Element</th>
<th>Vihanti Zn mine</th>
<th>Kuuhkamo prospect</th>
<th>Pattijoki prospect</th>
<th>Kaustinen prospect</th>
<th>Luopioinen prospect</th>
<th>Talvivaara low Ni-Mn black schists</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cgraf %</td>
<td>3.9</td>
<td>15.5</td>
<td>4.2</td>
<td>5.3</td>
<td>11.8</td>
<td>7.7</td>
</tr>
<tr>
<td>S %</td>
<td>9.0</td>
<td>5.2</td>
<td>8.7</td>
<td>2.7</td>
<td>7.3</td>
<td>8.9</td>
</tr>
<tr>
<td>Al %</td>
<td>5.7</td>
<td>5.5</td>
<td>5.3</td>
<td>6.9</td>
<td>5.8</td>
<td>6.3</td>
</tr>
<tr>
<td>Ca %</td>
<td>3.2</td>
<td>3.7</td>
<td>2.9</td>
<td>2.3</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Co ppm</td>
<td>25</td>
<td>35</td>
<td>35</td>
<td>10</td>
<td>25</td>
<td>50</td>
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<td>Cr ppm</td>
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<td>120</td>
<td>130</td>
<td>75</td>
<td>130</td>
<td>140</td>
</tr>
<tr>
<td>Cu ppm</td>
<td>285</td>
<td>120</td>
<td>400</td>
<td>100</td>
<td>570</td>
<td>610</td>
</tr>
<tr>
<td>Fe %</td>
<td>11.0</td>
<td>8.1</td>
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<tr>
<td>Hg ppb</td>
<td>70</td>
<td>17</td>
<td>400</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1420</td>
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<td>K %</td>
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<td>n.d.</td>
<td>35</td>
<td>30</td>
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<tr>
<td>Mg %</td>
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<td>1.8</td>
<td>1.5</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Mn ppm</td>
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<td>500</td>
<td>5550</td>
<td>375</td>
<td>405</td>
<td>2400</td>
</tr>
<tr>
<td>Mo ppm</td>
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<td>65</td>
<td>50</td>
<td>15</td>
<td>n.d.</td>
<td>60</td>
</tr>
<tr>
<td>Na %</td>
<td>1.5</td>
<td>1.2</td>
<td>0.3</td>
<td>1.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Ni ppm</td>
<td>425</td>
<td>320</td>
<td>300</td>
<td>140</td>
<td>445</td>
<td>380</td>
</tr>
<tr>
<td>P ppm</td>
<td>525</td>
<td>670</td>
<td>1200</td>
<td>775</td>
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<td>Sc ppm</td>
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<tr>
<td>Si ppm</td>
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<td>n.d.</td>
<td>26.1</td>
<td>20.3</td>
<td>21.4</td>
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<tr>
<td>Sr ppm</td>
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</tr>
<tr>
<td>Ti %</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
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<tr>
<td>V ppm</td>
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<td>885</td>
<td>545</td>
<td>330</td>
<td>780</td>
<td>740</td>
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<td>Y ppm</td>
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<td>50</td>
<td>50</td>
<td>40</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Zn ppm</td>
<td>715</td>
<td>430</td>
<td>605</td>
<td>255</td>
<td>2085</td>
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<td>Zr ppm</td>
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<td>90</td>
<td>75</td>
<td>135</td>
<td>110</td>
<td>100</td>
</tr>
</tbody>
</table>

n = 45

and Heino, 1996).

Copper and zinc concentrations in the Vihanti-Pattijoki black shales are elevated compared with ‘average’ black shales (Vine and Tourtelot, 1970) and evidence for hydrothermal input, although values are not as high as at Talvivaara (Table 1). Cobalt concentrations are higher at Talvivaara, but the nickel concentrations of the low Ni-Mn black shales of Talvivaara do not differ from those of the Vihanti-Pattijoki black shales. Mercury values are not high on average in the Vihanti black shales, but at Pattijoki two samples exhibit values greater than 1500 ppb. However, values at Talvivaara are much higher still, with a maximum of 7500 ppb.

Metamorphosed black shales from drill core 644 in profile 130 at the Vihanti mine were comprehensively analysed. Altogether 14 samples were selected, two of them from a thin separate layer (depths 5.75 m and 7.16 m in drill core) and the rest from the interval between 37.75 m and 66.90 m in the same drill core. Silver concentrations up to 5 ppm were encountered, boron concentration varied from 17 to 235 ppm, maximum Bi concentration was 0.4 ppm, Ce concentration ranged from 31 to 93 ppm, F concentration from 430 to 1600 ppm, Hf concentration from 3 to 5 ppm, maximum Nb concentration was 4 ppm, Pb concentration varied from 16 to 153 ppm, Sb concentration from 1 to 11 ppm, maximum Se concentration was 20 ppm, and maximum Sn concentration 2 ppm, Th concentration ranged from 2.2 to 5.6 ppm, Ti concentration from 2 to 10 ppm, U concentration from 2.6 to 19.3 ppm, maximum W concentration was 5 ppm. These values are comparable with those for the Talvivaara black shales; they show hydrothermal addition of certain elements, but not such pervasive alteration and enrichment as in certain parts of the Talvivaara occurrence.

Concentrations of iridium, platinum, palladium and gold were detected by ICP-MS from four samples of drill core 644 and from one sample from the Pattijoki prospect. All samples show Ir depletion,
and Pd/Ir ratio varies from 50 to 138 at Vihanti and is 154 at Pattijoki. The sample from Pattijoki contains 1.4% Mn and 7.3% Ca and has higher Pt and Pd but a lower Au concentration than the Vihanti samples. However, all values are low: maximum Pd concentration is 42 ppb, Pt 27 ppb, and Au 84 ppb. Higher Pt, Pd, and Au concentrations are found in the Kainuu-Outokumpu and Luopioinen black shales (Loukola-Ruskeeniemi 1995). The high Pd/Ir ratio in the Vihanti and Pattijoki black shales suggest that seafloor hydrothermal processes were responsible for the generally elevated but not high PGE concentrations encountered in these black shales, since MORBs show similar trends (Hertogen et al. 1980).

Carbon isotope $\delta^{13}C$ values were determined from three black shale samples at the Geological Survey of Finland by Juha Karhu. Two samples from the Kuuhkamo prospect, from drill core 13: 187.50 m (Fig. 2) containing 27% C and 2% S, and from drill core 23: 404.67 m (Fig. 2) containing 1% C and 9% S, have C isotope values of -26.71‰ and -25.77‰, respectively. An anomalously high C isotope value of -16.08‰ was determined from profile 130: drill core 641: 3.34 m, at the Vihanti deposit, from a black shale with 8% C and 8% S. The values from the Kuuhkamo black shales are within the range of organic matter in sedimentary rocks (Schidlowski 1987) and the black shales of Talvivaara (Loukola-Ruskeeniemi and Heino

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Fig. 3. Concentrations of sulphur, graphitic carbon, copper, zinc, calcium, manganese, mercury and vanadium in the metamorphosed black shales of the Vihanti Lampinsaari Zn deposit (most of the samples are in the diagonally hachured field and only some samples in the shaded area), and the Pattijoki, Vilminko, Kuuhkamo and Lukkaroinen prospects.
1996). The -16‰ value from the Vihanti deposit is probably the result of alteration processes in which the higher C isotope values of CO₂ from the present dolomites and calc-silicate rocks modified the primary organic C isotopic values during hydrothermal or metamorphic processes. The Vihanti sample contains 5% Ca, and the Kuuhtamo samples 2% Ca. An elevated C isotopic value of -19‰ has also been recorded from a black shale sample at the Outokumpu-type Kylylahti prospect in eastern Finland (Loukola-Ruskeeniemi 1991).

Conclusions

Metamorphosed black shales are present in the Vihanti-Pattijoki area in association with zinc ore deposit and prospects. Geochemically, these black shales show evidence of hydrothermal input, although not as strong as in the Talvivaara black shale-hosted Ni-Cu-Zn occurrence in eastern Finland. Proximity to dolomites and calc-silicate rocks is seen in elevated Ca concentrations and an anomalously high δ13C value. Comparison of the geochemistry of metamorphosed black shales of the Vihanti Lammasaari Zn deposit with those of the prospects reveals that black shales of the Pattijoki prospect are different from the others and reflect a different type of environment of deposition: the formations are thicker, manganese, phosphorus and mercury concentrations are higher and sodium and strontium concentrations are lower. At the Kuuhtamo prospect, black shales in certain parts of the profiles exhibit high graphitic carbon concentrations, probably because of enrichment of graphite during intense tectonic deformation.

What has been the role of sediments rich in organic matter in the ore forming processes of Vihanti-type Zn-Cu-Pb ores? It is possible that the same geological environment that is favourable for the formation of ores, is also suitable for the precipitation of sediments rich in organic matter and sulphur. Part of hydrothermal fluids escaped to seawater and precipitated in mud rich in organic matter, while at the same time or later, ore-forming fluids precipitated under the organic-rich layer.

References


ILMENITE EXPLORATION IN WESTERN FINLAND, AND THE MINERAL RESOURCES OF THE KÄLVIÄ DEPOSIT

by
Niilo Kärkkäinen, Olli Sarapää, Matti Huuskonen, Esko Koistinen and Jukka Lehtimäki

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
E-mail: niilo.karkkainen@gsf.fi

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Introduction

The exploration programme of the Geological Survey of Finland (GSF) at the Koivusaarenneva gabbro was completed in 1995. The total length of holes drilled was 7400 m. The data were analysed, interpreted and filed as non-public reports in the GSF’s central archives, Espoo. The results were delivered to the Ministry of Trade and Industry, which invited companies to apply for the rights to conduct geological and technical investigations for commercial development and exploitation of the Kälviä (Koivusaarenneva) Ilmenite Deposit.

Previous experience and the new data from Kälviä, and other parts of Svecofennian Domain, suggest that Svecofennian bedrock has good potential for high-quality ilmenite mineralization in mafic intrusions (Fig. 1).

Regional exploration

The GSF is continuing exploration in the vicinity of the Koivusaarenneva gabbro. One drilling prospect is the Peräneva claim on the southwestern side of the Koivusaarenneva intrusion (Fig. 2). Peräneva was revealed by a gravity high during recent regional gravity mapping (map sheet 2341 02).

Exploration is still under way on the 3-km-long Lylyneva ilmenite-apatite gabbro, east side of Koivusaarenneva. So far 12 holes (1.4 km) have been drilled, with 2—10 m long intersections of good-

Fig. 1. Ilmenite-potential Svecofennian gabbro provinces; Kälviä deposit (Koivusaarenneva) at the southern border of the Ylivieska gabbro province.
quality, weakly magnetic ilmenite ore (20—30% ilmenite, Table 1).

A new exploration target, the Kumiseva gabbro, is a large (50 km²) rounded, well-differentiated layered intrusion 60 km east of the Källivaä deposit. It has numerous showings of ilmenite and some prospects of pentlandite, gold-copper and PGEs. Oxide showings comprise ilmenite-rich boulders, ilmenite rich heavy mineral concentrates of till samples, heavily disseminated ilmenite and massive ilmenite-magnetite layers in outcrops. In its first phase, the ground geophysical study will cover an area of 35 km², and drilling 1—2 km. Mineralogical studies show that the Kumiseva gabbro is characterized by the common occurrence of individual grains of pure ilmenite and magnetite, a high bulk-rock ratio of titanium to iron (TiO₂/Fe₂O₃ > 0.25), and anomalous phosphorus contents (0.5—3.5% P₂O₅).

The Kauhajärvi gabbro, a pilot target of the GFS's ilmenite project, was investigated during 1991—1993. This intrusion, which lies in the Kauhajoki Ti-P gabbro province, was discovered due to high-altitude aeromagnetic anomalies, that were first studied for iron (Pääkkönen 1960) and later for phosphorus at Perämaa, Honkajoki (Pakarinen 1984, Rämö 1986).

The gabbros of the Kauhajoki area form a chain around late-orogenic granites of the Lauhanvuori type. The gabbros are typical layered mafic intrusions, in which the basal zone consists of gabbronorites and peridotites, and the upper part is rich in plagioclase (Kärkkäinen & Bornhorst 1995). The mineralized parts of the Kauhajärvi gabbro contain 4—7% apatite and 7—12% ilmenite. Much of the titanium is incorporated in separate ilmenite grains, although ilmenomagnetite is a common oxide (Kärkkäinen & Appelqvist, in prep.). The ilmenite/magnetite ratio is generally 2, but in magnetite rich layers 0.5—I.2. Good quality concentrates of ilmenite, magnetite and apatite have been obtained in concentrating tests. The deposit is subeconomic, partly because of the thick overburden. After the active exploration stage, the low-altitude aerogeophysical survey, conducted in 1994, revealed a new Ti potential target at Möykkykylä (Lumikangas), 20 km northwest of Kauhajärvi.

Preliminary studies are being carried out in southern Finland, where some mafic intrusions contain good-quality ilmenite in historical iron mines (Sipilä 1981, Vaasjoki & Heikkinen 1962, Härne 1955, Pehrman 1925).

Källivaä ilmenite deposit

General

The Källivaä ilmenite deposit is hosted by the Koivusaarenneva gabbro, a layered mafic intrusion emplaced into granitoids at the contact zone of the Central Finland Granitoid Complex and the Bothnian Schist Belt (Chernet & Kärkkäinen 1995). The intrusion consists of two zones: an older ilmenite gabbro, and a younger apatite gabbro. Only a few holes have been drilled into the apatite gabbro, and previous descriptions deal only with
the ilmenite gabbro (Chernet & Kärkkäinen 1995). Typical features of the ilmenite gabbro are well-developed layering, oxide-rich zones (8—48% ilmenite, 2—22% magnetite) and scarcity of apatite. The apatite gabbro in contrast, which contains

drilled at 50—150 m profile intervals. The drilling was based on geophysical studies, the results of which were also used to delineate the contacts of the intrusion, fault and fracture zones and the thickness of overburden.

Exploration geophysics

The Koivusaarenneva gabbro is situated on an areal gravity gradient, where the regional level increases 3 mGal over a distance of 1.5 km (Fig. 3). The maximum gravity anomaly caused by the Koivusaarenneva intrusion is 4 mGal as measured from the estimated level of the regional gravity field.

The most intensely mineralized parts of the intrusion are visible on the gravity map as local maxima and as a steep gradient of the anomaly near the southeastern margin. The dip of the ore layers cannot be estimated reliably, and is based on drilling data in calculations. The main features of the intru-
sion are visible only on various derivative gravity maps. The mineralized, southeastern side of the intrusion is clearly visible on the magnetic map (Fig. 4). The anomaly, at its highest 10 000 nT, is caused by magnetite and remanent magnetism. The northwestern side of the intrusion is magnetically almost neutral.

Gravity interpretation indicates that the deposit extends to a depth of 300—400 m (Fig. 5) when the differences in rock densities are as suggested in Figure 7.

The aim of the seismic refraction soundings was to study the thickness of glacial overburden and weathered bedrock, to localize fractured zones and to delineate the dimensions of the intrusion. Both the high seismic wave velocities (> 6000 m/s), typical of gabbro-class rocks, and the low velocities, typical of fractured zones, were observed in the mineralized part of the intrusion.

Classification and ore types

Four main petrographic types of oxide ore can be distinguished:

1) massive, banded or brecciated or heavily disseminated ilmenite ore (> 18% ilmenite), with the ratio of ilmenite to magnetite more than 2.5,

2) massive magnetite-ilmenite ore, in which the abundance of magnetite equals that of ilmenite, and which occurs as a thin layer (1—4 m) in the lower contact of the pyroxenite;

3) disseminated ilmenite ore (8—18% ilmenite) with or without magnetite, representing low-grade ore; and

4) ilmenomagnetite ore as part of the low grade ore (8—18% ilmenite). In this ore type separate Fe-rich layers occur near the basal zone of the intrusion, the ratio of ilmenite to magnetite is 1—1.5, and typical oxide grains are composed of lamellar ilmenite-magnetite intergrowths, but individual ilmenite grains or aggregates are common.

The mean grain size of ilmenite is 0.7 mm, rang-
Ilmenite exploration in western Finland, and the mineral resources of the Kälviä deposit.

Section 21.160

Fig. 6. Geological cross section of profile k=21 160.

Fig. 7. A plot of ilmenite against density; a basis for the geophysical resource estimation (see text). Two trends represent the main ore zone and the ilmenomagnetite-dominant basal zone.

Fig. 8. The two correlation trends of ilmenite and magnetite.
Table 2. Chemical compositions of ore minerals and mineral concentrates of the Kälvä ilmenite deposit.

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1—3. Representative microprobe analyses of oxides (by Bo Johanson, Lassi Pakkanen/GSF's Camec): 1. ilmenite R373-52.00; 2. ilmenite R373-190.70; 3. magnetite R373-196.00; 4. Ilmenite concentrate R342; a laboratory-scale mineral processing test; 5. Magnetic concentrate, XRF, mean of DDT R344 - 377, n=41.

The average titanium content of the Koivusaaren-ilmenite is about 50% TiO₂, ranging from 48% to 51% in microprobe analyses. The chromium and vanadium contents in ilmenite feed are lower than that of magnetic concentrates, but manganese and sulphur values are higher (Fig. 9). The uranium and thorium contents of the deposit are very low, 0 to 2 ppm U, and 0 to 1 ppm Th.

Near the surface the bedrock is weathered in places, resulting in subaerial oxidation of magnetite into martite and ilmenite, and partly into leucoxene components (Chernet and Kärkkäinen 1995). Weathering is prominent in fault zones. The average thickness of the weathered bedrock is 12 m.

The average abundances of ilmenite and magnetite in the four ore types are presented in Fig. 10.

In a mineral resource estimate based on ore grade, the ilmenite deposit is classified into two groups (Table 1): a) a high-grade type, TiO₂ > 9%, (ilmenite > 18%), and b) a low-grade type, 4—9% TiO₂, (ilmenite 8—18%).

In the first group, the total abundance of oxides averages 34.8%, of which 25.8% is ilmenite, 8.8% magnetite and 0.18% vanadium (Table 1). The lower grade ore contains 15.7% oxides, the majority being ilmenite (11.6%). The abundance of vanadium is anomalous, 0.12%. Chromium and nickel contents, both in bulk-rock samples and in oxide minerals, are highest in the metapyroxenite.

Mineral resources

Mineral resources are divided by chemical composition into those with more than 18% ilmenite and those with 8—18% ilmenite. The resources of the weathered part of the mineralization were calculated separately. The cutoff grade is 8% ilmenite.

The deposit is 2 km long, and composed of subvertical layers that were folded, deformed and partially fractured during syn- and post-orogenic movements. The ore layers are uniform for hundreds of metres. Fault zones cut the deposit along hundreds of metres. Fault zones cut the deposit along the longitudinal axis into three parts, called the southern, middle and northern bodies (Fig. 11).

The maximum thickness of a single mineralized zone is 107 m, in which the thickness of the high-grade ore is 50 m. As mentioned, the mineralization extends to a depth at least 300—400 meters according to gravity studies (Fig. 5). This is confirmed by a 330-m-long drill hole (DHS/Rautaruukki) with a vertical extension of 290 m. The average thickness of ore sheets is 61 m (range 24 to 107 m) in the 450-
Ilmenite exploration in western Finland, and the mineral resources of the Kälviä deposit

The main ilmenite ore lies above a pyroxenite layer in the upper section of the ilmenite-gabbro unit. A zone of disseminated oxides surrounds the massive oxide layers, but ore-grade oxide dissemination also occurs in separate layers, partly of ilmenomagnetite type (Fig. 6). Neither the ore grade dissemination of ilmenite in the apatite-gabbro unit nor some distant or isolated thin layers of a low-grade disseminated ilmenite ore are included in the resource estimation.

The mineral resources are divided by a confidence level into two classes: probable A and probable B (Fig. 12). Probable A resources include the volume within a distance of 25 m above and below a drill hole. The volume of the next 50 m upwards and downwards includes probable B resources.
Fig. 10. Average abundances of ilmenite and magnetite in different ore types (1-4, see text) of the Kälviä deposit. The percentage is from 842 analyses.
Probable A and B are summarized on the map (Fig. 11).

The mineral resources have been calculated to a depth of 150 m, based on 74 drill holes with a total length of 9100 m. Total resources are 44 Mt with 15% ilmenite and 5% vanadiniferous magnetite (0.7% V). This includes 25 Mt of higher grade resources with 18% ilmenite (cutoff 13%) and 6% magnetite or 3.5 Mt with 30% ilmenite (cutoff 25%) and 8% magnetite. Probable resources thus amount 6.6 Mt ilmenite (= 2 Mt titanium, or 3.3 Mt TiO₂) and 2.2 Mt magnetite as vanadium ore feed (15 400 t vanadium).

Geological in situ resources between 150 and 300 m amount to 45 Mt with 15% ilmenite. Thus, the probable (A+B) and possible resources of the Kälviä...
deposit (to a depth -300 m) total 90 Mt with 15% ilmenite, and 5—6% vanadiferous magnetite (0.7% V). Gravity interpretation increases the total resources, especially in the southern part of the Koivusaarenneva intrusion.

The deposit is overlain by a 10-m-thick peat and till cover. The surface of the ore is weathered to a mean depth of 12 m, and its proportion of the resources is 4.6 Mt, with 15% ilmenite.

**Conclusion**

The Koivusaarenneva gabbro at Kälviä, western Finland, hosts an economically interesting titanium resource in terms of the quantity and quality of ilmenite.

The ilmenite deposit is a layered body, and contains massive ilmenite ore, ilmenite-magnetite ore, disseminated ilmenite ore and ilmenomagnetite ore. The main ore minerals are ilmenite and magnetite with average ratios of 3:1 in the best quality ore. Ore minerals occur as separate, pure grains except in the ilmenomagnetite-dominant layers, which lie stratigraphically at lower levels than the main ilmenite ore. Magnetite and ilmenite can be separated using wet magnetic separation (DDT test). Ilmenite contains 47—51% TiO₂, and magnetite < 0.5—1.5% TiO₂. Magnetite has 0.7% V. The concentrations of Cr, Ni, Zn, U (0—2 ppm) and Th (0-2 ppm) are low (Tables 1 and 2).

The Kälviä ilmenite deposit is classified as a magmatic titanium ore hosted by a mafic intrusion. As an ilmenite deposit it is characterized by enrichment of vanadium, most of it in magnetite. The mafic intrusion was emplaced in Svecofennian (1.9 Ga) tonalitic surroundings. The deposit is a rather large (44Mt/150 m, or 90 Mt/300 m) low-grade (15% ilmenite, 6% V-magnetite) ilmenite occurrence containing high-quality ilmenite.

Containing 44—46% TiO₂, the ilmenite concentrate from the Kälviä deposit meets the quality standards of commercial ilmenite concentrates from hard rock mines. Kälviä ilmenite can also be suitable for the feed of titania slag (70—85% TiO₂), which is raw material of the chloride process and Ti metal.

**References**


THE FINGERPRINTS OF KNOWN GOLD OCCURRENCES IN THE KUUSAMO SCHIST BELT AS SHOWN BY AIRBORNE GAMMA-RAY SPECTROMETRIC DATA

by

Hilkka Arkimaa

Key words (GeoRef Thesaurus, AGI): mineral exploration, gold ores, schist belts, gamma-ray methods, airborne methods, uranium, imagery, Proterozoic, Kuusamo, Finland

Introduction

The gold bearing deposits in the early Proterozoic Kuusamo volcano-sedimentary schist belt can be divided into two main ore types, the first being of the replacement sulphide ore type and the other of the breccia and vein ore type (Pankka & Vanhanen 1989, Pankka et al. 1991, Pankka 1992). Deposits with features of both types also exist. The two main ore types differ both geologically and geophysically. In ductile shear zones the replacement type contains more sulphides and therefore produces small but distinctive magnetic and electromagnetic anomalies unlike the non-magnetic and resistive host rocks. The other type, consisting of hydrothermal breccia pipes in brittle shear zones, usually contains less sulphides and cannot be detected by magnetic and electromagnetic measurements. The most successful ground measurements in the exploration of breccia type deposits have been radiometric and IP methods (Pankka et al. 1991).

Typical of the many gold occurrences in the Kuusamo schist belt is their enrichment in uranium mainly in the form of uraninite and brannerite. Detailed radiometric ground surveys led to the discovery of Au-Co-U-bearing mineralizations at Konttiaho and Sivakkaharju in the mid-1980s (Vanhanen 1989). Airborne magnetic and electromagnetic measurements have been used with success in gold exploration in the Kuusamo schist belt. Encouraging results have been obtained also from studies of the use of airborne gamma-ray data in searching for fingerprints of the known gold occurrences in the area (Arkimaa 1996).

The main features of the data

After correction for background, height and scattering and estimation of the apparent radioelement concentrations, the airborne gamma-ray spectrometric data still showed some level errors between flight lines. These were corrected by median filtering. For image processing, grids with a cell size of 50 m * 50 m were interpolated.

The multichannel and statistical nature of gamma radiation allows the effective use of digital image processing techniques in enhancing and analysing the data. Even slight changes in the concentration of radioelements can be outlined (Fig. 1).

Approximately 90% of the gamma radiation measured comes from the upper 0.5 m of the ground (Grasty 1976). The usefulness of the data is not, however, limited only to areas of extensive outcropping. In glaciated areas the use of gamma radiation is comparable to that of geochemical data. By considering the transport distances for glacial till, the bedrock source can be found. The transport distances, based on geochemical studies, are known generally to be of the order of a few hundred metres in Finland (Salminen 1993). The precence of overburden and the moisture content of soils, however, reduce the amplitude of the radioactivity of the underlying bedrock. These effects can be minimized by using the ratios of different radioelements.
The study at the scale of lithostratigraphical formations

Hydrothermal alteration processes may modify the radioelement composition of rocks penetrated by fluids. Under lower-temperature hydrothermal conditions, U-bearing minerals are particularly susceptible to dissolution, and as a result U is transported and redeposited differently from Th and K. One typical outcome of hydrothermal processes is the enrichment of wall-rock alteration zones in K (Darnley & Ford 1987).

In the Kuusamo schist belt the ore-potential unit comprises the Sericite Quartzite Formation, Siltstone Formation and Greenstone Formations I and II. The main surrounding formations are Rukatunturi Quartzite Formation, Archean Granite Gneiss Complex and Greenstone Formation III (Silvennoinen 1972, Pankka et al. 1991). The ratios of eU, eTh and K characteristic of the ore-potential formations were studied using a triangular diagram and compared with the corresponding ratios for the surrounding formations. As the radioelement values are not constant over areas covered by water, these values as well as those measured over wetlands were rejected. In Figure 2 the ratios have been divided into two groups: a) those indicating all ore-potential formations and b) those indicating the surrounding formations. By merging these two distributions into the same image it was possible to establish the differences between them (Fig. 2c).

The centres of the two distributions almost coincide but their spreading directions differ. The most distinctive enrichment of eU and eTh relative to other radioelements characterizes the distribution of the ore-potential formations compared to the surrounding formations. The effect of K-silicate alteration in the host rocks of the gold occurrences in the Kuusamo schist belt is not clear at this scale, and thus studies at a larger scale are needed if it is to be identified by a method such as this.

The study at the scale of occurrences

Due to the enrichment of the gold-bearing occurrences in the Kuusamo schist belt in uranium, the...
uraniu anomalies around each occurrence were carefully studied. At sites where the overburden was less than 1 m thick the indicative uranium anomaly was directly above the occurrence. At sites where the soil cover was thicker there were no anomalies directly above the occurrences except at the largest gold deposit, Juomasuo. The main ice flow directions, also shown clearly by gamma-ray data (Fig. 1), allows us to assume that the indicative radiometric anomalies are to be found in a direction somewhere between east and south. Around each occurrence, within a radius of 250 m, the nearest uranium anomaly in the direction of ice flow is considered to indicate the target. If no anomaly was found in that direction, the nearest one in any other direction was selected to indicate the target.

Closer study of the distribution of indicative ratios showed that they could be divided into two main groups. One group contained all the occurrences in which the indicative uranium anomaly lies directly above the occurrence or in a direction between east and south (red dots in cover of this issue). The other group comprised all the remaining occurrences, that is, those in which no uranium has been found or the overburden is about 10 m thick (green dots in the cover). At Juomasuo the sources of the radiometric anomalies are less distinct due to the thickness of the overburden, which, at 10 m, may include long-distance material. On the other hand, the enrichment of K relative to other radioelements, may also reflect the influence of potassium alteration of the host rocks (yellow dots in the cover). This alteration zone, which is wider than the deposit itself, runs from northwest to southeast through the Juomasuo deposit (Pankka 1992). The red dots furthest to the right in the diagram in the cover correspond to the Isoaho occurrence, where uranium enrichment in the occurrence and potassium alteration in the host rocks are known from field studies (Vanhanen 1992).

Discussion

The enrichment of uranium together with gold in
the Kuusamo schist belt makes the use of gamma-ray spectrometric data feasible in exploration. The abundance of sulphides in breccia-type gold occurrences is not always sufficient to be detected by magnetic and electromagnetic methods. Fingerprints are therefore worth seeking in gamma-ray data. As shown here, ratios of radioelements can be used to classify gamma anomalies in order to find potential targets for gold exploration. The gold occurrences in the Kuusamo schist belt appear to be controlled by fault systems. Although many of the bedrock structures are well shown by airborne magnetic and electromagnetic maps, some structural information can be extracted also from gamma-ray data when enhancing by image processing methods.

Airborne gamma-ray data are affected by many factors, e.g. the distribution of radioactive elements in lithostratigraphical formations, the mineralizing processes modifying these formations, glacial and, in general, Quaternary geology, and the water content of the overburden. Thorough knowledge of the information is necessary if we are to understand the role of these factors. The present type of study, in which not only the absolute abundances but also the ratios of the radioelements are considered, contributes to our understanding of some of the factors.

References


NONDESTRUCTIVE ANALYSIS OF MORPHOLOGY, CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF LARGE GOLD NUGGETS FROM FINNISH LAPLAND

by

Kari A. Kinnunen, Bo Johanson, Mauri Terho and Risto Puranen

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: kari.kinnunen@gsf.fi

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Introduction

Nondestructive optical, chemical and physical methods of analysis are needed for the characterisation of scientifically and commercially valuable geological samples. The Geological Survey of Finland (GSF) has tested several nondestructive methods on large gold nuggets (Kinnunen et al. 1995, 1996).

Gold nuggets are studied for many purposes. These include (1) exploration (transport distance and provenance, element selection for pathfinder use), (2) the jewellery trade (classification, specification and identification of suspected fakes), and (3) geological studies (paragenesis of auriferous veins, geochemical environment of gold deposition and sedimentary clast micromorphology). Loen (1995) has reported how the characteristics of small placer gold grains can be used to locate bedrock gold mineralisation. The methods described here provide numerical data on some of the parameters suggested by Loen (1995).

Material

The gold nuggets studied are from the Lemmenjoki, Ivalojoki and Tankavaara gold washing areas in Inari, Finnish Lapland (see Saarnisto et al. 1991 for a description of the localities). About 40 nuggets, their diameter ranging from 2 to 57 mm, were studied in detail. Analytical data are given for the largest nuggets: Aleksi, livari and Backlund.

Nondestructive analytical methods

The characterisation of large gold nuggets is based on nondestructive chemical and physical measurements and on the analysis of various morphological aspects (Fig. 1). Gold nuggets are detrital particles and therefore combined mineralogical and sedimentary petrographic data are needed for the interpretation of their provenance and transport history. The nuggets discussed here were studied using nondestructive methods commonly used for other purposes at the GSF. Some of the methods, which had been developed specifically for gem materials (Kinnunen 1995a) and meteorites (Terho et al. 1993), formed the basis for the procedures adopted for large gold nuggets.

Morphology

The components of rock particle shape are form, roundness and surface texture (Barret 1980). There are 12 parameters for form aspects and eight for roundness in sedimentological use. Form can also be described verbally using nominal classes. Former gold nugget classifications did not make a clear distinction between any of the above components (cf. DiLabio 1990). In our study we classified the form of gold nuggets verbally following the classification of DiLabio (1990). Roundness was measured using two procedures: the Wadell roundness index and the Cailleux flatness index (see Barret
Fig. 1. Scheme of the integrated nondestructive analysis of gold nuggets at the Geological Survey of Finland.

For surface textures a new procedure was designed (Kinnunen 1996). The surface texture of a nugget was copied on an acetate peel (Kinnunen 1995a). The peels were then photographed under the microscope with a combined colour-filter and shadowing method. The photographs were scanned into digital format, and the digital images analysed with a freeware image...
analysis program: UTHSCSA ImageTool, developed at the University of Texas Health Science Center at San Antonio, Texas and available from the Internet by anonymous FTP from maxrad6.uthscsa.edu. The surface textures were identified and their areal percentages determined. The surface marking types were classified genetically as primary (formed in bedrock), secondary (formed in sediments) or anthropogenic (human action) and these were further subdivided into 16 marking types. The genetical classification of the marking types will be reported in a separate study.

Chemical composition

In this study we used the automatic Cameca SX50 electron microprobe of the Geological Survey of Finland. The instrumentation and laboratory procedures were as described by Johanson and Kojonen (1995). The microprobe is capable of making nondestructive chemical analyses, even on micrometre-sized spots. The chemical composition of each sample was the average of tens of individual analyses. Compositional variations are characterised by the standard deviations of the analyses.

The largest nuggets, however, were too big to fit in the sample chamber. Their composition was therefore analysed on microscopic gold flakes (only some tens of a micrometer in diameter) that were detached under the stereomicroscope from the bottom of the primary cavities below the pure gold-rich rim; this rim is common in gold nuggets from Finnish Lapland (Saarnisto et al. 1991) and elsewhere (Groen et al. 1990). Polished sections were then prepared from the flakes. For large gold nuggets the method is practically nondestructive. For smaller nuggets, though, which can be analysed as such with the microprobe, only the chemical composition of the pure gold-rich rim (if present) is obtained, unless polished sections are used.

Mineral composition

In bedrock pristine gold grains typically host primary mineral impurities. Eroded nuggets tend to be mechanically and chemically purified of mineral inclusions, with only some grains of quartz remaining here and there. Microscopic gangue and ore mineral inclusions are common in small gold grains (see Saarnisto et al. 1991). Their identification with the electron microprobe or optical microscope requires the cutting of polished sections - a destructive procedure. The presence of magnetic ore mineral inclusions can be inferred from the high values of natural remanent magnetisation (NRM). Some nuggets contain detrital mineral grains trapped during sedimentological folding. These features complicate interpretation and impair the diagnostic usefulness of inclusion studies.

The morphology of weathered minerals can be deduced from the size and shape of the primary cavities, which record the shapes of embedded weathered grains. Information is thus obtained on the petrography of the auriferous host vein. The cavities of large nuggets often have loose or slightly compacted detrital material on their bottoms. The mineral composition and grain size distribution of this material can be determined on immersion grain samples under a petrographic microscope or on polished sections with an electron microprobe. Such determinations may provide data useful for localising the source of particular nuggets.

Physical properties

The petrophysical methods used earlier in studies on scientifically valuable meteorite samples (Terho et al. 1993) are nondestructive and suitable for gold nuggets as such. These methods include the measurements of mass, volume, density, porosity, magnetic susceptibility, natural remanent magnetisation and electric conductivity conducted at the Petrophysics Laboratory of the GSF (Puranen et al. 1993). The measurements are rapid and many of the properties contribute to the characterisation of gold nuggets. Remanent magnetisation indicates the presence of magnetic impurities (magnetite, hematite, etc.) in the nugget. The densities and porosities of the nuggets depend on their crystallisation and deformation history. We have also made colour determinations of the nuggets with Munsell comparison cards. The dominant wavelength corresponding to the Munsell designations was obtained using the quantification procedure of Deaton (1987).

Photomacrographic documentation

Photomacrography of the specimens is a basic documentation method in investigations of valuable geological materials. In the jewellery trade and at museums the photo-macrographs serve as readily archivable copies of the specimens (Scoivil 1996). Digital photographic techniques add to the usefulness of photographs as research material. Many morphological measurements can be performed automatically on digitized photomacro-
The photographic methods used are described in fibre optic cables enhanced the microrelief, while call on the digital images. The photomacrographs diffused light rendered the overall shape properly Kinnunen (1991, 1995a, 1995b). were scanned into digital image files for analysis.

In our study the gold nuggets were photographed with photomacrographic equipment on 35-mm colour negative and positive film (Fig. 2). Lighting setups were adjusted to obtain a correct record of the morphology. Directional oblique lighting with fibre optic cables enhanced the microrelief, while diffused light rendered the overall shape properly with soft shadows. The lighting technique set limits on the features that could be analysed automatically on the digital images. The photomacrographs were scanned into digital image files for analysis. The photographic methods used are described in Kinnunen (1991, 1995a, 1995b).

**Graphs with image analysis programs and PCs.**

Interpretation of results

The results for the three largest nuggets, Aleksi, Livari and Backlund, are presented in Table 1. The morphology of the large gold nuggets reflects their bedrock origin (shape and size of primary cavities), transport history (types of secondary surface markings) and degree of human action (areal percentage of the anthropogenic surface markings). Although these observations alone do not provide explicit genetic answers, they do contribute to the success of combined interpretations.

The main chemical components of the nuggets, gold and silver, determine practically alone the grain densities computed from the nugget chemistry (Table 1). The computed densities, particularly those of the Aleksi and Livari nuggets, are much higher than the measured bulk densities, most likely due either to porosities or to hidden impurities in...
the nuggets. The latter seem to be the more probable explanation because the computed porosities are so much higher than those estimated from the areal proportions of the primary cavities on nugget surfaces (Table 1). The mean diameter of the primary cavities is negatively correlated with the Ag/Cu ratio of the nuggets. The diameter reflects the original grain size in the auriferous host vein. According to Antweiler and Campbell (1977), higher values of the Ag/Cu ratio indicate lower crystallisation temperatures.

Typical elements of natural gold alloys worldwide are Ag, Cu, Bi, Hg, platinoids and As (Ramdohr 1975, Boyle 1979). In large Finnish gold nuggets the main element association is Ag, Bi, Hg, Cu, As and Te (Table 1). The elements occur in solid solution (Ag) or as lattice impurities, but not as inclusions as shown by narrow-beam electron microprobe analyses. Typical of Finnish nuggets are the absence of platinoids and the high concentrations of Hg and Te.

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Table 1. Integrated analytical results of the Aleksi, Iivari and Backlund gold nuggets from Finnish Lapland (see Fig. 2).

<table>
<thead>
<tr>
<th>Gold nugget</th>
<th>Aleksi</th>
<th>Iivari</th>
<th>Backlund</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locality</td>
<td>Hangasoja</td>
<td>Puskuola</td>
<td>Sotajoki</td>
</tr>
<tr>
<td>Basic map sheet</td>
<td>3831 04</td>
<td>3812 07</td>
<td>3813 11</td>
</tr>
<tr>
<td>X coordinate</td>
<td>ca 7519</td>
<td>7617.5</td>
<td>ca 7596</td>
</tr>
<tr>
<td>Y coordinate</td>
<td>ca 519</td>
<td>447.0</td>
<td>ca 494</td>
</tr>
<tr>
<td>Year of find</td>
<td>1910</td>
<td>(22.8) 1995</td>
<td>ca 1880</td>
</tr>
<tr>
<td>Physical properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass (g)</td>
<td>385.36</td>
<td>126.95</td>
<td>20.14</td>
</tr>
<tr>
<td>Volume (cm³)</td>
<td>29.46</td>
<td>11.09</td>
<td>1.17</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>57 x 52 x 28</td>
<td>36 x 31 x 28</td>
<td>25 x 20 x 6</td>
</tr>
<tr>
<td>Color (Munsell code)</td>
<td>10 YR 7/6</td>
<td>10 YR 7/6</td>
<td>10 YR 7/6</td>
</tr>
<tr>
<td>Dominant wavelength of color (nm)</td>
<td>580</td>
<td>580</td>
<td>580</td>
</tr>
<tr>
<td>Remanent magnetisation NRM (mA/m)</td>
<td>70</td>
<td>12</td>
<td>200 - 700</td>
</tr>
<tr>
<td>Bulk density (g/cm³)</td>
<td>13.081</td>
<td>11.451</td>
<td>17.230</td>
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<tr>
<td>Computed density (g/cm³)</td>
<td>18.20</td>
<td>17.27</td>
<td>17.56</td>
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<tr>
<td>Computed porosity (%)</td>
<td>28.1</td>
<td>33.7</td>
<td>1.9</td>
</tr>
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<td>Chemical composition (wt %)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>93.7</td>
<td>95.2</td>
<td>86.74</td>
</tr>
<tr>
<td>Ag</td>
<td>6.11</td>
<td>4.34</td>
<td>9.84</td>
</tr>
<tr>
<td>Bi</td>
<td>0.47</td>
<td>0.77</td>
<td>0.61</td>
</tr>
<tr>
<td>Cu</td>
<td>0.67</td>
<td>0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>Hg</td>
<td>0.12</td>
<td>0.75</td>
<td>0.10</td>
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<tr>
<td>Fe</td>
<td>0.00</td>
<td>0.45</td>
<td>0.23</td>
</tr>
<tr>
<td>S</td>
<td>0.02</td>
<td>0.55</td>
<td>0.03</td>
</tr>
<tr>
<td>As</td>
<td>n.d.</td>
<td>0.41</td>
<td>n.d.</td>
</tr>
<tr>
<td>Te</td>
<td>n.d.</td>
<td>0.34</td>
<td>n.d.</td>
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<tr>
<td>Pb</td>
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<tr>
<td>Sb</td>
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<td>0.02</td>
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<tr>
<td>Au/Ag ratio</td>
<td>15</td>
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<td>9</td>
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<tr>
<td>Ag/Cu ratio</td>
<td>87</td>
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<td>492</td>
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<tr>
<td>Fineness of gold</td>
<td>939</td>
<td>956</td>
<td>898</td>
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<tr>
<td>Morphology</td>
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<td></td>
<td></td>
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<tr>
<td>Form</td>
<td>DiLabio classification</td>
<td>rounded block</td>
<td>folded block</td>
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<tr>
<td>Roundness</td>
<td>Caillé fl atness index</td>
<td>1.95</td>
<td>1.19</td>
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<tr>
<td></td>
<td>Wadell roundness index</td>
<td>0.38</td>
<td>0.19</td>
</tr>
<tr>
<td>Surface textures (areal %)</td>
<td>Primary features</td>
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<td></td>
<td>Primary cavities</td>
<td>10</td>
<td>18</td>
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<tr>
<td></td>
<td>Secondary features</td>
<td></td>
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<tr>
<td></td>
<td>Rimmed pits</td>
<td>35</td>
<td>28</td>
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<tr>
<td></td>
<td>Groove and shaving scratches</td>
<td>15</td>
<td>20</td>
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<tr>
<td></td>
<td>Rippled grooves</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Impact pits</td>
<td>3</td>
<td>8</td>
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<tr>
<td>Anthropogenic features</td>
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<td>Burnished projections</td>
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<td>22</td>
</tr>
<tr>
<td></td>
<td>Lines</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Mean diameter of primary cavities (mm)</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>1.9</td>
<td>3.6</td>
</tr>
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</table>
Conclusions and applications

The main findings of our study on large nuggets from Finnish Lapland are:

1. In morphology and chemical composition the large nuggets are similar to smaller gold grains (cf. Saarnisto et al. 1991). A common origin is therefore implied.

2. The primary bedrock origin of gold is revealed by the high contents of foreign elements in both large and small nuggets. The supergene gold from Western Australia, in contrast, is deficient in metallic impurities (< 0.01 wt %), including Ag (Lawrance 1988).

3. Nuggets originating from different areas differ in chemical composition and densities but are similar in morphology and colour. The gold particles may therefore have several parent bodies but a similar transport history.

4. In addition to the photomicrographs, the mass, density and surface textures can be used as fingerprints of large nuggets in the jewellery trade. The high contents of Hg and Te in Finnish nuggets suggest that these elements may be used as pathfinder elements.

Both the chemical composition and the morphological and petrophysical properties of gold nuggets could be determined nondestructively with routine laboratory equipment when proper preparation methods were used. Such methods are also applicable to valuable gem materials and archaeological specimens.

High-accuracy analytical data are useful in the detailed characterisation of samples. However, jewellers, traders and connoisseurs all need simple gold-testing methods that they can perform with their own equipment (see Mercer 1992). The surface textures can be reproduced simply with the acetate sheet replication technique. Bulk density (and mass) can be determined fairly precisely using a jeweller's balance. These methods, including photomacrography, provide a practical means for characterising specific nuggets.

Determining the gold content of a nugget is more problematic without the use of an electron microprobe. As shown by this study, the bulk density does not correlate with the gold content. The latter can be assayed in a nondestructive manner with digital gold probes, but only on the outermost surface layer. This layer is enriched in gold as described earlier and therefore its chemical composition does not represent that of the whole nugget. The classic technique based on chemical reactivity, commonly known as “touchstone testing” (Mercer 1992), requires small-scale grinding of the gold piece. This technique and small-scale drilling have done substantial damage to many valuable gold nuggets, and should be avoided.

References

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CARBONATE ROCK UNITS IN THE SVECOFENNIAN UUSIMAA BELT, SW FINLAND

by
Jukka Reinikainen

Geological Survey of Finland, P. O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: jukka.reinikainen@gsf.fi

Key words (GeoRef Thesaurus, AGI): schist belt, carbonate rocks, dolostone, limestone, alteration, deformation, dolomitization, dedolomitization, Paleoproterozoic, Kemiö, Nummi-Pusula, Finland

Introduction

The Geological Survey of Finland has been exploring calcite rock deposits potentially providing raw material for paper pigment. The present study aims to locate carbonate rock units with the aid of structural geology and geophysical methods.

The study areas are situated in the Uusimaa Belt, which is the southernmost part of Svecofennian Domain in Finland (Fig. 1). The term Uusimaa Belt is proposed to should replace the commonly used names, Kemiö-Mäntsälä Belt or Leptite Belt (Y. Kähkönen, T. Koistinen, pers. comm.). The

![Lithological map of the southern Svecofennian area in Finland and the study areas in the Uusimaa Belt. Modified after Simonen (1980a).]
Uusimaa Belt is a high-grade metamorphic schist belt mainly composed of felsic and bimodal volcanic rocks with abundant intercalated carbonate rocks (marbles), mica gneisses, mylonitic gneisses and intrusive rocks (mostly granites). Eskola et al. (1919) recognized that the Sveco-fennian carbonate rock deposits typically form oval-shaped, lensoidic structures. The study areas were chosen on the basis of preliminary field work and laboratory tests of selected samples. Detailed profile mapping including structural and petrological studies, magnetic measurements and drilling were carried out to define the primary nature and sedimentary environment of the carbonate rock units.

**Rock descriptions and structures**

Norr-Lammala area, Kemiö

The Norr-Lammala area (Fig. 1), in the southwestern part of the Uusimaa Belt, consists mainly of felsic and mafic volcanics with intercalated carbonate rock units and minor granite pegmatites. The carbonate rock at Norr-Lammala forms a horizon, 20—50 m wide and about 2 km long, surrounded by felsic to intermediate tuffs, tuffites and mafic volcanics. The isoclinally folded and WSW—ENE-trending carbonate rock units in the area form several boudinaged oval-shaped and about 100—300 m long deposits, which are pinching out at both ends. The contacts between carbonate and silicate rocks are usually sheared, typically showing a reaction rim of metamorphic calc-silicate minerals with an elongated lineation (Fig. 2D). The mafic volcanics, which are mainly composed of hornblende, plagioclase (An-rich) and quartz, usually lie concordantly to the carbonate rock units, showing in places slightly cross-cutting features (Fig. 2A). The tuffs and tuffites are very fine-grained rocks composed of K-feldspar, plagioclase, quartz and biotite, and showing sometimes lapilli textures (Figs. 3C and 3D). The tight and isoclinal folding with penetrative F₁ foliation is clearly visible especially in the intermediate (biotite-rich) tuffites. The F₁ folding has locally remobilized the granite pegmatites in the fold axis direction (Fig. 2C). The volcanics in the adjacent Vestlax area have been studied by Lindroos and Ehlers (1994),

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**Fig. 2.** Field pictures from the Norr-Lammala area, length of compass is 12 cm. A) a mafic volcano with pillow lava-structures, B) a post-metamorphic dolostone (2.) as an alteration product of a calcite rock (1.) along crack zones, C) an intensive F₁ folded acidic tuffite which has undergone F₁ refolding (kink-type); note also re-orientation of pegmatite granite (upper part of the picture) parallel to the F₁ fold axial, D) a F₁ lineation direction shown in a reaction rim (composed of calc-silicates) of a calcite rock and a mafic volcano (sill).
who found pillow lavas and pyroclastic flow structures e.g. ignimbrites.

The carbonate rock is coarse-grained (grain size 3—8 mm), light grey in colour and calcitic in composition (Fig. 3A). Individual calcite rock horizons are 2—8 m wide and contain some narrow (5 mm-2 cm) quartz-feldspar-tremolite-diopside-phlogopite bands. The carbonate rock layers dip steeply (70—80°) to south and they appear to be strongly boudinaged in the F1 lineation (fold axis) direction. The F1 foliation, shown by the orientation of the silicate minerals in the carbonate rock, may represent also the original bedding direction. There are several, narrow (0.2—0.5-m-thick) dolostone layers forming elongated and oval-shaped structures along fracture joints (Figs. 2B and 3B).

**Nummi-Pusula area**

In the Nummi-Pusula area (Fig. 1), in the northeastern part of the Uusimaa Belt, there is a distinct carbonate rock unit bordered by potassium granite. The unit has been mapped as a NW—SE-trending, 20—50 m wide and at least 2 km long horizon, that is locally cut by coarse-grained microcline granite. In places the fabric of the host granite resembles sedimentary features such as bedding. There is no structural or microscopic evidence that could be used to estimate the degree of K-metasomatism caused by the intruding granite, even though the process seems to have occurred locally at least.

The carbonate rock in the Nummi-Pusula area is mainly calcitic in composition and usually very coarse-grained, up to 8 cm in grain size (Fig. 4A). Individual calcite rock horizons are 3—8 m wide and separated by calc-silicate rock layers or granite bodies, up to 10 m thick. The very coarse-grained greyish white calcite rocks form strongly recrystallized vein-like layers which are 1—5 m wide and free of silicate minerals. Along the boundaries of the horizon there is a 5—10 m wide wollastonite-bearing calcite rock layer which is fractured and

Fig. 3. The carbonate and country rocks in hand specimen (left) and in photomicrograph (right, crossed polarisers) from the Norr-Lammala area, magnification two times the original size. A) a coarse-grained and light greyish calcite rock with calc-silicate layers (calcite stained red), B) a porous dolostone, which is "dusty" and yellowish brown in colour, C) and D) a K-feldspar-plagioclase-quartz lapillus in a fine-grained tuff.
The carbonate rock units of the study areas in the Uusimaa Belt are believed to have undergone several phases of diagenetic to metamorphic mineralogical alteration and deformation. The following is a hypothetical model for those events.

**Discussion**

The carbonate rock units of the study areas in the Uusimaa Belt are believed to have undergone several phases of diagenetic to metamorphic mineralogical alteration and deformation. The following is a hypothetical model for those events.

**Sedimentation** of carbonate and silicate mineral layers (quartz, K-feldspar and plagioclase) occurred as simultaneous events, with the silicate minerals plausible representing original tuffite layers. A mechanism or reason for precipitation of carbonates from seawater is not known in the study area, but it could have been mainly chemical in character. Owing to high-grade metamorphism, we are unlikely to be able to find or recognize any stromatolite structures, but still a biogenetic factor cannot be ruled out. A close connection between volcanicite and carbonate rocks in Svecofennian carbonate rock deposits may imply that CO₂ (and/or some other gases) produced by volcanic eruptions acted as catalysts to carbonate precipitation.

**Pre-metamorphic dolomitization** of the calcitic horizon could either have been restricted to the calcite layers adjacent to silicate minerals or it could have altered the entire calcite rock unit. The process is not needed if the MgO component in calcite is capable of producing the calc-silicate bands during metamorphism. Dolomitization of a
carbonate layer could have occurred as a diagenetic process with seawater as described elsewhere, e.g. by Högberg (1961).

Metamorphic dedolomitization between carbonate and silicate minerals, i.e. dolomite or Mg-rich calcite with quartz, K-feldspar and plagioclase, produced silicate minerals during regional metamorphism. The presence of metamorphic minerals, e.g. tremolite, diopside and phlogopite, implies that a reaction took place between dolomite + quartz + K-feldspar, producing the above silicates and ophtalcalcite by the metamorphic dedolomitization, as recognized earlier from the Kuusamo (Pekkala, 1974) and the Virtasalmi areas (Reinikainen, 1991). These silicate minerals also testify that in a pre-metamorphic stage there were enough dolomite and quartz to react together as shown by Bowen (1940) and Winkler (1979).

Folding and deformation (F1 and F2) produced boudinaged, multiplied and, in some places, remobilized carbonate rock units. Although the Svecofennian carbonate rock units probably deposited during the same event and formed a uniform horizon, they are now separated from each other by a boudinage related to intensive F1 folding. During the next deformation phase the steeply dipping units were locally refolded into gently dipping and open F2 folds in which the carbonate rock units seem to be strongly multiplied and to some extent remobilized, resembling the structures described by Fjäder (1991) from the Pariainen district. The carbonate rock units also form boudinages in the direction of the F1 fold axis, producing well developed, elongated lineation structures, e.g. tube-like cigars. The mineralogically purest and whitest parts of the carbonate rock units in the Uusimaa Belt were apparently refolded and are now situated at the F2 fold hinges. In that sense the economic carbonate rock deposits are metamorphically generated stratabound orebodies which were "purified" and multiplied by folding and metamorphism.

Post-metamorphic dedolomitization of the calc-silicate-bearing dolostone unit or restricted dolomitization of calcite rock occurred adjacent to silicate layers in a metamorphic (or pre-metamorphic) stage. Both processes could have produced the dolomite-free and calc-silicate-bearing calcite rock units now dominant in the study areas. The processes can be ruled out, if calc-silicates can be produced by the reaction of MgO-bearing calcite with quartz in metamorphism. Dedolomitization is proposed as an explanation for the absence of dolomite in the study areas, whereas calc-silicates were clearly produced by the reaction between dolomite and quartz. Post-metamorphic dedolomitization in the Uusimaa Belt could be related to the shear zones and mylonitization facilitated by the presence of excess fluids, as described by McCallum (1974) from the Wyoming district. Another explanation is restricted dolomitization close to the crack zones, giving rise to dolomite grains that react with quartz and feldspar to produce calc-silicate bands.

References

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MINING IN FINLAND DURING THE PERIOD 1530—1995

by
Kauko Puustinen

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: kauko.puustinen@gsf.fi

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Introduction

Mineral commodities have been utilized in Finland for at least 4500 years. Asbestos from Paakkila served as a binding material for the early Neolithic Comb-Ceramic pottery found in the south of the country. Finds of these thin-sided cooking vessels show what long distances mineral commodities were transported even then (Aurola 1954a, Palomäki & Halonen 1968). Limestone has been burned to make quicklime from time immemorial. The introduction of mortar dates back to the building of medieval stone churches and castles in the 11th and 12th centuries. The oldest information on the quarrying of limestone in Finland is contained in a letter recorded in the Black Book of Turku Cathedral, dated 12 June 1329. We read there about three residents of Kemiö who donate a limestone hill called Krakanäs to the Cathedral. This hill still exists nearby the present Förby mine (Boström 1986).

Over the years, the products mined in Finland have ranged from metallic ores, industrial minerals and industrial rocks to limestone. The first metallic ore mine to have a specific name was probably Remojärvi, in the Mikkeli region in eastern Finland, where small-scale mining had been conducted around 1530 (Hultin 1897). There are records suggesting, however, that there had been an even older mine in the Åland Islands, as it was already in ruins when King Gustav Wasa of Sweden came to the throne in 1496. The first true industrial enterprise was the Ojamo iron ore mine, which went into operation in 1542 (Hultin 1897, Neovius 1911).

The first industrial mineral mine, recorded in 1737, was the Skogsböle pegmatite occurrence at Kemiö, in southwestern Finland (Linder 1737). Feldspar and quartz are still produced in the same area today. The pegmatite quarries at Somero and Tammela, where quartz was extracted as a raw material for the Åvik glass plant at Somero from 1748 to 1830, date from the same year.

Compared with present methods, mining consisted of little more than primitive quarrying in the early years. Mining was nevertheless a very important undertaking, and a decision to start operations could not be taken lightly. Finland’s mining history thus starts with small pits and continues in the large underground mines of today.

Finnish mining felt the impact of the industrial revolution around 1860. Coke replaced charcoal in large-scale metallurgical processes, and steam energy became a widely used source of energy. The old-fashioned Finnish mining industry was unable to compete and almost ceased to exist (Laine 1952, Laine 1955, Saltikoff et al. 1994). Many small iron ore mines in southern Finland, for instance, were forced to close down. In the early 20th century the situation changed dramatically. The discovery of the major Outokumpu and Petsamo ore deposits heralded a new era, marked by the introduction of modern mining and dressing methods and the application of sophisticated metallurgical processes.
Reference material

The first true description of economic geology and mines in Finland is the report written by Daniel Tilas after his travels in the country in 1737 and 1738 (Tilas 1738). He was sent to Finland by the King of Sweden to look into the state of mines, both active and closed ones, to undertake exploration, and to make recommendations concerning future operations. During his travels Tilas even discovered a small copper deposit at Tilasinvuori in Tammela and an iron ore occurrence at Ansomäki in Hämeenkyrö. A few years later, around 1794, the iron ore deposit of Haveri was discovered not far from Ansomäki, and some 1 700 tonnes of ore were extracted there between 1794 and 1866. From 1942 to 1960 the new Haveri was in operation as a gold-copper mine.

Tilas’s report (1738) deals exclusively with metallic ore mines and occurrences. The same emphasis is apparent in descriptions of economic geology in Finland in the 19th century, those by Bremer (1824, 1825), Holmberg (1858), Furuhjelm (1884a, 1884b, 1886, 1887) and Hultin (1897), for instance. Almost every present-day reference to the economic history of mining in this country draws on these papers in some way.

As the mining superintendents with the Central Board of Industry ceased to produce annual reports after 1885 (Furuhjelm 1887), we have no complete records of mining in Finland between that date and the 1940s. The gap can partly be filled by the figures on the production of mines and mineral commodities recorded in the yearbooks of Industrial Statistics (Teollisuustilasto 1900—1996). In January 1942, the Mining Office was established at the Ministry of Trade and Industry, and in 1944 a new Mining Law entered into force (Kauppa- ja teollisuusministeriö 1950—1995). The authority of the Office extended only to those mineral mentioned in the Law. Since the revision of the mining legislation in 1965, information has been available on most mineral commodities mined in this country, in particular on industrial minerals and limestone.

Many general descriptions of Finnish mines and related subjects have been published in this century, among others, by Eskola (1919), Eskola et al. (1919), Mäkinen (1920), Laine (1952, 1955), Aurola (1954b), Isokangas (1978), Boström (1986) and Salitikoff et al. (1994). The present paper contributes to this and by summarizing the historical data given in the reports of Puustinen (1995, 1996).

Methods of estimating production

The production statistics for metals and industrial minerals given in the present paper are liable to several inaccuracies. Ore recovery, for example, could not be taken into consideration. The figures presented are thus economic geological estimates of the significance of the various mines and commodities. Wherever annual mine statistics (Teollisuustilasto 1900—1996, Kauppa- ja teollisuusministeriö 1950—1995) were available, the production of metallic mines was calculated according to the feed to the concentrator (in tonnes) and the average grade. The total amount of metal estimated is thus the sum of annual recovery. Otherwise, production was estimated from total mine output or even the size of old quarries. The production of industrial mineral mines was calculated following the same principles as in Puustinen (1996).

The size of metallic mines can be expressed by the total metal content mined, and by proportioning the amounts of different metals with given equivalent constants (Kahma et al. 1976, Lafitte 1984, Puustinen 1995). Different types of industrial mineral mines cannot, however, be compared with each other using these principles. Lafitte (1984) has calculated constants for columbotantaltite, graphite, kaolin-clay, phosphates and talc, but quartz and feldspar, which are important to Finland’s mining industry, are not on his list. Metallic and industrial mineral commodities and the output of individual mines can only be compared on the basis of the production value of the mineral commodity mined, which is equivalent to the gross value. This is different, however, from the commercial value used by mining economists, who express the production value as net present value or net smelter return (e.g., Goldie & Tredger 1991).

Originally for land-planning purposes, Brew et al. (1992) have used a probabilistic method of calculation that is a nonaggregated, individual mineral-resource-tract-oriented assessment. This leads to the use of gross-in-place values (GIPV) of a tract, which is defined in terms of the value of mineral commodities in the ground. It does not take into account the costs of discovering, developing, mining, beneficiating or transporting the resource. Different mineral commodities have thus an equal and consistent measure, regardless of their ore type or geographic location.

The unit prices used here to determine the value of each mineral commodity are shown in Table 2. The majority correspond to world prices in December 1995. The historical production of each mine is

44
evaluated to correspond to its aggregate present value (in Finnish monetary units, FIM) what could have been paid for the commodities at the mine gate. This method can be applied to all types of mineral commodities, such as metals, industrial minerals, industrial rocks or limestone.

The localities of mines on the maps give here are shown uniformly with symbols, their size proportional to the calculated total value of production. The diameter of the symbols equals the cubic root of the value.

**Mine and commodity production**

Mining in Finland has expanded since the Second World War (Fig. 1). The production of metallic ore mines reached its peak in 1979, when ore output totalled 10.3 Mt, and thereafter declined to its present level, 3.2 Mt. At the same time the ore output of industrial mineral mines began to rise, reaching 9.3 Mt in 1995. This is mostly due to the opening of big talc and apatite mines in the 1970s. Since 1987, output has surpassed that of metallic ore mines. Production of limestone has always been in balance with the consumption of cement by the construction industry and of agricultural lime by the farming.

**Metallic ore mines**

From 1530 to 1995 at least 280 metallic ore mines were in operation; some are still in operation today. Most of these mines have exploited iron ores (52.7 %) or copper ores (23.9 %). In tonnes, however, the total output of the iron ore mines has been only 21.8 % and ore output 24.9 %. This is a consequence of the modest production of the numerous pre-industrial iron ore mines.

As mentioned, the first metallic mine in Finland may have been that at Remojärvi in the Mikkeli area (Hultin 1897), which is believed to have been in operation around 1530. Information on early mines is scarce, and even the precise location of Remojärvi is uncertain. The opening of the Ojamo iron ore mine at Lohja in 1540 marked the real start of mining in Finland. The number of ore deposits discovered since then seems to have varied greatly from time to time. Not many mines were opened before 1650, but after that year, steady progress was made, excluding a possible recession during 1675—1720. From 1850 to 1940, only a few new economically viable ore deposits were discovered. The mines with the longest history of operations were those at Ojamo (323 years) and Orijärvi (197 years). The most recent ore deposit to be brought into production is that at Pahtavaara in Sodankylä, where the development of a gold mine got under way in 1995.

The location of all metallic mines in operation since 1530 is presented in Figure 2. From the distribution of the mines we see that: (1) many small pre-industrial iron and copper ore mines were located in the coastal area of southern Finland. They all belonged to the same metallogenic province with its parallel ore-bearing belts. The concentration of these old mines, such as Viiniemi, Malmberg and Sillböle, in this area is partly a consequence of the demand for iron in populated areas, where also labour and charcoal were readily available. The copper-zinc-lead deposits in the Orijärvi field will be described later; (2) major nickel mines in the southwest (Vammala) and central parts of the country (Hitura, Kotalahti and Laukunkangas) are associated with the Svecofennian Vammala and Kotalahti nickel belts; (3) major copper-zinc-lead mines (Vihanti, Pyhäsalmi, Luikonlahti and Outokumpu) in central Finland lie in the so-called Main Sulphide Ore Belt; and (4) the Kemi chromium and Mustavaara vanadium mines are hosted by a 2.4 Ga old layered intrusion.

The ore output of all metallic mines until 1995 was 253.7 Mt (Table 1). Of this, sulphide mines accounted for 169.9 Mt (67.0 %) and oxide mines for 83.8 Mt (33.0 %). Although the true historical output of all old mines is not available, the figures
Fig. 2. Location of metallic ore mines in Finland during 1530—1995. The size of the symbols indicates the total value of metals mined. Mines in localities that are no longer part of Finland are also shown.
can be regarded as a good estimate. According to their ore output, the biggest individual mines have been Outokumpu (28.5 Mt of copper, zinc, cobalt and gold ore plus 3.2 Mt of tailings), Pyhäsalmi (29.4 Mt of zinc, copper, silver and gold ore), Vihanti (27.9 Mt of zinc, silver, copper and lead ore), Otanmäki (25.4 Mt of iron ore with titanium and vanadium) and Kemi (20.6 Mt of chromium ore).

Because the production of the various metals cannot be compared by tonnages, a comparison based on their gross-in-place value will be adopted. Historical production figures, unit prices and the value of metals in Finland are presented in Table 2. Until 1995, the most significant metals were chromium (FIM 37 191 million), copper (FIM 22 588 million), cobalt (FIM 22 461 million), zinc (FIM 11 481 million) and nickel (FIM 9 331 million).

### Industrial mineral mines

By 1995, a total of 192 industrial mineral ore or industrial rock mines and quarries had operated in Finland. The oldest mine, that at Skogsböle in Kemiö, has been dated at least to 1737 and is mentioned by Linder (1737) in his treatise on the Skogsböle tin-bearing pegmatite and by Tilas (1738) in his discussion of small-scale mining of the Somero-Tammela pegmatites. The mining area at Kemiö thus has an unbroken history of almost 260 years that continues right up to the present day. Other long-lived operations were those at Hiekkamäki for quartz, from 1914 to 1988 (74 years), and at Paakkila for asbestos, from 1904 to 1975 (71 years).

#### Table 1. Mines in Finland according to total mine output and ore output.

<table>
<thead>
<tr>
<th>Main commodity</th>
<th>Mines number</th>
<th>Total output 1000 tonnes</th>
<th>Ore output 1000 tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td><strong>Metallic ore mines:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>14</td>
<td>5.0</td>
<td>8 003</td>
</tr>
<tr>
<td>Copper</td>
<td>67</td>
<td>23.9</td>
<td>82 168</td>
</tr>
<tr>
<td>Lead</td>
<td>20</td>
<td>7.1</td>
<td>1 014</td>
</tr>
<tr>
<td>Zinc</td>
<td>12</td>
<td>4.3</td>
<td>74 240</td>
</tr>
<tr>
<td>Iron</td>
<td>147</td>
<td>52.5</td>
<td>87 634</td>
</tr>
<tr>
<td>Nickel</td>
<td>14</td>
<td>5.0</td>
<td>55 373</td>
</tr>
<tr>
<td>Chromium</td>
<td>1</td>
<td>0.4</td>
<td>91 487</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1</td>
<td>0.4</td>
<td>1 156</td>
</tr>
<tr>
<td>Uranium</td>
<td>4</td>
<td>1.4</td>
<td>72</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>280</td>
<td>100.0</td>
<td>401 147</td>
</tr>
<tr>
<td><strong>Industrial minerals mines:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apatite</td>
<td>3</td>
<td>1.6</td>
<td>121 800</td>
</tr>
<tr>
<td>Talc</td>
<td>11</td>
<td>5.7</td>
<td>31 859</td>
</tr>
<tr>
<td>Asbestos</td>
<td>6</td>
<td>3.1</td>
<td>5 009</td>
</tr>
<tr>
<td>Graphite</td>
<td>23</td>
<td>12.0</td>
<td>6 465</td>
</tr>
<tr>
<td>Feldspar</td>
<td>60</td>
<td>31.3</td>
<td>6 465</td>
</tr>
<tr>
<td>Quartz</td>
<td>47</td>
<td>24.5</td>
<td>6 364</td>
</tr>
<tr>
<td>Diatomite</td>
<td>7</td>
<td>3.6</td>
<td>?</td>
</tr>
<tr>
<td>Industrial rocks</td>
<td>24</td>
<td>12.5</td>
<td>4 565</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>5.7</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>192</td>
<td>100.0</td>
<td>176 076</td>
</tr>
<tr>
<td><strong>Other mines, only during 1944—1995:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonate rocks</td>
<td>26</td>
<td>100.0</td>
<td>214 295</td>
</tr>
<tr>
<td>Marble</td>
<td>3</td>
<td></td>
<td>158</td>
</tr>
<tr>
<td>Soapstone</td>
<td>6</td>
<td></td>
<td>3 465</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>35</td>
<td></td>
<td>217 918</td>
</tr>
<tr>
<td><strong>Grand total</strong></td>
<td>507</td>
<td></td>
<td>795 141</td>
</tr>
</tbody>
</table>
Table 2. Historical production of metals and industrial minerals in Finland. Unit prices of metals in FIM/kg, industrial minerals and rocks in FIM/tonne.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Production 1000 tonnes</th>
<th>Unit price FIM/kg-tonne</th>
<th>Value FIM million</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold (kg)</td>
<td>50</td>
<td>54 860.00</td>
<td>2 716</td>
<td>2.3</td>
</tr>
<tr>
<td>Silver (kg)</td>
<td>835</td>
<td>750.00</td>
<td>626</td>
<td>0.5</td>
</tr>
<tr>
<td>Copper</td>
<td>1 832</td>
<td>12.33</td>
<td>22 588</td>
<td>19.5</td>
</tr>
<tr>
<td>Lead</td>
<td>145</td>
<td>3.12</td>
<td>454</td>
<td>0.4</td>
</tr>
<tr>
<td>Zinc</td>
<td>2 621</td>
<td>4.38</td>
<td>11 481</td>
<td>9.9</td>
</tr>
<tr>
<td>Tin</td>
<td>0</td>
<td>27.12</td>
<td>13</td>
<td>0.0</td>
</tr>
<tr>
<td>Iron</td>
<td>19 088</td>
<td>0.16</td>
<td>3 054</td>
<td>2.6</td>
</tr>
<tr>
<td>Nickel</td>
<td>282</td>
<td>33.07</td>
<td>9 331</td>
<td>8.1</td>
</tr>
<tr>
<td>Chromium</td>
<td>3 519</td>
<td>10.57</td>
<td>37 191</td>
<td>32.1</td>
</tr>
<tr>
<td>Cobalt</td>
<td>70</td>
<td>319.09</td>
<td>22 461</td>
<td>19.4</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2</td>
<td>41.10</td>
<td>67</td>
<td>0.1</td>
</tr>
<tr>
<td>Tungsten</td>
<td>2</td>
<td>26.44</td>
<td>53</td>
<td>0.0</td>
</tr>
<tr>
<td>Vanadium</td>
<td>164</td>
<td>28.96</td>
<td>4 754</td>
<td>4.1</td>
</tr>
<tr>
<td>Titanium</td>
<td>3 269</td>
<td>0.33</td>
<td>1 079</td>
<td>0.9</td>
</tr>
<tr>
<td>Uranium</td>
<td>0</td>
<td>112.71</td>
<td>6</td>
<td>0.0</td>
</tr>
<tr>
<td>Lanthanides</td>
<td>1</td>
<td>1.95</td>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>Sulphur</td>
<td>11</td>
<td>0.23</td>
<td>3</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>115 879</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Industrial minerals:**

- Ambylygonite 1 772 1 0.0
- Apatite 7 733 210 1 624 11.0
- Asbestos 416 718 299 2.0
- Beryl 0 3 727 0 0.0
- Graphite 1 1 127 2 0.0
- Garnet 2 910 1 0.0
- Calcite 1 200 100 1 20 0.8
- Kaolin 0 417 0 0.0
- Mica 26 975 26 0.2
- Quartz 5 631 90 507 3.4
- Kyanite 0 568 0 0.0
- Feldspar 2 061 215 443 3.0
- Diatomite 39 2 328 91 0.6
- Talc 7 238 1 467 10 618 71.8
- Tantalite 0 19 000 0 0.0
- Industrial rocks 4 437 50 222 1.5
- Wollastonite 457 1 834 839 5.7
| Total          |                        |                         | 14 793           | 100.0 |

Other commodities, only during 1944—1995:

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Units</th>
<th>Unit price FIM/kg-tonne</th>
<th>Value FIM million</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate rocks</td>
<td>197 247</td>
<td>100.00</td>
<td>19 725</td>
</tr>
<tr>
<td>Marble</td>
<td>60</td>
<td>4 000.00</td>
<td>242</td>
</tr>
<tr>
<td>Soapstone</td>
<td>762</td>
<td>2 555.00</td>
<td>1 946</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>21 913</td>
</tr>
<tr>
<td><strong>Grand total</strong></td>
<td></td>
<td></td>
<td>152 585</td>
</tr>
</tbody>
</table>

The industrial mineral mines are here grouped according to their main commodities, which also define their genetic types. For instance, ultramafic bodies host asbestos and talc-bearing deposits, and granitic pegmatites feldspar-bearing deposits, in which quartz, beryl or tantalite occur as by-products.

Most industrial mineral mines have produced feldspar and quartz from pegmatites (31.3 %), although in ore tonnages, they make up only 4.4 % of the total number of mines (Table 1). Apatite mines account for 121.8 Mt (69.2 %) and talc mines for 31.9 Mt (18.1 %) of total mine output of 176.1 Mt. The figures express only the output at a specific type of mines.

The total mine output of industrial mineral mines, 176.1 Mt, was divided between Siilinjärvi (121.7 Mt), Ihalahainen (34.1 Mt of wollastonite and limestone), Lahnaslampi (20.6 Mt), Horsmanaho (5.4 Mt), Paakkila (4.9 Mt), Kemiö (4.5 Mt mined after the year 1965) and Kinahmi (4.2 Mt) mines.

In ore output and main products, the largest individual mines were again Siilinjärvi (93.6 Mt of apatite), Ihalahainen (30.3 Mt of limestone and wollastonite), Lahnaslampi (9.7 Mt of talc), Kemiö (after 1965 4.1 Mt mined of feldspar and quartz), Kinahmi (4.0 Mt of quartz) and Horsmanaho (3.4 Mt of talc).

The location of Finnish industrial mineral mines is shown in Figure 3. Geographically they are divided as follows: (1) feldspar and quartz mines in pegmatites at Kemiö, Somero - Tammela and Orivesi, and in Central Ostrobothnia; (2) small graphite mines extending as a train from Vammala via Mäntyharju to Kuopio; (3) industrial rock mines, mainly in south Finland, between Parainen and Lappeenranta, in the area with the highest demand for rock wool for the construction industry; (4) major talc mines extending from North Karelia to Kainuu, and asbestos mines around Tuusniemi and Outokumpu, immediately to the west of the talc mines; (5) the Lappeenranta limestone mine producing wollastonite, and the Siilinjärvi apatite mine in a carbonatite complex; (6) quartz mines associated with the Savo quartzites; and (7) the Peri-Pohja schist belt, which has produced quartz, mica and industrial rocks. According to this list, almost all industrial mineral mines have been located in the coastal area of the Gulf of Finland or the Gulf of Bothnia. There are practically no mines in the central part of the country or in northern Finland.

The value of the historical production of industrial minerals is presented in Table 2. In decreasing order, the most important minerals have been talc (FIM 10 618 million), apatite (FIM 1 624 million), wollastonite (FIM 839 million), quartz (FIM 507 million), feldspar (FIM 443 million), asbestos (FIM 299 million) and industrial rocks (FIM 222 million).

Limestone mines

Limestone has been mined mainly as a raw ma-
Fig. 3. Location of industrial mineral mines in Finland during 1737—1995. The size of symbols indicates the total value of minerals mined. Mines in localities that are no longer part of Finland are also shown.
terial for burning lime and making cement but also for agricultural lime. Earlier, excavation was largely on a domestic scale. Most of the companies mining limestone today have been in existence since the late 19th century. The location of the limestone mines in production since 1944 is presented in Figure 4, in which a rough distinction is made between limestone- and dolomite-producing mines. The major limestone mines are located in southern Finland, where the demand for cement is heaviest.

During 1944—1995, total mine output was 214.3 Mt and limestone output 197.2 Mt (Table 1). For comparison, total output from industrial mineral mines was 176.1 Mt and ore output 126.7 Mt. In respect of ore output, the most prominent mines were Parainen (66.4 Mt), Ihalainen (35.6 Mt), Tytyri (32.5 Mt), Ruokojärvi (10.4 Mt) and Mustio (8.4 Mt). The value of the total production of limestone is estimated to have been FIM 19 724 million (Table 2).

Case mines

The following looks at some mines as examples of the production of certain mineral commodities or because of the special position they hold in the mining history of Finland. Included are the well-documented metallic ore fields of Orijärvi and Outokumpu. As Finland’s first proper mine, the iron ore deposit at Ojamo is discussed in detail. Examples of industrial mineral mines include the pegmatite mines in the Somero-Tammela area and at Kaatiala. All asbestos and talc mines are genetically associated with similar ultramafic intrusions in North Karelia and Kainuu. In total mine output, the Siilinjärvi apatite mine is the biggest in operation in Finland today. Several metallic and industrial mineral mines have been in operation in localities that are no longer part of Finland, for example, the well-known copper-tin-iron ore mine at Pitkäranta and, above all, the large nickel-copper ore mine at Petsamo.

Ojamo

The Ojamo estate was first mentioned in 1384. The next time it appears it is already an iron ore mine (Bremer 1825, Holmberg 1858, Hultin 1897, Neovius 1911). Erik Fleming, the powerful Counselor of State in Finland, obtained the area of Lohja as a fief on 15 October 1538. Soon afterwards he applied to King Gustav Wasa for “the authorization to begin mining, because he had recently discovered an iron or steel hill, for the test mining of which he had already spent money, but had not ventured to spend more before he had made a humble plea to the King to permit him to engage in mining operations for the benefit of himself and his descendants”. The request was granted on 5 September 1542 that “for the good of the country, such gifts given by God could be utilized, and that Lord Erik, who was the discoverer and originator of the ore, was granted the privilege to mine and smelt rock without let or hindrance, and whatever the Lord Almighty would give him for this work, iron or steel, he could keep it for himself and his descendants, although on condition that the Crown should be given every 12th kippunta (170 kg) of pure iron, were it soft iron, cast iron or pig iron”. As to the mine or coal wood, “Lord Erik had to agree with the owners of the forests, and moreover the King should be informed about how mining advanced, so that other honest people, land proprietors and townsfolk or the like would also be able to take part in this Crown mining operation”. Finally the King forbids his bailiffs and sheriffs or any other person to harm or hinder the aforementioned mining.

The quoted correspondence between King Gustav and Erik Fleming constitutes one of the first exploration licences and mining concessions granted in Finland. It also gives orders for the taxes, concession fees and royalties collected by the Crown. The Ojamo mine was probably closed from 1562 to 1610, because no records remain of those years. In 1615, King Gustav II Adolf ordered that the mine should be opened once more. Then in 1657, it was suddenly almost half filled with water from the adjacent lake, and a large amount of hoisted ore fell into the shaft. The miners were in imminent danger of life and could not rescue their tools. The ruined shaft was some 53 m deep and 4—5 m wide. The ore layer had been 1—1.2 m wide, and in total some 32 m of adits had been excavated.

Although Ojamo is an authentically recorded mine, statistics on it are very sparse and difficult to decipher. Unambiguous figures are not available until the period 1826—1863, when Ojamo was once again in operation and the total hoist was 1 563 tonnes of ore. The average grade is said to have been relatively high, so much so that the aim throughout all the years it was operational was to extract ore with more than 50 % Fe.

Somero and Tammela

During his travels in 1737 and 1738 Daniel Tilas discovered, among other things, the small Hopiavuori sulphide-bearing deposit in Somero (Tilas
Fig. 4. Location of limestone mines operating in Finland during 1944—1995. The size of the symbols indicates the total value of limestone mined.
1738, Holmberg 1858, Virkkunen 1962). As a result of later exploration in the area several pegmatite bodies were also found in the Torro area. J.R. Pont and Jacob Bremer, two businessmen from Turku, established the Ävik glassworks, which obtained its raw material from these pegmatites. Quartz was taken from almost 30 separate places, probably still during 1824—1825. When E.J. Westling visited these places in 1839, the mines were already filled with water.

Orijärvi field

The Orijärvi copper deposit was discovered by Juhana Iisakinpoika, owner of the Orijärvi estate, in 1757 (Bremer 1824, Holmberg 1858, Hultin 1897, Trüstedt 1909, Nikander 1929, Laine 1952, Laine 1955, Turunen 1957, Warma 1975). After coming to an agreement with the discoverer, J.A. Liljeqvist, a bailiff from the Koski iron smelter, started mining the next year. With only minor interruptions, about 211 200 tonnes of copper ore were extracted, possibly at an average grade of 3.01 % Cu, between 1758 and 1882. The mine was later in operation once again between 1932 and 1955. During that time 699 400 tonnes of ore were mined at an average grade of 0.82 % Cu, 3.32 % Zn, 1.03 % Pb, 40 g/t Ag and 0.4 g/t Au. The total mine output is estimated to have been in the region of 1.3 Mt.

In the vicinity of Orijärvi, iron ore was also mined at Orijärvi and Grananatinkokka (18th century), Pahalahti-Loviseberg (1826—1866), Aitsaari (1829 and 1842), and Perkiö (probably in 1842). There were copper mines at Iijärvi (18th century, 1833 and 1852—1853) and Paavanholma (18th century and 1851—1855). The Orijärvi field is a good example of a polymetallic metallogenic district. Together with the nearby Atjala copper-zinc mine (1948—1960), the Metsämonttu zinc-lead-copper mine (1951—1974) and the Malmberg (or Leila) iron ore mine (1670—1707 and 1813—1866), it was probably the most significant and active mining district in Finland of all time.

Pitkäranta and Lupikko

There were at least 35 separate copper-tin-silver and iron ore bodies in operation from 1813 to 1904 within a small area at Impilahti on Lake Ladoga (Holmberg 1858, Trüstedt 1907, Trüstedt 1914, Palmunen 1939, Laine 1955). Total ore output was about 1.1 Mt at an estimated average grade of 1.5 % Cu, 0.1 % Sn, 40 g/t Ag and 50 % Fe. The Pitkäranta ores contained cassiterite in such abundance that tin was also recovered. The genesis of the ores has still not been established, mainly because the effect of the rapakivi granite on the ore-forming processes is not fully understood.

Paakkila

As mentioned earlier, the anthophyllite asbestos from the ultramafic intrusions at Paakkila has been known since the Stone Age (Aurola 1954a, Aurola & Vesasalo 1954, Palomäki & Halonen 1968). Interest focused on the asbestos deposit as an industrial target in the late 1890s. Samples containing this mineral were sent to Johan Fabritius, an engineering colonel in St. Petersburg, who immediately contacted the civil and military authorities in Kuopio. A company named Suomen Asbesti Oy was founded and it obtained the concession in 1900. During the period 1904—1910, the deposit was leased to a Danish company, I.L. Smith & Co., that mined asbestos-bearing rock and built the first concentrating plant. The mine was short-lived, however, as production was not profitable. Suomen Mineraali Oy began operations at Tuusniemi in summer 1918. Things got off to a good start and even during that first summer a lot of 1 307 777 kg of raw asbestos rock was sent to Helsinki and from there to Germany. The company built a new grinding plant in 1919, and continued mining until 1975, when demand for asbestos slumped. It is estimated here that some 0.65 Mt of asbestos rock was mined from at least six major sites in North Karelia, including Paakkila. The total amount of different types of asbestos products recovered may have been 416 000 tonnes.

Outokumpu field

The Outokumpu copper-zinc-cobalt deposit (Kuusma 1985, Häkli 1987) was discovered in 1908 during exploration conducted by Otto Trüstedt of the Geological Survey of Finland. From 1910 to 1989, 28.50 Mt of ore was hoisted at an average grade of 3.36 % Cu, 0.88 % Zn, 0.23 % Co and 0.8 g/t Au. Some 3.18 Mt of tailings at an average grade of 0.52 % Cu, 0.52 % Zn and 0.11 % Co was reprocessed during the period 1955—1980. The Vuonos deposit was discovered in 1965 in the eastern extension of the Outokumpu deposit. From 1967 to 1986, some 11.00 Mt of ore was extracted at an average grade of 2.14 % Cu, 1.31 % Zn and 0.14 % Co. The roughly 5 Mt of nickel ore mined at Vuonos between 1972 and 1985 assayed about 0.16 % Ni.

The Luikonlahti deposit (Eskelinen et al. 1983) is part of the same ore district as the Outokumpu -
Vuongos deposits. There 6.87 Mt of ore at an average grade of 0.94 % Cu, 0.89 % Zn and 0.11 % Co was extracted between 1958 and 1983.

Petsamo

The extensive nickel-copper deposit in the Petsamo (Pechenga) area is associated with a major ultramafic belt (Haapala et al. 1945, Autere & Liede 1989) and was discovered by the Geological Survey of Finland in 1921. The Kautatunturi ore body was already in operation from 1936 to 1944, and some 0.46 Mt of ore was extracted at an average grade of 3.87 % Ni and 1.96 % Cu. The deposits have later been exploited by the Russians.

Kaatiala

The Kaatiala pegmatite (Holmberg 1858, Nieminen 1978) had been known long before Suomen Mineraali Oy started to quarry feldspar and quartz from it in 1942. From 1942 to 1968, 516 000 tonnes of pegmatite and 136 000 tonnes of wall rock were mined, which means a total mine output of 652 000 tonnes. Around 160 000 tonnes of potassium feldspar, 30 000 tonnes of quartz, 700 tonnes of mica, 18 tonnes of beryl, 5 tonnes of columbite and 5 tonnes of löllingite were produced.

Talc mines

The ultramafic intrusions in North Karelia and Kainuu have been known since the end of the 19th century (Aurola & Nieminen 1954, Vesasalo 1965, Boström 1986). Suomen Mineraali Oy had mined talc at Jormua from 1952 to 1971, but large-scale mining did not get under way until 1969 when Suomen Talkki Oy started its operations at Lahnaslampi. Talc from all deposits in Finland has been an important raw material for filler and coating material in paper, and also as an export commodity. Talc mines have been operated by several companies, for instance, Suomen Mineraali Oy, Suomen Talkki Oy (owned by Yhtyneet Paperitehtaat Oy and Lohja Kalkkitehdas Oy), Yhtyneet Paperitehtaat Oy, Oy Lohja Ab, Myllykoski Oy and, most recently, Finminerals Oy. As of 1950, the total output of all 11 talc mines has been 16.6 Mt and ore output 10.6 Mt, and some 7.2 Mt of talc has been produced. Besides talc, small amounts of nickel concentrate has been recovered annually as a by-product.

Siilinjärvi

The first hint of the existence of apatite at Siilinjärvi was given by an amateur prospector in 1950 (Puustinen & Kauppinen 1989). Between 1958 and 1960, Lohjan Kalkkitehdas Oy located apatite-bearing glimmerite, silicocarbonatite and sövite, all of which appeared to be a part of a carbonatite complex, within a distance of 10 km. Exploration was continued by Typpi Oy from 1964 to 1967 and then by Apatitii Oy until 1968. In 1966, small-scale test mining was carried out at Saarinen in the north of the complex and at the site of the present mine. The mine area is now in the possession of Kemira Oy, which after a development stage started the beneficiation of the apatite ore. Since 1975 the total output at Siilinjärvi has been 121.7 Mt and the ore output 93.6 Mt. Approximately 7.7 Mt of apatite has been produced as raw material for the nearby fertilizer plant, together with some 1.2 Mt of calcite and 25 000 tonnes of mica as by-products.

Conclusions

By 1995, the total output of Finland’s 507 or so mines was 795 Mt and the ore output 579 Mt. The estimated historical value of Finnish mining products is FIM 152 587 million. Of this, metals account for FIM 115 881 million (75.9 %), limestone (including marble and soapstone) FIM 21 913 million (14.3 %) and industrial minerals FIM 14 793 million (9.8 %). The most significant commodities in decreasing order have been chromium, copper, cobalt, limestone, zinc, nickel, vanadium and iron.

All in all then, Finland’s total mine output has been quite small compared with that of other countries. Nevertheless, for almost 500 years, the production of metallic concentrates, industrial minerals, industrial rocks and limestone has provided a basis for this country’s mining and metal industries, and also material for export.

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ISOTOPIC STUDIES ON THE KUTEMAJÄRVI GOLD DEPOSIT, ORIVESI, SOUTHERN FINLAND

by
Irmeli Mänttäri1), Ari Luukkonen2) and Pentti Grönholm3)

1) Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
2) VTT, Communities and Infrastructure, FIN-02044 VTT, FINLAND
3) Department of Geology, FIN-00014 UNIVERSITY OF HELSINKI, FINLAND
e-mail: irmeli.manttari@gsf.fi

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Introduction

The Kutemajärvi gold deposit lies in the Palaeoproterozoic volcanic-sedimentary Tampere Schist Belt (TSB) in the Svecofennian Domain. The TSB mainly consists of turbiditic metasedimentary and mafic to felsic arc-type metavolcanic rocks. The main metagreywacke association deposited at ca. 1.9 Ga (Huhma et al. 1991, Claesson et al. 1993), and the volcanic rocks have U-Pb zircon ages of 1904±4 Ma to 1889±5 Ma (Kähkönen et al. 1989). The schist belt encloses the zone. Galena generally occurs in vertical pipes where the host rocks are deformed and the latter is considered to be syntectonic with respect to the D2 deformation. The aim of the study was to obtain Pb-isotope and U-Pb-age data on the Kutemajärvi gold deposit.

Local geology and ore deposit

Around Lake Kutemajärvi, the east-west-trending TSB is bound in the north and south by synkinematic granitoid rocks (Fig. 1). The northern tonalitic-granitic Pukala pluton is crosscut by narrow mafic dykes of a late or postkinematic dyke swarm (cf. Aro & Laitakari 1987). The southern batholith is mainly composed of coarse-grained porphyritic granites and granodiorites. The contact zone of the batholith is muscovitized and occasionally tourmalinized. Two major shear zones in the biotite-quartz and northern felsic metavolcanite layer are extensively mylonitized (Fig. 1).

The Kutemajärvi gold deposit is connected with strongly hydrothermally altered rocks bound in the east, west and south by metavolcanites (Fig. 1). In the north, the altered rocks are in contact with the Pukala pluton (Fig. 1). Sericite-rich schists are dominant on the fringes of the altered zone, whereas quartz-rich rocks are common in the central parts of the zone.

The typical host rock of the mineralization is sericite-quartz schist with abundant quartz veins. Gold generally occurs in vertical pipes where the host rocks are deformed and the correlation between the quartzose rocks and gold is distinct (Grönholm 1992). The chemical evolution of the ore-forming fluids has been demonstrated by mineralogical and geochemical studies (Luukkonen 1994). Ore deposition started with sulphides and sulphosalts (including galena), continued with tellurides, and ceased with native element precipitation. Gold mainly deposited during the telluridic and metallic precipitation stages.

Pb-Pb and U-Pb data

Galena

A galena sample was taken from the Kutemajärvi open pit. Galena occurs as grain accretions in
METAPELITE AND METAGREYWACKE SCHISTS
METACongLOMERATE
QUARTZ-SERICITE AND SERICITE-QUARTZ SCHISTS
BIOTITE-QUARTZ SCHIST
FELSIC METAVOLCANITE AND FELDSPAR PORPHYRY
INTERMEDIATE METATUFF
INTERMEDIATE AND MAFIC METAVOLCANITES
TONALITE AND GRANITE
PORPHYRITIC GRANITE AND MUSCOVITE GRANITE
MAFIC DYKE
COUNTRY ROCK FRAGMENT
Au-ORE DEPOSIT

SYMBOLS IN THE DETAILED INSET:
- ANDALUSITE
- PYRITE
- TOPAZ
- MAGNETITE
- Au-ORE PIPE AND OTHER MINERALISATION

Fig. 1. Location and geological map of the Kutemajärvi area (modified after Luukkonen et al. 1992). The distribution of hydrothermally altered rocks around the Kutemajärvi gold deposit is shown in the detailed inset.
chlorite schist with pyrite, sphalerite, chalcocpyrite, pyrrhotite, sulphosalts, tellurides, and gold.

The data (Table 1) indicate a homogeneous lead isotope composition, with an average model age of 1888 Ma and μ-value of 9.33. The composition plots roughly on the mantle lead evolution curve of Zartman and Doe (1981) (Fig. 2).

Monazite and zircon

Monazite and zircon were separated from ore-hosting chlorite schist with coarse phlogopite lath aggregations. The non-transparent, pale zircons show thin internal fissures, and one broken piece of zircon was detected in chlorite mass. Both the zircon and monazite contain black microinclusions. Notable are the extraordinarily low ²⁰⁶Pb/²⁰⁴Pb ratios of both minerals despite the insignificant total procedural lead blanks (20—30 pg for monazite, 10—20 pg for zircon samples less than 0.4 mg, and ca. 500 pg for zircon samples over 4.0 mg).

Two U-Pb analyses were made on monazite (Table 2). The HF-leached fraction shows slight reverse discordancy, possibly due to the excess of ²⁰⁶Pb originating from ²³⁰Th. In this case, the ²⁰⁷Pb/²³⁵U age of 1879±5 Ma may be the best estimate. However, the concordant age of 1880 Ma of the abraded fraction defines the age of monazite crystallization independently. The low ²⁰⁶Pb/²⁰⁴Pb ratios of the monazites analysed may be due to inclusions rich in common lead; the ages are sensitive to the isotopic composition of the common lead correction. However, it is assumed that the common lead composition of the galena well represents the initial lead composition of a monazite.

Because of the unusually low ²⁰⁶Pb/²⁰⁴Pb ratios shown by the zircons (Fig. 3), no U-Pb ages could be determined. These low ratios are due to the extremely high common lead contents, which may originate from inclusions and/or later microfissure fillings. When the results are plotted in a ²⁰⁶Pb/²³⁵Pb vs. ²⁰⁷Pb/²³⁵Pb diagram (Fig. 3), five of seven data points fall on an isochron corresponding to an age of 1808±32 Ma. As one data point plots on the upper side of the compositional line, the other data points most probably indicate the time of post-crystallization Pb loss.

Table 1. Lead isotopic compositions, model ages, and μ-values of galena from the Kutemäjärvi ore deposit.

<table>
<thead>
<tr>
<th>SAMPLE/ MINERAL</th>
<th>LEAD ISOTOPES RATIOS</th>
<th>MODEL (1)</th>
<th>μ-VALUE (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>²⁰⁶Pb/²⁰⁴Pb</td>
<td>²⁰⁷Pb/²⁰⁴Pb</td>
<td>²⁰⁸Pb/²⁰⁴Pb</td>
</tr>
<tr>
<td>A144#1PbS</td>
<td>15.214</td>
<td>15.154</td>
<td>34.928</td>
</tr>
<tr>
<td>A144#2PbS</td>
<td>15.214</td>
<td>15.156</td>
<td>34.929</td>
</tr>
<tr>
<td>A144#3PbS</td>
<td>15.208</td>
<td>15.147</td>
<td>34.904</td>
</tr>
</tbody>
</table>

\(1\): Model ages and μ-values according to the two-stage model of Stacey and Kramers (1975).

---

Table 2. U-Pb analytical data on monazite from the Kutemäjärvi gold deposit, Orivesi.

<table>
<thead>
<tr>
<th>Sample</th>
<th>weight</th>
<th>U</th>
<th>Pb</th>
<th>Meas.</th>
<th>Isotopic ratios (1):</th>
<th>Apparent ages, Ma (±2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MON/HF</td>
<td>0.9</td>
<td>165</td>
<td>520</td>
<td>157</td>
<td>0.3441±19</td>
<td>5.366±30  1906  1879  1850±2</td>
</tr>
<tr>
<td>MON/abr</td>
<td>0.4</td>
<td>176</td>
<td>478</td>
<td>170</td>
<td>0.3387±29</td>
<td>5.369±56  0.113±1  1881  1880  1879±2</td>
</tr>
</tbody>
</table>

\(1\): Isotopic ratios corrected for blank and common lead (Stacey & Kramers (1975) model). \(2\): Uncertainties (2σ) refer to last digits of corresponding ratios. \(3\): HF-leached monazite fraction. \(4\): Air-abraded monazite fraction.

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Fig. 2. ²⁰⁶Pb/²⁰⁴Pb vs. ²⁰⁷Pb/²⁰⁴Pb plot of the lead isotopic composition of the Kutemäjärvi galena.
Discussion

During the syntectonic stage of the Svecofennian orogeny vast amounts of granitoid rocks intruded the volcanic-sedimentary supracrustal association. As indicated by low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Käkönen et al. 1987) and positive $E_{\text{Nd}}(T)$ values (Huhma 1986), these granitoids consisted of juvenile mantle-derived material. Because the galena lead contains only a small crustal component and the model age corresponds to the time of the Svecofennian culmination, the lead may be related either to the granitoid magmatism or to the slightly earlier volcanism. The occurrence of the galena as grain aggregates in strongly hydrothermally altered rocks favours a genetic relationship to a plutonic source. This is corroborated by the monazite crystallization in the same rocks at 1880 Ma, which clearly postdates the volcanic activity. Moreover, the volcanogenic ore prospect at Kierikkala, Hämeenkyrö, contains galena with a significantly larger crustal component (Vaasjoki, pers. comm.).

The low isochron age (1808±32 Ma) of the Kutemajärvi zircons is controversial. It most probably reflects later hydrothermal activity in the area after the primary zircon and monazite crystallization.

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References


GLACIAL AND LATE-GLACIAL DEVELOPMENT IN NE KITTILÄ, NORTHERN FINLAND

by

Peter Johansson¹, Raimo Kujansuu² and Kalevi Mäkinen³

¹ Geological Survey of Finland, P.O. Box 77, FIN-96101, ROVANIEMI, FINLAND
² Geological Survey of Finland, P.O. Box 96, FIN-02151, ESPOO, FINLAND
e-mail: peter.johansson@gsf.fi

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Introduction

During the various stages of the Ice Age in Finland, the ice divide was often located in central Lapland, which, for this reason, is known as the ice divide zone. The erosion and accumulation of the ice sheet was weak in this zone and as a result till beds of different ages with intervening interstadial and interglacial deposits are common in the area. The glacial stratigraphy and flow directions of the continental ice sheet in Finnish Lapland have been established in a comprehensive and systematic investigation based on test pit studies (Hirvas et al. 1977, Hirvas 1991). The findings provide an excellent overview of Lapland’s till stratigraphy. Glaciofluvial forms, such as eskers deposited during deglaciation, and erosional forms caused by meltwaters interpreted as older than the last deglaciation, have also been found in the area (Kujansuu 1967, 1994, Mäkinen & Maunu 1984, Mäkinen 1985, Johansson 1995).

Detailed site-specific and local investigations have revealed till units and flow directions of ice that contradict the general pattern (Aario 1984, Tervo 1986, Sutinen 1992). Difficulty has arisen with efforts to link the glaciation stages (tills) to the corresponding deglaciation stages (eskers). There is also a certain discrepancy between the flow direction of the youngest ice sheet (flow stage II) and the direction of the ice retreat as reflected in late-glacial palaeohydrography. Attempts have been made to eliminate this discrepancy in the northern parts of central Lapland and in eastern Lapland. There the till stratigraphy and the eskers reflecting the deglaciation stages have been linked to each other fairly well (Johansson & Kujansuu 1995, Kujansuu & Eriksson 1995).

The present study seeks to clarify the glaciation stages in northeastern Kittilä (Fig. 1) and the glaciofluvial forms deposited during deglaciation stages, and further to establish the relation of these forms to those in central and eastern Lapland with special emphasis on ice flow during the last glaciation, changes in flow direction during the deglaciation stage. Aerial photo interpretation was used in compiling the glaciomorphological classification and planning the field work. The stratigraphic studies were conducted in summer 1996 using a tractor excavator.

Glaciation and flow directions of the continental ice sheet

The oldest till unit in the area corresponds to till bed III of the general till stratigraphy of Lapland (Hirvas 1991). Aario (1984), Åyräs and Koivisto (1984) and Tervo (1986) have reported observations on a till bed in the same stratigraphic position. Aario and Tervo call this till unit the Silas till. In all likelihood it deposited during the Early-Weichselian, when the ice sheet flowed approximately from northwest to southeast across the study area.
Most of the glacial striae found in the area indicate this direction (Fig. 1). The northwest-southeast-trending moraine ridges, often with a rocky core, were formed in the valley of the River Kapsajoki at the same time.

Younger till units cover till bed III/Silas till. According to Tervo (1986), there are indications in the area of a till unit that was probably deposited by ice flowing from the NNW. This flow stage would have preceded the southwesterly flow, to which there are numerous references in the area. The till unit deposited by the ice flowing from the NNW, called the Suas till (Aario 1984, Tervo 1986), occurs in test pits excavated north of Suasselkä. The transport of magnetite-bearing surface stones at Suasselkä southwards from their source is compatible with the NNW flow (Sutinen 1992). A corresponding till bed or flow stage is not included in the North Finland till stratigraphy of Hirvas (1991). One reason for the occurrence of the till unit in a very restricted area on the northern slope of Suasselkä hill may be that the site was protected from the last ice flow. It is also possible that a unit corresponding to the Suas till was previously thought to have been deposited by a younger ice flow from the south (Tervo 1986). The flow from the NNW has been linked by Sutinen (1992) to the Early-Weichselian glaciation (Lapland stage),
the largest extent of which is shown by the Kuusajärvi–Nunospujut end moraine. A till unit deposited by ice flowing from the north and corresponding subglacial meltwater systems (eskers) have been found in eastern Lapland. On the basis of stratigraphy, these eskers are younger than till bed III and presumably Early- or Mid-Weichselian (Johansson & Kujansuu 1995). We could not, however, find convincing evidence of the NNW flow and the corresponding till unit in northeastern Kittilä.

During the younger flow stage, the ice sheet flowed, on average, from southwest to northeast in northeastern Kittilä. In the general till stratigraphy of Lapland this flow stage is called flow stage II. Till bed II, common in the area, deposited during this stage (Hirvas 1991), as evidently did some of the Rova and Nuuti tills described by Aario (1984) and Tervo (1986). Glacial striæ (240°) of the younger flow stage have been found only in the south of the area, at Sorvetiavuoma, where they cross striæ (350°) interpreted as older (Keinänen et al. 1988). Further west, the younger flow turns and runs from south to north (Kujansuu 1967, Mäkinen et al. 1977, Hirvas 1991, Johansson & Nenonen 1991).

Observations on the youngest ice flow direction vary greatly from one part of the study area to the other. The directions measured by Hirvas (1991) on the surficial till fluctuate between south and west. Some of them may represent an ice flow direction during deglaciation, but some may be merely due to solifluction or other frost action. Likewise the fabric of the Rova and Nuuti tills reported by Aario (1984) and Tervo (1986) are in part clearly not compatible with a southwestern-northeastern direction during the younger flow stage.

Meltwater systems

Towards the end of the last glaciation an ice divide ran across central Lapland from Kolari via the northern parts of Kittilä and Sodankylä to Korvatunturi fell. The study area lies right at the northern edge of this divide. Typical of it, as indeed the whole ice divide area, is the scarcity of subglacial meltwater systems; only six esker chains have been identified (Fig. 1).

One esker chain begins north of Pokka and runs NNE towards Inari through Naatsukkapalo. It is composed of discontinuous ridges and hillocks, except at Haminalammet, where there is a steeply sloping esker, 3 km long, that rises more than 10 m above the surface of an adjacent mire.

A low northwest-southeast-trending esker runs from Kuusiselkä to west of Paatoselkä, crossing the latter west of its highest point whereafter it assumes a north-south direction. North of Lake Vesmajärvi it is joined by an almost parallel esker that follows the Loukinnen valley and by a minor lateral branch on the northeastern slope of Nunosvaara hill. West of Vesmajärvi the esker chain continues southwards. Known as the Vesmajärvi esker it is a distinct, steeply sloping ridge in morphology and composed of gravel and sand. No signs of a till cover have been observed.

A west-east-trending till-covered esker chain, its surface often flattened by glacial erosion, runs from Majuriselkä via Silläsetelkä towards the Porttipahta reservoir. The till covering the esker is sandy and of glaciofluvial origin, containing abundant highly rounded stones. The fabric of the till covering the esker at Silläsetelkä is 210—240° corresponding to that of flow stage II in the area.

The fourth esker chain follows the Lismajoki river valley in a north-south direction to Hanhimmaks and the Pokkajoki river valley, and from there to Sorvetiavuoma and Nilivaara south of the study area. The esker comes to an end on the western flank of Pikku Torsavaara hill, in the Kuusajärvi–Nunospujut end moraine (Kujansuu 1967). The esker is covered with till, 1—2 m thick, at Nilivaara (Kujansuu 1967), in the Pikku Torsavaara area (Johansson et al. 1992) and at Hanhimmaks. In many places, however, especially in steeply sloping and sharp-ridged parts, the till cover is lacking. The Hanhimmaks esker is joined by two branches. The northern one comes from Parttokusuikko through Paanappytöövuoma to Hanhimmaks, where it joins the main esker south of Hanhimmaks. The other branch from the west joins the main esker at Sukispulju, south of Loukinnen. The main esker is also joined by a discontinuous esker that is composed of several parallel glaciofluvial ridges and extends northwards from Lismapuljut. Following the eastern flank of Silasselkä it then continues as a low and narrow ridge via Mieliolaki to Olletanrova. No till covering glaciofluvial sediments has been found at Lismapuljut. At Parttkusuikko the glaciofluvial sediments are covered with till and highly deformed by ice flowing from the southwest. East of Rikikonkoski, in the southwestern corner of the area, there is a low and discontinuous till-covered esker, about 3 km long, running parallel to the Hanhimmaks esker.

The sixth esker chain is composed of two successive till-covered ridges on the western flank of Suasselkä. Small individual hillocks that may be-
long to this esker chain have also been met with on the northern slope of Iso-Kuotko.

The esker north of Pokka and the Vesmäjärvi esker were both formed during the last deglaciation; basal till covering glaciofluvial sediments has not been found on either. The orientations of eskers (direction of meltwater flow in a subglacial system) usually coincide with the direction of ice flow during the corresponding deglaciation. In this case, however, the observations are inadequate as the presence of deglaciation till has not been confirmed everywhere. The orientations of the four other esker chains in the area are not compatible with the flow directions of ice during the last deglaciation. The Hanhimaa and Riikonkoski eskers probably deposited before the last glaciation, during deglaciation either at the end of the Early-Weichselian or in the Mid-Weichselian. Their orientation corresponds to that of the Lapland stage till of Sutinen (1992). The orientation of the Suasselkä esker corresponds approximately to that of the older till (III) in the study area. The esker chain running from Mujurinselkä towards the Porttipahta reservoir may represent an even older glaciation; no till of this glaciation has, however, been found in the area. The orientation of the esker chain is approximately the same as that of the Taivalselkä esker (Kujansuu & Eriksson 1995) and may thus be of the same age, that is, deposited during the Saale deglaciation. Hence it is older than Suasselkä, Hanhimaa and Riikonkoski eskers. In the valleys of the headwaters of the Kapsajoki and in the Kainulauttasenoja river valley there are large, till-covered gravel and sand deposits, several metres thick. In all likelihood, they are delta or sandur deposits predating the last glaciation and formed when meltwaters flowed from northwest to southeast.

**Parttokuusikko**

At Parttokuusikko there are two parallel north-south-trending ridges about 1 km apart. According to the glaciomorphological interpretation, the ridges are part of the western branch of the Hanhimaa esker chain, which joins the main esker south of Hanhimaa (Fig. 1). The ridges are from 3 to 4 m high, rising at their maximum to about 5 m above the slightly eastward sloping ground in the vicinity. The surface of the ridges is stony and bouldery but the boulders are not very numerous.

In summer 1996 a tractor excavator dug an exploration trench across the western ridge of Parttokuusikko (Fig. 2). On the bottom of the trench there was stony, dense and homogeneous basal till overlain by sandy till with fissility and small, deformed sand and gravel lenses (Fig. 3). Outside the ridge the topmost till unit is less than 1 m thick. The ridge itself is mainly composed of this till, which, in the ridge, is at least 2.5 m thick. In places at the eastern edge of the ridge the sandy till is underlain by heavily deformed gravel and sand layers (Figs 2 and 3). The till continues over the gravel and sand layers as a blanket about 0.5 m thick, thinning out towards the eastern edge. At the contact of the sorted material the till is dense and it has a fissile structure but on the eastern flank of the ridge it grades into a less dense till composed of
sorted material. The ridge was formed when the ice sheet overran the previously deposited sorted sediments and possibly even a small esker. Deformation was intense at the contact between the till and sorted material, where the subvertical layers turn sharply horizontal. Closer to the eastern edge the angle becomes more gentle and at the eastern edge the layers are subhorizontal (Figs. 2 and 3).

Fabric analyses on till units show that the lower till with 320° orientation represents an older ice flow direction, i.e. flow stage III. The orientation of the topmost till in the central part of the ridge is 230° (Fig. 2) in harmony with the estimated direction of movement deduced from the deformation structures in the sorted material. The southwesterly flow direction corresponds to the direction of ice flow during the last deglaciation, which, here, is approximately the same as the direction of flow stage II.

**Ice lake stages and deglaciation**

During the deglaciation stage an ice (glacial) lake started to develop at the front of the ice sheet, south of the water divide, between the Ounasjoki, Ivalojoki and Kitinen river valleys because the terrain sloped there towards the ice. This lake is called the Kapsajoki Ice Lake after the Kapsajoki, a tributary of the Ounasjoki flowing through the area (Fig. 4 A). Initially, the waters flowed over the main water divide between the Ounasjoki and the Ivalojoki, heading northeastwards along the Ivalojoki to the Inari basin. As extensions of headwater branches of the Naskamajoki, there are channels carved in the terrain by meltwater erosion. The first major discharge channel ran through Latvajarvi gorge to Lake Taatsijärvi, and the level of the ice lake beyond the threshold west of Latvajarvi stabilised at about 307 m. The next discharge channels directed waters through Paanosenkuru gorge (about 284 m) and the River Jalkajoki into the Kitinen watercourse (Tanner 1915, Kujansuu 1967). While the Jalkajoki channel was open the surface of the Kapsajoki Ice Lake remained at about 282 m; this stage lasted for decades. The Pulju Ice Lake, which had developed at an elevation of 295 m in the vicinity of Pulju, drained from the west into the Kapsajoki Ice Lake (Kujansuu 1967). To start with, the waters of the Pulju Ice Lake streamed along the channel south of Olletanrova. When the ice front withdrew to south of Silasselkä, however, a new discharge channel opened on the southern flank of Silasselkä. A marginal outwash delta with its flat surface at about 280–284 m deposited at the mouth of the discharge channel at the
level of the Kapsajoki Ice Lake. The delta was composed of poorly sorted stony gravel and sand, indicating a catastrophic discharge. As a result the water level of the Pulju Ice Lake dropped rapidly to 290 m (Fig. 4 A).

While the marginal delta was forming the ice front was on the southern flank of Silasselkä. At the same time the ice front was at Ruoppapalo, south of the Jalkajoki channel, at the eastern edge of the ice lake basin, because the next discharge channel (Seurujärvi) at a lower elevation had not opened yet. Although it is hard to establish accurately the position of the ice front in the ice lake basin these two "benchmarks" allow us to estimate that it ran approximately from WNW to ESE. Consequently, the ice front withdrew towards the SSW.

One of the major discharge channels in the study area runs through the valley of the Lake Seurujärvi.

Fig. 4. History of the ice retreat and the corresponding ice lake stages (A—D) in NE Kittilä. 1 = direction of ice flow, 2 = discharge channel in action, 3 = previous discharge channel, 4 = ice margin, 5 = area covered by ice lake and 6 = hill top.
and the Hannukanoja. Its threshold, at about 270 m, is in the low neck of land between Seurujärvi and Hannukanoja. Outcrops washed by flowing water and erosional forms in moraine occur in the Hannukanoja river valley. Almost simultaneously with the opening of the Seurujärvi discharge channel the front of the withdrawing ice sheet reached Suasselkä, then a nunatak, which divided it into two lobes. Both lobes continued their withdrawal south-westwards. The eastern lobe rested on the slope of the Seurukarkea hill, impounding the ice lake. The western lobe covered a part of the Kapsajoki river valley, and while flowing towards the ENE deformed ridges at Partokuusikko.

North of Porskuna, which lies in the south of the study area, there is the Pitslomäärvi gorge, a typical discharge channel, with its bottom at 265 m. Clearly enough, it was not a discharge channel for the extensive ice lake that covered the Ounasjoki valley, as previously suggested (Kujansuu 1967), but an ephemeral discharge channel for a local ice lake that developed in the vicinity of Vesmajärvi (Fig. 4 B). The ice sheet that had remained beyond the fall chain of Kumputunturi and Hanhilaki was divided into two lobes that withdrew in different directions and between which the ice lake developed. The southern lobe impounded the ice lake until it withdrew westwards south of Kumputunturi fell. The northern lobe was part of the ice sheet withdrawing from the Suasselkä area. At Suasselkä the glacial lobe withdrew south-westwards, in the Seurukarkea and Paartoselkä area westwards and north of Vesmajärvi towards the WNW. Hence, the discharge channel of Seurujärvi long served the ice lake that had formed in the vicinity of Suasselkä. The ice margin rested on the slopes of Seurukarkea and the fell chain south of it, preventing new discharge channels from opening southwards (Fig. 4 B).

As the ice continued its withdrawal a set of discharge channels opened south of Vesmajärvi. Following the western slope of Porskona – Haurespää, these channels directed the water into the Sattanen valley. When the ice margin retreated from Seurukarkea, a new southward discharge channel opened for the Kapsajoki Ice Lake. The withdrawal of the ice margin and the subsequent drop in water level are recorded in the marginal and extramarginal channels around Paartoselkä, along which the waters of the Kapsajoki Ice Lake drained into the valley between the Kumputunturi and Porskona – Haurespää hill chains. The lowest discharge channel in the Kiutasautoja (218 m) finally directed the waters of the ice lake into the Jeesijöjoki river valley (Fig. 4 C).

South of the study area, in the surroundings of Tepasto, there are several ancient shores on hill slopes at heights of 268 m to 238 m (Kujansuu 1967). The uppermost shore level corresponds to the elevation of the threshold of the Seurujärvi discharge channel, implying that the ice sheet had withdrawn from the southern flank of Silasselkä and that the ice lake that had covered the valley of the main Ounasjoki basin had joined the Kapsajoki Ice Lake. The other ancient shores in the Tepasto area, at elevations of 258 m, 250 m and 238 m (Kujansuu 1967), show that the water level in the above ice lake dropped stepwise along the channels at Paartoselkä to the discharge channel of the Kiutasautoja.

The ice margin withdrew south-westwards from around Kiistala, to south of the mountain range formed by Holkkuaavaa and Kukkuravaara hills on the one hand, and Levitunturi and Kääntäntunturi, two fells to the southwest, on the other. The recent faults at Rautuskylä and Riikonkumpu and landslides south-west of Akanvankko and Hanhilaki were caused by crustal movements during the withdrawal of the ice sheet (Kujansuu 1964, 1972). The area covered by the ice lakes was reduced substantially once the ice margin had withdrawn south-west of Hanhilaki. The waters of the ice lake could then drain into the Jeesijöjoki, first through Kuortisvuoma (208 m) and later through a channel west of Lake Jeesijöjärvi (207 m). Thick layers of outwash gravel were deposited around Jeesijöjärvi as a consequence of the drop in water level (Kujansuu 1967, Johansson et al. 1992) (Fig. 4 D).

In conclusion, correlation of the glaciofluvial landforms in eastern and central Lapland with those in western Lapland requires further research, on older landforms in particular. It would also be important to find organic or minerogenous deposits suitable for dating. As shown here, the waning of the continental ice sheet reflected in late-glacial palaeohydrography and the deposits related to deglaciation can be recognised accurately enough and are found to be consistent with the findings of previous studies.

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WIND-BLOWN SILT: A LOESS-LIKE DEPOSIT IN FINLAND. AN EXAMPLE OF AEOLIAN ACTIVITY AND DEPOSITS ASSOCIATED WITH DEGLACIATION NEAR THE CENTRE OF A GLACIATED AREA

by

Heikki Rainio

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: heikki.rainio@gsf.fi

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Introduction

A number of observations of deposits of fine sand, 0.5—1.5 m thick, covering other Quaternary deposits have been made in Finland over the past 100 years. It has been understood that this material and the underlying deposit are not products of the same geological process or at least that the layer, in the light of contemporary geological knowledge, was in the "wrong" place. Its genesis has been explained in a number of ways.

During the last 40 years it has cautiously been proposed that the material might be aeolian or even loess or "loess-like" in origin. After all it satisfies the definition of loess made by Flint (1971, pp. 251—252): "A sediment, commonly nonstratified and nonconsolidated, composed dominantly of siltsize particles, ordinarily with accessory clay and sand, and deposited primarily by the wind".

Even experts from countries where loess is common do not seem to be unanimous about what loess is. Flint’s definition is not universally accepted. Says Zárate: "Broadly different concepts on the definition of loess were proposed.... They ranged from those regarding loess as an eolian silt to those who viewed it as a result of a more complex process taking place after deposition" (Zárate 1993, p. 3).

The genesis or importance of the loess-like sediments found in Finland has prompted little debate so far. The material is so scarce that people are not generally aware of its existence let alone agreed about what it should be called. Nevertheless, in mode of occurrence and composition, the sediment is such that deposits are easy to recognize from their descriptions, irrespective of where they are located.

A report currently being compiled at the Geological Survey of Finland will contain the latest findings on this material as well as data and interpretations published earlier. The present article deals briefly with these findings. I use the genetic term "wind-blown silt" for both the material and the deposit. Where necessary the material is called "aeolian coarse silt or fine sand".

Brief history of the research of wind-blown silt in Finland

Several Finnish researchers have expressed opinions on wind-blown silt. Some of them have reported random observations; some have elaborated earlier concepts.

Hult (1891) seems to have been the first to correlate occurrences of this material in Finland with loess. Okko (1958a, p. 40) linked it even more clearly to the concept of loess although quoting another researcher: "According to Lougee, this sediment is loess." Berghell (1916, 1927), Leiviskä (1920) and Aarnio (1938) all noticed that there was something unusual about this material. Leiviskä (1920, p. 140) explained it as a weathering remnant and Aarnio (1938a, p. 4, 1938b) as till. Kivinen

67
Helsinki Geological Survey of Finland, Special Paper 23
Heikki Rainio

Fig. 1. Wind-blown silt occurrences in the Salpausselkä zone (hatched area).

Distribution of wind-blown silt

The main occurrences of wind-blown silt in Finland are in the Salpausselkä zone, particularly on the distal sides of Salpausselkä II and the Koitere end moraine, a formation of the same age (Rainio 1978, 1982a and b) (Fig. 1). The main sources of the aeolian material were probably the large glaciofluvial plains of these big end moraines made up of glaciofluvial sediments. On the proximal side of the Salpausselkä II-Koitere end moraines the aeolian material is scarce.

At Lieksa, southeast and east of Pankakoski, wind-blown silt has been encountered within a small area, as it has at Eno and Kontiolahti, very near Salpausselkä II (Rainio 1982b). The observation of Hult (1891) suggests that wind-blown silt may occur in larger amounts in the zone of the Central Finland Ice Marginal Formation, although the only place where it has been encountered is Mäntänvuori.

The occurrences of wind-blown silt seem to be linked to the land that lay above the large watercourses in existence at the time the deposits were formed, but not to the highest shore. The most extensive continuous deposits are in eastern Finland, in North Karelia, where there is abundant supra-aquatic land as well as land that emerged after the draining of the Baltic and Ilomantsi glacial lakes. At its most extensive, the zone of wind-

(1941a,b and c) refined the concept of Aarnio and interpreted it as a special component of the "hill till".

Mielonen (1965) drew attention to the considerable variation in the grain size composition of Kivinen's "hill till" samples and to the fact that "well-sorted samples were almost invariably from North Karelia and the less well-sorted from Savo". According to him, the well-sorted "hill till" (Vaara-Feinsand) was aeolian in origin.

Rainio (1978, 1982a, b, 1996) pointed out that "loess" occurs in variable amounts on the distal side of Salpausselkä II, from Lammi to North Karelia, but only very sporadically on the proximal side of the ridge. It would have derived mainly from the plains of Salpausselkä II, and possibly also from those of Salpausselkä I.

Hyypää (1943), M. Okko (1962), Repo and Tynni (1969), Virkkala (1969), Jauhiainen (1972), Lindroos (1972), Wisniewski (1973) and Nuñez and Alhonen (1974) have also reported observations of this sediment and interpretations of its genesis.

Jauhiainen and Rainio both call it loess; Lindroos (1972) says it is loess-like. It has been considered aeolian by at least M. Okko (1962) and Nuñez and Alhonen (1974). It is not always clear, however, whether the authors are referring to material transported and deposited by wind like loess or to a deposit resembling dune sand or cover sand (Flint 1971, p. 244).
blown silt is 20—30 km wide. Farther west, where the distal side of Salpausselkä II was initially submerged, i.e. subaquatic, wind-blown silt occurs in small, intermittent patches.

At Ilomantsi wind-blown silt occurs well below the highest water level, the Ilomantsi glacial lake (Hyvärinen 1971). Elsewhere in North Karelia it occurs below the level of the Baltic glacial lake, although less distinctly than at Ilomantsi, as the lowest sites are not very much below the level of the latter lake.

The thickness of the deposit ranges from 0.5 to...
1.5 m in a 15–20-km wide zone on the distal side of the Salpausselkä II–Koitere end moraines (Fig. 2). Thicknesses exceeding 1 m are, however, rare and the deposit thins out in a distal direction. Close to the Russian border, layers 20–30 cm thick have been observed at sites 40 km from the end moraines. The thinner the layer the more difficult it is to interpret it correctly and, above all, to take uncontaminated samples.

As a continuous blanket the wind-blown silt seems to cover a few square kilometres at the most. The largest unbroken stretches are at Ilomantsi, Kitee, and Tohmajärvi, as reported by Mielonen (1965, p. 29). Covering the basal till, the deposit occurs on the tops and slopes of cultivated supraxial hills. It is poorly permeable and so highly suitable for agriculture (Fig. 3), thus permitting cultivation even on glaciofluvial deposits, which are not usually amenable to arable use.

Wind-blown silt has been encountered on till, glaciofluvial deposits and bedrock, and presumably on littoral deposits of the Ilomantsi glacial lake.

Grain size distribution of wind-blown silt

According to Smalley, Bugnold has demonstrated "that the particles of diameter about 80 μ (0.08 mm) are most easily lifted by the wind and that particles both larger and smaller than this require a higher wind velocity" (Smalley 1966, p. 671). "Particles larger than about 200 μ will tend to fall fairly quickly, and the smaller particles may be carried in suspension for a considerable distance"... "Sediments which are deposited after being transported for a long distance by eolian action will therefore consist of particles less than 200 μ in diameter, and the expected mode diameter will be 80 μ or less" (op. cit., p. 672).

On the basis of samples we have collected, the wind-blown silt in North Karelia contains 85–90% coarse silt, and 10–15% fine sand (Fig. 4). Data published from elsewhere in Finland show that part of the material is wind-blown silt and that part is clearly coarser and obviously represents wind-blown cover sand (Flint 1971, p. 244). Some may be coarse wind-blown silt (Table 1). For instance, the grain size distribution curves 1–3 (Abb. 7) and 1 (Abb. 9) of Mielonen (1965) are of coarse silt (< 0.06 mm about 55–65%), i.e. similar to most of the samples collected for the present study, curves 4–6 refer to a coarser than average material (< 0.06 mm about 37%) and 7–8 probably to cover sand (Abb. 9). Two of the samples of Okko (1958a, p. 21) are coarse silt (< 0.06 mm 56.0% and 53.0%) and two are fine sand (< 0.06 mm 38.0% and 30.0%); one sample is sand.

The abundance of coarse silt and finer material (< 0.06 mm) is usually 50–70%, but in places it rises to 90% or declines to 40%. The clay fraction (< 0.002 mm) commonly accounts for 2–5%. The top layers, especially on cultivated fields, contain secondary coarse material. Wind-blown silt in Finland is generally coarser than reference samples from Continental Europe (Jauhiainen 1972, p. 155 and Fig. 3; Rainio 1982, Fig. 3) or samples referred to in textbooks (Flint 1971).

Genesis of the wind-blown silt deposit

Judging by its distribution, the wind-blown silt was deposited immediately after the formation of Salpausselkä II and the drainage of the Baltic glacial lake. According to revised varved clay chronology (Strömberg 1990), the Baltic glacial lake drained 10,643 years before AD 1950. On the basis of the elevations of Quaternary deposits the Ilomantsi glacial lake (Hyvärinen 1971) must have drained at about the same time. Large barren areas - the readily erodible marginal plains of the
Salpausselkäs - were exposed to aeolian erosion. Wind-blown silt continued to deposit until vegetation fixed the surficial parts of the soil and prevented the wind from blowing it away.

Nuñez & Alhonen (1974, p. 115) argued that at Lammi "the period of colization can be estimated to have lasted between 500 and 1000 years". Without indubitable proof this period would seem too long; more likely the period did not last more than a few decades, that is, until vegetation had stabilized the soil.

There are very few unambiguous observations of the age relations between wind-blown silt and dunes. Nowhere has wind-blown silt been seen to rest on dunes. This fact together with the case reported by Lindroos (1972, pp. 52—53), namely, that at Tohmajärvi loess-like material lies beneath a sand dune about 3 m thick, suggests that wind-blown silt is older than dunes.

Otherwise, too, the connection between dunes and wind-blown silt is unclear. At Tohmajärvi and Kitee dunes and loess abound; at Ilomantsi, though, dunes are rare even when wind-blown silt is plentiful.

The most extensive, continuous areas and thickest deposits of wind-blown silt are in regions with the highest proportion of supra-aquatic land, i.e. in North Karelia. The main sources of silt were obviously the glaciofluvial marginal plains of the Salpausselkä II and Koittere end moraines (cf. Lindroos 1972, pp. 57—63). The fine-grained sediments in their distal parts contained abundant material less than 0.02 mm in diameter. Other glaciofluvial deposits with fine-grained sediments were also sources of wind-blown silt.

Grain size distribution analyses reported by Kivinen (1941a and b) from the Salmi area suggest a local source, most likely the large esker or interlobate formation at Salmi (Berghell 1916). The genesis of the thin wind-blown silt deposit at Pankakoski-Siikavaara (Rainio 1982b) would seem, however, to be associated with aeolian activity at Lieksa after the Salpausselkä II stage. Drainage of the glacial lakes on the proximal side of the Kontiovaara-Kitsi-Louhivaara water divide at Lieksa may have provided material for this activity. It is also possible that the material derived from the extensive riverine deposits of the Lieksanjoki, Jongunjoki and Viekijoki, which also provided material for the numerous dunes around Lieksa.

Wind-blown silt in Finland is an example of a phenomenon of extreme conditions. The silt was formed during a short period, no more than a few decades, towards the end of the last deglaciation. From its probable sources we can estimate that the material was transported by the wind for a few kilometres or at most a few tens of kilometres.

In Finland, where loess-like wind-blown silt is rare, problems with its definition and other aspects
have not arisen, and the concept as such is not charged with passion. Nevertheless, the concept of loess and its status in the nomenclature of aeolian processes need to be established, possibly after a comprehensive re-evaluation. Wind-blown silt in Finland needs a name that unambiguously defines its place among aeolian deposits.

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TWO TILL-COVERED POTHOLES AT PIHLAJAMÄKI, HELSINKI, SOUTHERN FINLAND

by
Heikki Hirvas and Pekka Huhta

Introduction

The potholes are at 17 m asl on the steep northern slope of a rocky area at Pihlajamäki, northeastern Helsinki (Fig. 1). They were found by Sulo Savolainen, an architect, during construction of a ramp for the Rapakiventie underpass in 1993 and 1994. In spring 1995 the City of Helsinki had the potholes protected as natural monuments under the Nature Conservation Act.

The potholes were emptied of soil in May 1995 by the Geological Survey of Finland in cooperation with Helsinki City Real Estate Office and Helsinki City Public Works Department. Considerable voluntary help was also provided by members of the Finnish Gem Hobbyists' Society and the Pihlajamäki Lions Club. The soil, about 74 m³, was removed partly with an excavator and partly manually, taking care not to damage the walls carved out by nature.

Once measured, the larger pothole turned out to be one of the biggest ever found in Finland, having a longer diameter of 6.9 m, a shorter diameter of 6 m and a depth of 8.45 m (Fig. 2). It is asymmetrical and has three erosional levels in its lower part (Fig. 3). The smaller pothole, which is circular and symmetrical, has a diameter of 1.6 m and a depth of 3.2 m. As shown by grinding marks, the water rotated anticlockwise in the potholes. The biggest pothole found in Finland, at Sukulanrakka, Hirvas, has a diameter of 8.0 m x 5.7 m and a depth of 15.4 m (Johansson 1996). The largest pothole at Askola is 4.2 m in diameter and 10.3 m in depth (Kananoja & Grönholm 1993).
Pothole filler

The filler materials in both potholes were very alike, differing only in the thicknesses of sediments. The larger pothole had about 4.5 m of grinding stones, boulders and gravel on the bottom (Fig. 3, A), the grinding stones and boulders ranging from a few centimetres to 1.6 m in diameter. The roundest stones were those with diameters of less than 10 cm. The grinding material was overlain by a layer of sand less than 0.5 m thick (B) that is interpreted as having deposited on the bottom of a subglacial river when the flow had already slowed down and the carving out of potholes ceased. The sand layer was covered with about 1 m of stones and boulders (C) that had probably either dropped off ice floes or rolled down from an upper slope after the subglacial tunnel had disappeared. The stony and bouldery layer was overlain by 30—40 cm of sand (D) interpreted as having deposited by meltwaters streaming from the ice sheet when the area was already free of ice. Topmost there were less than 2 m of basal till deposited during the last glaciation (E). This was sandy till in grain size as is the topmost till in southern Finland in general. The till, which is grey when below the watertable, contains 3% clay fraction.

The potholes were carved out into a 1.9 billion-year-old migmatite (F). An interesting detail is the fault, a few centimetres high and a few metres long, that was found at the bottom of the larger pothole (Fig. 4), the displacement having occurred after the pothole had formed. Young faults of this size have been described from elsewhere in southern Finland by Tynni (1965), among others.

A piece of clay found between boulders in the grinding stone layer, the sand in layer B and the sand in upper layer D were analysed for diatoms and pollen. The samples were devoid of diatoms and contained only a few pollen grains; even these had been redepored from older sediments. The uppermost sand layer could not be TL dated because depositional conditions had prevented complete zeroing of the sand. The results support previous understanding of the mode of formation of the soil layers, i.e. that they were laid down in cloudy and silty water under subglacial conditions, with the upper sand layer probably very close to the ice front.

The lithological compositions of the grinding stone layer and till are very similar. The main rock types were pegmatite granite (44% in grinding stones and 35% in till) and equigranular granite (36% and 34%, respectively). The other main rock types were migmatite and quartz-feldspar gneiss. The greatest difference was in the abundance of amphibolites, the grindstones containing only 1% but the till 10%. Both layers had occasional clasts of calcitic limestone, Jotnian sandstones, gabbros and iron formation skarns. Sandstones excluded, the stony material seems to be very local, the bulk
of the material having been transported for only a few kilometres at the most.

The heavy mineral contents, too, were very alike in both layers. In order of abundance, those observed were garnet, ilmenite, magnetite and hematite.

Pihlajamäki potholes and their formation

While the potholes were being emptied it became obvious that they predated the last glaciation since they were covered with a basal till laid down during that glaciation. Till beds deposited in three glaciation stages have been encountered in southern Finland, the oldest of them occurring only at Vuosaari, Helsinki (Hirvas et al. 1995). Observations of the middle till bed, in contrast, abound from all over southern Finland (Rainio & Lahermo 1976, Hirvas & Nenonen 1987, Kurkinen et al. 1989, Bouchard et al. 1990). This bed, which is a dense, dark grey till rich in fines, contains 10—15% clay fraction. The till was deposited during a glaciation stage when the ice sheet flowed approximately from north to south. Attempts to date the deposition have failed so far but it could be anywhere between the Saalian and late-Weichselian (op.cit.). The youngest bed is of loose sandy till with only 1—3% clay fraction.

As inferred from glacial striae and fabric analyses, the ice sheet flowed from northwest to southeast. Striae corresponding to the two latest ice flows were detected at the edges of the potholes. The younger striae strike 315—320°, and the older, protected from the younger flow, 350—10°.

The material in the potholes could not be dated with either microfossils or isotope methods. It
would nevertheless seem that the potholes at Pihlajamäki were formed during the penultimate deglaciation, i.e. during the melting of the ice sheet that, flowing from the north, had deposited the dark, fines-rich till. We do not yet know exactly when that happened. Several researchers think, however, that the clay fraction of the dark till derives from reworked Eemian sediments (Rainio & Lahermo 1984, Bouchard et al. 1990, Lundqvist 1973) and that the till had deposited during the mid-Weichselian (Hirvas et al. 1995). If so, then the Pihlajamäki potholes were formed during a mid-

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**Fig. 4.** A young fault on the bottom of the larger pothole. Trowel 28 cm long.

**Fig. 5.** The biggest grinding boulder being lifted from the bottom of the pothole from a depth of 8 m. Photo J. Väätäinen/ GSF.
Weichselian interstadial, 74 000—24 000 years ago.

During the late-Weichselian at the very latest, the continental ice sheet covered the area once again, depositing till on the potholes. On the southeastern wall (stoss side) of the larger pothole the till is compacted and as hard as concrete.

Potholes form on the bottom of a glacial meltwater stream, where stones and boulders start to rotate through the force of streaming water carving a hole in the underlying rock (Alexander 1932). Most often, as at Sukulanrakka, Hirvas, and at Askola, potholes are associated with esker chains, where the esker itself represents the depositional activity of meltwaters, and the potholes the abrading action of the stream.

It is easy to imagine the power of the subglacial meltwater stream at Pihlajamäki if we remember that the largest grinding boulder lifted from the bottom of the pothole was 1.6 m in diameter and weighed about 6 tonnes (Fig. 5). Some potholes may form rapidly. For example, in the late 1800s a dam was constructed in southern Sweden at a site where the water ran over the dam into a small pothole from a height of 4 m. Within five months this pothole had deepened from 0.3 m to 1.3 m, and the grinding stones, 30 cm in diameter, had shrunk to a mere 14 cm. Similarly, potholes, half a metre deep, have developed in less than a decade in hydropower plant canals blasted in rock (Ramsay 1912).

Conclusions

As far as we know all the other potholes in Finland are "young", that is, they were formed either during the last deglaciation, about 10 000—12 000 years ago, or in waterfalls during postglacial time. Askola is the only place where an erosional remnant of a till-covered pothole has been found and where it has not been possible to date the pothole itself (Hokkanen 1982). The Pihlajamäki potholes, which were carved out before the last glaciation, are therefore unique features in Finland and indeed all Scandinavia.

References


**LAPPAJÄRVI IMPACT CRATER ROCKS AND MINERALS IN QUATERNARY SEDIMENTS**

by

Marjatta Koivisto and Juha V. Korhonen

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: marjatta.koivisto@gsf.fi

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**Introduction**

The Lappajärvi crater is a well studied impact site (e.g. Lehtinen 1976, Pipping 1979, 1991, Pipping and Vaarma 1992) and one of the type craters of the world (Fig. 1). The crater is 23 km in diameter and its gravimetric expression is a circular negative Bouguer anomaly about 17 km in diameter (Elo 1976, Elo et al. 1992). The impact lithologies consist of impact melt breccia (kärnäite), fallback ejecta (suevite) and impact breccia. The impact occurred on crystalline Palaeoproterozoic basement covered by unmetamorphosed Mesoproterozoic sedimentary rocks of unknown thickness. At the present erosion level the eroded complex crater occurs in a crystalline bedrock composed of plutonic and metapelitic supracrustal rocks. Ejecta has been found inside the crater only; elsewhere it is eroded. Remnants of the sedimentary cover have been intersected in holes drilled into the annular depression of the crater (Pipping and Lehtinen 1992). The $^{40}\text{Ar}/^{39}\text{Ar}$ age of the impact is $77 \pm 0.4$ Ma (Jessberger and Reimold 1980).

Kärnäite lies to the west-northwest of the gravity centre of the crater, with suevite, impact breccia, sandstone and rocks with weak shock-metamorphic features surrounding the centre as rings. The asymmetrical occurrence of the impact melt suggests that the impact was oblique (Schultz and D’Hondt 1996). Kärnäite crops out and almost all the boulders on the shores of Kärnänansaari and some other islands, e.g. Lokkisaari (Fig. 2), are kärnäite (Mölder 1948, Saksela 1949, Pipping 1979) and other lithologies intersected by drill holes (Pipping and Lehtinen 1992).

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Fig. 1. Location of the study area in western Finland. Sample sites with sediment type are indicated. Kärnäite fan (dashed line) according to Lehtinen (1976), impact structure (circle) according to Pipping and Lehtinen (1992).
1989, 1991, Lehtinen 1990, Pipping and Lehtinen 1992). Suevite does not crop out; its main source is at the bottom of Lake Lappajärvi. The thickness of both the kärnäite and the suevite intersected in drill holes exceeded 100 m.

The two impact rock types differ greatly in character. Kärnäite is a hard, fine-grained rock containing rock fragments, calcite and chalcedony amygdaltes (xenocrysts), and open vesicles; Suevite, which also contains rock and mineral fragments, is soft and friable (Lehtinen 1976). Kärnäite in the bedrock exhibits vertical and horizontal fractures due to which the continental ice sheet could easily detach large fragments. Both rocks are porous; the porosity of kärnäite is about 1% and that of suevite up to 20%. Their bulk and mineral densities and magnetization are lower than the averages of those of the host rocks (Kukkonen et al. 1992). Pyrrhotite is the main carrier of remanent magnetization in the kärnäite. The magnetic minerals of suevite are not known. The palaeomagnetic age of the impact is \( \sim 195 \) Ma (Pesonen et al. 1992).

Laitakari (1942), Mölder (1948) and Saksela (1949) studied the glacial transport of dacite/kärnäite in till. Saksela concluded that the boulders of these rocks had been transported at least 150 km. On the basis of samples received from amateur prospectors, Kulonpalo (1969) compiled a boulder train in which the southernmost one was found at Myrskylä (over 290 km from Lappajärvi). Lehtinen (1976) has described metamorphic minerals from the various rock types but nobody has described them from the Quaternary sediments. Salonen et al. (1992) have investigated the Pleistocene stratigraphy and lithology of a 74.3 m thick sequence of unconsolidated sediments, intersected by a drill hole in the eastern rim of the crater. They defined two till units, the lower one deposited by ice flowing from the north or even from the northeast and the upper, younger one deposited by main Late Weichselian ice flowing from the northwest.

**Objectives of the study**

The study seeks to establish the abundances of kärnäite and suevite in the overburden and also the occurrence of shock-metamorphic rocks, taking into account the directions of ice flows. Sediment samples will be analysed for heavy minerals of impact rocks, and the abundances of coesite and stishovite - two high-pressure polymorphs of quartz - will be determined. The abundances of quartz, plagioclase and biotite with shock lamellae, not previously reported from the overburden, will also be determined. At the same time attempts will be made to find minerals that have not been described from Lappajärvi, such as pseudomorphs after graphite (diamonds), and altered forms of zircon and spinels. Should zircons granulated in the impact be found in granite fragments of the suevite boulders their U-Pb age will be determined, if possible, with SIMS. Knowledge of their age will facilitate unra-
velling of the later geological history of the Fennoscandian Shield.

Diamonds have recently been described from some impact craters in Russia (Khar'kiv 1992, Masaitis 1992, Masaitis et al. 1994, Koeberl et al. 1995, Gurov et al. 1995, Hough et al. 1995a and b). Worldwide, these diamonds have been found in nine large or medium-sized impact craters (V. Masaitis 1996, pers. comm.). It is possible that diamonds also occur at Lappajärvi because the crater there is a medium-sized complex structure and the Precambrian bedrock contains black schists with carbon that may have been metamorphosed in the shock.

Some of the suevite boulders found in Quaternary sediments have a weathering crust and a fresh core. These help us to assess the behaviour of suevite in the weathering process and to establish how the bulk and mineral densities in weathered rock differ from those in unweathered rock.

The findings of the study will make it easier to trace impact craters in glaciated terrains with the aid of indicator rocks and minerals. New craters are continuously being found on the Earth; even in Finland the rate has recently been one crater per year. Irrespective of the mode of assessment applied, the surface area affected by impacts within an area the size of Finland is geologically significant. Short-distance ejecta have covered large areas, and long-distance ejecta the whole country several times. New craters found facilitate ground water intake. Resources of hard rock ground water are important for Finland’s water supply, and will be even more so in the future or during crises as they are less vulnerable to pollution. It is thus essential to protect them from contamination. The findings can also be applied to petrology. Maps of Pre-Quaternary rocks are more reliable when impact craters and impact-produced rocks are brought within the scope of geological studies. Moreover, some craters host ore mineralization, and rocks produced by impact have been used as building stones, industrial minerals and gemstones.

Age

The palaeomagnetic age differs by about 120 Ma from the radiometric age. The reason for this discrepancy is not known (Pesonen et al. 1992), and we shall attempt to find the answer with the aid of zircons altered by the impact. To this end zircons will be taken for dating from granite fragments embedded in suevite boulders. The crater was formed in rocks containing abundant zircon. Krogh et al. (1993a and b) demonstrated that the age of the impact can be determined on zircon granulated in the impact from the lower intersection (Bohor et al. 1993). Zircon is present both in Svecofennian granites and in schists. The populations are dissimilar, however, the granite population exhibiting one age but the zircons in schists two or more ages (detrital zircons). It can be assumed that the granites give a linear, but the schists a fanlike (dis)cordia measured on single zircons with SIMS.

Diamonds

At Lappajärvi there are black schists that were also observed in the sediment samples by counting the rock types (10—2 cm). It is possible that graphite in these black schists has altered to diamond. In the Popigai crater in Russia graphite occurs in metamorphic gneisses and in some places the diamond crystals are pseudomorphs after graphite. The diamonds vary in colour from colourless to graphite black, brownish or yellowish and have a specific gravity of about 3500 kg/m³ (V. Masaitis 1996, pers. comm.). The identification criteria for diamonds differ from one crater to the next. Impact diamonds are amongst the hardest diamonds, e.g. lonsdaleite from Canyon Diablo (Carter and Kennedy 1966). Impact diamonds are thought to be associated with the suevite and massive impactites formed in the crater at shock pressures exceeding 35 mb.

Field work of the pilot study

Sample procedures

At the initial stage of the study the sampling was based on field observations rather than following a predetermined grid. Marjatta Koivisto was responsible for the sampling, and Juha Korhonen collected the suevite boulders. Our aim was to collect sediment samples containing products of the impact crater from adjoining areas. Local roads provided access for sampling. Only one sample (stream sediment) was collected 500 m from a road in a catchment to ensure that the sample represented original material without any contamination. A total of 26 surface samples (depth 0—1 m, excluding the cores of eskers) were handdug from around Lappajärvi (within 3.5 km of its shores and

81
Hietakangas glaciofluvial formation) in a belt running south of the lake from west to east taking into account the ice flow directions and the kärnäite boulder train (Mölder 1948, Saksela 1949, Lehtinen 1976) (Fig. 1). Samples were taken from five sediment types: 1) till; 2) glaciofluvial sediments; 3) postglacial littoral sediments (washed from till); 4) stream sediments, and 5) recent beach sediments.

The samples are being treated according to the following flow sheet: Samples (20 1 < 2 cm) are wet-sieved into the following fractions: 20—4 mm, 4—2 mm, 2—0.4 mm and < 0.4 mm. Rock types associated with the impact crater are identified in fractions 20—4 mm and 4—2 mm. Fraction 2—0.4 mm is concentrated with a Knelson hydrostatic concentrator and then with heavy liquids (SG 2900 kg/m³) after which its heavy minerals are studied. Fraction < 0.4 mm is being treated with a shaking table and heavy liquids (SG 3200 kg/m³) before the heavy minerals are investigated. The light fractions are being studied on shock metamorphism in quartz, feldspars and biotite.

In the course of sampling, 100 clasts (10—2 cm) were collected per sample for pebble counts. Boulders in Quaternary sediments were also collected and observations of their occurrence recorded, particularly if they were suevite or kärnäite.

Preliminary results of the pebble counts

At the initial stage the sediment samples that contained mainly source rocks were identified by counting the clasts and pebbles (10—2 cm). In Figure 3 the results of the pebble counts are divided into five major groups: 1) impactites: kärnäite, suevite, impact breccia; 2) shock rocks: mainly mica gneisses (the population was identified in four thin sections representing different types of pebble with shock-metamorphic features (see Lehtinen 1976); 3) plutonic rocks; 4) supracrustal rocks (metamorphic supracrustal rocks); and 5) Others, e.g. black schist, sandstone. Only one of the recent beach sediment samples (73) contained sandstone, and then only 1.6%. The sandstone pebbles were not, how-ever, the local sandstone that occurs in the depression of the complex crater (M. Vaarma, pers. comm. 1996).

Rocks of the impact crater were found in all five sediment types except the samples taken from the west and south of Lappajärvi (Fig. 3). Suevite boulders were common in the gravel pits in the Hietakangas glaciofluvial formation. During the field work a farmer told us that suevite boulders frequently get stuck in fishing nets in southern Lake Lappajärvi.

Depending on the specific objectives, all five sediment types can be used in the study.

Till

The till of the samples has been deposited basically from ice sheet. It occurs as ground moraine and partly as small hummocky moraines. The mean of grain-size distribution for the samples 52, 55, 56, 60, 63, 64, 65, 66, 69, 70 and 75 varies from 0.373 to 0.078 mm. They are classified as sandy till. The samples 54 (mean 0.031 mm) and 67 (mean 0.055 mm) are silty till.

Impact crater rocks are most abundant in sandy till (55) at Viitaniemi, south of Lake Lappajärvi (Fig. 3), which contains 77% suevite and 1% kärnäite. It has been transported for short distance by ice sheet. On the western side of Kärnänsaari (67), the local kärnäite predominates in silty till (no less than 60%), whereas outside the crater suevite is more common within the studied radius of 3.5 km. Other samples from Kärnänsaari contain only small amounts of kärnäite. In the basal till from the western side the kärnäite clasts are angular, implying local origin. The anomalous abundances of kärnäite may thus be attributed to a boulder field. If so, the continental ice sheet would have transported these boulders for only a few tens of metres.

The sphericity of local plutonic (granites and pegmatites) and supracrustal rocks (mica gneisses and volcanic rocks) is angular and subangular.

Far-travelled subrounded fine-grained granites (group 4: plutonic rocks) are found at low concentrations (4%) in the sandy till (60). They are interpreted as redeposited glaciofluvial sediments. Fine-grained granites are present in the Hietakangas glaciofluvial formation (58, 4%) and in postglacial littoral sediments (72A, 2%).

Sample 54, which is silty till, contain mainly (99%) fine-grained rocks as shocked mica gneiss and supracrustal mica gneiss and volcanic rocks.

The samples 64, 65 and 69 contain black schists in the amounts of 1%. The carbon content, examined in the thin sections, is about 5%. They were found also in the Hietakangas glaciofluvial formation (59A, 1%) and in the postglacial littoral sediments (72A, 1%).

Hietakangas glaciofluvial formation

The gravel pits currently in use in the north-northeast - southward trending Hietakangas gla-
Fig. 3. Pebble counts (10—2 cm) showing the distribution of rock types. The group 'Others' includes e.g. black schist, sandstone.
Glaciofluvial formation contain conspicuously large numbers of subrounded suevite boulders, 20 cm x 30 cm in size (Lehtinen 1976). Rounded/subrounded kärnäite boulders of the same size were also found but they were clearly less abundant than the suevite boulders, even though they are more resistant during the glacial transport. Pebble counts in the gravel pits showed that the abundance of kärnäite (Figs. 3 and 4) was a mere 4% (57), 1% (58) and 0% (59) and that of suevite 1% (57), 4% (58) and 9% (59), respectively. Numerous suevite fragments measuring 1—2 cm (74) were found in the esker delta.

Stream, postglacial littoral and recent beach sediments

The porosity was measured by weighing the samples saturated with water and after drying 3 days in 110°C (Kivekäs 1993). The data was divided into paramagnetic and ferrimagnetic parts using the method described by Hrouda (1994) and Lahtinen and Korhonen (1996).

The suevite boulders of the Hietakangas glaciofluvial formation contained angular fragments of host rocks (Figs. 5a and b). Petrophysical measurements which test the effect of weathering showed that the weathered rock was from 3 to 7 per cent units more porous than an unweathered portion (22%) of the same boulder (Fig. 6) and that the shocked mica schist fragments in the unweathered portion were 5% less porous than the suevite. The residual ferrimagnetic grain susceptibility (K_r=820 10^6 SI) was found to have decreased from 30% to 70% in the weathering process (Fig. 6).

The target crystalline rock is represented in Figure 7 by black schist sample where susceptibility is carried by pyrrhotite (T_c ~ 320°C, 87%) and magnetite (T_c ~ 590°C, 12%). At 700°C about 1% of ferrimagnetic susceptibility is left and may be caused either by other original minerals of black schist or minerals generated by the heating during measurement. The fresh suevite contains a magnetization carrier that alters in weathering, thus lowering the grain ferrimagnetic susceptibility by at least 35%. At high temperatures both weathered

Fig. 4. A kärnäite boulder with a fragment of a shocked felsic rock. (Photo Jari Väätäinen).
and unweathered suevite exhibit a ferrimagnetic component of order $10^6$ SI. The component is caused by a magnetization carrier characterized by a higher Curie-point, e.g. iron-nickel alloy (see Pesonen et al. 1992). Because this component does not disappear in weathering, the carriers may be found in glacial sediments and used as indicator minerals of impact. The carriers are being identified mineralogically.

The main mass of suevite causes only minor magnetic anomalies due to low susceptibility. The dark melt fragments in suevite are, however, more magnetic ($J_{tot}=7.4$ A/m with $Q=0.6$). The carrier of magnetization is magnetite with less than 4% contribution of pyrrhotite to susceptibility.

![Fig. 5a. A suevite boulder containing shocked fragments of felsic igneous rocks (the major fragment), mica schist and gneiss. (Photo Jari Väätäinen).](image1)

![Fig. 5b. A suevite boulder with shocked fragments of mica schist (the major fragment) and felsic igneous rocks. (Photo Jari Väätäinen).](image2)

![Fig. 6. The effect of weathering on porosity and ferrimagnetic susceptibility of suevite.](image3)

![Fig. 7. Ferrimagnetic grain susceptibility as a function of temperature for suevite boulder 214/SMK/1996 and black schist pebble 59/SMK/1996.](image4)
Preliminary results of minerals

Zircons

Zircon grains were picked from 2—0.4 mm and <0.4 mm heavy fractions (SG 3200 kg/m³ and 4000 kg/m³). The surface morphology of single zircon grains was studied with SEM at the University of Helsinki. A few grains showed tracks of shock metamorphism. Shock cracks are most clearly visible in an angular glacially transported zircon grain, 0.5 mm in size (till sample 55) shown in Figs. 8a and 8b.

Interpretation

Within a certain sector (Fig. 3) all the sediments studied contained suevite. The average abundance of suevite is 1—10% but in one sample it was exceptionally high (77%) owing to the friability and softness of suevite. This high percentage may be due partly to a boulder weathered at the site and partly to weathered boulders that had been transported for some distance by the glacial ice. The site in question is only some hundreds of metres from the shore of Lake Lappajärvi. Other sampling sites similar distances from the crater have only 1% suevite. The uneven distribution is typical of soft rocks. Too, it might inform as the farmers’ fishing net evidence of bare suevite source at the bottom of Lake Lappajärvi.

The samples studied contained kärnäite in such low abundances that the distribution of this rock in the overburden cannot be established until samples have been collected for a specific transport distance investigation (cf. Mölder 1948, Saksela 1949, Kulonpalo 1969). Suevite has been found only near the source.

The source areas, impact crater and Precambrian basement, are easily traced by Quaternary sediment clast and pebble lithologies within the distance of 25 km. The far-travelled lithologies represent a small portion.

The next step is to determine the minerals. This will be done in the course of this winter and the report on the pilot study will be released in 1997. The second stage of the study will deal with the glacial transport of rocks and minerals from the complex crater.

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References


ALMOST 100 M OF QUATERNARY DEPOSITS ON SANDSTONE AT KARHUKANGAS, KAUHAJOKI, WESTERN FINLAND

by
Pekka Huhta

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: pekka.huhta@gsf.fi

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Introduction

A hole was drilled at Karhukangas, Kauhajoki, in February 1996 to establish the stratigraphy and thickness of the overburden (Fig. 1). Karhukangas was selected as the target of investigation as it is part of an extensive till-covered occurrence of sorted material with a mode of formation that cannot be deduced from morphology (Kujansuu & Uutela, this volume). Several holes have already been drilled in the area but they have seldom got deeper than 10—20 m, at which point the corer has tended to stick. At Karhukangas the deepest hole so far has reached 40 m. As a rule, the overburden is rather shallow in Finland, averaging no more than 8.6 m (Okko 1964).

The material in the Karhukangas till-covered deposit is mainly highly compacted medium or fine sand. Some of the sand grains are rounded and have a matt surface resembling the grains in sandstone. The location of the hole was selected on the basis of refraction seismic investigations undertaken by the Geological Survey of Finland (Kurkinen & Palmu 1992 and Kauhajoen sora- ja hiekka­varat 1994). Seismic soundings indicated thicknesses of several tens of metres at many sites. In the Karhukangas area the thickness of the overburden is over 100 m and it is probably underlain by sandstone or weathered bedrock. The hole was sunk with a heavy hydraulic GMT 300 drill belonging to Maa ja Vesi Oy and the work took three weeks.

Sampling

The heavy hydraulic corer takes samples through percussion barrels fitted with appropriate tube samplers of different diameters. The casing housing the percussion barrel was driven into the soil and the sample was taken downwards at the depth of its lower end in an attempt to obtain a continuous sample through the overburden. Stones encountered in the soil were penetrated with drill bits. Sampling was, however, hampered by the poor...
penetration of the drill in dry, medium and fine sands and stony till layers. The casing could only be driven to a depth of 74 m, at which it stuck.

The hole, totalling 103.2 m in depth, of which 95.3 m was soil, yielded 43.7 m of sample core, in places continuous. Samples were also taken with the aid of water-flushing from the soil layers in the lower part of the hole and from the underlying sandstone. Attempts were also made to take samples from the sandstone with a small core sampler, but the percussion barrel broke when it was lifted and the sampler remained in the hole along with about 30 m of casing.

**Coring profile**

About 2—3 m of soil had already been removed from the coring site, probably for road construction. In a nearby study pit excavated earlier, a 2-m thick layer of sandy gravel on the ground surface was underlain by a thin layer (0.2 m) of sandy till. Lowermost in the pit were 5 m of medium sand with an average grain size of 0.2—0.6 mm (Kauhajoen sora- ja hiekkavarat 1994, liite II, K5). Sampling started with this medium sand, which extended to a depth of 10.1 m (see Fig. 2, coring profile). The sand is underlain by 4.1 m of sandy till with 11.2% fines (<0.06 mm) and 1.4% clay fraction (<0.002 mm) on average. Beneath the till, to a depth of 35.7 m, there is fine sand that grades downwards into coarse silt. This is underlain by till, sandy in its upper part and fines-rich, with 37% fines and 4.9% clay fraction, in its lower part. The high abundance of clay fraction is due to the underlying clay. Clay, which grades into medium silt in its lower part, extends to a depth of 49.8 m as a 2.2-m thick layer. This sorted material is underlain by a thin layer of sandy till, 1.9 m thick, containing 18.2% fines and 2.2% clay fraction. The till is succeeded by 2 m of coarse silt to a depth of 53.7 m. The silt is underlain by almost 24 m of fines-rich till with 47.1% fines and 8.6% clay fraction. The till ends at a depth of 77.4 m, at which a silt layer, 9.2 m thick, begins. The grain size of the silt varies from fine in the upper part via coarse to medium in the lower part. The last continuous core was obtained at a depth of 87.4 m from the sandy till under the silt. The till contains 29.9% fines and 5% clay fraction, being thus close to the fines-rich till. The till continued to a depth of 95.3 m, at which sandstone started. Coring ended at 103.2 m, when the sampler’s percussion barrel broke off.

![Fig. 2. Karhukangas coring profile.](image-url)
survey area, and in the course of the survey a gravimetric profile was measured over the drill hole. Preliminary results indicate that the thick overburden produces a distinct, wide gravimetric anomaly about -2.8 mGal in intensity. On the basis of one profile it has not been possible to assess the contribution of the sandstone (S. Elo, pers. comm.). Wet densities of till ranged from 2150 to 2200 kg/m³ and those of sorted matter (sand and silt) from 1940 to 2020 kg/m³. These values can be used to assess overburden thickness when interpreting gravimetric survey data.

Conclusions

Eemian deposits covered with one till layer have been found at a depth of only a few metres in many places in Ostrobothnia. These deposits usually occur in till-covered eskers but some have been encountered in flat basal moraine areas (Nenonen 1996 and references therein). Thermoluminescence (TL) dating on the sand beneath the till has yielded ages suggesting the Eem interglacial or Late-Saalian. Therefore, the lowest parts of the Karhukangas core may even represent the Lower Pleistocene. Deposits such as these cannot be studied easily in Finland and the sampling technique needs to be refined. The tube sampler penetrates dry soils with difficulty and only short till cores could be taken and even then from stoneless parts of the till.

References


PALAEOZOIC ACIRITARCHS IN TILL-COVERED SAND DEPOSITS AT KAUAHJOKI, WESTERN FINLAND

by

Kujansuu Raimo1 and Uutela Anneli2

1) Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
2) University of Helsinki, Finnish Museum of Natural History, Geological Museum, P.O. Box 11, FIN-00014 UNIVERSITY OF HELSINKI, FINLAND
e-mail: raimo.kujansuu@gsf.fi; anneli.uutela@helsinki.fi

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Introduction

Several till-covered old eskers and other formations of sorted sediments were discovered in southern Ostrobothnia and western Finland in conjunction with the national assessment of gravel resources (Kurkinen 1973, Iisalo et al. 1974, Niemelä & Tynni 1975, 1979, Niemelä 1976, 1978, 1979, Niemelä & Jungner 1991). The most extensive continuous area of old formations is in the west of Kauhajoki municipality (Fig. 1).

The western part of Kauhajoki is characterised by large gently sloping elevations, their summits rising to 130—170 m a.s.l (Karhukangas 158.5 m, Kivistönkangas 158.0 m and Hiukkakangas 160 m). Valleys covered with postglacial sediments and partly paludified are at 60—100 m lower elevations. The cover of the Quaternary deposits tends to be fairly deep, even as much as 20—50 m in many places. Of particular geological interest is the extensive coherent occurrence of fine sand in the Karhukangas–Kivistönkangas–Hiukkakangas area (Kauhajoen sora- ja hiekkavarat 1994). Bedrock outcrops are rare, reflecting the considerable thickness and continuity of the Quaternary cover.

There are observations of two superimposed till formation in southern Ostrobothnia, of which the lower was deposited by the continental ice sheet flowing roughly from the northwest and the upper one by ice flowing from the north (Hirvas & Nenonen 1987, Nenonen 1995). The deposits of sorted sediments are mainly covered by the Kauhajoki till formation. Rich in fines and clay fraction, this formation was deposited by ice flowing from the north (Bouchard et al. 1990). The fine fractions in till derive partly from interstadial water-laid sediments and so may have participated repeatedly in erosion-sedimentation cycles (Lintinen 1995). Till may thus have been transported for

Fig. 1. Sampling sites in the Kauhajoki area: 1) Karhukangas, 2) Kivistönkangas and 3) Hiukkakangas. The area of till-covered sand deposits (hatched) according to the assessment of Kauhajoki gravel and sand resources (Kauhajoen sora- ja hiekkavarat 1994).
long distances, although, according to Punkari (1979), the ice sheet was passive during the last deglaciation. As suggested by the orientation of the esker chains, the sediments in the formations without till-cover were mainly transported from the north and those in the till-covered formations from NNW—NW, corresponding to the directions from which the ice that deposited the till formations flowed.

To establish the geological structure and origin of the thick soil cover, coring was undertaken in 1996 at Karhukangas, Kauhajoki, at a site where seismic sounding indicated the drift was about 100 m thick (Huhta 1997). Samples for preliminary studies had already been collected from existing cuts at Karhukangas, Kivistönkangas and Hiukkakangas back in 1993. For TL/Osl dating, samples were taken separately from both Karhukangas and Hiukkakangas, the aim being to establish the age and depositional type of the highly compacted fine sand.

The data on the surface areas, material and stratigraphy of the formations presented here are mainly from the assessment of gravel and sand resources conducted at Kauhajoki (Kauhajoen sorajä hiekkavarat 1994).

Samples

Karhukangas (Fig. 1.1) is an extensive (1120 ha) gently sloping elevation covered in many places with a gravelly littoral deposit of varying thickness (1—4 m). The latter is underlain by 1—2 m of silty till that rests on a sandy deposit and from which it is separated by a sharp contact. Karhukangas with its surroundings comprises an area several square kilometres in extent. However, as there are only a few cuts, test pits and coring points, our concept of the stratigraphy and the size of the fine sand formation suffers from a scarcity of information.

The Karhukangas samples are from a sand pit south of the highest point of the formation (x=6909.67, y=1549.17 and z=140). The fine sand, which shows current bedding, is highly compacted, the grain size varying slightly from one stratum to the other (Fig. 2). The grains are predominantly quartz; only the abundances of micas vary significantly (Fig. 3).

East of Karhukangas there is a distinctly smaller (175 ha) isolated elevation, Kivistönkangas (Figs. 1.2), that is similar to Karhukangas in stratigraphy. At the sampling point, which is a sand pit only slightly deeper than 2 m on the western slope of the formation (x=6910.42, y=1554.99 and z=147), there is no till between the coarse littoral deposit and the fine sand. The till was probably so effectively washed during the Holocene littoral stage that only the coarsest fractions, i.e. the stony gravel covering the sand, remained. At the southern end of the formation, however, there are fairly deep till deposits. Paukonmäki, a hill to the north, is similar in structure to but even smaller than Kivistönkangas.

Kivistönkangas is composed of fine sand (Fig. 2) almost identical in grain size distribution to that in the lower sample from Karhukangas and differing only slightly from Karhukangas in mineral composition (Fig. 3).

Hiukkakangas (Figs. 1.3) lies 2—3 km northeast of Kivistönkangas. It, too, is covered with a coarse, stony littoral deposit over 5 m thick in places. The littoral deposit is underlain by 1 m of silty till under which there is compacted sand to a depth of 35—40 m. The Hiukkakangas samples are from two shallow sand pits: the southern one (x=1911.00, y=1558.32 and z=152) and the northern one (x=6911.53, y=1558.36 and z=152). The TL sam-

![Fig. 2. Grain size distributions. 1) Kivistönkangas, 2) Karhukangas, depth 2 m, 3) Karhukangas, depth 4 m, 4) Hiukkakangas (South) and 5) Hiukkakangas (North).](image-url)
The grain size distributions in the southern sample from Hiukkakangas and in the upper sample from Karhukangas are almost identical (Fig. 2) as are their mineral compositions (Fig. 3). The northern sample from Hiukkakangas is silt in grain size composition.

At all sample sites most of the grains are angular or slightly rounded and have clean and clear surfaces; a few, however, are highly rounded with matt surfaces resembling the grains in sandstone (Fig. 4). Material in all the samples react to hydrochloric acid (10%) and thus contain some limestone grains.

**Microfossils**

Organic-walled microfossils, i.e. pollen grains and cysts of acritarchs were studied from Karhukangas and Hiukkakangas. Diatoms were studied only from Hiukkakangas. Because sandy material is poor in microfossils a sample size of 1 kg was required. Diversity of pollen and acritarchs was low in all samples and diatoms were altogether lacking.

The acritarchs in the microfossil assemblage at Karhukangas and Hiukkakangas are about 450 million years old and so date back to the Ordovician. Acritarchs are pollen-like remains of predecessors, now extinct, of present-day algae. Only the most durable of the Quaternary pollen grains have been preserved; inside limestone grains the acritarchs have been protected from chemical and physical wear.

The lower sample from Karhukangas (depth 4.0 m) contained one cyst of *Veryhachium trisulcum* (Fig. 5,1), which lived from the Early Ordovician to the Late Devonian (Eisenack et al. 1979). The sample also contained four pine pollen grains, one birch grain and one heather grain. The time span of the occurrence of *Baltisphaeridium microspinosum* (Fig. 5,2) found in the upper sample (depth 2.0 m) is from the Early Ordovician to Early Silurian (Uutela & Tynni 1991). *Polygonium pellicidum* (Fig. 5,3) inhabited the seas from the Late Cambrian to the Middle Ordovician (Volkova 1990, Uutela & Tynni 1991), *Michystridium stellatum* (Fig. 5,4) from the Early Ordovician to the Late Jurassic (Eisenack et al. 1973) and *Revinotesta parva* (Fig. 5,5) from the Early—Late Ordovician (Uutela & Tynni 1991). The pollen assemblage contained pine (9 grains, Fig. 5,7), spruce (1 grain), birch (2 grains, Fig. 5,6), alder (1 grain), lycopod (1 grain) and heather (2 grains). The upper sample (depth 2.0 m) contained only one

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**Fig. 3.** Mineralogical composition of fine sand samples. 1) Kivistönkangas, 2) Karhukanga, depth 2 m, 3) Karhukangas, depth 4 m and 4) Hiukkakangas (South). Analyzed by P. Huhta.

**Fig. 4.** Microphotograph of the Kivistönkangas material. Grains are highly or moderately rounded with matt surfaces and are mainly of quartz. Length of scale bar 1 mm. Photo J. Väätäinen 1996.
pine pollen grain. The southern sample from Hiukkakangas, depth of 2.0 m, contained only two pine pollen grains. The silty northern sample from the same locality and the same depth had two pine pollen grains and one spruce pollen grain. As well as pollen of pine and spruce, the layer immediately above the silt contained one acritarch: *Balitsphaeridium multipil-osum*, which flourished from the Early Ordovician to Early Silurian (Eisenack et al. 1973).

**Dates**

The samples from Karhukangas (TL-386) and Hiukkakangas (TL-387) were TL dated at the Dating Laboratory of the Finnish Museum of Natural History of the University of Helsinki. Both samples gave an age exceeding the range of the method.

**Discussion and conclusions**

The till-covered fine sand deposits in the Kauhajoki area are probably erosional remnants of a large, coherent formation that was laid down before the last glaciation in shallow waters under tranquil flow conditions. The majority of the sediments in the deposit obviously derive from the sedimentary rocks on the floor of the Gulf of Bothnia. Some of the grains are highly rounded, probably due to an earlier geological process. The grain size distribution corresponds to that of aeolian sands in Finland. Transport by the continental ice sheet during various glacial stages was predominantly from the northwest (Hirvas & Nenonen 1987, Nenonen 1995). Hence, abundant material was transported from sea bed deposits to the Kauhajoki area and, in general, to Ostrobothnia. The fairly long transport distance can be attributed to repeated transport in the same direction (Lintinen 1995).

The present morphology of the fine sand deposit provides no clues as to its mode of formation. In both morphology and material composition, however, it differs clearly from the till-covered old eskers in the area (cf. Niemelä 1978), which are elongated ridges composed of different, often coarse, sediments typical of glaciofluvial formations. The fine sand deposits could be remnants of an extensive, partly eroded fluvial delta, although in the present morphological environment and topographical position it is difficult to reconstruct a normal river at the site. For depositional conditions to have developed it was probably necessary for the front of the continental ice sheet to have remained stationary in the north of the deposit and the water to have been at a level of about 160 m in the south. Hence, waters impounded by the ice sheet in Bothnian Bay,
with the Karhukangas area as threshold, would have flowed southwestwards controlled by the ice front, depositing extensive deltas and littoral formations in the ice-free area. Note, however, that no proper ice-contact forms or deposits have been found and, moreover, there are no indisputable indications of a glacial water stage at this elevation. We can nevertheless assume that the level of the Eemian Baltic Sea at its highest reached this height at least (cf. Grönlund 1991). The Saale deglaciation in Ostrobothnia was probably a very rapid event, without the long stagnation stages that would have permitted the formation of such deposits. The glaciofluvial formations are predominantly eskers, and the fine sand deposits do not seem to be associated with any longitudinal/radial glaciofluvial system. However, as suggested by the oxygen isotope ratios, there may have been long periods during the Ice Age when the ice front could have resided in these areas.

At any rate, due to their till cover the deposits must have formed before the last glaciation. TL dating indicates an age older than the Late Pleistocene, although depositional conditions may have prevented the material from proper zeroing. Deformation of the morphology of the deposit into shapes difficult to recognise also indicates old formation. Nor did the microfossils studied shed any light on the age and formation environment of the deposits. Some of the pollen grains may have been redeposited or brought to the deposit by gravitational water. Diatoms may either have dissolved or never originally existed under such conditions.

An interesting new result to emerge from the microfossil studies is that the Early Palaeozoic sea stages probably extended to the Bothnian Bay basin. In efforts to establish the extent of ancient seas even the smallest microfossil observations are important as the only remnants.

According to Hagenfeld (1989), the Early Cambrian sea covered the Baltic Sea basin up to Bothnian Bay (the Vergale and Early Rauves Horizons), as well as in the Middle Cambrian (the Kibartai Horizon). Later in the Middle Cambrian (the Panerai Horizon) the sea covered only the Bothnian Sea basin. The model of Hagenfeld is based on acritarch data from drilling undertaken in southern Sweden, Estonia, Latvia, Lithuania and western Russia. Seismic soundings conducted in Bothnian Bay corroborate the interpretation of Hagenfeld (Wannäs 1989). The Late Cambrian sea covered only the southern part of the Baltic Sea (di Milia et al. 1989).

Owing to the lack of in situ deposits, we have been able to estimate the extent of the Ordovician sea only on the basis of deposits in Estonia and Sweden. According to Thorslund (1960), the sea covered the Bothnian Sea up to the Quark at the beginning of the Early Ordovician but almost the whole of Finland, northeastern Lapland excluded, in the Middle Ordovician. Röömusoks (1960), Jaanusson (1963) and Männil (1966) restrict the sea area markedly. According to them, a large land tongue extended from Bothnian Sea to the Gotland basin, and at the end of the Early Ordovician the sea covered only the western part of Bothnian Sea. Our results support the concept of Thorslund (1960). According to the interpretations of Männil (1966), the Bothnian Sea basin was covered by sea during six out of nine Middle Ordovician Estonian regional stages. At the beginning of the Late Ordovician the sea covered the entire Bothnian Sea, the northeastern corner excluded (Männil 1966). In the Silurian, the sea occupied only the area from Gotland to western Estonia (Kaljo & Jürgenson 1977).

Early Palaeozoic sandstones and siltstones occur on the floor of Bothnian Bay and the Bothnian Sea but limestones only on the latter (Winterhalter 1992).

In Ostrobothnia a high diversity of microfossil assemblage has been found at a depth of over 30 m in the middle of the Lappajärvi meteorite crater. As the meteorite fell the overburden exploded into the air, ending as a sludge moistened by rainwater in the basin thus formed. The sediments, which are composed of material from very diverse sources, contain 95% Cambrian and 3% Ordovician acritarchs, and 2% unknown spores (Uutela 1993).

Among the microfossils in an Eemian clay at Mertuanaja, central Ostrobothnia, there are a few redeposited Ordovician microfossils, 470—430 Ma old (Eriksson et al., in prep.). Mertuanaja lies 225 km northeast of Karhukangas.

To summarise, in Ostrobothnia 1) the prevailing flow and transport direction of the continental ice sheet was from northwest to southeast, 2) the Quaternary deposits have Ordovician microfossils that most probably derive from areas now covered by sea or thick Quaternary deposits, and 3) there are/ were deposits in the Quark and Bothnian Bay area implying that the area was covered by sea in the Ordovician.

Ostrobothnia offers many opportunities to fill the gaps in the geological history of Finland from the Cambrian to the Early Pleistocene. Before we can establish the structure and composition of the thick overburden, however, a much greater input is needed in both drilling and sounding.
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INDICATION OF PREHISTORIC HUMAN ACTIVITY IN AN AREA RICH IN CAIRNS IN OSTROBOTHNIA, WESTERN FINLAND

by
Irmeli Vuorela

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: irmeli.vuorela@gsf.fi

Key words (GeoRef Thesaurus, AGI): Palaeoecology, bogs, pollen analysis, charcoal, stratigraphy, human activity, absolute age, C-14, Bronze Age, Iron Age, Laihia, Finland

Introduction

In 1994—1995 the Geological Survey of Finland carried out palaeoecological investigations for the municipality of Laihia, southern Ostrobothnia, in order to shed further light on the prehistory of the

Fig. 1. A reconstruction showing the new-born lake basin and the shore line (27-m isobase) in the early Bronze Age, and present-day rivers and roads. X = study site.
The landscape more or less stabilized during the next few centuries. At a later stage of development, a shallow lake basin, 3 km long and 1.5 km broad, formed close to the estuary of the Madesjoki, on the eastern side of Helaalanneva (Fig. 1). As a result of uplift, which nowadays is 8.5 mm y⁻¹ (Kääriäinen 1953), the lake was grown over relatively soon and turned into a moist shore meadow. The landscape more or less stabilized during the Iron Age, when the coast line withdrew further and peat deposits started to form on the mire. In structure, the western 4-ha area of the mire today resembles an early-stage peat bog preceded by limnotelmatic and minerotrophic stages. Large stretches of Helaalanneva have now been drained, and the clayey soil on both sides of the Madesjoki is cultivated. Agricultural activities have, however, hardly ever been practised closer than 300 m to the sample site, where, still today, the size of the fields is very modest.

The development of the early landscape as is reflected in the peat stratigraphy was reconstructed (Vuorela 1995) using digital elevation model (National Land Survey of Finland) and numerical land uplift data (Geological Survey of Finland).

**Material and methods**

The sample site is located in the undrained part of the bog, where limnic sediments of the former lake basin were found (point A 200; Fig. 3). The material was cored using a piston sampler, 5 cm in diameter and 90 cm long. The total length of the profile is 330 cm. The profile was cored as overlapping sequences as follows: 0—85 cm, 60—150 cm, 130—220 cm, 160—250 cm and 240—330 cm.

The core was studied down to the gytija clay section at a depth of 296 cm. Pollen slides were prepared by the KOH and HF methods (Faegri & Iversen 1989). For each sample, 500 arboreal pollen grains (AP) were counted at a sampling interval of 4 cm. The results are given as percentages of AP for trees and shrubs and as percentages of total pollen (P) for herbs. For aquatics and cryptogams a basic sum of P+n was used. Pollen concentration values were calculated by the *Lycopodium* spore.
method of Stockmarr (1971). Relative frequencies of charcoal particles exceeding 5 μm in size were expressed in % AP. Loss on ignition, which was determined at 4-cm intervals, was used to identify the limnic material on the bottommost part of the profile and the wind-transported mineral material in the total organic matter of peat samples taken from Vuorela 1983). 14 C determinations were made on

Pollen taxa were divided into ecological groups as follows: trees, shrubs, natural mineral soil vegetation, settlement indicators, anthropochores, aquatics and hygrophytes and open land vegetation - including local bog vegetation.

The diagrams were divided into five local pollen assemblage zones (p.a.z.) (a–e; Figs. 5–7) representing changing ecological conditions. P.a.z. a (296–270 cm), with high aquatic pollen taxa, covers the limnic period preceding the overgrowing of the lake and p.a.z. b (270–230 cm) the limnotelmatic phase and shore vegetation. P.a.z. c (230–180 cm), d (180–120 cm) and e (120–0 cm) represent the development of the Helaalanneva bog; the zone boundaries are mainly based on fluctuations in settlement indicators.

Stratigraphy

The stratigraphy of the profile was as follows (cf. Fig. 4):

0–20 cm unhumified Sphagnum peat
20–50 cm Sphagnum peat, Eriophorum vaginatum and wood fragments
50–195 cm Sphagnum peat. The grade of humification increases downwards
195–235 cm Sphagnum-Eriophorum-Carex peat with wood fragments at a depth of 215–220 cm and stems of Equisetum at a depth of 235 cm

235–264 cm Magno Caricetum peat, partly mixed with gytta. Stems of Equisetum at the 250–260 cm level
264–296 cm clay gytta
296–330 cm gytta clay grading into clay.

Results and discussion

Radiocarbon dates

The 14 C dates obtained were as follows (Table 1; Kankainen 1995):
Pollen stratigraphy

Pollen assemblage zone a (296—270 cm)

At the time this part of the profile deposited, the site was submerged. As the lake basin gradually dried, the organic debris in the sediment increased slightly from 11% to 14% (Fig. 5). Even though the aquatic pollen taxa already represent a lacustrine environment, the preceding brackish stage may — perhaps due to floods and heavy storms — still be reflected by charcoal particles in the bottommost clay gyttja deposits. The particle size increases upwards and their number decreases in p.a.z. a. High-grade fractionation of charcoal particles is typical of sea-shore deposits (cf. Vuorela et al. 1990) strongly affected by wave action; in lake deposits, the particles are fewer and their size spectrum is larger. Moreover, the smaller the lake basin, the less the secondary fractionation of these particles. At p.a.z. boundary a/b the rapid increase in loss on ignition reflects the final emergence of the site.

The relatively high pollen concentration in the clay gyttja (100 000 — 140 000 cm⁻³) reflects slow sedimentation. P.a.z. a seems to represent a far longer period than do later deposits of the same vertical volume. An isolating, lagoon-like lake basin, however, acts as a collector of floating pollen material, and this hampers interpretation.

Pinus pollen dominates in p.a.z. a, partly for ecological reasons, but perhaps also due to concentration of this pollen type in a coastal lagoon. The expansion phase of Picea (ca 3500 BP; Tolonen 1983) in this area seems almost to have been reached at the time represented by the bottommost part of the diagram.

The pollen frequencies of broadleaved deciduous trees decrease in p.a.z. a. However, the regular pollen occurrences of Corylus, Ulmus and Quercus reflect favourable conditions. Tilia, too, is represented by an evenly distributed but modest pollen occurrence. The sporadic pollen grains of Carpinus should be attributed to long-distance transport. Judging by the present-day distribution of Fraxinus, it is possible that the sporadic pollen grains in the uppermost part of p.a.z. a are of local origin. Juniperus and Salix pollen represents shrubs typical of coastal vegetation.

Aquatics (Fig. 7) are represented by pollen of Potamogeton, Sparganium, Sagittaria, Nymphaea, Alisma, Scirpus and Nuphar and hygrophytes by Equisetum, Cyperaceae, Thalictrum, Scutellaria, and Lysimachia.

Among open land vegetation, spores of Poly podiaceae are dominant in the lower part of p.a.z. a (Fig. 7). Frequencies of Calluna, Ericaceae, Lycopodium annotinum and Pteridium aquilinum are lower in the upper part of the p.a.z. a.

Shore meadow vegetation around the sample site is represented by pollen of Poaceae, Filipendula ulmaria, Ranunculaceae, Artemisia, Apiaceae, Achillea and Aster types, and Rosaceae, most probably Rubus idaeus (Fig. 8). Settlement indicators, such as Chenopodiaceae, Rumex, Lamiaceae and Caryophyllaceae, are, in this context, mainly indicators of open coastal conditions.

Pollen assemblage zone b (270—230 cm)

P.a.z. boundary a/b at the 260 cm level corresponds to the limno-telmatic horizon, i.e. to the final emergence of the sample site. Even though the regional forest composition was affected by the emerging land (Kujala 1926, Miettinen & Vuorela 1988) no major changes occur in the tree pollen data. Betula is well represented, and a clear occurrence of Populus was recorded at the 254—244-m level.

The limno-telmatic peat layers (265—235 cm) are characterized by aquatics and high pollen frequencies of Poaceae and Cyperaceae (Figs 5 and 6), as well as by a rapid decrease in mineral matter and charcoal frequencies (Fig. 5). The 235-cm horizon represents a change in the peat stratigraphy, as Magnocaricetum peat grades into Carex peat of lower species. The lowering of the groundwater level along with uplift, as well as the local development of the mire are reflected in the herb vegetation. The earlier Poaceae maximum is replaced by

<table>
<thead>
<tr>
<th>Lab.no.</th>
<th>Depth cm</th>
<th>¹³C % O PDB</th>
<th>¹³C date years BP</th>
<th>Calibrated date cal AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Su-2578</td>
<td>77—83</td>
<td>-24.5</td>
<td>350±35</td>
<td>cal AD 1480—1630 (cal AD 1500, 1580, 1610)</td>
</tr>
<tr>
<td>Su-2579</td>
<td>173—179</td>
<td>-26.8</td>
<td>1300±50</td>
<td>cal AD 670—780 (cal AD 690)</td>
</tr>
<tr>
<td>Su-2580</td>
<td>213—219</td>
<td>-26.8</td>
<td>1680±30</td>
<td>cal AD 360—420 (cal AD 400)</td>
</tr>
</tbody>
</table>

Table 1. The ¹³C dates and corresponding calibrated dates of the peat deposits on Helaadanneva, Lahtija.
Fig. 5. Pollen concentration, charcoal frequencies, loss on ignition (drawn on two scales), water content, total frequencies of apophytes and anthropochores and $^{14}$C dates of the Helaalanneva profile, Laihia.
Fig. 6. Relative pollen frequencies of trees and shrubs, AP/NAP ratio and \(^{14}\)C dates of the Helaalanneva profile, Laihia.
Cyperaceae, and shore meadows are now also represented by pollen of Fabaceae, Galium and Potentilla.

The oldest cairns and a fireplace found on the bank of the Madesjoki (2370±100 BP; Hel-2445; ca 530—370 cal BC; Miettinen 1989) may date from this period. Clear agricultural evidence was earlier found in the peat deposits on Rajaneva, a mire approximately 17 km east of Helaalanneva (Miettinen, in press). There are, however, no indisputable indicators of human activity in the pollen flora of p.a.z. b. The reason may be the high groundwater level of the coastal areas, which prevented people from using the moist shore meadows, even as grazing land. Settlement indicators - Urtica, Plantago major and Plantago lanceolata - however, appear at the p.a.z. b/c boundary, which evidently coincides with the late Roman Iron Age, that is approximately AD 400.

**Pollon assemblage zone c (230—180 cm)**

Pollon data from p.a.z. c reflect intensive human activity (Figs 5 and 8) dated to the Migration and Merovingian periods (AD 400—700), the 14C age of the b/c zone boundary being 1680±30 BP (Su-2580) and that of the c/d zone boundary 1300±50 BP (Su-2579).

Human impact is reflected at the 188—192 cm level in high charcoal frequencies and a slight decrease in loss on ignition reflecting increasing erosion. The third anthropogenic indicator is the clear decrease in Picea pollen frequencies. Deforestation is suggested primarily by the increase in Alnus and Betula, together with the heliophytic species, Prunus padus, Salix and Populus tremula.

Since the peat deposits of the local mires contain considerable amounts of bog iron (Mirja Miettinen, oral comm.) and the rock immediately north of Helaalanneva is called Rautakallio (in English: Iron Rock), it is possible that the deforestation was associated with mining. Pollon of Humulus type, which was found at four levels in p.a.z. c, probably indicates natural vegetation as does the increase in pollen of meadow plants, Poaceae in particular. The rapid fluctuations in the pollen frequencies of Cyperaceae and Sphagnum spores and the high frequencies of Rubus chamaemorus are connected with local development of Helaalanneva.

**Pollon assemblage zone d (180—120 cm)**

After the Merovingian period, human activity declined and Picea seems to have regained its earlier abundance in forest composition. No indicators of cultivation were found (Fig. 8) and the number of apophytes remains very low. Spores of Pteridium and pollen of Epilobium angustifolium may, however, reflect local use of fire.

 Pollon of Calluna vulgaris and Ericaceae and spores of Polypodiaceae (Fig. 7) indicate natural bog vegetation, whereas fluctuations in Sphagnum spores and Cyperaceae pollen reflect local development from minerotrophic peat deposits to an ombrotrophic bog.

**Pollon assemblage zone e (120—0 cm)**

P.a.z. e represents a period of advanced agriculture on riverside fields south and east of Helaalanneva. The most important anthropogenic indicators are concentrated in this phase, which, according to the 14C dates, corresponds to the period spanning the 14th to 20th centuries (Kankainen 1995). The first Humulus type pollen grains appear at the 108 cm level and are found up to the surface. Pollon of Cannabis type was only found at a depth of 92—96 cm (Fig. 8). The earlier Cerealia pollen appears at a depth of 80 cm. The single pollen grain of Fagopyrum esculentum found at the 76-cm level is from the 16th or early 17th century.

Agriculture was introduced in the archipelago of southern Ostrobothnia during the pre-Roman Iron Age (500 cal BC - 0; Miettinen & Vuorela 1988, Wallin & Segerström 1994). The earliest evidence of this activity in Helaalanneva, in the form of Cerealia and pollen of Fagopyrum esculentum, is considerably more recent, dating to the Middle Ages (approximately cal AD 1500). The first Cerealia pollen most probably represents slash-and-burn cultivation, which was not fully established until the 18th century (Kankainen 1995). Intensification of the practice can be seen at the 48-cm level, where pollen frequencies of Cerealia and Rumex, together with the total weed pollen taxa, increase. In addition to earlier taxa, pollen of Cichoriaceae, Spergula arvensis, Brassicaceae and Polygonum aviculare, together with more sporadic grains of Urtica, Plantago lanceolata and Epilobium angustifolium, are now found (Fig. 8).

The increase in pollen of herb flora and Juniperus communis indicates more intensive human activity in the p.a.z. e (Fig. 6). Anthropogenic erosion is recorded in the slightly fluctuating (98—100%) loss on ignition of ombrotrophic Sphagnum peat (cf. Vuorela 1983; Fig. 7). Among open land vegetation, frequencies of certain pollen types — especially of Calluna and Ericaceae — are, however, closely linked to the natural development of the mire.
Fig. 7. Relative pollen and spore frequencies of aquatics, hygrophytes, open land/open forest herbs and 14C dates of the Helaalanneva profile, Laihia.
Fig. 8. Relative pollen frequencies of natural mineral soil vegetation, settlement indicators, anthropochorens and 14C dates of the Heitalamäeva profile, Laihia.
Conclusion

The results cover approximately 3000 years. Even though the study site lies in the middle of an area with an exceptionally high density of prehistoric — partly Bronze Age — cairns, indicators of human activity are very few.

The most striking evidence of prehistoric human activity in the area with cairns is the high charcoal frequencies, especially in the Migration and Merovingian periods (approximately cal AD 400—700). There are no signs of cultivation until the 17th century; in addition to Cerealia, pollen of Cannabis type, Humulus type and Fagopyrum esculentum was found in the medieval and post-medieval peat deposits. Agriculture had, however, been practised as early as in the pre-Roman Iron Age at Solf, in the then Vaasa archipelago (Wallin & Segerström 1994) and, in the Iron Age, in the more central — and drier — parts of Laihia (Miettinen, in press), as well as in most of the surrounding municipalities, that is Vöyri (Vuorela 1987a, b), Maalahiti (Miettinen & Vuorela 1988, Vasari et al. 1996) and Jurva (Hyvärinen 1987, Vuorela & Hicks 1996).

References


COMBINING QUATERNARY GEOLOGICAL AND DIGITAL ELEVATION MODEL DATA

by

Jukka-Pekka Palmu

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: jukka-pekka.palmu@gsf.fi

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Introduction

The combination of hillshaded surface relief and geological mapping data has until recently been rare. With improvements in software, data sets and output devices, however, this mode of representation is gaining currency (ESRI 1996). One of the first, if not the very first, to couple elevation data with Quaternary geological mapping data in GIS was Sauchyn (1993), who used a surface net to visualize topography.

The Geological Survey of Finland (GSF) first combined hillshaded relief with data on Quaternary geological mapping using Arc/Info in late 1994. The advantages of the technique were immediately obvious and its use has increased steadily since then.

The hillshaded Quaternary geological map is a highly successful form of representation particularly in visualizing the geology of southern Finland. Owing to glacial erosion during ice ages the topography of the bedrock controls the main features of the ground surface, too. The overburden was deposited mainly during and after the withdrawal of the last ice sheet.

Quaternary geological relief

Quaternary geological mapping data and digital elevation model data were combined with the gridcomposite hsv-technique of the Arc/Info GRID module. This method of combination was also tested with ER-Mapper software. Most of the work was done with Arc/Info, which is better suited than ER-Mapper to the combined processing of vector data sets and, in particular, classified raster data sets. Continuous data sets, on the other hand, are easier to process with ER-Mapper.

The elevation model data (25-m cell size) of the National Land Survey of Finland (NLSF) can be used directly at 1:50 000—1:100 000 scale. For more detailed applications the cell size must be reduced. Due to inaccuracies in the NLSF digital elevation model data and the insufficient accuracy of the source material (elevation and shoreline contours of the Basic map) for geological applications, the GSF has also calculated elevation models from contour lines and the bathymetric and shoreline contours of watercourses.

Details in the terrain such as sandur channels, small end moraines and flutings are not visible in elevation models. This is partly due to inaccuracies in the digitized contour data of the Basic map. Hence, in detailed work the GSF has used contours of orientation maps digitized by itself.

In hillshaded maps the illumination has been from the north (300°—60°). The direction depends on the objective: in the zone of Salpausselkä end moraines it is from the northwest and in the drumlin area of Savo from the northeast. The illumination angle has varied in the range 40°—60°.

The colour palette should not have too many classes, otherwise they will be too close to one
another. Some output devices and displays may combine classes that are not far enough apart. The colours must be of different hues, not merely of different brightness values, because the hillshading technique is based on brightness. In places the shadows might get too dark and it may happen that a deposit cannot be identified at these sites. This, however, is a fact we have to live with if we want the relief to be visible.

The automated production of hillshaded Quaternary geological maps with Arc/Info at the GSF is carried out with macros. Grids are processed from vector data on Quaternary geological mapping and from elevation data and then printed out with a separate macro that produces the output file.

Geological use of hillshaded maps

A rough (80-m cell) elevation model data and a 1 : 100 000-scale map of Quaternary deposits provide information on large structures, that is, Quaternary geological provinces. The clarity with which rocky areas can be distinguished from the detailed topographic pattern depends on the rock type. Drumlin and hummocky moraine fields are also clearly visible. It is easy to delineate the macrostructures of the bedrock, as masking by the overburden can be eliminated at the interpretation stage. Among the interesting targets of research thus to emerge are ring structures, which are indicated by combinations of shading, clay and peat depressions and lakes.

Large mosaics at 1 : 100 000—200 000 scale have proved useful. The GSF has compiled a wall mosaic at 1 : 100 000 scale of the area south of the Pori-Tampere-Imatra line. Based on Quaternary geological mapping data at the same scale and the 25-m elevation model data, this hillshaded map has found many uses. An advantage of the mosaic is that it makes it easier to visualize large entities. A corresponding mosaic was compiled for northern Finland, for which the data originally published at 1 : 400 000 scale were transformed into a hillshaded 1 : 200 000-scale map.

The hillshaded map of Quaternary deposits was first used for sand and gravel resources assessments and groundwater investigations, but also to facilitate the detailed mapping of Quaternary deposits. The first application of the map in Precambrian geology was in studies on fracture zones for nuclear waste disposal investigations. Since then it has been used in basic research on pre-Quaternary rocks, exploration, and studies on groundwater in fracture zones.

The maps are also important in the many branches of engineering geology. They provide the basic material for planning land-use, roads and railways, etc. and are also useful in planning underground structures. In military geology they provide information on conditions in the terrain.

The maps illustrate the diversity of the physical environment and the differences in natural features between areas; these after all largely control biodiversity. The diversity of the landscape is displayed excellently by the maps and can also be interpreted with them.

The maps will have extensive use in efforts to explain geology to the general public. Initial experience has shown that the relief map of Quaternary deposits depicts the physical environment particularly clearly and is excellent material for teaching local geography and environmental science in schools. Rocky areas, eskers and sandy heaths as well as flat-lying clay and peatland areas show up distinctly on these maps. These are part of the environment in which we live, not just splashes of colour on paper.

The maps are easy to read and sites can be localised rapidly, even by people unfamiliar with map reading.

Examples of the relief of Quaternary deposits

1. A hillshaded map of Quaternary deposits in the Kuusijoki-Kiikala-Somero area (Fig. 1). The scale of the map, which covers part of two sheets of Quaternary deposits at 1 : 100 000 scale, 2023 (Niemelä 1985) and 2024 (Haavisto 1974), is approximately 1 : 150 000. Hillshading is from NW, angle is 45 degrees. In the Kuusijoki area the thickness of the clay deposit can be estimated from the depth of erosion in the river valley (1). Eskers deposited by earlier meltwater streams cross the deltaic plain of Salpausselkä III at Kiikala (2). The bedrock shows fracture zones and a fractal-type diamond-shaped fracturing systems (3).

2. Hillshaded image of Quaternary deposits of the Loppi-Kiikala esker area (Fig. 2). The map, which is approximately at scale 1 : 75 000, covers part of sheets 2042 05 and 08 of Quaternary deposits (Haavisto-Hyvärinen 1990, with complementary data). Hillshading is from NW, angle is 55 degrees. The map shows the positions of the ice margins interpreted for the area, the outflow routes of meltwaters discharging from the ice sheet and the location of deltas laid down by meltwaters at the ice margin. The interpretations are partly based on field observations of pit walls.
Fig 2. Hillshaded Quaternary geological map of Loppi-Karkkila area, Salpausselkä II, southwestern Finland, with interpreted ice-marginal positions, glaciofluvial flow routes and fan/delta components. Scale approximately 1:75 000. Coordinates of lower left corner: x = 2514 000, y = 6720 000. Map compiling and processing by Jukka-Pekka Palmu, Espoo 1996. Base map copyright for 1:20 000 shoreline and elevation contour data National Land Survey of Finland, Permit No 125/MAA/97).
Three-dimensional relief map

The GSF first became aware of the ChromaDepth method and glasses (developed by R. Steenblik at Chromatek Inc.) at a geophysics exhibition held in the Netherlands in June 1996. An example of the use of the glasses in remote sensing was reported in Canada in 1995 (Toutin and Rivard 1995). The GSF had data suitable for 3D processing available, e.g. images of geophysical and geochemical data sets and digital elevation models, and the ChromaDepth method could be implemented without further delay in June 1996.

In chromostereoscopy the depth dimension is encoded into images with colours. With appropriate optics the colours can then be decoded to produce a stereoscopic effect and thus only one image is needed. The ChromaDepth glasses combine the diffraction and refraction of light, resulting in thin optics that work like thick glass prisms. Different colours are shifted for different distances, generating a differential angular parallax, which is translated into a linear parallax at eye level. The targets in the foreground are red and those in the background blue; targets in between are of different colours of the electromagnetic spectrum. Thus, an orange target is farther away than a red one but closer than a green one (Toutin and Rivard 1995).

The colours used range from red to blue, leaving out purple and indigo. At the red end the limit should be at 650 nm and at the blue end at 440 nm. In the classification of elevation data it is advisable to decide beforehand what needs to be stressed. Likewise, it should be decided whether or not the boundaries at which the colours change should be sharp and easy to see. Both Arc/Info and ER-Mapper software incorporate solutions that speed up automatic colour ramping. It is often important, however, that the images should be produced with accurate elevation and colour boundaries, particularly when the elevation values are used to study shoreline displacement.

Oblique illumination intensifies the stereoscopic effect. Depending on the location of the targets to be studied, it may be necessary to change the direction of the oblique illumination. The above technique can also be used in oblique observation applications.

Most of the maps have been processed with the Arc/Info GRID. When an elevation model alone was processed, ER-Mapper software was also used. Rough elevation colour ramping can be done rapidly with the ER-Mapper, and the direction and angle of the oblique illumination can be changed instantly.

An advantage of the ChromaDepth-3D method is that the maps are easy to process with different software and output devices. Moreover, maps can also be viewed directly on the screen, transparencies or slides. The GSF and the National Board of Antiquities used these 3D maps during field work in summer 1996.

Regional classified data, for example, the pattern data of a map of Quaternary deposits, can be combined with a 3D relief image with surface rasters (grids, balls, lines). Line and point data can be represented in a similar manner. For this purpose black gives the best result. Purple or bright red can be used to accentuate certain aspects. Maps of this type have already been used in groundwater studies and mapping of Quaternary deposits. Any kind of continuous and classified data can be combined in this way.

Another approach is to couple two surfaces and examine them together. For example, the bedrock surface can be displayed from "under" the overburden. First, 3D visualization models are compiled for the soil and bedrock surfaces as described above using the same classification of elevation and colours for both of them. Buffers are then established for the profiles of the bedrock surface. With the aid of these buffers bands of bedrock surface are cut from bedrock surface grids profile by profile. Finally these are merged with the ground surface. For instance, the width of the lines at 1:10 000 scale is 60—100 m, or 6—10 mm on the map. Continuity is important for the stereoscopic impression to form.

The relief of the ground surface is either that of the elevation model (DEM) of the NLSF or that calculated with the Arc/Info Topogrid element. The bedrock surface was interpolated with the Arc/Info GRID module components idw or Topogrid.

Examples of 3D relief

3. The colour relief map of Keräkankare at a scale of about 1:50 000 (Fig. 3). The surface contains data from the 1:20 000-scale map of Quaternary deposits as reclassified raster representation (parts of sheets 2023 12 and 2024 10, Haavisto-Hyvärinen 1995, 1996). Hillshading is from NW, angle is 45 degrees. This map has been used as a basis for planning in groundwater studies as it enables a preliminary estimate to be made of the positions of the surface of the bedrock and the groundwater table in the overburden.

4. Ground surface and bedrock surface merged
Fig. 3. Topography of Keräkankare glacifluvial deposit combined with Quaternary geological mapping data. Scale approximately 1: 50 000. Map processing by Jaana Jarva, Espoo 1996. Coordinates of lower left corner: x = 2490 000, y = 6705 000. Base map copyright for digital elevation model data National Land Survey of Finland, Permit No 125/MAA/97.
Fig. 4. Combined ground and bedrock surface topography of southern part of Vehoniemenharju, Kangasala. Scale approximately 1 : 22 500. Coordinates of lower left corner: x = 2508 900, y = 6807 000. Map compiling and processing by Jukka-Pekka Palmu, Espoo 1996. Base map copyright for 1 : 20 000 1-bit raster, shoreline and elevation contour data National Land Survey of Finland. Permit No 125/MAA/97.
with the 3D image of the Vehoniemenharju area, Kangasala (Fig. 4). The map is approximately at 1 : 22 500 scale. The elevation data on the target were calculated from the elevation and shoreline contours of the NLSF. The data on the bedrock surface are from gravimetric and seismic profile surveys, and from drilling and outcrop information. The geophysical surveys were commissioned from the GSF by the Tampere district water supply project (TAVASE). The project provided the GSF with drilling data; the outcrop information was collected from Basic maps and from the GSF’s mapping data on Quaternary deposits. In the esker area the relief can for a large part be interpreted as caused by the relief can for a large part be interpreted using this type of combination map. The colour classification of the deposits includes the geological processes that also created the morphology of the deposits. The hillshaded map reveals relations between and variations within quaternary geological deposits.

How can we display two surfaces simultaneously? The ground surface is displayed as hillshaded colour-classified elevation model and is cut open along study profiles and points, through which the bedrock surface, displayed in a similar manner, is visible. These two surfaces can then be viewed simultaneously in 3D with ChromaDepth glasses.

Summary

The intelligibility of Quaternary geological maps is significantly enhanced when they are combined with hillshaded relief. The processes which have caused the relief can for a large part be interpreted using this type of combination map. The colour classification of the deposits includes the geological processes that also created the morphology of the deposits. The hillshaded map reveals relations between and variations within quaternary geological deposits.

References

CHEMICAL COMPOSITION OF CLAYS IN SOUTHWESTERN FINLAND

by
Reijo Salminen, Marjatta Kukkonen, Tarja Paukola and
Seppo Töllikkö

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: reijo.salminen@gsf.fi

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General

The properties of clays in Finland have been investigated mainly with industrial use in mind. The emphasis has therefore been on properties other than the chemical composition (Hyyppä 1960, Romu 1977, 1978, Holma 1970). Data on the concentrations of the main elements have been available from studies undertaken by Soveri (1956). Although advanced analytical techniques have long been used in geochemical studies on other surficial deposits, investigations on the trace element composition of clays have been few in number and restricted mainly to determinations of nutrient concentrations for agriculture (Erviö & Palko 1984). The chemical composition of sulphide clays in Ostrobothnia has been studied from time to time (Erviö 1975, Palko 1994, Aström 1996), because these clays, due to intensive land use, have caused problems to agriculture and fish stocks.

With the progress made in research on contaminated soils and their remediation it has become clear that the natural background concentrations of heavy metals in clay areas are much higher than those in areas of till or glaciofluvial sediments. In summer 1994, the Geological Survey of Finland therefore undertook a pilot study on clays in southwestern Finland the aim being to obtain geochemical background data and, in addition, to study the geochemical properties of the clays and their relation to the clay stratigraphy with the aid of three sample cores and ten separate sampling sites, where the uppermost (0—120 cm) part of clay deposit was sampled; to find out whether the differences in chemical compositions corroborate current understanding of the ages of clays; and to establish geochemical changes caused by human activity in the surficial parts of clay deposits.

Sampling and analytical methods

In the course of the mapping of Quaternary deposits at 1 : 20 000 scale at Loimaa in summer 1994 undisturbed continuous sets of samples were taken with a piston corer from Yoldia and Ancylus clay deposits in Metsäjoki village, Mellilä, and Suokulma village, Loimaa, and from Littorina deposits at Paimio (Fig. 1). As well as these complete stratigraphic cores, samples were taken at ten points in a nearby area across the sedimentation basin from depths of 0—10 cm, 40—50 cm and 100—120 cm.

The geology and stratigraphy of the samples were described and the samples were measured for electrical conductivity, pH and humus and clay fraction content. To establish the depositional environment of the clays, microfossil analyses were performed at selected points in the three cores. For chemical analysis, continuous samples, 1 m long, were taken from the three cores and, after homogenization, about 50 g of clay from other samples. These samples were freeze-dried.

Chemical analyses were done at three levels:
total concentrations, concentrations of elements soluble in acids (aqua regia) and nutrient concentrations. The total concentrations were determined by XRF for Al, Ba, C, Ca, Ce, Cl, Co, Cr, Cu, Fe, Ga, Hg, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, REEs, Rb, S, Sc, Si, Sr, Th, Ti, V, Y, Zn and Zr and, from the hydrofluoric acid-perchloric acid-boric acid leach, for 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, Si, Sr, Th, Ti, V, Y and Zn. To study the background concentrations in contaminated soil, samples were analysed by ICP-AES for Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, S, Sr, Ti, V and Zn soluble in hot aqua regia. To analyse the samples for nutrient concentrations, i.e. for those that can be utilized by organisms, samples were leached in ammonium acetate at pH 4.5 after which the concentrations of Al, Ba, Ca, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sc, Si, Sr, Ti, V, Y, Zn and Zr were determined by ICP-AES.

Clay stratigraphy at Loimaa

According to Sauramo (1923), the Loimaa region was deglaciated about 9800 years ago. In a more recent study, however, Strömberg (1990) argues that the region was ice free 10 250 years ago. The low-salinity Yoldia Sea stage that succeeded the melting of the ice sheet lasted slightly less than thousand years in southwestern Finland. The Ancylus transgression that followed has been radiocarbon-dated to 9500-9200 BP (Eronen 1983, Glückert 1994, Ristaniemi & Glückert 1988, Ikonen 1993, Kankainen 1993). The pollen-analytical age of the early Ancylus Lake stage in the Kisko-Karjalohja area is slightly higher than the Betulal/ Pinus (IV/V) zone boundary (Ristaniemi 1984).

By comparing the shore observations in southwestern Finland (Glückert 1994, Ristaniemi 1984) with those on the Säkylä-Mellilä esker we can deduce that the maximum water level of the Ancylus Lake on the Loimaa-Mellilä area was at about 110 m a.s.l. (Glückert 1976). The esker chain
Fig. 2. Humus abundance, electric conductivity, moisture, clay fraction content (<0.002 mm), and SiO₂ concentration in the core samples from Loimaa (upper) and Paimio (lower).
trending towards NNW from Mellilä exhibits a set of ancient shores of the late Yoldia Sea and Ancylus Lake at 120—85 m a.s.l. After the Ancylus transgression the water level dropped rapidly but by 8500 BP the rate had slowed down. The Loimaa area started to emerge about 8300 years ago, when, according to Kankainen (1993), peat began to develop in Pesäsuo mire at Mellilä. According to Ikonen (1993), Pesäsuo deposited on a small island in an Ancylus Lake bay. Its clay bottom is at 80—80.5 m a.s.l.

At Paimio, the Littorina Sea was at about 48-50 m a.s.l. at its maximum. During the Littorina transgression (7000—6000 BP) uplift almost equalled the rise in water level, the former, however, exceeding the latter by about 0.5 m (Glückert 1994).

Results

Geology of the clay profiles

The sample tubes of the clay profiles at Metsäjoki, Mellilä and Suojoki, Loimaa were deep-frozen immediately after sampling to keep the samples unchanged. This made it more difficult to examine the varves. Nevertheless, by comparing them with the accurately described clay cores taken from Suokulma and Ypäjänkylä, Loimaa in 1975 (Kukkonen et al. 1993) we established that lowermost there are 4—5 m of Yoldia clay with varves 10 cm thick on average. The paler silty summer layer and the darker winter layer rich in clay fraction could be clearly distinguished. Higher up, the varves get thinner before petering out at a depth of 4—4.5 m as measured from the surface. From that depth upwards there are fresh-water Ancylus Lake sediments with occasional undulating silt layers.

The diatom analyses indicate that diatom-poor Yoldia Sea deposits extend from the bottom to a depth of about 4.8 m. Above them there is the diatom assemblage of a great lake reflecting the Ancylus stage. At about 1.5 m depth there are signs of a slight increase in salinity, which, however, declines towards the surface (T. Grönlund, oral comm.). Pollen analyses, too, place the boundary between the Ancylus Lake and Yoldia Sea deposits at about 4.5 m from the surface (B. Eriksson, oral comm.), assigning it a pollen-analytical age of zone

<table>
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<th>Clay</th>
<th>Total concentration</th>
<th>Aqua regia leach</th>
<th>Nutrient concentration</th>
<th>Total concentration</th>
<th>Aqua regia leach</th>
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<tr>
<td>Na %</td>
<td>1.39</td>
<td>0.08</td>
<td>51.75</td>
<td>2.30</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Ni ppm</td>
<td>56.50</td>
<td>48.50</td>
<td>&lt;1.00</td>
<td>27.90</td>
<td>13.90</td>
<td>17.20</td>
</tr>
<tr>
<td>P ppm</td>
<td>971</td>
<td>898</td>
<td>11.80</td>
<td>695</td>
<td>597</td>
<td>725</td>
</tr>
<tr>
<td>Sc ppm</td>
<td>18.70</td>
<td>-</td>
<td>0.27</td>
<td>10.90</td>
<td>2.39</td>
<td>3.40</td>
</tr>
<tr>
<td>Si ppm</td>
<td>26.93</td>
<td>-</td>
<td>143</td>
<td>29.80</td>
<td>0.13</td>
<td>-</td>
</tr>
<tr>
<td>Sr ppm</td>
<td>147</td>
<td>40.20</td>
<td>10.20</td>
<td>240</td>
<td>6.57</td>
<td>9.52</td>
</tr>
<tr>
<td>Ti ppm</td>
<td>5460</td>
<td>2770</td>
<td>0.08</td>
<td>4000</td>
<td>1100</td>
<td>1220</td>
</tr>
<tr>
<td>V ppm</td>
<td>136</td>
<td>89.00</td>
<td>&lt;1.00</td>
<td>83.00</td>
<td>32.70</td>
<td>38.00</td>
</tr>
<tr>
<td>Y ppm</td>
<td>33.90</td>
<td>-</td>
<td>4.42</td>
<td>21.20</td>
<td>7.67</td>
<td>19.1</td>
</tr>
<tr>
<td>Zn ppm</td>
<td>156</td>
<td>131</td>
<td>1.02</td>
<td>94.80</td>
<td>26.95</td>
<td>30.8</td>
</tr>
<tr>
<td>Zr ppm</td>
<td>210</td>
<td>-</td>
<td>0.25</td>
<td>217</td>
<td>7.59</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>66</td>
<td>66</td>
<td>46</td>
<td>1057</td>
<td>1057</td>
<td>82062</td>
</tr>
</tbody>
</table>

(Koljonen 1992)
(Salminen 1995)
Fig. 3. Median values of total and aqua regia soluble concentrations of some elements in the fine fraction of till (Koljonen 1992) and in the whole data of this study (N=66).
Table 2. Coefficients of variation (% of total and aqua regia soluble concentrations of some elements in clay and till. N = number of samples.

<table>
<thead>
<tr>
<th>Clay</th>
<th>Total concentration</th>
<th>Aqua regia leach</th>
<th>Total concentration ²</th>
<th>Aqua regia leach ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>9.2</td>
<td>22.9</td>
<td>9.2</td>
<td>54.5</td>
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<tr>
<td>Ca</td>
<td>19.8</td>
<td>19.6</td>
<td>23.8</td>
<td>88.1</td>
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<tr>
<td>Co</td>
<td>27.9</td>
<td>18.4</td>
<td>45.9</td>
<td>63.3</td>
</tr>
<tr>
<td>Cr</td>
<td>15.4</td>
<td>20.8</td>
<td>48.4</td>
<td>107.2</td>
</tr>
<tr>
<td>Cu</td>
<td>27.8</td>
<td>24.7</td>
<td>67.8</td>
<td>89.8</td>
</tr>
<tr>
<td>Fe</td>
<td>22.1</td>
<td>23.1</td>
<td>30.9</td>
<td>51.2</td>
</tr>
<tr>
<td>K</td>
<td>11.5</td>
<td>30.9</td>
<td>24.4</td>
<td>74.5</td>
</tr>
<tr>
<td>Mg</td>
<td>21.4</td>
<td>24.0</td>
<td>39.4</td>
<td>62.0</td>
</tr>
<tr>
<td>Mn</td>
<td>28.8</td>
<td>40.8</td>
<td>23.9</td>
<td>106.2</td>
</tr>
<tr>
<td>Ni</td>
<td>24.5</td>
<td>21.0</td>
<td>76.8</td>
<td>159.8</td>
</tr>
<tr>
<td>P</td>
<td>24.3</td>
<td>21.5</td>
<td>44.9</td>
<td>36.2</td>
</tr>
<tr>
<td>Sr</td>
<td>13.9</td>
<td>17.5</td>
<td>19.3</td>
<td>64.3</td>
</tr>
<tr>
<td>Ti</td>
<td>11.3</td>
<td>21.5</td>
<td>22.5</td>
<td>40.4</td>
</tr>
<tr>
<td>V</td>
<td>23.2</td>
<td>24.0</td>
<td>35.7</td>
<td>53.1</td>
</tr>
<tr>
<td>Zn</td>
<td>24.4</td>
<td>19.5</td>
<td>529.5</td>
<td>71.7</td>
</tr>
<tr>
<td>N</td>
<td>66</td>
<td>66</td>
<td>1057</td>
<td>1057</td>
</tr>
</tbody>
</table>

²Kolonen 1992

boundary IV/V.

As shown by the thick varves, the sedimentation rate was very high at the front of the continental ice sheet in the early Yoldia Sea stage. As the ice withdrew the sedimentation rate decreased, and, for example, in the Mellilä profile at a depth of about 6 m the varves in the clay are very thin, implying that in the late Yoldia stage, when the ice was already some distance away, only small amounts of new material were transported to the deposition basin. From the number and thickness of the varves it is inferred that the Yoldia stage was shorter at Loimaa than previously thought.

With its microfossils typical of Littorina clays, the Paimio core represents Littorina Sea deposits exclusively. The clays are homogeneous, without any variation of grain size composition. Under the dry crust, down to a depth of 7 m, electrical conductivity is high, varying in the range 92—119 mS/m, as against 22—32 mS/m in the Ancylus and Yoldia clays in the Loimaa area. The average humus content is 1.7% in the Paimio Littorina deposit and 1.5% at Loimaa. The average moisture content in the Paimio samples is 80%, whereas in the Mellilä samples it is 55% and in the Loimaa Yoldia clays 60% (Fig. 2).

Geochemical results

The median values of some element concentrations determined with the three aforementioned methods are given in Table 1. For comparison, total concentrations and aqua regia-soluble concentrations in till are also given (Kolonen 1992). The glacial clays are mainly composed of fines washed from mineral matter transported by the ice sheet. The Ancylus clays are mainly redeposited Yoldia clays. In the course of these processes the element ratios changed radically from those in glaciogenic till. Of the main elements, the clays were enriched in Al, Fe, K and Mg and depleted in Si, Na and Ca. The change in major elements was not, however, as great as it was in heavy metals, for which the concentrations of Ni, Co, Cr and V are double, and those of Cu and Li triple, those in till (Fig. 3). Only the concentrations of Zr and P remained about the same. In addition, both the main elements and heavy metals are in a more soluble form in clays than in till (Fig. 3).

Comparison of stratigraphy and geochemistry is somewhat hampered by the routine taking of samples for analyses in 1-m-long cores. Although clay is homogeneous in relation to the fines in till (Table 2), the sample profile shows marked compositional differences even within one geological unit (Fig. 4), implying that the clays differed in sources, grain size distributions and deposition mechanisms. The differences may also reflect the geochemical changes that occurred during sedimentation.

The chemical composition of clay does not correspond very well to that of till fines in the same map-sheet area. Owing to the coarser grain size, the concentration level of till fines is naturally lower than that of clay (Nikkarinen et al. 1984, Schilts 1975) but the element ratios show that the material derives either from elsewhere, farther away or a larger area (Table 3). As suggested by the pinkish hue of some clay layers, the clay in the Loimaa area presumably contains a fair amount of material from the large Satakunta sandstone occurrence in the northwest. Geochemically the sandstone differs clearly from the other rocks in the vicinity, yet no corresponding features are visible in the geochemistry of the clays.

Due to the dissimilar depositional conditions, clays differing in age also differ in geochemistry. The difference is most marked between the Littorina clay and the other clays (Fig. 5). Having deposited in saline water the Littorina clay has a high chloride concentration (median 0.079%) in relation to other clays (median 0.015%). Also the higher concentration of easily soluble sodium (0.148% in Littorina clay and 0.075% in other clays soluble in aqua regia, and 540 ppm and 48 ppm, respectively, as nutrient concentration) imply deposition in saline
Fig. 4. Concentrations (%) of Na₂O and MgO in the core samples from Loimaa (upper) and Paimio (lower).
Table 3. Median concentrations of some elements soluble in aqua regia in clay profiles at Mellilä, Loimaa, and at Paimio and the corresponding median concentrations in till in the same basic map sheet area (Geological Survey of Finland, regional geochemical till mapping in 1996). N = number of samples.

<table>
<thead>
<tr>
<th>Element</th>
<th>Clay</th>
<th>Till</th>
<th>Clay</th>
<th>Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al %</td>
<td>3.34</td>
<td>1.05</td>
<td>3.64</td>
<td>0.96</td>
</tr>
<tr>
<td>Ca %</td>
<td>0.59</td>
<td>0.34</td>
<td>0.70</td>
<td>0.32</td>
</tr>
<tr>
<td>Mg %</td>
<td>1.47</td>
<td>0.46</td>
<td>1.73</td>
<td>0.42</td>
</tr>
<tr>
<td>Cu ppm</td>
<td>59.5</td>
<td>22.7</td>
<td>65.5</td>
<td>26.8</td>
</tr>
<tr>
<td>Ni ppm</td>
<td>0.48</td>
<td>15.2</td>
<td>51.0</td>
<td>15.1</td>
</tr>
<tr>
<td>V ppm</td>
<td>83.5</td>
<td>33.5</td>
<td>91.5</td>
<td>33.2</td>
</tr>
<tr>
<td>N</td>
<td>14</td>
<td>25</td>
<td>12</td>
<td>25</td>
</tr>
</tbody>
</table>

The humus content is lower in Yoldia clay than in Ancylus clay. Although erosion of the tillage layer has been amply demonstrated (Rekolainen 1993), impoverishment of this layer in several elements (both in total concentrations and particularly in nutrient concentrations) is surprisingly high (Table 4 and Fig. 6). The situation with regard to elements incorporated in fertilizers naturally depends on the amount of fertilizers used, but for the other elements there is a significant difference between the tillage layer and unaltered subsoil.

The depletion of the surficial layer of the clay deposit in elements can be attributed to nutrient intake by plants and erosion of the loose tillage layer. Erosion is suggested by the decrease in the total concentrations of certain elements. Since, however, the decrease in nutrient concentrations is clearly higher than that in total concentrations and, further, the decrease is not equal for all heavy metals, the nutrient intake of cultivated plants clearly plays an important role in the process. On the basis of total concentrations, the abundance of silica in the tillage layer increased at the majority of, but not all, observation points. As the abundances of micas and feldspars that are more soluble...
and erodable than quartz decreased, the abundance of quartz increased (Fig. 7).

A clay deposit in a natural state does not erode; on the contrary, in some cases at least, the rise of capillary water in clay with an appropriate grain size may gradually enrich the surface in elements dissolved in water. Indications of this phenomenon were indeed found in the data. The most striking exception to topsoil element depletion is seen in the behaviour of phosphorus, whose concentrations remained unaltered or even increased in relation to those in clay in a natural state, implying the heavy use of relatively insoluble phosphorus fertilizers.

Discussion

With research into contaminated soil and its re-conditioning in mind an important finding was that the concentrations of several heavy metals in clays are double or triple to those in till fines and that, moreover, the heavy metals are in a more soluble form in clays than in till. The heavy metal concen-

### Table 4. Total and nutrient concentrations of some elements in tillage layer (0—10 cm) and subsoil (100—120 cm). Total concentrations of the main elements (Al—C) in %, others in ppm. Ten samples.

<table>
<thead>
<tr>
<th></th>
<th>Total concentrations</th>
<th>Nutrient concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Topsoil</td>
<td>Subsoil</td>
</tr>
<tr>
<td>Al</td>
<td>7.11</td>
<td>8.28</td>
</tr>
<tr>
<td>Ca</td>
<td>0.89</td>
<td>0.82</td>
</tr>
<tr>
<td>Fe</td>
<td>4.54</td>
<td>5.83</td>
</tr>
<tr>
<td>K</td>
<td>2.51</td>
<td>3.26</td>
</tr>
<tr>
<td>Mg</td>
<td>1.12</td>
<td>1.87</td>
</tr>
<tr>
<td>Na</td>
<td>1.31</td>
<td>1.51</td>
</tr>
<tr>
<td>Si</td>
<td>26.84</td>
<td>26.32</td>
</tr>
<tr>
<td>C</td>
<td>3.34</td>
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<tr>
<td>Co</td>
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<td>30.6</td>
</tr>
<tr>
<td>Cr</td>
<td>97.1</td>
<td>122.4</td>
</tr>
<tr>
<td>Cu</td>
<td>48.4</td>
<td>63.9</td>
</tr>
<tr>
<td>Li</td>
<td>57.3</td>
<td>67.0</td>
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<td>Mn</td>
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<td>866</td>
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<td>60.7</td>
</tr>
<tr>
<td>P</td>
<td>1248</td>
<td>960</td>
</tr>
<tr>
<td>Sr</td>
<td>133</td>
<td>150</td>
</tr>
<tr>
<td>Ti</td>
<td>4595</td>
<td>5290</td>
</tr>
<tr>
<td>V</td>
<td>121</td>
<td>143</td>
</tr>
<tr>
<td>Zn</td>
<td>128</td>
<td>169</td>
</tr>
</tbody>
</table>

Fig. 7. Total (%) and nutrient (ppm) concentrations of SiO₂ in the tillage layer (0—10 cm) and in the unaltered subsoil (100—120 cm) from the ten sampling sites from the Loimaa area.
trations in clays vary little with depth and the differences in composition between genetically dissimilar clays of different ages are not significant.

In older Yoldia clays greater proportions of some elements (Na, P, S, Mn) are in more soluble form than in younger, Ancylus clays. The Ancylus clay is mainly made up of re-eroded and redeposited Yoldia clay, which lost some of its soluble elements through transport by water to the sea. The cultivability of soil in clay areas thus depends on the age of the clay deposits. Further studies are needed to distinguish between Ancylus and Yoldia clays and so to delineate the area covered by the Ancylus Lake; geochemically at least the Littorina clays differ clearly from other clays.

Erosion and human activity have caused marked changes in the element ratios in the tillage layers of clay deposits. Interdisciplinary cooperation is needed with agriculturists to shed further light on this change.

References


EFFECTS OF PRETREATMENT AND PARTIAL DECOMPOSITION TECHNIQUES ON THE LEACHABILITY OF ELEMENTS IN PODZOLIZED TILLS

by
Lea Hämäläinen, Marja Liisa Räisänen and Olli Lehto

Geological Survey of Finland, P.O.Box 1237, FIN-70211 KUOPIO, FINLAND
e-mail: lea.hamalainen@gsf.fi

Key words (GeoRef Thesaurus, AGI): geochemistry, tills, Podzols, chemical elements, leaching, reagents, grain size, milling, Finland

Introduction

Understanding the variations in element leachability in soils and sediments requires knowledge of soil grain size. The texture of soils and sediments, for instance, may control the concentration of heavy metals through a number of mechanisms: (1) fine fractions have a higher metal scavenging and adsorbing capacity than coarser ones; (2) some minerals (clay minerals, heavy minerals etc.) may be concentrated in certain grain sizes, depending on the dynamics of the sedimentary environments (Dreimanis & Vagners 1971, Berrow & Mitchell 1980, Haldorsen 1983, Nikkarinen et al. 1984); and (3) organic matter and secondary precipitates bind elements.

The fine fraction sieved to <0.06 mm is commonly used in geochemical studies in Nordic countries (Bølviken et al. 1986, Koljonen 1992). However, the international standard, ISO 11464, specifies the unpulverized coarse fraction (<2.0 mm) as the standard grain size for soil samples. Several problems thus arise in the interpretation of soil data.

In northern Europe, surface deposits on crystalline bedrock are mostly glacial till and to a minor extent glacioluvial materials. The till consists of fresh (unweathered) rock clasts and mineral matter mechanically comminuted by glacier transport. Due to mineral sorting during comminution, i.e. to their terminal grades (Dreimanis & Vagners 1971), and the sorting caused by glacioluvial meltwaters (Haldorsen 1983), the sand fraction (0.06—2 mm) becomes heavily enriched in quartz and feldspars, and the fine fraction in Mg and Fe-bearing silicates, clay minerals and amorphous compounds. In Finland, sandy till, which is a common till type (75%, Haavisto 1983), contains less than 5% clay in matter less than 20 mm in size (Lindroos & Nieminen 1982). The heavy metal content in the coarse fraction of this till will clearly then be very low due to the predominance of minerals with low adsorption capacity. Räisänen et al. (1995) argue that regional differences in till geochemistry are not so readily detected in the composition of the coarse fraction as they are in that of the fine fraction. The above study, the distribution patterns due to textural variations (glacigenic factor) are better perceived in the fine fraction than in the coarse fraction (see also Shilts 1976, Mäkinen 1995). On the other hand, according to Tarvainen (1995), a feldspar-bearing coarse fraction reflects lithological features more clearly than does the fine fraction in reconnaissance-scale mapping, and the trace element concentrations in the two fractions exhibit similar distribution patterns on maps. However, the concentration levels are much higher in the fine than in the coarse fraction. The same has been reported by Nikkarinen et al. (1984).

We sought here to investigate the distribution of elements in different grain-size fractions, differences in the leachability of elements and the effects of sieving and grinding. The grain-size fractions studied were <0.06 mm (fine), <0.5 mm and <2.0 mm...
The leachability of elements was determined with two partial digestion methods, hot (90°C) aqua regia and microwave-assisted concentrated nitric acid digestion. The latest study of Niskavaara (1995) discusses the validation of these two acid digestion methods and their instrumental applications. Our study is part of the investigation on weak and strong extractions (Räisänen et al. 1996, Righi et al. 1996). The rate of uplift decreases from west to east. The age of ancient shorelines is based on pollen analysis and radiocarbon dating on adjoining organic sediment layers (Okko 1967, Saarnisto 1970, Eronen 1992).

Pretreatments

The air-dried samples were sieved through a 2-mm sieve. The <2 mm fraction was divided into four equal subsamples using a plastic riffle sample splitter.

Two of the subsamples were sieved separately to a grain size of <0.06 mm and <0.5 mm and divided into two equal subsamples. One subsample from the fractions of <0.5 mm fraction and one from the <2 mm fraction were pulverized in a planetary mill with zirconium oxide grinding bowls to avoid metal contamination.

Sample preparations

Aqua regia digestion

Coarse unpulverized sample of 1—2.00 g was weighed accurately in a borosilicate tube, and 9.0 ml of hydrochloric acid followed by 3.0 ml of nitric acid was added. The samples were left to stand overnight and were digested at 90°C in a computer-controlled aluminium heating block for two hours. After digestion the volume was made up to 60 ml and mixed thoroughly. Analyses were made on centrifuged aliquots. The aqua regia digestion method has been modified according to the specifications of standard ISO 11466. Pulverized and fine sample materials were dissolved as described by Niskavaara (1995).
Nitric acid digestion

Nitric acid digestion was made according to EPA 3051 (1990) as follows:
0.500 g of sample was weighed in a Teflon digestion cup and 10 ml of concentrated nitric acid was added. The cup was closed and inserted in a CEM MDS-2000 microwave oven. The digestion time was 60 min at 120 psi pressure. After cooling, the volume was made up to 50 ml with water. Only the pulverized material was dissolved with the EPA 3051 method, because the unmilled coarse material with a sample weight of 0.5 g is not representative. Therefore no data are shown in Table 2 for other materials.

Measurements

Sample solutions were analyzed by inductively coupled plasma atomic emission spectrometry (ICP-AES). An atomic absorption spectrometer equipped with a graphite furnace (GFAAS) was used for Pb, As, and Cd determinations for fine < 0.06 mm and pulverized coarse sample materials. The concentrations of elements in the sieved coarse fractions were analyzed with the ICP-AES instrument alone. Si was not included due to inconsistent precipitation during digestion. Quality assurance and validation of the ICP analyses are reported by Niskavaara (1995).

**Instruments**

The samples were sieved with an Edmund Buhler SM 25 horizontal bench top shaker with plastic frames and nylon meshes.
A Fritsch Pulverisette 5 planetary mill with zirconium oxide grinding bowls and grinding balls was used for pulverizing, and a Prelab 30 computer-controlled aluminium heating block for aqua regia digestion.

The CEM Microwave Sample Preparation System MDS-2000 was used for nitric acid digestion, and a combination ICP-AES Thermo Jarrel Ash Polyscan 61E consisting of a polycromator (ICA 61V) with 31 fixed channels and a monocromator (Atomscan 25V) for ICP-analyses. For analyses in the UV-spectral region the instrument is equipped with a vacuum system.

AAS measurements were conducted with a Perkin Elmer Model 3030/Zeeman atomic absorption spectrometer equipped with an HGA-600 graphite furnace. An As-EDL lamp provided the 197.3-nm line for As measurement.

**Results and discussion**

Effects of grain size on the leachability of elements in aqua regia digestion

Hot aqua regia results in partial dissolution of most elements, particularly the main components.
of silicates (e.g. Si, Al, Ca, Mg, Na, Ti) (Doležal et al. 1968). According to Doležal et al. (1968), the elements bound to sulphides, phosphates, carbonates and related crystalline salts are entirely soluble in aqua regia. Räisänen et al. (1992) report that trioctahedral micas (biotite), Mg-bearing clay minerals and short-range ordered aluminosilicates and iron hydroxides are decomposed in hot aqua regia. Quartz, feldspars and amphiboles remain undecomposed (Doležal et al. 1968).

In general, element concentrations and distributions varied from profile to profile, particularly from podzol layers (E, B and BC) downwards to the less altered C layer (parent till). Indubitably, this

<table>
<thead>
<tr>
<th>Eluvial layer</th>
<th>Mean (N=10)</th>
<th>Median (N=10)</th>
</tr>
</thead>
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<td>0.35</td>
</tr>
<tr>
<td>sieved &lt;0.5</td>
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<td>0.21</td>
</tr>
<tr>
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<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>ground &lt;2.0</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>sieved &lt;0.06</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>sieved &lt;0.5</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>ground &lt;0.5</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>ground &lt;2.0</td>
<td>0.29</td>
<td>0.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>Median (N=10)</th>
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</thead>
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<td>2.67</td>
</tr>
<tr>
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<td>1.76</td>
</tr>
<tr>
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<td>1.82</td>
<td>1.80</td>
</tr>
<tr>
<td>ground &lt;2.0</td>
<td>1.80</td>
<td>1.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>BC layer</th>
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<th>Median (N=10)</th>
</tr>
</thead>
<tbody>
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Table 2. Mean and median values of the element concentrations in sieved and ground fractions of the samples from the eluvial, illuvial and BC layers and parent tills.
is due to the geochemical variation in tills and the variation in the intensity of podzolization along the study line. Even so, the distributions of the elements in the sieved <0.06 mm, <0.5 mm and <2.0 mm fractions are analogous at the mean and median concentrations of the aqua regia soluble elements presented in Table 2.

The mean and median values of elements are greatest in the fine fraction and lowest in the coarse, unpulverized <2.0 mm fraction from all layers. The ratio of the mean values in the fine fraction to those in the <2.0 mm fraction ranged from 1.2 to 2, being highest for S and P (for S see Fig. 2a). In contrast, the difference between the

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The behaviour of Mn in the eluvial layer differed from that of the other elements, as seen in Figs 2 and 3 for S, Zn, K and Mg. The behaviour of trace elements was similar to that of S.

The behaviour of Mn in the eluvial layer differed from that of the other elements, see Table 2. In some profiles the concentration of Mn was very high in the sieved coarse <2 mm fraction as compared with the mean and median values. This may be due to the sorbing capability of Mn hydroxides on the broken surface of coarse grains (Kabata-Pendias & Pendias 1992).

The distribution of Mg, K, Al and Fe concentrations and those of many trace elements are similar in the fine fraction of the C layer and, to some

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<td>6 23 8 11</td>
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<tr>
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<td>6 22 8 11</td>
<td></td>
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<tr>
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<th>Cr c(ppm)</th>
<th>Cu c(ppm)</th>
<th>Ni c(ppm)</th>
<th>Pb c(ppm)</th>
<th>As c(ppm)</th>
<th>Cd c(ppm)</th>
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<td>Aq.r.</td>
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<td>Aq.r.</td>
<td>HNO₃</td>
<td>Aq.r.</td>
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<td>6 24 12</td>
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<tr>
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<td>5 20 11</td>
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<tr>
<td>sieved &lt;2.0</td>
<td>5 19 11</td>
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<td>ground &lt;0.5</td>
<td>5 6 22 25  12 12 11 11 4.7 5.3 2.0 1.5 0.05 0.07</td>
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<tr>
<td>ground &lt;2.0</td>
<td>5 5 22 25  13 11 11 11 4.3 6.1 1.7 1.2 0.07 0.07</td>
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</table>
and precipitates in the surface till layers during podzolization, and that heavy metals and As are concentrated in organic compounds and clay minerals of the <0.002 mm fraction (Kabata-Pendias & Pendias 1992, Tarvainen 1995). Their concentrations were low and increased downwards in the profile (Table 2). In the eluvial layer the concentrations of Co, Ni, As and Cd (except Pb) were close to instrumental detection limits. Pb concentrations were higher in the E and B layers than in the underlying layers.

Effects of grinding on the leachability of elements

Grinding of the <0.5 mm and <2.0 mm fractions increased the leachability of elements (Table 2), the more so for major than for trace elements. The difference in concentrations of elements was generally smaller in the eluvial layer than in the underlying layers. Manganese was the only element with concentrations that increased consistently in every soil layer after grinding of the <2 mm fraction.

As shows Figure 2c, the difference in the leachability of K between the sieved and ground fractions is considerable. It is seen, that the mean concentration of K was even higher in the ground coarse fractions than in the fine fraction from the E and BC layers. During podzolization most of the fine grains of K-micas have weathered in the higher podzol layers but not in the parent till (Räisänen 1996). Grinding of the coarse micaceous minerals promotes dissolution. Unlike Mn, Mg, K, Na, Al and Fe, the change in the leachability of many trace metals and As after grinding was insignificant. Houba et. al (1993) have also reported that grinding of coarse fractions of soil does not increase the concentration of heavy metals after aqua regia digestion.

Leachability of elements in concentrated nitric acid digestion

Analogously to aqua regia data, concentrations of elements in conc. nitric acid digestion assisted by microwave were higher in the sieved fine fraction than in the ground coarse (<0.5 mm, <2.0 mm) fractions, as seen in Table 2. As in aqua regia digestion, the difference in concentrations between the ground <0.5 mm and <2.0 mm fractions was small in nitric acid leaches. Although the sieved coarse fractions were not analysed with the conc. nitric acid digestion method, it can be assumed that the difference between the sieved fine and coarse

---

**Fig. 2.** Mean concentrations of aqua regia soluble a) sulphur, b) zinc and c) potassium in sieved and ground fractions of the samples from the eluvial, illuvial and BC layers and parent till.
fractions would have been close to that obtained with the aqua regia digestion method.

We can see in Table 2 that the leaching capacity of nitric acid assisted by microwave was higher for most elements of silicates than that of hot aqua regia leach at atmospheric pressure. The change was greatest for Ca in all three fractions and in every mineral soil layer (Fig. 4). Evidently, plagioclase is partially dissolved at a pressure of 120 psi.

In some samples Pb was markedly more soluble in nitric acid digestion than in aqua regia digestion owing to the tendency of Pb to precipitate as chloride in the presence of the chloride ions when existing in solutions in oxidation states (I) or (II). The plumbous ion, Pb\(^{2+}\), is partially hydrolyzed in water and, as chloride, forms in solution complex species PbCl\(^+\), PbCl\(^{3-}\), etc. or insoluble precipitates, depending on the matrix (Cotton & Wilkinson 1976).

In contrast to the other elements measured As values were lower in nitric acid leaches. This is, however, more likely due to problems with instrumental techniques during measuring than to decreased solubility of As in nitric acid.

**Conclusions**

Mean and median concentrations of elements are highest in the fine fraction and lowest in the coarse sieved <2.0 mm fraction of all soil layers. By contrast, the difference between the <0.5 mm and...
concentrations of major and trace elements between the <0.5 mm and <2.0 mm fractions compared with that in the fine fraction.

Analogously to aqua regia data, concentrations of elements in conc. nitric acid leaches assisted by microwave oven were higher in the sieved fine fraction than in the ground coarse (<0.5 mm, <2.0 mm) fractions. The leachability of most silicate elements under pressure in nitric acid assisted by microwave was more effective than that in hot aqua regia at atmospheric pressure.

The coarse sieved <2 mm fraction is a standardized grain size for soil samples according to the international standard, ISO 11464. For geochemical studies this coarse <2 mm fraction is, however, not appropriate because of the diluting effect of the quartz and feldspars. Grinding of the <0.5 mm and <2 mm fractions results in higher concentrations for most elements in acid digestions. The increase was more significant for major elements than for trace elements, indicating better dissolution of coarse micaceous minerals. The processing of coarser materials, implies higher costs and lower capacity. For environmental purposes it is important that the standardized unmilled <2 mm grain size fraction of soil should be used with a view to producing internationally comparable data.

Fig. 4. Leachability of Ca by conc. HNO₃ dissolution vs leachability of Ca in hot aqua regia dissolution of a) sieved <0.06 mm, b) ground <0.5 mm and c) ground <2 mm fractions of podzolized till layers.

<2.0 mm fractions was insignificant for most elements. The terminal grades and selective dissolution of minerals cause an insignificant difference in

References


Okko, M. 1967. The relation between raised shores and present land uplift in Finland during the past 8000 years. Annales Academiae Scientiarum Fennicae Series A III 93, 59 p.


US EPA Method 3051, Revision 0 1990. Microwave assisted acid digestion of sediments, sludges, soils and oils.
GEOCHEMICAL ENVIRONMENT IN AREAS OF LOW AND HIGH CORONARY HEART DISEASE MORTALITY

by
Anne Kousa and Maria Nikkarinen

GEOCHEMICAL ENVIRONMENT IN AREAS OF LOW AND HIGH CORONARY HEART DISEASE MORTALITY

Introduction

Regional differences in mortality from cardiovascular disease in Finland are well established (e.g. Näyhä, 1989). Mortality from coronary heart disease (CHD) is about 50% more frequent in eastern than in western Finland. Although the geographical differences have long been known (Kannisto 1947), the reasons are ambiguous and not satisfactorily explained by the known risk factors of CHD (Koskinen 1994). CHD is a multifactorial disease, that is, it results from several lifestyle, genetic and environmental factors (Puska et al. 1981, Tuomilehto et al. 1989, Vartiainen et al. 1994 and Joulsaari et al. 1995). The factor that has received the least attention is the natural environment (Koskinen 1995) (Fig. 1). Some investigations have suggested a link between natural environmental factors and deaths from, or the development of, CHD. Szalay et al. (1981) investigated the relation of micronutrient deficiency in bedrock to the incidence of CHD in North Karelia, and Masironi (1987) presented the hypothesis that a deficiency or excess in the content or availability of trace elements in rocks and soils, or in water flowing through them, may be a cause of certain chronic ailments, including cardiovascular diseases. A search for the hypothetical factor in drinking water that might influence mortality from CHD was made in two rural areas in western and eastern Finland (Punsar et al., 1975). In the course of the investigation it was found that pH, F, Ca, Mg, Na and Cr concentrations in drinking water were higher in the western test area whereas K, Cu, Co, Ni and Ba concentrations were higher in the eastern area. It is well established that cardiovascular diseases are inversely related to the hardness of drinking water (e.g. Crawford et al. 1968, Karppanen et al. 1978). Recent studies have provided evidence that high blood Fe and Cu stores increase the risk of CHD (Salonen et al. 1991a, 1991b). It has been assumed that the soil contains more harmful elements, such as Fe and Cu, in areas of high CHD mortality than in coastal areas of low CHD mortality. The geochemical characteristics of soil in areas of high and low CHD mortality have, however, not previously been studied in Finland.

Due to the enormous increase in the amount of geochemical data available in Finland in recent years, opportunities for studying the geochemical environment in areas of low and high CHD mortality are now better than ever. The geochemical databases of the Geological Survey of Finland (GTK) provide information on geographical differences countrywide in the distribution of elements. Geochemical mapping programmes have produced knowledge of the elemental composition of soil (mainly till), groundwater, and streamwater and organic stream sediment on either reconnaissance or regional scale (Koljonen 1992, Salminen 1995, Lahermo et al. 1990, Tarvainen 1996).

The aim of our pilot study was to investigate the geochemical composition of groundwater and soil in areas of different mortality from CHD using the...
Materials and methods

Study areas

The areas used in this pilot study were selected on the basis of the coronary heart disease (CHD) mortality index of males in Finnish municipalities. The original CHD mortality index was classified into five categories as described by Näyhä (1989). The adjusted index of CHD mortality by municipality in the period 1961—1985 for males aged 35 years and over was 100 in the whole of Finland (Näyhä 1989). We selected three of the original five categories: the areas with the lowest, middle and highest CHD mortality indexes. In area I, which comprises four municipalities, Halikko, Lieto, Paimio and Uusikarlepyy, the index was 42—80. The index of area II, which included three municipalities, Merikarvia, Ruukki and Siikainen, was 91—101 and that of area III, comprising Outokumpu and Vaala, was 114—152 (Fig. 2). The target areas were all approximately 2000 km² in size.

In the selection of target areas for categories I
and II, one of the criteria was a similar coastal location. Here, coastal areas comprise not only areas now on the sea shore but also those that were on the shore when the Littorina Sea covered large areas after the last glaciation.

**Geochemical databases**

The results of regional soil mapping and hydrogeochemical mapping were both utilized for the study. Regional-scale till sampling at 1 sample/4 km² was completed in 1991 and yielded a total of 82,000 samples (Salminen 1995). The sampling depth was 1.5 to 2.5 m and each sample was a composite of three to five subsamples. The < 0.06-mm fraction was decomposed in hot aqua regia and about 30 elements were determined by the ICP-AES method (Kontas et al. 1995). The data have been published as individual 1 : 400,000 map sheets. For our study we used the data on Al, Ba, Ca, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Ni, P, Sc, Sr, Ti, V, Y and Zn. The analytical reproducibility of these elements was sufficient and their concentrations were above detection limit.

Hydrogeochemical mapping of groundwater (1 sample/ 50 km²) was carried out during 1978—1982 (Lahermo et al. 1990). Natural springs, and
drilled and excavated wells were sampled. The results were published in 1990 as the Geochemical Atlas of Finland, Part 1, Hydrogeochanical Mapping of Finnish Groundwater (Lahermo et al. 1990). Dozens of groundwater samples, mainly from wells, are gathered and analysed yearly and the data added to the GTK's hydrogeochemical database. We used the analytical data from this database for our study. The data on Ca, Cd, Cl, Co, Cr, Cu, F, Fe, K, Mg, Mn, Na, Ni, Pb, U, Zn and water hardness were available. Element concentrations were determined with different methods, e.g. ICP-MS, ICP-AES, ionography and AAS. If the concentrations of a certain element were determined using several methods, we used the calculated mean value.

**Statistical analyses**

The average concentrations of elements were used for the geochemical characterization of the selected areas. As the distributions of elements in both water and soil samples were skewed, non-parametric tests were used. The differences between three areas were compared with the Kruskall-Wallis test and those between two areas with the Mann-Whitney test. Statistical analyses were performed using SPSS for WIN software.

**Results**

Element concentrations in soil versus CHD mortality

The total number of geochemical soil samples in the study was 1255: 371 from area I, 428 from area II and 456 from area III.

The mean concentrations of Ba, Co, Cr, Cu, Ni, and Ti were lowest in area I and highest in area III, which had the highest CHD mortality index (Table 1). The median values of these elements were in line with the mean levels. Only the median levels of Ba and Cr were slightly lower in area III than in area II. The mean levels with 95% confidence intervals of these geochemical elements in soil are shown in Figure 3.

The mean values of Al, Ca, Fe, K, Mg, Mn, P, Sc, and V were lowest in area I (the lowest CHD mortality index) but there was no difference between the mean levels for area II and area III (Table 1). The median values were in line with the mean values. The median and mean levels of Zn were lowest in area I and highest in area II. The highest mean and median levels of La, Li, and Sr were in area II. The highest mean and median values of Y were in area I and the lowest in area III. Yttrium was the only element with the highest concentration in area I.

Element contents of groundwater in dug wells and drilled wells in the selected areas

We used analyses of both dug and drilled wells in this study. Dug wells were the most common well type. In the past wells were often lined with wood or stone, but nowadays concrete rings are preferred. Private dug wells were generally 3—10 m deep (Lahermo et al. 1990), and the wells drilled into bedrock 40—80 m deep. The groundwater in drilled wells reflects the composition of the bedrock better than does the water in dug wells (Lahermo et al. 1990).

The total number of water samples taken from dug wells in this study was 119: 29 from area I, 40 from area II and 50 from area III. Data on Ca, Cd, Cl, Co, Cr, Cu, F, Fe, K, Mg, Mn, Na, Ni, Pb, U and Zn were used; some elements were excluded as there were insufficient data in one or two CHD mortality categories.

There was no significant difference in concentrations of Ca, Co, Cu, U and Zn in the water of dug wells. A statistically significant difference between three areas of CHD mortality was, however, found in concentrations of Cd, Cl, Cr, F, Fe, K, Mg, Mn, Na, Ni and Pb (Table 2). The highest Cr, Fe, Mn, and Ni mean and median concentrations were in area II. The mean level of Cl was highest in area I whereas the median level was highest in area II. The mean and median concentrations of Cd and Pb were lowest in area I. The mean and median levels of F and Mg were highest in area I and lowest in area III. The median and mean levels of Na were lowest in area III (Fig. 4).

Water hardness (concentrations of Ca and Mg) in the samples from dug wells ranged from 0.5 to 18.0°dH (in German degrees). The highest median value of water hardness, 3.64°dH, was in area I and the lowest 2.97 °dH, in area III (p=0.0280). The median value of the total hardness of water in dug wells was 3.22 °dH (Fig. 4).

Thirty wells were drilled into bedrock: 10 in area I, 11 in area II and 9 in area III. Data on Ca, Cd, Cl, Co, Cr, Cu, F, Fe, K, Mg, Mn, Na, Ni, Pb, U and Zn were used here (Table 3).

The mean and median values of Ca, F, Na and U
Fig. 3. Mean values and 95% confidence intervals (CI) of Ba, Co, Cr, Cu, Ni, Ti and Y concentrations in soil in three different areas of coronary heart disease mortality.
Table 1. Medians, mean values and standard deviations (SD) of elements in soil in three CHD mortality areas.

<table>
<thead>
<tr>
<th>Element</th>
<th>Area I CHD mortality index 42-80 (n=371)</th>
<th>Area II CHD mortality index 91-101 (n=428)</th>
<th>Area III CHD mortality index 114-152 (n=456)</th>
<th>p-value</th>
<th>Whole of Finland</th>
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</thead>
<tbody>
<tr>
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<td>median mean SD</td>
<td>median mean SD</td>
<td>median mean SD</td>
<td></td>
<td>median</td>
</tr>
<tr>
<td>Al %</td>
<td>0.70 0.90 0.60</td>
<td>1.15 1.21 0.60</td>
<td>1.01 1.17 0.56</td>
<td>&lt;0.001</td>
<td>1.15</td>
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<td>Ba ppm</td>
<td>24.10 33.14 22.32</td>
<td>64.30 70.85 40.67</td>
<td>60.95 103.56 80.85</td>
<td>&lt;0.001</td>
<td>60.10</td>
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<td>Ca %</td>
<td>0.25 0.25 0.09</td>
<td>0.29 0.30 0.08</td>
<td>0.29 0.30 0.08</td>
<td>&lt;0.001</td>
<td>0.27</td>
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<tr>
<td>Co ppm</td>
<td>4.01 4.63 2.97</td>
<td>7.96 8.32 4.21</td>
<td>9.01 10.68 6.81</td>
<td>&lt;0.001</td>
<td>7.95</td>
</tr>
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<td>Cr ppm</td>
<td>15.50 18.88 10.49</td>
<td>32.10 35.29 17.11</td>
<td>30.20 40.74 25.75</td>
<td>&lt;0.001</td>
<td>31.30</td>
</tr>
<tr>
<td>Cu ppm</td>
<td>11.10 13.20 7.21</td>
<td>19.45 21.37 12.56</td>
<td>20.75 31.56 23.58</td>
<td>&lt;0.001</td>
<td>21.80</td>
</tr>
<tr>
<td>Fe %</td>
<td>1.14 1.35 0.67</td>
<td>1.95 2.06 1.04</td>
<td>1.72 2.08 1.00</td>
<td>&lt;0.001</td>
<td>1.80</td>
</tr>
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<td>K %</td>
<td>0.13 0.16 0.10</td>
<td>0.29 0.34 0.23</td>
<td>0.23 0.38 0.30</td>
<td>&lt;0.001</td>
<td>0.19</td>
</tr>
<tr>
<td>La ppm</td>
<td>25.00 27.45 18.89</td>
<td>28.35 28.45 9.58</td>
<td>25.25 27.18 9.56</td>
<td>&lt;0.001</td>
<td>24.00</td>
</tr>
<tr>
<td>Li ppm</td>
<td>8.49 11.51 8.52</td>
<td>16.25 17.01 9.51</td>
<td>11.00 14.80 10.00</td>
<td>&lt;0.001</td>
<td>11.10</td>
</tr>
<tr>
<td>Mg %</td>
<td>0.25 0.31 0.18</td>
<td>0.57 0.61 0.31</td>
<td>0.47 0.63 0.43</td>
<td>&lt;0.001</td>
<td>0.47</td>
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<tr>
<td>Mo ppm</td>
<td>118.00 142.90 97.93</td>
<td>195.00 210.55 97.01</td>
<td>193.00 217.76 107.89</td>
<td>&lt;0.001</td>
<td>177.00</td>
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<td>Ni ppm</td>
<td>8.85 10.37 5.57</td>
<td>15.80 18.43 11.47</td>
<td>17.85 33.54 62.14</td>
<td>&lt;0.001</td>
<td>17.20</td>
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<tr>
<td>P ppm</td>
<td>716.00 689.70 167.55</td>
<td>812.50 824.77 213.58</td>
<td>762.00 835.66 238.17</td>
<td>&lt;0.001</td>
<td>725.00</td>
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<td>Sc ppm</td>
<td>2.16 2.59 1.41</td>
<td>3.82 4.26 2.19</td>
<td>3.35 4.58 2.77</td>
<td>&lt;0.001</td>
<td>3.40</td>
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<td>Sr ppm</td>
<td>9.22 9.84 4.23</td>
<td>10.70 11.24 3.82</td>
<td>9.29 9.57 3.35</td>
<td>&lt;0.001</td>
<td>9.52</td>
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<td>Ti ppm</td>
<td>973.00 1052.12 376.48</td>
<td>1220.00 1303.13 484.90</td>
<td>1315.00 1422.77 512.19</td>
<td>&lt;0.001</td>
<td>1220.00</td>
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<td>V ppm</td>
<td>22.20 25.84 12.15</td>
<td>41.55 44.23 18.09</td>
<td>37.45 45.27 20.93</td>
<td>&lt;0.001</td>
<td>38.00</td>
</tr>
<tr>
<td>Y ppm</td>
<td>11.66 13.07 4.81</td>
<td>11.50 11.81 3.33</td>
<td>9.26 10.36 3.32</td>
<td>&lt;0.001</td>
<td>10.10</td>
</tr>
<tr>
<td>Zn ppm</td>
<td>23.60 29.01 16.82</td>
<td>41.65 44.65 25.12</td>
<td>28.20 43.25 31.64</td>
<td>&lt;0.001</td>
<td>30.80</td>
</tr>
</tbody>
</table>

*p* Kruskal-Wallis test (df=2) between three categories

were highest in area I, where the CHD mortality index was lowest; those of Cd, Fe, Mn and Pb were highest in area II. The highest mean and median levels of Ni were in area III (the highest CHD mortality index). The mean concentrations of Ca, F, Na and Ni with 95% confidence intervals are presented in Figure 5.

The hardness of water in drilled wells ranged from 1.75 to 20.60 °dH (in German degrees). The highest median level of water hardness, 6.04 °dH, was in area I and the lowest, 2.75 °dH, in area III. The median value of the total hardness of water in drilled wells was 4.32 °dH (Fig. 5).

The concentrations of Ca, Cl, F, Mg, Mo, Na, Rn, Sr and the value for were higher in drilled than in dug wells. High Al, Cd, Co, Ni, and Pb concentrations were found in dug wells. Ca and F trends were parallel in dug and drilled wells. Ca and F levels being highest in area I and lowest in area III.

**Differences between coastal and inland areas in dug wells and drill wells**

Forty-two per cent of water samples from dug wells were from inland areas and 58% from coastal areas (n=119). Some elements were excluded because of insufficient data on them from the inland area. Al, Ca, Cd, Cl, Co, Cr, Cu, F, Fe, K, Mg, Mn, Na, Ni, Pb, Rn, and Zn concentrations were used in this part of study (Table 4). The mean and median levels of Al, Ca, Cl, Cu, F, Fe, Mg, Mn and Na were lower in the inland than in the coastal area. The median concentration of water hardness was 2.97 °dH in the inland area and 3.57 °dH in the coastal area (p=0.008).

Thirty per cent of drilled wells were in the inland area and 70% on the coast (n=30). Data on Ag, Al, As, B, Ba, Be, Bi, Br, Ca, Cd, Cl, Co, Cr, Cu, F, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Rb, Rn, Sb, Se, Si, Sr, Th, Ti, U, V and Zn were used. The mean concentrations of As, B, Br, Ca, Cl, F, Li, Mo, Na, Sr,
Table 2. Medians, mean values and standard deviations (SD) of elements in water in dug wells in three CHD mortality areas.

<table>
<thead>
<tr>
<th>Element</th>
<th>Area I CHD mortality index 42-80</th>
<th>Area II CHD mortality index 91-101</th>
<th>Area III CHD mortality index 114-152</th>
<th>p-value*</th>
<th>Whole of Finland</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>median</td>
<td>mean</td>
<td>SD</td>
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<td>Ca mg/l</td>
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<td>11.84</td>
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<td>Zn ug/l</td>
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<td>112.16</td>
<td>318.43</td>
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* Kruskall-Wallis test (d.f=2) between three categories.
Fig. 4. Mean values and 95% confidence intervals (CI) of F and Mg concentrations and water hardness in dug wells in three different areas of coronary heart disease mortality.

U and V were highest in the coastal area. The median values were in line with the mean values. The median value of water hardness was 2.75 °dH in the inland area and 5.59 °dH in the coastal area (p=0.0092).

Discussion

Differences were found in the geochemical environment between areas of high CHD mortality and those of low CHD mortality. Characteristic geochemical features of the soil in the area of high CHD mortality (area III) were higher Ba, Co, Cr, Cu, Ni, and Ti concentrations and a lower Y concentration than in the area of low (area I) CHD mortality. Concentrations of Ba, Co, Cr, Cu Ni and Ti in the soil in areas II and III were in line with the levels countrywide. Concentrations in the soil in the area of low CHD mortality tended to be lower than the geochemical levels on average in Finnish soil.

The earlier findings of Punsar et al. (1975) were that concentrations of Ba, Co, Cu, K, and Ni in water are significantly higher in the eastern area. Our results for element concentrations in soil follow the same trend. The exception is Cr, which in the earlier study (Punsar et al. 1975) was found to be highest in water in the western low CHD area; this result is not borne out by our study. Presumably because Cr is mainly bound in soil to stable, almost in soluble oxide minerals.

In this study characteristic geochemical features of the water in both drilled and dug wells in the area of high CHD mortality were low F, Mg, Ca, CI concentrations and low water hardness. The F and Mg concentrations in water of dug wells were higher in the area of lowest CHD mortality than were the median values of these elements in the whole of Finland. This result supports the hypothesis presented by Luoma et al. (1983) that low F intake is associated with cardiovascular disease. They found that F concentrations of around 1 ppm in household water were not harmful; on the contrary they may even be beneficial.

Water hardness has been reported to be inversely related to CHD mortality (Karpunanen et al., 1978, Nerbrand et al., 1992). The findings of our study support this presumption; water hardness being lowest in the area of high CHD mortality. The result would have been similar if the constituents of water hardness, Ca and Mg, had been observed sepa-
Table 3. Medians, mean values and standard deviations (SD) of elements in water in wells drilled into bedrock in three areas of CHD mortality areas.

<table>
<thead>
<tr>
<th>Element</th>
<th>Area I</th>
<th>Area II</th>
<th>Area III</th>
<th>p-value*</th>
<th>Whole of Finland</th>
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<tr>
<td></td>
<td>IHD mortality index 42-80</td>
<td>IHD mortality index 91-101</td>
<td>IHD mortality index 114-152</td>
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<td>median</td>
<td>mean</td>
<td>SD</td>
<td>n</td>
<td>median</td>
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<tr>
<td>Ca mg/l</td>
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<tr>
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<tr>
<td>Cl mg/l</td>
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<td>118.77</td>
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<td>Co ug/l</td>
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<td>0.21</td>
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<tr>
<td>Cr ug/l</td>
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<td>Cu mg/l</td>
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<td>K mg/l</td>
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<td>Mg mg/l</td>
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<td>Mn mg/l</td>
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<td>Ni ug/l</td>
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<td>Pb ug/l</td>
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<td>U ug/l</td>
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<tr>
<td>Zn ug/l</td>
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<td>59.25</td>
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</table>

*p-value* Kruskall-Wallis (d.f=2) between three categories.
Coronary heart disease mortality

Coronary heart disease mortality

Coronary heart disease mortality

Coronary heart disease mortality

Fig. 5. Mean values and 95% confidence intervals (CI) of Ca, F, Na, Ni concentrations and water hardness in drilled wells in three different areas of coronary heart disease mortality.

rately, because they are both at their lowest in area III. If the coastal areas are examined together and compared with the inland area, the F concentrations and water hardness values are lower in the inland area (high CHD mortality) than in the coastal area (low CHD mortality).

High Cl concentrations have been reported in the area of low CHD mortality (Schroeder, 1966); our results confirm this. It is characteristic of the area of low CHD mortality that Cl concentrations are higher in the water of drilled wells than they are in the reference area.

Conclusions

The aim of this study was to establish whether there are any differences in the geochemical environment that might have a bearing on CHD mortality. Characteristic geochemical features of soil were high Ba, Co, Cr, Cu, Ni and Ti and low Y concentrations in the area with a high CHD mortality index. Characteristic geochemical features of groundwater were low F concentrations and low water hardness values in both the dug wells and drilled wells in the area of high CHD mortality. Concentrations of F and water hardness values were
lower in the inland area than in the coastal area. These observations are tentative. It is beyond the scope of this study to assess the association between these findings and CHD because clinical evidence is lacking on many of the elements used. The study does indicate, however, that there is a regional variation in the geochemical environment between areas of low and high CHD mortality. The relationship between the above elements and cardiovascular disease is therefore worth investigating further.

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Health Science, University of Oulu and Regional Institute of Occupational Health, Oulu. 48 pages.


A NEW APPARATUS FOR ELECTRIC CONDUCTIVITY AND TEMPERATURE LOGGING OF SOFT SEDIMENTS

by

R. Puranen, M. Mäkilä, K. Sulkanen and A. Grundström

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: risto.puranen@gsf.fi

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Introduction

Finland is being systematically mapped with airborne magnetic, electromagnetic (AEM) and radiometric measurements from a low flight altitude (30—50 m) and with a line spacing of 200 m (see Poikonen 1991). The mapping now covers about 70% of Finnish territory. The sources of most anomalies on the AEM maps lie in the overburden. In coastal areas the anomalies are generally due to clays, but inland they are often connected with mires and lakes, which cover more than 40% of Finland. The sources of these AEM anomalies are not known adequately and can only be established with further studies.

The electric conductivities of Finnish mires and their bottom sediments vary mainly in the range 2—200 mS/m according to DC resistivity soundings (Pernu 1991). The lower end of this range (2—20 mS/m) is valid for most surface waters of the mires (Kivinen 1935; Tolonen & Hosiaisluoma 1978). The conductivity of mire waters is usually controlled by their electrolyte content (Kivinen 1935; Theimer et al. 1994) although hydrogen ions (acidity) also contribute to the conductivity of bog waters (see Kivinen 1935). Detailed conductivity profiles have not been published for Finnish mires, but Theimer et al. (1994) recently presented such profiles for Canadian mires showing locally quite high conductivities (up to 380 mS/m).

The interpretation of AEM maps requires more detailed data on the conductivity variations in mires and lakes and their bottom sediments. Such data can be obtained by laboratory measurements of samples or, more rapidly, by logging methods in the field. The logging data are more reliable, as any disturbances caused by sampling, sample transport and storage can be avoided. We could not, however, find a commercially available logging apparatus for soft sediments satisfying our requirements (low-cost, light-weight and easy-to-use). We therefore constructed such an apparatus, and this, together with some examples of applications, is the subject of the present paper.

Logging apparatus

Conductivity depends on temperature and so the probe of our logging apparatus (Fig. 1) has sensors for both electric conductivity and temperature. The probe is small as we wanted to make detailed conductivity and rapid temperature measurements. A small probe also facilitates calibration, portability, sediment penetration and data interpretation. Mires and their bottom sediments were taken as the first logging targets, which fixed the conductivity range at 2—200 mS/m and the temperature range at 0—25°C. We use the standard shafts of peat samplers to press the probe into mires.

The conductivity sensor is located on one side of
the probe head and the temperature sensor on the other (Fig. 2). The sensors are connected to the electronics unit with a high-strength Kevlar braided cable. The probe can be attached directly to the shafts of a Russian peat sampler. The plastic (PVC) head of the probe easily penetrates most soft sediments. If the mire contains abundant wood remains, the logging route must first be cleared with a peat sampler, which is somewhat smaller than the probe.

Sensors and calibrations

The conductivity sensor is composed of current and potential electrodes (acid-proof steel screws) fixed into the probe head 1.5 cm apart (Fig. 2). With this four-electrode (Wenner) configuration and the relatively high measuring frequency (500 Hz), disturbances due to electrode polarisation are largely eliminated. The sensor was tested and calibrated by measuring electrolytes with known conductivities in the range 2—200 mS/m.

Test measurements showed that the sensor obeys approximately (error less than 5%) the theory of a Wenner array at the surface of a homogeneous half space. This facilitates calibration and theoretic analysis of the sensor, which proved to be practically unaffected by conductivity changes (layer boundaries and inhomogeneities of sediments) taking place more than 5 cm away from the sensor (Puranen et al. 1996c). At this scale the logged apparent conductivity and the true conductivity of

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Fig. 1. Components of logging apparatus. P=probe, E=electronics unit, C=Kevlar cable, S=sampler shaft and L=lifting tool.

Fig. 2. Plastic head of probe in front, back and side views. A) Current (I) and potential (U) electrodes of conductivity sensor. B) Temperature sensor (T) with aluminum backplate (grey). C) Side view of probe head.
sediment can be regarded as equal.

The temperature sensor is mounted on an aluminum plate (Fig. 2) fixed to one face of the probe. The output current of the sensor (integrated circuit AD590) is proportional to temperature. The sensor and its backplate are thermally insulated from the plastic body of the probe with an air pocket, which makes the temperature measurements reasonably rapid. The sensor was calibrated in water at a low (5°C) and a high (20°C) temperature with the aid of precision thermometers.

Measuring specifications

The logging apparatus (probe+cable+electronics) weighs only 1.2 kg and one alkaline battery (9 V) keeps it running for several weeks. The present depth range of logging (0—7 m) is determined by the cable length, and logging can be made in peat, mud, gyttja, some clays and water. Conductivity measurements take a few seconds per reading but temperature measurements require 30—60 seconds before the result is stabilised.

The calibration error of conductivity measurements is less than 5% in the range 2—200 mS/m. Differences between repeated conductivity loggings at the same site of a mire are generally less than 10% (Fig. 3A). The logged apparent conductivity is mainly controlled by the material in front of the probe within a half sphere with a radius of 5 cm. The apparent and true conductivities are identical only for homogeneous materials.

The calibration error of temperature measurements is less than 0.2 degrees in the range 0—25°C, and within this range the probe attains a new temperature (±0.2°C) in less than one minute. Temperature loggings repeated during one hour at the same mire site are generally within 0.3 degrees (Fig. 3B). For a more detailed description of the apparatus, see Puranen et al. (1996c).

Fig. 3. Within site (±1 m) repeatability of logging data. A) Conductivity loggings at Haukkasuo bog (Anjalankoski, 18.10.1995), B) Temperature loggings at Mankaa bog (Espoo, 16.2.1996).

Fig. 4. Case histories. 1=Ahteesuo fen in Utajärvi area, 2=Koivusuo mire in Lievestuore area, 3=Haukkasuo bog in Anjalankoski area.
Logging applications

So far we have mainly used the logging apparatus in mire environments. We have studied mires and their bottom sediments for the sources of AEM anomalies, and we have delineated polluted parts of some mires with conductivity logging. We have also mapped the temperature variations in mires that control the growth and decomposition processes of peat. The application case histories are from fens and bogs in different parts of Finland (Fig. 4).

Logging at AEM anomaly sites

The sources of AEM anomalies are demonstrated in the case of Ahteensuo, a fen that has been geologically described by Pajunen (1989). Comparison of the peat thickness map with the AEM anomaly map of the mire (Fig. 5) clearly connects the anomalies with mire depressions. The stratigraphy and conductivities were studied at depression sites A—C (Fig. 6). Conductivity was highest near the bottom of the main depression (point A), where there is gyttja, sediments are rich in fines and the bottom layers of peat are nutrient rich. Within the depressions the thickness-conductivity product of the overburden is high, which explains the anomalies. The AEM anomaly of the main depression is caused almost equally by the peat layer (45%) and the bottom sediments (55%), as shown by layer model calculations (see Puranen et al. 1996b). If the conductivities of mires and their bottom sediments were to behave regularly, the thicknesses of mires could be estimated from the AEM anomalies, which would facilitate peat inventories. The conductivities logged in different mire surroundings proved to vary so much, however, that reliable estimates of peat thickness cannot be based on AEM anomalies (Puranen et al. 1996b). Still, in inland areas of Finland the anomalies often indicate

Fig. 5. a) Map of peat thickness (contours in meters) of Ahteensuo fen according to Pajunen (1989). The fen margin (peat thickness > 0.3 m) is shown with a dotted line. b) AEM anomaly map (imaginary component in ppm) of Ahteensuo fen. Conductivity logging sites A-C are marked with dots.

Fig. 6. Vertical conductivity profiles and stratigraphy for logging sites A—C located at the AEM anomaly sites of Ahteensuo fen (cf. Fig. 5). SC=Sphagnum-Carex peat, CS=Carex-Sphagnum peat, GY=gyttja, SI=silt, SF=fine sand, SA=sand.

Fig. 7. Vertical conductivity profiles for Koivusensuo mire and Lipeälampi waste pond. 1=unpolluted mire (logging site B), 2=polluted mire (site C), 3=waste pond (site L), 4=earlier laboratory measurements (Mäkelä 1986). Logging sites shown in Figure 8.
The thickest peat layers. The anomalies may also indicate growth centers of mires, overgrown lakes or groundwater discharging into the mires. In coastal areas of Finland the AEM anomalies mainly reflect thickness and conductivity variations in clay deposits.

Logging of polluted mires

Many of Finland’s refuse dumps are located at or near mire margins, where there is a risk that harmful substances may leak into the environment. Sometimes leakage is indicated by elevated conductivities in the vicinity of the dump (e.g. Hannula & Lanne 1995). The new logging apparatus can trace well conducting pollutants that have been leaking or have discharged into mires. This was demonstrated at the Koivusensuo mire, where a waste pond, Lipeälampi, had formed due to the discharge of effluent into the mire for over 30 years (1935—1967) by the now closed Lievesuore pulp mill. When spreading into the mire, the highly conductive effluent raised the peat conductivity in the polluted area well above the background level (Fig. 7). The geology of the Lievestuore area has been described by Mäkelä (1986).

As shown by the logged conductivities, which increase gradually downwards (Fig. 7), the dense effluent has tended to sink to the bottom and towards the deepest parts of the pond and the mire. Conductivities are highest (heaviest pollution) near the pond bottom, although their level was clearly decreased after the pond was temporarily emptied in 1989—1991 (Fig. 7). Near the bottom of the mire the polluted area extends for more than 200 meters northwards from the pond, as shown by the logged conductivity map (Fig. 8). Natural background conductivities are attained beyond the oldest bordering ditch, which in the west sharply separates the polluted area from the background. The electric mapping conducted in the area is reported in detail by Puranen et al. (1996a).

Logging of bog temperatures

Temperature variations within mires affect their growth and decomposition processes (see Clymo 1984). Temperature measurements should thus be included in any study of these processes. Generally, however, only the surface temperatures of mires during the growth season have been measured. Temperatures deeper in the mires have been estimated by heat conduction modelling (Clymo 1984), but, to our knowledge, thermal cross-sections of mires measured during different seasons have not been published. Therefore, we logged the spatial and temporal variations in temperature within the Haukkasuo bog, southern Finland (Fig. 4). For a detailed description of the bog, see Mäkilä (1997).

Fig. 9. Temperature cross-section of Haukkasuo bog logged in May, 1996. Dots indicate measuring points.
The temperatures in Haukkasuo bog were logged along a profile traversing the bog center from north to south. The profile was 2 km long and the distance between logging points was 100 m. Measurements were made from the bog surface to the bottom using 25 cm spacings. With these specifications it took one day to measure the Haukkasuo profile, which has now been logged during all seasons (October 1995, March 1996, May 1996 and August 1996). Here we only present the temperature data logged in May at the beginning of the growth season (Fig. 9). The temperatures show a clearly zonal pattern, the thermal cross-sections near the center and margin of the bog being quite different. Further, the bog surface and bottom are somewhat warmer in the sunnier southern half of the bog.

The seasonal temperature fluctuations are shown for the margin (Fig. 10A) and center (Fig. 10B) of the Haukkasuo bog. In the thin marginal parts the fluctuations penetrate the bog, whereas in the central parts the temperature is almost constant at depths greater than 3 m. The temperature fluctuations measured near the bog center agree reasonably well with the theoretic results (Fig. 10C) computed using the heat conduction model proposed for bogs by Clymo (1984). Thermal conditions (mean temperatures, temperature fluctuations) in marginal and central parts of the bog are so different that they probably lead to different rates of anaerobic decay. This could affect, for example, estimates of methane production.

Conclusions

The new logging apparatus can be used for rapid mapping of the electric conductivity and temperature of mires, shallow lakes and rivers, and their soft bottom sediments. The conductivity data have been applied in the interpretation of AEM maps, and for tracing pollutants within mires. Electric conductivity also reflects the nutrient conditions (salinity, acidity) of mires, which, together with temperature, control the growth and decay processes within mires. The logging data can thus be helpful in studies of these processes.

Fig. 10. Vertical temperature profiles for Haukkasuo bog during four seasons. Logged profiles: A) site M at bog margin and B) site C at bog center (cf. Fig. 9). Logging dates: 1=autumn (18.10.1995), 2=winter (13.3.1996), 3=spring (13.5.1996) and 4=summer (5.8.1996). C) Computed profiles for the same dates based on heat conduction model of bogs (Clymo 1984). In modelling only the annual temperature fluctuations were considered and the model parameters were: diffusivity= 1.4x10^{-7} m^2/s, mean temperature=6°C, amplitude of sinusoidal fluctuations= 8°C, date of maximum temperature=31.7.

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A new apparatus for electric conductivity and temperature logging of soft sediments


PETROPHYSICS IN THE CRUSTAL MODEL PROGRAM OF FINLAND

by
Juha V. Korhonen, Heikki Säävuori and Liisa Kivekäs

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: juha.korhonen@gsf.fi

Key words (GeoRef Thesaurus, AGI): crust, magnetic anomalies, bedrock, petrophysics, physical properties, bulk density, magnetic susceptibility, magnetization, Koenigsberger ratio, Precambrian, Finland

Introduction

The Geological Survey of Finland (GSF) has collected a wealth of aerogeophysical data since 1951, when the first national aerogeophysical survey programme was launched. The second programme started in 1972 and still continues. The results have been used nationwide in mineral prospecting, bedrock mapping, crustal studies and other geological work (Korhonen 1991, 1993). The Geophysics Department of the GSF handled distribution of the maps and data to users, and promoted their use by giving lectures and publishing advisory texts and case studies (e.g. Marmo and Puranen 1990, Puranen et al. 1968). Resources for developing and systematizing the use of geophysical data on a regional scale were allocated in 1981, when the GSF established a research group for regional geophysical studies. One of the first tasks was to collect a basic petrophysical data set needed for potential field studies all over the country. High and low altitude data were combined for regional studies. The group further participated in data exchange projects between Finland and neighbouring countries to make available geophysical and petrophysical data on lithospheric geophysical anomalies and anomaly sources, both those crossing national borders and those located just beyond them. Specific regional petrophysical projects and case studies began. It was understood that the future tool in systematizing the interpretation and exchange of information would be a networked digital data base - a geophysical crustal model for Finland. It would provide an access to information on geometrical lithospheric structure, the physical properties of anomaly sources, the geological processes affecting both and an evolutionary framework to tie them all together. Like many items of basic survey data to day the information would be available on line. The model would serve as a source of information on existing results and possibly find use for testing alternative solutions. A set of reviewed versions would be available.

The basic issues in the geological interpretation of potential field anomalies refer to what can be concluded of the composition, structure and evolution of the bedrock by using physical properties and how this can be done. The specific questions that we shall ask are:

- What are the minerals, rock types and stratigraphic and tectonic units containing the sources of geophysical anomalies?
- What components of the anomalies are caused by near surface parts of geological units visible at the Earth’s surface and what is due to their downward extensions? Further, what are the contributions to and causes of deep, unexposed anomaly sources? What else may be said of their geometrical structure?
- What are the geological and physical processes that have influenced the evolution of present day physical properties and when did they occur?
- What is the total picture of the bedrock in space and time that we can deduce by using geophysical anomalies and the distribution and petrophysical properties of their sources together with other geo-
logical data?

The Crustal Model Program

The Crustal Model Program of the GSF aims to find answers to some of the above questions at the Finnish regional level and to build an updatable specialist system of the information in form of a complex, computer-based model of the upper lithosphere. Current work comprises the subprojects described in Kortman and Aumo (1996). The references to the publications of the subprojects and also joint projects are available from the Geological Survey of Finland (1996).

Studying the petrophysical properties is in a key position. The agenda is as follows:


Petrophysical properties and aeromagnetic interpretation map of Finnish dyke swarms, 1986—2000

Petrophysical properties of Finnish stratotypes, 1992—2000

Petrophysical properties of sulphide-bearing rocks and interpretation of the corresponding aerogeophysical anomalies, 1989—1998

Magnetic properties of the Finnish lithosphere, 1996—2000

The test cases are:

Regional interpretation of aerogeophysical and petrophysical data from the Peräpohja area 1984—1997 (Säävuori and Korhonen 1991a)


The international joint projects of the Crustal Model Program for standardization, exchange and interpretation of geophysical and petrophysical data in nearby areas comprise:

The Nordkalott project 1980—1986 (Korhonen 1989)

The magnetic map of the Gulf of Finland and surrounding area 1990—1997 (Korhonen et al. 1995a)

The magnetic map of Central Finland - Karelia 1990—1997 (Korhonen et al. 1995b)

The magnetic map of Northern Finland - Kola, 1997—2000

Geophysical maps of Fennoscandia, compilation scheduled to begin in latter half of 1997.

Regional Petrophysical Programme

The petrophysical studies of the GSF started at local scale in 1954 and at regional scale in 1963. The aim was to support the interpretation of aeromagnetic maps for mineral prospecting and bedrock mapping. From 1972 the data were collected into a computer based data archive. The data were gathered from measurements on 40,000 samples covering c. 20% of the country. Summaries of density and magnetic susceptibility were published (Puranen et al. 1978, Puranen 1989). The development of laboratory instrumentation and procedures has been described by Puranen (1991) and Kivekäs (1993).

The need for a more extensive regional petrophysical data set increased in the 1970s. To interpret the sources of regional magnetic anomalies on the Finnish aeromagnetic high altitude 1 km x 1 km grid (Korhonen 1980), and especially to separate smooth, near surface anomalies and their sources from deep-seated ones, coverage of surficial magnetizations was required (Korhonen 1981). Another reason was that in 1972 the GSF launched a new aerogeophysical low altitude mapping programme to aid prospecting for sulphide and power metal ore deposits. It included the measurement of absolute total field intensity and, from 1975, its horizontal gradient. The survey was later extended to cover the whole country and thus formed the second national aerogeophysical programme (Peltoniemi 1982, Korhonen 1984, Ketola 1986). The maps became a widely used multipurpose geological tool. The reliable and rapid geological interpretation of the maps required rapid access to the true petrophysical properties of any area. For most areas, however, no petrophysical data existed and the statistics available were not very useful, because of the great variation in magnetic properties within rock types. The data could further be used in planning more detailed studies, involving supplementary sampling and the samples for other geological studies, including geochemical ones. The combined low- and high-altitude magnetic maps could be used together with the petrophysical data set to compile a magnetic crustal model (Korhonen 1988). The overall benefits of aerogeophysical surveys were thus expected to increase substantially with only a modest new investment.

In 1980 the Geophysics Department of the GSF set up a regional petrophysical mapping and research programme. The existing data were augmented with new measurements of bedrock sample sets available and the network was completed with new samples where necessary. The aim was to cover the whole country with a coarse petrophysical net in c. 10 years. The parameters measured were bulk density, volume susceptibility and intensity of remanent magnetization. The coordinates of sampling sites...
and the lithological names were merged with the measurement data. The sampling was completed in 1992 and all data were stored in a new petrophysical data base in 1995 (Säävuori and Hänninen 1995a). Interim reports of the programme were published in this series by Korhonen et al. in 1989 and 1993.

The data base is continuously updated, and contains measurements of 131 085 samples at the end of 1996. The sampling grid is inhomogeneous and the data density varies due to variation in the distribution of existing samples and in the density of the road network in different parts of the country. The up-to-date official version of the data set is stored as a Paradox data base (Säävuori and Hänninen 1995b) in a Pentium PC in net of the petrophysical laboratory at Otaniemi. Subsets of the data have been used by joint scientific and commercial projects (e.g. Henkel 1991, Korhonen 1992, Elo and Korja 1993, Airo 1995, Laine 1997).

The data may be summarised for numerous purposes. To show the areal distribution of basic and derived parameters nine of them have been averaged, interpolated in 2 km x 2 km cells and represented as maps at a scale of 1:4 mill. (Korhonen and Säävuori 1995). Average bulk density, abundance of ferrimagnetic samples and intensity of magnetization and Q-value of ferrimagnetic samples are shown in Figures 1—4.

**Petrophysical characteristics**

In an attempt to find out what rock types cause magnetic anomalies and how their highly magnetic population differs from low magnetic population, Figures 5—9 are given for the whole country. The data are divided into major lithological groups whose suggested origin is inherent in the names of rock types. The total magnetization of each sample was first calculated assuming that remanent magnetization was in the same direction as that of induced magnetization. The susceptibility was divided into paramagnetic and ferrimagnetic components using a correlation between the chemical composition of paramagnetic ions and the bulk density (Lahtinen and Korhonen 1996). The data were further divided into two populations characterized by paramagnetic and ferrimagnetic susceptibility ranges. For the latter the ferrimagnetic Koenigsberger ratio \( Q_f \) was calculated and the samples divided into three subpopulations of different \( Q_f \)-range. Low \( Q_f \)-values \( Q_f < 2 \) are caused mainly by coarse magnetite, high values \( Q_f > 15 \) by pyrrhotite or hematite and intermediate values by a mixed population of fine grainend or altered magnetite and hematite (Lahtinen and Korhonen op. cit., Pennanen 1991).

The ratio of magnetic anomaly causing samples (defined as \( k > 2000 \text{ 10}^6 \text{SI} \)) to all samples \( (\text{Fep, %}) \) varies regionally from almost 0% (Svecofennian migmatite belts) to near 100% (granite batholith of central Finnish Lapland) (Fig. 2). The Fep varies from 30% for less dense (acidic) average compositions of bedrock to 70% for more dense (basic to ultrabasic) compositions (Fig. 5). The magnetic susceptibility, total magnetization and Q-value are higher for basic than for acidic compositions on average, exhibiting linear semilogarithmic trends (Fig. 6). This trend for magnetic susceptibility, reported by Krutikhovskaja et al. (1979), is attributed to the decreasing concentration of total iron with decreasing density; the smaller the iron content is, the smaller is the concentration of ferrimagnetic minerals that may form, on average, in a major and varying population. The most common density class is at \( D=2670 \text{ kg/m}^3 \). It comprises of 174 rock types, of which the most common are granodiorites (20%), tonalites (11%), grani tes (10%) and mica gneisses (10%). The class corresponds to Fep=34%, and an average total magnetization of 0.32 A/m with a Q-value of 1.8. The average magnetization of the weak susceptibility part (66%) is 0.07 A/m. These values give an idea of magnetic background properties for Finnish local geophysical studies. The properties vary greatly spatially, however, and depending on the purpose, more numbers may be calculated from the data base for each real case.

The dykes and volcanites are most magnetic major rock types. The cumulative frequencies of total magnetizations exceeding 0.25 A/m are 37% and 28% respectively (Fig. 7). The other rock types exhibit frequencies of c. 15%. The more magnetic character of dyke and volcanoite groups is due to their mainly basic composition. The metamorphic rocks are slightly more magnetic than plutonic and sedimentary rocks, thus supporting the idea that metamorphism generally increases the magnetization of rocks.

The magnetization population of the paramagnetic susceptibility domain is unimodal with a peak near the threshold value of remanence measurement (c. 30—50 mA/m, Puranen 1989 op.cit.). For less than one per cent the total magnetization exceeds 0.25 A/m and values higher than 1 A/m are rare (Fig. 8).

The magnetization population of the ferrimagnetic susceptibility domain is bimodal due to a
Fig. 1. Bulk Density of bedrock of Finland. The map is based on 2 km x 2 km unweighted averages calculated from the petrophysical database of the GSF.
Fig. 2. The frequency of rock samples associated with susceptibilities greater than $2000 \times 10^{-6}$ SI (Fep, %). The map is based on similar averages than in Figure 1.
Petrophysical mapping of Finnish Precambrian strongly magnetic rocks

Magnetization

The map is based on average magnetizations calculated from 122.497 remanent magnetism and 80,079 NRM values by assuming external magnetizing field of 41 A/m and scaling magnetisms greater than 0.005 A/m. Project 3223 and 3224 / 1995.

Fig. 3. Total magnetization of samples characterized by susceptibilities greater than 2000 $10^{-6}$ SI. The map is based on similar averages than in Figure 1.
Fig. 4. Koenigsberger ratio (%) of samples characterized by susceptibilities greater than $2000 \times 10^{-6}$ SI. The map is based on similar averages than in Figure 1.
Fig. 6. Intensities of total and induced magnetizations and Q-value calculated for bulk densities from similar averages than in Figure 1.

major contribution (> 70% for \( J_{\text{tot}} > 0.25 \) A/m) from the low \( Q_r \)-subpopulation, which is related to the distribution of magnetite (see Puranen 1989 op. cit.). The frequency of higher \( Q_r \)-populations exceeds that of the low \( Q_r \)-population above 20 A/m. Less than 1% of the samples exhibit these high magnetizations. The rocks belonging to the higher magnetization mode, especially those of low \( Q_r \)-subpopulation, are responsible for the main part of magnetic anomalies. The lower \( Q_r \)-mode at 80 mA/m consists of the threshold value of remanence and induced magnetization of the low susceptibility part of the ferrimagnetic domain. The magnetic anomalies are higher than caused by rocks in the paramagnetic k-domain, but despite this are weak and normally in background intensity range, and could be traced in favorable circumstances, only by applying enhancement techniques to the magnetic data.

The frequencies of the higher \( Q_r \)-populations decrease continuously towards the higher magnetizations, exhibiting only slight deflections corresponding to the magnetite mode of the low \( Q_r \)-subpopulation. At magnetizations higher than 0.25
A/m, the dyke rocks exhibit the highest abundance of low Qr-values in all major rock types, and the metamorphic rocks the lowest (Fig. 9). The high Qr-samples are most common in dyke rocks and least common in plutonic rocks. The highest Qr-subpopulation is most common in volcanic and metamorphic rocks (6%), reflecting the abundance of pyrrhotite in these rock types. The intermediate Qr-values partly reflect the alteration of magnetite. Twenty five per cent of dyke rocks belong to this subpopulation; the corresponding abundance is 14% for volcanic and metamorphic rocks and 12% for plutonic rocks. Further studies of magnetic mineralogy are needed to better understand these distributions and their causes. The analysis of the basic petrophysical properties is being extended into lithological subdivisions and stratigraphical units and will be presented in the final report of the petrophysical programme.

Remanent magnetization is a related topic that needs more attention. In most part of the country it is an important component of the average total magnetization as indicated by Q-values of strongly magnetic rocks (Fig 4). Low Qr-values are understood to be normally associated with NRM. Directions of remanence associated with higher Qr-values are not normally known, causing uncertainty in both local and regional estimates of the intensity and direction of total magnetization. Thus the validity of the common assumption of its direction (parallel to the main field) must be tested for various geological formations and parts of the country. So far a recommendation has been given to check by measurement the contribution of remanent magnetization to local magnetic anomalies in supracrustal and metamorphic areas. A part of the higher Qr-values is probably inherited from the main processes that formed the rocks, including regional metamorphism. Another part may be caused by later alteration, drifting of the remanence and lightning strikes. It is necessary to identify these causes and their relative abundances in Finnish rocks in order to make successful geological interpretations of magnetic anomalies.

**Near surface versus deeper magnetic sources**

The trend of average magnetization of the Precambrian upper surface increases from 0.1 A/m to 30 A/m when bulk density increases from 2600 kg/m³ to 3200 kg/m³. The Koenigsberger ratio also increases from 1 to 10 for the same density interval.
(Fig. 6). It can be expected that corresponding magnetic anomalies will also increase with increasing density of bedrock. To check this the total magnetization and bulk density of cells of 25 km x 25 km have been calculated for the whole country by density classes of 50 kg/m³ and correlated with magnetic total intensity anomalies (Korhonen 1995, 1996): The highest regional magnetic anomalies (up to 800 nT) have been measured in low density areas, where ferrimagnetic magnetizations up to

![Graphs showing frequency of total magnetization for different rock types](image)

Fig. 9. Frequency (%) of total magnetization of four major genetic rock groups in ferrimagnetic domain and its three subpopulations distinguished by Qf. a) dyke rocks (upper left), b) volcanic rocks (upper right), c) plutonic rocks (lower left), d) metamorphic rocks (lower right).
only a fraction. This suggests that the average thicknesses of exposed sources are as are either excessive, but the average anomalies are threefold of this, but the average anomalies are partly due to additional deeper sources of the anomalies, lying. The most likely explanation is that both causes reflect their local variations (and structure lies). Batholiths in upper crust are underlain by magnetic masses shown in Figures 10 and 11.

There is a significant scatter in average properties, reflecting their local variations (and structure for magnetic anomalies), and is partly due to nonweighted averaging. Therefore only broad trends are commented upon here. As in the Ukrainian Shield (Krutikhovskaya et al. op. cit.), both areal induced and remanent magnetizations are important magnetic field sources for most of the magnetization range (Fig. 10a). The logarithm of average total magnetization correlates positively and linearly with magnetic anomalies, except for the high magnetization part, where the Q-values are also higher (Fig. 10b). Areal magnetizations tend to be higher for higher densities (Fig. 11a). The average magnetic anomalies exhibit negative correlation with average density for the areas of low density.

Fig. 10. Remanent versus induced magnetization and Q-values (top). Total intensity anomaly versus total magnetization calculated from induced and remanent magnetizations, supposing that both components are in the same direction (down). The average values have been calculated in 25 km x 25 km cells from 2 km x 2 km averages for whole country and the trend lines by averaging in total intensity classes.

Fig. 11. Comparison of bulk densities with a) total magnetizations (top) and b) total intensity anomalies (DGRF-65 subtracted from absolute total field) (middle) plus c) magnetic anomalies with total magnetization (down). The cell values have been calculated as in Figure 10 and the trend values by averaging in bulk density classes.
positive correlation
average magnetic anomalies tend to increase with decreasing magnetization. Upward deviations from within these two the medium density range exhibits a low average magnetic field trend (Fig. 11b.). The correlation between magnetization and the magnetic field, calculated by density classes, exhibits the same segments (Fig. 11c). Projected in this way average magnetic anomalies tend to increase with decreasing magnetization. Upward deviations from this tendency at densities around 2600 kg/m³ and 2820 kg/m³ may record influence of crustal reactivation due to heat from magmatic mantle sources. Within the intermediate density range the average of magnetic anomalies is near zero and does not correlate with magnetization. In this range the contribution of the uppermost magnetic layer to average lithospheric magnetic anomalies is negligible, or alternatively the surficial and deep anomaly sources compensate for the effects of each other, or the average is zero because the reference field contains a crustal component.

From the dense to light end these three correlation segments are tentatively interpreted as representing palaeorifts (average basic composition), areas consisting mainly of juvenile continental crust (intermediate composition) and late stage stable accreted terrains (acid composition), partly in continental arcs, and rapakivi batholiths. Tying the average properties and potential fields together spatially with a crustal model makes it possible to determine more of the true nature of the correlations.

Starting palinspastically from the youngest major events, the spatial study of the Meso-Palaeoproterozoic low-density blocks was initiated with an analysis of radial variation of properties. The low density population occurs as four major, roughly circular symmetric clusters, two of which are known to represent the Wiborg and Åland rapakivi batholiths (1650 - 1620 Ma and 1580 - 1570 Ma, Laitakari et al. 1996) and the two others the granite complexes of Central Finland (Fennia structure, > 1880 Ma) and Central Finnish Lapland (Marras structure, > 1830 Ma). The low density parts of the structures are from 80 to 160 km in diameter, depending on the criterium used (Fig. 1). Numeric values of petrophysical properties vary from one structure to another. Overall average petrophysical characteristics, however, effectivey describe the nature of common trends and are shown in Figure 12. In their central parts the structures exhibit minima in density, magnetization and Q-value and maxima in Fep. These are surrounded by rings of elevated magnetization, partly due to higher remanence and partly to higher induced magnetization, and slightly elevated bulk density. The properties of the central parts are explained by the presence of granites with coarse magnetite as the main carrier of magnetization, and by melting of older crust as an agent of homogenizing. The higher magnetizations may be caused on the one hand by higher frequencies of basic and ultrabasic rocks within intermediate surrounding rocks and on the
other hand by metamorphic effects on magnetic minerals and their magnetization.

The Wiborg rapakivi batholith is underlain by an excess basic mass (Elo and Korja 1993 op.cit.), originally a partial mantle melt whose heat further melted the upper crust, thus producing the rapakivi magma (Rämö 1991). The Åland rapakivi batholith is explained in the same way (Eklund 1993). The Marras structure, too, is underlain by an excess mass (Korhonen 1990). The Fennia structure does not exhibit major circular, symmetric gravity anomalies. It is, however, wide enough to have been compensated isostatically during the late stages of the Svecofennian orogeny. If this structure is not caused by endogenic processes, it may represent a major extraterrestrial impact site (Korhonen 1995 op.cit.).

**Petrophysics of Middle and Lower Crust**

Major deep, crustal-scale magnetic sources probably exist. Their contribution may be estimated by comparing satellite magnetic anomaly interpretations with measured upper lithospheric magnetizations. Nolte and Hahn (1991) suggest by inversion depth integrated magnetization (DIM) values for the upper lithosphere in southwestern Finland ranging from 40 kA to 60 kA and in northwestern Finland from 50 kA to 90 kA. The thickness of the high-velocity layer (Korja et al. 1993) does not correlate with satellite magnetic anomalies. Thus this layer is considered to be nonmagnetic by Ravat et al. 1992. The temperature of 585 °C (Curie temperature of magnetite) is reached at 50 km in southwestern Finland and considerably deeper in the northwestern part of the country (Kukkonen 1996). The thickness of the crust between the high velocity layer and the Earth’s surface varies from 31 to 41 km in both parts (Korja et al. 1993 op.cit.), being on average 34 km. The average magnetizations of surficial rocks calculated from data of the regional petrophysical programme are 0.78 A/m for southwestern and 0.95 A/m for northwestern part of Finland (Korhonen and Säävuori 1995). Supposing for simplicity that the surficial causes of magnetization continue down to the high velocity layer and that the rising temperature at depth does not materially change its strength, we may calculate that, on average, 23 kA and 38 kA of integrated magnetization remains unexplained for the two parts of the country. The best known and most extensive high grade rocks in Finland, e.g. granulite facies rocks at Inari and Sulkava, are low magnetic, and thus cannot represent the necessary deep sources. Some deep crustal sections are, however, highly magnetic. The charnocksites at Varpaisjärvi exhibit a total magnetization of 6.5 A/m with a Q-value of 1.8 and an average density of 2774 kg/m³. With a thickness of 4 km, a middle crustal layer of this intensity of magnetization for the southwestern part and 7 km for the northwestern part is sufficient to explain the residual integrated magnetizations.

Recent discoveries of kimberlites in Finland have made it possible to analyse lower crustal xenoliths and thus obtain information on the real properties of deep potential field sources instead of ambiguous interpretation numbers. Malmikaivos Co. has provided the GSF a set of xenoliths (one pipe), seven of which are considered to be of lower crust origin. Hölttä (1996) proposes depths of 25 km to 30 km for the metamorphism of these mafic granulites and depths of 10 to 15 km at the time of intrusion of the host kimberlite. Thus the samples do not represent the true lower crust of the shield in Devonian times. The average grain density of the four samples analysed petrophysically is 3175 kg/m³, corresponding well to the lower crust, and total magnetization is 5.6 A/m (2.2—11.2 A/m) with Q=1.4. A reasonable 7.5 km average thickness of these rocks, as either a solid layer or having a more fragmented distribution, may explain the interpreted residual magnetization of the northwestern part. Considering that 30 to 50 % of middle crust is nonmagnetic (cf. high density range of Fig. 5) the effective thickness of the source area may be 15 km and its average magnetization 3 A/m. The excess integrated magnetization may therefore be located above the high velocity zone in the middle crust. The other alternative is that both the lower crust and the mantle are major source areas and that the Curie isotherm limits magnetization at depth.

Malmikaivos Co. reports having already found more than 20 kimberlite pipes in Finland (Laapas 1994). Numerous kimberlite pipes and dykes are probably still to be found in the Archaean-Karelian domain of northeastern Finland. Supplementary analyses of xenoliths from different locations may help us to see the spatial variation in magnetic properties of unexposed sources and their depth distribution.

To determine magnetization behaviour at depth, thermal measurements of magnetic properties and efforts to identify magnetization carriers are under way. The magnetic masses of the deep crustal part of the model will be localized by combining the magnetic information on xenoliths and exposed
deep sections with interpretation of potential fields, a thermal model of the lithosphere and the forthcoming reflection profile sections.

**Correlation with rock geochemistry**

One of the original aims of the petrophysical programme was to explain the mineralogy, magnetic properties and origin of the rocks by correlating petrophysical properties with rock geochemistry. Before it got that far, however, a parallel data set became available. The Department of Geochemistry established a rock geochemical mapping of the country in 1991, and it was decided to measure basic petrophysical properties on its c. 6500 samples. As data from geochemical analyses (c. 60 elements including REE) of these samples were quite comprehensive the geochemical analyses of samples of the petrophysical programme were postponed until the results of the Rock Geochemistry Research Project were available.

The petrophysical measurements of rock geochemical drill core samples were made at the petrophysical laboratory of the GSF in Espoo. The data will be analysed jointly by the Rock Geochemistry Research Project and the Crustal Model Program of the GSF. So far all samples have been measured for the density, susceptibility, intensity and direction (most samples) of remanence, porosity and seismic velocity. A summary and interpretation of analytical data for 403 samples from a test area (120 km x 160 km) in southern Finland have been published to date (Lahtinen and Korhonen 1996 op. cit.).

Chemical composition versus petrophysical properties shows that the bulk density of samples is well explained by FeO+Mn+MgO for igneous rocks, but less well for metasediments owing to their more complex mineralogy.

Paramagnetic susceptibility was calculated from chemical analyses by Curie’s law. Compared with measured susceptibilities, it was found that 78% of the samples exhibited higher induced magnetization due to paramagnetism than to other causes and were defined as forming the paramagnetic population. The remainder were defined as ferrimagnetic population. Of all samples 16% were capable of causing magnetic anomalies higher than 50 nT and 4% higher than 500 nT for sheet like bodies, a typical model suitable for magnetic local sources of the area.

Q-ratios were calculated for ferrimagnetic susceptibilities and were used together with sulphur contents to classify the ferrimagnetic samples as pyrrhotite and magnetite-dominant populations. The Q values ranged from 0.2 to 2.1 for magnetite dominant, from 2.1 to 7.7 for mixed and from 15.1 to 16.0 for pyrrhotite dominant populations.

Pure paramagnetic samples were rare or totally absent as indicated by thermomagnetic analyses of selected samples, first considered paramagnetic on chemical basis. A low ferrimagnetic mass susceptibility component of order 20 pm/kg was found and may explain the occurrence of natural remanent magnetization.

Subduction-related, pyroclastic volcanics and highly evolved or contaminated mafic plutonic rocks contain magnetite. Late- to post-tectonic granites often contain small amounts of magnetite that has been partly martitized. The syntectonic granitoids are mainly paramagnetic. This is in agreement with the observations of magnetic properties in the course of Svekokarelian evolution made on mafic dykes in Finland (Korhonen 1987).

Magnetite is the main carrier of magnetization in three geological subunits of the area; in one it is pyrrhotite (due to the overall reducing environment) and in one subarea both are carriers. Deep magnetic sources, correlating with positive regional magnetic anomalies, were detected below three of the magnetite-bearing formations of mainly igneous origin; in one of them a probable excess deep mass was indicated by comparing gravity anomalies and mean bulk density. The major negative regional anomaly area coincides with the pyrrhotite domain consisting mainly of metasedimentary rocks and associated with low average total magnetization due to overall reducing environment prohibiting magnetite to form.

**Other adjoining studies**

Dyke rocks are a source of magnetic properties of basic plutonic rocks at depth and being normally well dated they provide information on the change of the petrophysical properties of basic magmatism in time. The density distribution reveals the depth of origin and degree of differentiation. Magnetic anomaly patterns reflect the crustal tectonic regime. The alteration of primary magnetic minerals tells us about the metamorphic history of the rocks (Korhonen 1987).

Because petrophysical properties are stratiform in supracrustal rocks they and corresponding anomalies may be used in localizing strata, thus assisting in geochronological correlation, and characteriz-

Conclusions

The petrophysical programme has provided information on sources of magnetic and gravity anomalies in whole country. The data and summaries of properties may be retrieved from a relational database. The scientific report of the project is being compiled. More information is needed on direction of remanent magnetization, thermal behaviour of magnetization components and magnetic mineralogy and its primary and metamorphic causes in different geological formations and in time.

The data, together with geothermal, geoelectric and reflection information provides an opportunity to make a 3D-potential field interpretation for Finnish upper lithosphere, and tied with known and indicated geological processes and time, provide an evolutionary model of the central part of the Fennoscandian Shield. The model with its different kinds of information and their causal and spatial links is planned to be materialized in a form of a reviewed and updatable, computer based specialist system.

Acknowledgements

Altogether 62 persons, most of them undergraduate students, employed by the Geophysics Department of the GSF, have been working in the petrophysical programme in 1980—1996. Numerous professional persons in the GSF, universities and companies have payed their time for discussions and rock type and coordinate determinations. The samples have been measured in three petrophysical, house made laboratories of the GSF by many operators guided by laboratory heads. We thank them all. Special thanks are to Professor Maunu Puranen, the former Head of Geophysics Department, and his team, for their successful pioneering petrophysical work in Finland, on which the present study is founded. Dr Peter Ward is thanked for critically reading the manuscript and Mrs Gillian Häkli for revising the language.

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DEFINING JOINTING AND FRACTURING FROM PHOTOGRAPHS OF DRILL CORES

by

Koistinen Esko and Kärkkäinen Niilo

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: esko.koistinen@gsf.fi

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Introduction

The main issues in the exploration of a mineral deposit are the grade and tonnage of the deposit and the mode of occurrence of the ore minerals (Hyvärinen & Eskola 1986). Engineering-geological studies for mine planning are done in conjunction with technical and economic feasibility investigations (Peltola & Rauhamäki 1986) after the discovery. We here discuss the possibility of making some engineering-geological observations for mine planning already during the exploration project.

The national Finnish engineering-geological rock classification system, the RG classification (Korhonen et al. 1974, Gardemeister et al. 1976) was commissioned by the Finnish Ministry of Finance and has now been officially accepted for public use (Niini & Parkkinen 1995) in engineering-geological applications. The RG classification defines bedrock quality by (1) rock type and (2) jointing of the bedrock (terms in English according to Niini, pers. comm.; also Vähäsaarja et al. 1974). Rock type is determined by (a) degree of weathering, (b) component arrangement, (c) dominant grain size of minerals and (d) main minerals. Jointing requires the determination of (a) type of jointing, (b) frequency of joints, and (c) quality of joint. Based on purely visual observations, the RG classification could therefore also be used for routine exploration-stage core logging.

In a mineral deposit development project the RG classification can partly be based on observations made at the exploration stage (logging reports, profiles, thin section studies etc.). The rock types described in mineral exploration reports can be adjusted by relogging the cores at the feasibility stage. Textural features can be analysed on thin sections with image processing methods. Much information is, however, lost when cores are split for chemical analyses; that on jointing and fracturing is totally destroyed. The complete rock quality classification may need specific detailed mapping, detail-line mapping or fracture-set mapping at outcrops or in quarries (Peters 1978), completed with fracture studies on drill cores.

Some rock quality properties can be investigated on photographs of drill cores. The usefulness of photographs in determining the primary joint frequency (later jointing), total core fracturing frequency (later fracturing) and rock quality designation (later RQD number) was tested in this study.

Research material

The study was based on material gathered during the investigations of the Kälviä ilmenite deposit (Kärkkäinen et al. 1997). Joints and fractures were counted in a drilling profile, k=21010, where two holes (R351, R352) intersect a 75-m-thick mineralized layer. The rock type in the cross-section is homogeneous, oxide-rich medium-grained (1—3 mm) gabbro. It is composed of almost massive ilmenite-magnetite layers, dense or low-grade dis-
semination of oxides, and thin layers of pyroxenite and barren gabbro.

Thin fractured or mylonitic zones were reported during logging. Sheared and granulated zones are shown by reddish or white-spotted changes in the colour of plagioclase. Thin quartz veins and schistose bands indicate strong deformation in these zones. In this section the fractured zone intersects the massive ore; elsewhere mylonitic rocks tend to occur beside the ore layer, probably due to the difference in ductility between the rock types.

A thin (0—20 m), slightly weathered zone underlies the unconsolidated till and peat cover (8—13 m). Fracturing due to weathering is a common surficial phenomenon. The cracks are often filled with carbonate. Weathering was checked by geophysical logging of the drill holes (Kärkkäinen et al. 1997). Magnetite having altered into martite, the magnetic susceptibility of the rock decreases to almost zero in the weathered zone. Seismic refraction sounding was used to locate the main faults and fracture zones, such as low velocity zones, to supplement the other information on rock types and soil cover thickness (Lehtimäki 1996).

The drilling profiles were 124.8 m (R351) and 160.0 m (R352) long, and the holes were drilled with a T46 diamond drill bit (32 mm). The samples were photographed in a series of two boxes, with about 8 m of core in each box. The photos are colour prints (10x15cm), which are easy to handle, and show the faint changes in colour due to strong deformation, mylonitization or faulting.

The measuring of jointing and fracturing

Jointing was measured as the frequency of joints (counts/metre) (Korhonen et al. 1994; Gardemeister et al. 1976). The joint frequency is the sum of all primary joints within one metre. Cracks caused by breaking during drilling were excluded. The joint frequency of the RG classification is as follows:

<table>
<thead>
<tr>
<th>Joint frequency (count/metre)</th>
<th>Designation</th>
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<tbody>
<tr>
<td>&lt; 1</td>
<td>Sparsely jointed</td>
</tr>
<tr>
<td>1—3</td>
<td>Slightly jointed</td>
</tr>
<tr>
<td>3—10</td>
<td>Abundantly jointed</td>
</tr>
<tr>
<td>&gt; 10</td>
<td>Densely jointed</td>
</tr>
</tbody>
</table>

Fracturing was measured as the fracture frequency, which is the number of all cracks within one metre (counts/metre). Here cracks include both open natural joints and any fractures induced by drilling. Fracturing was earlier defined in the same way, and its significance for rock excavation was studied by Niini (1968). To estimate fracturing in the sense of engineering geology the following division is used (Niini & Parkkinen 1995):

<table>
<thead>
<tr>
<th>Fracture frequency (count/metre)</th>
<th>Meaning in engineering geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1</td>
<td>rock is intact</td>
</tr>
<tr>
<td>1—10</td>
<td>rock is fairly intact</td>
</tr>
<tr>
<td>10—30</td>
<td>(strengthening may be necessary)</td>
</tr>
<tr>
<td>&gt; 30</td>
<td>Rock is strongly crushed</td>
</tr>
</tbody>
</table>

The mechanical quality of the rock was also measured with the commonly used rock quality designation (RQD) number (Hartman 1992, Matikainen et al. 1982). The RQD number was calculated for each metre by summing up the percentages of core recovered, counting only pieces of unbroken core at least 10 cm long. Where there are no fractures the RQD number is 100%. If there are no pieces of core over 10 cm long within one metre, the RQD number is 0%. The value of the RQD number is decoded as very poor (0—25%), poor (25—50%), fair (50—75%), good (75—90%) or excellent (90—100%) by Peters (1978). A more generalized classification is the following (Niini & Parkkinen 1995):

<table>
<thead>
<tr>
<th>RQD number %</th>
<th>Meaning in engineering geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 80</td>
<td>Bedrock stability good</td>
</tr>
<tr>
<td>50—80</td>
<td>Stability uncertain, excavation difficulties possible</td>
</tr>
<tr>
<td>&lt; 50</td>
<td>Stability low and excavation costs considerable</td>
</tr>
</tbody>
</table>

Results and discussion

The joint frequencies, fracture frequencies and RQD numbers measured in cross-section k=21010 (R351,R352) of the Kälviä deposit are presented in Figure 1. Joint frequency and fracture frequency
are shown in one bar chart (Fig. 1a) and the RQD number in another (Fig. 1b). Some photographs of drill cores are presented in Figure 2. The statistics of the parameters measured are given in Table 1 and the correlations of the parameters in Table 2.

Table 1. Statistics of joint frequency, fracture frequency and RQD number, 224 samples:

<table>
<thead>
<tr>
<th></th>
<th>Joint frequency</th>
<th>Fracture frequency</th>
<th>RQD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum value</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum value</td>
<td>10</td>
<td>42</td>
<td>100</td>
</tr>
<tr>
<td>Mean</td>
<td>1.0</td>
<td>10.3</td>
<td>62.5</td>
</tr>
<tr>
<td>Variance</td>
<td>2.7</td>
<td>55.1</td>
<td>888.8</td>
</tr>
</tbody>
</table>

Table 2. Correlation coefficients of joint frequency, fracture frequency, and RQD, 224 samples:

<table>
<thead>
<tr>
<th></th>
<th>Joint frequency</th>
<th>Fracture frequency</th>
<th>RQD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint frequency</td>
<td>-</td>
<td>0.69</td>
<td>-0.55</td>
</tr>
<tr>
<td>Fracture frequency</td>
<td>0.69</td>
<td>-</td>
<td>-0.82</td>
</tr>
<tr>
<td>RQD %</td>
<td>-0.55</td>
<td>-0.82</td>
<td>-</td>
</tr>
</tbody>
</table>

In terms of RG classification, the bedrock in the

Fig. 1a. Joint frequency and fracture frequency defined for each metre from photographs of drill cores R351 and R352, Kälviä deposit.
cross-section studied is slightly jointed, on average (mean joint frequency = 1.0, Table 1). According to its fracture frequency, the bedrock is broken and partly weathered, and there would be a high risk of collapse (mean fracture frequency = 10.3, Table 1). The mean of RQD number is 62.5 (Table 1), implying that the stability of bedrock is rather uncertain in the area studied and that there might be difficulties with excavation.

In the cross-section under study there are zones with a dominant fracture frequency of clearly over 10, and even over 30. In other words, the bedrock in these zones is broken, and partly strongly crushed. In same zones the RQD number is less than 50%. Surficial weathering is shown by all methods (Figure 1). The most heavily crushed zones are in the lowermost and thickest ore layer. Above and below this layer the rock is more intact. Excavation in this section might therefore be difficult and much strengthening would be needed if the deposit were to be mined. On the other hand, this could mean also lower costs in quarring and crushing the core.

With some experience of core logging, colour photographs can be used for measuring the jointing and fracturing and for making other observations related to structural patterns. Problems arise in identifying secondary fractures caused by drilling. These are usually thin or correlate well with natural fracture zones. In the homogenous igneous rock of the Kälviä deposit, secondary breaking completes the natural jointing of the fault zones, and the core breaks easily into very small pieces. Numerous gently intersecting cleavage planes and colour changes are clearly visible in the natural jointing.

Fig. 1b. RQD number defined for each metre from photographs of drill cores R351 and R352, Kälviä deposit.
zones, even in those of less importance or in those welded together by metamorphic recrystallization.

A high percentage of the structural data used in mine planning comes from diamond drill cores, so the fracture spacing and other observations made in the subsurface environment must be logged as carefully as possible (Peters 1978). Once a core is split, the structural data are lost if good-quality photographs are not available. Rock quality can also be studied indirectly with seismic investigations (Peters 1978), which in Kälviä indicate well the main fracture zones (Lehtimäki 1996).

When cores are logged in exploration, the main attention is paid to ore minerals and their occurrence, rock types and other features that enable the cross-section and 3-dimensional model of the deposit to be outlined. Because of the cost, drill-core logging for engineering-geological applications is not likely to become routine practice in exploration drilling. If needed at an early stage of mine development, it is recommended that colour photographs should be used for determining technical rock quality. Revision logging can be done when new holes are drilled for further delineation of the ore body. Some of the unsplit cores should, however, be saved from all drill holes likely to be of use in mine planning (Peters 1978).

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References


DIGITIZED GEOLOGICAL MAPS OF FINLAND

by

Boris Saltikoff, Markku Tiainen, Mikko Tontti, Matti Lehtonen and Esko Koistinen

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: boris.saltikoff@gsf.fi

Key words (GeoRef Thesaurus, AGI): geologic maps, lithologic maps, tectonic maps, digitization, Precambrian, Finland

Introduction

The increasing importance of computer processing in the geosciences has created a distinct demand for geological maps in digital form that are suitable for combination with various other data sets for either graphic presentation or statistical comparisons. A set of such digitized general geological maps of Finland has been compiled by the mineral resources department of the Geological Survey of Finland.

All the digitized maps concerned are based on the geological map of Finland by Simonen (1980a). The map is at 1 : 1,000,000 scale, and the smallest units drawn are ca 2 km in size. This map is still the most recent uniform overview of the distribution of various rock units and types in the country. In accordance with the tradition in Finland, it is essentially a lithological map with less emphasis on formational divisions. Therefore, any generalization requires a special standpoint regarding the desired units in the legend of the product map. The four map digitations described here each serve different geological goals.

Map 1: Scanned geological map

The map image was prepared from the Simonen map by a colour scanner with a resolution of 600 dpi. The map is a raster image intended for use as a background map with GIS programs, at 1 : 500,000 to 1 : 2,000,000 scale. It faithfully duplicates all the features presented on the original map and in its legend. Therefore, no vector image was constructed from the raster one, because on the original map there are numerous rock units which are distinguished only by overprints only without colour changes and precise boundary lines between them. The dimensions of the image are 14,300 x 23,500 pixels and the pixel size corresponds to ca 50 m in the terrain. The .tif image is registered for both ArcInfo and MapInfo users.

The map image is available as a file in TIFF 4.2 format. It occupies 14 MB space on disc in a PackBits compression form, which means about 300 MB in uncompressed (processable) format.

Map 2: Map of geotectonic units

The map of the principal geotectonic units (Fig. 1) was designed in conjunction with the monograph on the nickel metallogeny of Finland (Puustinen et al. 1995), and has been generalized to 1 : 5,000,000 scale (minimum unit size ca 5—10 km). Special emphasis is laid on distinguishing the major geoblocks, using an approach analogous e.g. to that of Gaál and Gorbachev (1987). The territory of Finland is divided into two first order domains: (I) the Kola-Karelian Domain mainly of Archaean age and (II) the Svecofennian Domain of Early Proterozoic age. In the Kola-Karelian Domain there are presented (I) areas made up of Archaean...
MAIN GEOLOGICAL UNITS

Phanerozoic and Late Proterozoic

- Paleozoic Caledonian allochthon
- Riphean Jotnian sedimentary sequences

Post-Svecofennian

- Rapakivi granite intrusions

Svecofennian Domain

- Proterozoic, Late Svecofennian granite and migmatite complexes
- Proterozoic, Main Svecofennian granitoid complexes
- Proterozoic Svecofennian schist belts

Kola-Karelian Domain

- Proterozoic granitoid complexes
- Proterozoic schist belts
- Lapland granulite belt
- Central Lapland greenstone belt
- Early Proterozoic layered intrusions
- Archean schist (greenstone) belts
- Archean granitoid and gneiss complex

Fig. 1. Map of the principal geological units of Finland.
granitoids and gneisses, (2) Archaean schist (greenstone) belts, (3) areas covered by Proterozoic intracratonic and epicratonic (autochthonous) or oceanic (allochthonous) schist belts resting on the Archaean basement, (4) Proterozoic granitoid complexes inside the domain, (5) the Lapland granulite belt, and (6) the Central Lapland greenstone belt. Separately presented is (7) the Early Proterozoic layered intrusion complex situated roughly in the unconformity between the Archaean and the Proterozoic. The Svecofennian Domain is divided simply into (8) supracrustal schist belts and (9) granitoid complexes. The younger formations presented are (10) the Late Svecofennian granite and migmatite complexes, (11) Post-Svecofennian rapakivi granite intrusions, (12) Jotnian sediment basins and (13) the Palaeozoic cover of the Caledonian orogeny cycle.

The map is available as four MapInfo files with a total size of ca 300 KB on disc.

Map 3: General geological map

This map is a simplified version of the former and can be regarded as a modern analogue to the popular map published by Simonen (1962, 1980b). The Proterozoic supracrustal belts are united into one item in the legend, regardless of their position on the Archaean basement or within the Svecofennian Domain; similarly, the areas of the Svecofennian plutonics are united into one item, including also the Late Svecofennian granitoids. Thus, the map represents the major geological formations as exposed on the day surface, and the entities of the legend are as follows: (1) Archaean granites and gneisses, (2) Archaean schist belts, (3) Lapland granulite belt, (4) Central Lapland greenstone belt, (5) layered intrusions, (6) Early Proterozoic schist belts, (7) Early Proterozoic (Svecofennian) plutonic complexes, (8) rapakivi granite intrusions, (9) Jotnian formations and (10) Caledonian cover.

The map is available as four MapInfo files with a total size of ca 250 KB on disc.

Map 4: Pixeled geological map

A totally different derivative of the original map by Simonen is the pixel representation of the bedrock map. This map, produced by Lehtonen et al. (1987) serves areal statistical calculations in geomathematical applications. The map is divided into 5 x 5 sq.km cells (pixels) and all the different rock types in the legend of the Simonen map occurring in each cell are listed in decreasing order of areal coverage. The territory of the country contains ca 16,000 pixels registered in a simple ASCII data file. The material has frequently been used in similarity analysis and other geo-mathematical studies (cf. Koistinen (1981), Saltikoff & Koistinen (1989), Puustinen et al. (1995)).

The map of Quaternary Deposits of Finland (Kujansuu & Niemelä, 1984) has been pixeled in a similar way and on an identical grid.

Discussion

The amount of details that can be shown on a map depends on its scale, and is very limited on maps covering the whole country in a size used in publications (1 : 5,000,000 to 1 : 8,000,000). Therefore, the selection of the geological features to be displayed must be defined each time separately, depending on the issues under discussion.

Maps 1 to 3 presented here were made to illustrate a few features only. Map 1 is a passive copy of the original map of Simonen and can be used at 1 : 500,000 to 1 : 2,000,000 scale - when smaller it becomes blurred due to the many details. Map 2 represents the generalized structure of the lithosphere in Finland, and map 3 shows the structures visible on the day surface.

The different approaches favoured in the three maps can be illustrated by a profile through eastern Finland, based on the presentation by Kohonen (1995) (Fig. 2). Here we see an area of Archaean basement gneiss; a transition zone coated by a mixture of epicratonic autochthonous rocks (Jatulian quartzite and Kalevian schist) and overthrust allochthonous rocks (Svecofennian gneiss), all of Proterozoic age, resting on the Archaean basement; an area of Proterozoic supracrustal rocks identical to the allochthon in the previous zone, but with no basement detected; and batholiths of Proterozoic intrusions. The two former areas are interpreted as belonging to the Kola-Karelian Domain and the latter ones to the Svecofennian Domain. Now, the map of Simonen (and, accordingly, Map 1) tends to display all the various lithological rock types in the territory, regardless of the structural zones; Map 2 shows the major geoblocks (the surficial complexes plus the basement) in the profile (blocks I - II - III - IV), and Map 3 the principal complexes on the surface (blocks I - II - III). Of course, these interpretations are not the only ones possible. For some purposes it would be desirable
to separate the allochthonous 'Svecofennian' supracrustals from the autochthonous 'Karelian' supracrustals. Such maps have not yet been prepared, however. Map 4 is intended for statistical manipulations rather than illustrative purposes. The above digital maps are available from the authors.

References


MID-NORDEN PROJECT, GEOPHYSICAL SUB-PROJECT: INTRODUCTION TO COMBINED GEOPHYSICAL MAPS OF CENTRAL AND NORTHERN FENNOSCANDIA

by T. Ruotoistenmäki¹, S. Elo², S. Aaro², E. Kauniskangas³, C. Kortman¹, J. Skilbrei⁴ and T. Tervo⁵

¹Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
²Geological Survey of Sweden P.O. Box 670, S-75128 UPPSALA, SWEDEN
³Geological Survey of Finland, P.O. Box 1237, FIN-70211 KUOPIO, FINLAND
⁴Geological Survey of Norway, P.O. Box 3006 - Lade, N-7002 TRONDHEIM, NORWAY
e-mail: tapio.ruotoistenmaki@gsf.fi; sven.aaro@sgu.se; jan.skilbrei@ngu.no

Key words (GeoRef Thesaurus, AGI): geophysical surveys, geophysical survey maps, gravity survey maps, magnetic survey maps, seismic profiles, Mid-Norden project, Scandinavia, Finland, Sweden, Norway

Introduction

The internordic Mid-Norden Project is a joint venture of the Geological Surveys of Finland, Norway and Sweden to provide regional geoscientific information of central Fennoscandia. The project has received valuable contributions also from individual scientists at the Geological Survey of Denmark and Greenland. The project, which is sponsored by the Nordic Council of Ministers, covers an area in central Fennoscandia between latitudes 62°50'N and 66°N (Fig. 1). The information has been compiled as both digital databases and as maps. The latter are available from the Geological Surveys.

The results of the Mid-Norden Project combined with those of the previously published Nordkalott Project (e.g. Kautsky 1986) offer a comprehensive overview of a wide range of geoscientific data from northern and central Fennoscandia. They give information on the bedrock, structural geology, Quaternary geology, magnetic and gravity anomalies, and occurrences of ore deposits and industrial minerals. The bedrock and geophysical maps of the Mid-Norden area cover not only land areas but also most of the offshore areas along the Norwegian continental shelf and parts of Bothnian Bay. The advantage of the maps is that geophysical and the corresponding lithological features can be followed across national borders when the large scale tectonic processes that created the Fennoscandian crust have to be modelled. Understanding of bedrock evolution is also needed when the location of ore showings and changes in fracture zones around radioactive waste repositories are predicted and modelled.

Eight thematic maps at a scale of 1 : 1 000 000 covering the Mid-Norden area will be produced in 1996–1997, as will a volume containing a series of environmental geology test cases and memoirs for the bedrock and Quaternary geology maps.

The main goal of the Mid-Norden geophysics sub-project is to prepare gravity and magnetic data matrices and maps covering central Fennoscandia. Airborne magnetic data is provided by the Geological Surveys of Finland, Norway and Sweden and gravity data by the Geological Surveys, the Finnish Geodetic Institute, the Norwegian Mapping Authority and the National Land Survey of Sweden. The maps are published as paper maps (Ruotoistenmäki et al. 1996a, b) showing anomalies in colours, the regional trends emphasized with hillshading. The maps also include general descriptions of the data, statistics, index maps and national descriptions of data from Norway, Sweden and Finland in English and vernaculars (Norwegian, Swedish and Finnish).

Digital versions of the maps and their deriva-
Fig. 1. The Mid-Norden (MN) and Nordkalott areas (NK). The Lambert conformal conical projection is used. Standard parallels are 54°N and 68°N, the centre meridian is 18°E. Lat=66°N and long=18°E corresponding to x=8472.976; y=1000.000. The Lambert coordinates of the corner points are shown in parentheses.
tives are available from the Geological Surveys. They can be used interactively with PCs and include an information file system with which vectors and point symbols can be displayed on or extracted from the maps. The information files distributed by the authors contain deep-seismic sounding profiles, regional fractures (vectors) and ore indications (symbols) of the Mid-Norden area. Users can create new information files separately from any location (x,y) data.

The data matrices of the Mid-Norden area (Ruotoistenmäki et al. 1996a, b) and the Nordkalott project (Korhonen et al. 1986a, b) have been combined into a common data base. The resulting gravity and magnetic maps at 1:2 000 000 scale are given as separate sheets in the map pocket at the end of this volume.

Other geophysical information available from the Geological Surveys includes regional and local scale gravity and magnetic maps (paper and digital) and grids, low-altitude gamma radiation and electromagnetic response data and maps, and ground profiles measured with various geophysical methods. The petrophysical databases for the Mid-Norden area contain information (mainly density, magnetic susceptibility intensity of remanence and less often electrical conductivity) on about 47 300 samples from Finland, 3800 from Norway and 16 000 from Sweden.

The following takes a brief look at the existing Mid-Norden geophysical data and maps and their combinations with Nordkalott data and gives preliminary examples of data interpretation.

Gravity maps and data

The gravity anomaly map of the Mid-Norden area was prepared by the Geological Surveys of Finland, Norway and Sweden during the period 1989—1996. A Bouguer density of 2670 kg/m$^3$ was used for onshore data. The water volume in offshore areas was replaced by a mass of the Bouguer density using a water density of 1027 kg/m$^3$ for the Norwegian Sea, and 1000 kg/m$^3$ for the Bothnian Bay. The International Gravity Standardization Net 1971 (IGSN-71) and the Gravity Formula 1980 for normal gravity were applied. The data were interpolated to a square grid of 2.5 km by 2.5 km. Anomaly gradients were emphasized by ‘illuminating’ them from northwest and northeast.

The gravity field of mainland Norway was measured by the Geological Survey of Norway (NGU), the Norwegian Mapping Authority (Statens kartverk) and other Norwegian and foreign institutions. The original data spacing ranged from less than 0.4 km to 10 km. The onshore Bouguer values were terrain-corrected. The marine gravity data used in this compilation were provided by the Norwegian Petroleum Directorate (Oljedirektoratet), NGU, the Norwegian Mapping Authority, Statoil, Norsk Hydro and other Norwegian and foreign oil companies. Extensive areas are covered with a dense grid of ship tracks (spacing 0.5 km to 4 km). The varying areal distribution of the original gravity observations was homogenized using a minimum separation of 600 m between points.

Gravity data on the Swedish Mid-Norden area were provided by the Geological Survey of Sweden (SGU), the National Land Survey of Sweden (LMV), the Boliden Mineral Company and the University of Uppsala. Measurements made over Bothnian Bay when covered with ice were made by SGU, LMV and the Finnish Geodetic Institute working in collaboration. Original data on the 2.5 km by 2.5 km grid have a spacing of 3—10 km. The onshore Bouguer values were terrain-corrected.

The gravity data on Finland were measured by the Finnish Geodetic Institute at an original grid spacing of about 5 km. About 20% of onshore Finland is currently covered with a denser grid measured by the Geological Survey of Finland (GSF), the station spacing varying from 0.4 km to 0.7 km. Where possible, GSF observations were used to give an average station interval of about 2 km. Because of the generally flat topography, the Finnish data were not terrain-corrected.

The combined gravity map of Mid-Norden and Nordkalott area at 1:2 000 000 scale is given as a separate sheet in the map pocket at the end of this volume. The interpreted gravity lineaments of the Mid-Norden area combined with the hillshaded gravity map are shown in Figure 2 as an example of use of the data. It can be seen that the main gravity minimum A—A' (yellow in the figure) controlling the ore potential Ladoga-Bothnian Bay zone (LBZ) on its northeastern side continues northwest to Sweden, where it coincides with the Archaeen palaeoboundary defined by Öhlander et al. (1993) by Sm-Nd isotope analyses.

Note that there is no evidence in the gravity maps of the existence of a large north-south fracture system in the Bothnian Bay (the "Baltic Bothnian megashear" suggested by Berthelsen et al. 1986). The linear continuation of LBZ fractures A—A' on the Swedish side is a strong argument against such a system.
Fig. 2. The interpreted gravity lineaments of the Mid-Norden area combined with the hillshaded gravity map of Mid-Norden and Nordkalott areas. A—A' indicates the main gravity minimum controlling the ore potential Ladoga-Bothnian Bay zone (LBZ).
Fig. 3. The interpreted magnetic lineaments and base metal showings in the Mid-Norden area combined with the hillshaded magnetic map of Mid-Norden and Nordkalott areas. A—A' indicates the main gravity minimum controlling the ore potential Ladoga-Bothnian Bay zone (LBZ).
Magnetic maps and data

The magnetic data matrices were interpolated to a common net with a cell size of 1 km by 1 km and the Definite International Geomagnetic Reference Field 1965.0 (DGRF-65) was subtracted. Anomaly gradients were emphasized by ‘illuminating’ them from the northwest and northeast.

The airborne magnetic data on mainland Norway and offshore areas were measured by the NGU between 1959 and 1976. The aeromagnetic map is based on a matrix digitized from manually drawn contour maps. Nearly half of central Norway (mainly the Trøndelag region) is covered by data with a line spacing of 500 m and a terrain clearance of 150 m. Most of the remaining onshore areas were measured with a line spacing of 1000 m and at a flight altitude of 300 m. In the offshore areas of the map the flight altitude was 200—500 m and the line spacing ranged from 2 km to 5 km. At present about 10% of central Norway is covered by low altitude (60 m) data in form of paper and digital maps.

The airborne magnetic measurements in the Swedish Mid-Norden area were carried out by the Boliden Mineral Company, LKAB and SGU, the latter with partial financing from the Swedish Nuclear Fuel and Waste Management Company (SKB). Most of the remaining onshore areas were covered with low-altitude (30—50 m), 200 m by 40 m data and the offshore areas with 600 m by 80 m data. In the Caledonides, ten low-altitude (c. 50 m) profiles were measured by SGU for the University of Uppsala, using a line spacing of 5—20 km. The aeromagnetic data sets were compiled on a 200 m by 200 m grid, which was then continued upwards from 30 to 150 m and regridded to 1 km by 1 km.

The airborne magnetic data on Finland were measured by the GSF during 1951—1971 and 1993 (eastern border zone), with a terrain clearance of 150 m and line spacing of 400 m. The original analogue format data were digitized to a 1 km by 1 km grid. About 75% of onshore Finland is currently covered by low-altitude (30 m) data and maps with a line spacing of 200 m, and observations made every 12.5 metres.

The combined magnetic map of the Mid-Norden and Nordkalott area at 1:2 000 000 scale is given as a separate sheet in the map pocket at the end of this volume. The interpreted magnetic lineaments and base metal showings of the Mid-Norden area combined with the hillshaded magnetic map of the Mid-Norden and Nordkalott area are shown in Figure 3 as an example of the usage of the data. The main gravity minimum A—A’ shown above is included in the figure. It can be seen that the majority of Finnish ore showings in the Mid-Norden area are connected with the magnetic maximum zone northeast of the main gravity minimum A—A’. This magnetic maximum zone is also a regional gravity maximum referring to large amounts of mafic rocks in the upper crust (e.g. Elo et al. 1978; Ruotoistenmäki 1993, 1996).

Seismic profiles

During the Mid-Norden project we digitized two deep seismic refraction profiles from the Norwegian Sea and two from onshore areas in Sweden and Finland. These profiles are included in the ‘extra info files’ of the digital map browser. As an example of these profiles Figure 4 depicts the deep seismic refraction profile SVEKA (e.g. Luosto et al. 1982) in Mid-Finland.

The northeastern part of the SVEKA profile overlapping the Mid-Norden area was digitized along the shot points. In the figure the profile is ‘projected’ along a straight line between the end points (heavy black line). The main reflectors were drawn with black lines. The profile is framed so that along the profile the scale is the same as that of the map. In vertical dimension, however, the scale factor is 2. The height of the frame is 70 km. Note that ‘stretching’ in a vertical dimension makes the dips of the reflector surfaces steeper.

The figure shows that the ore potential area northeast of the gravity lineament A—A’ in Figure 2 is characterized by very thick crust, c. 60 km, possibly due to tectonic thickening (e.g. Ruotoistenmäki, 1996) and or introduction of mafic mantle
melts in the lower crust (e.g. Lahtinen 1994; Korja 1995).

Conclusions

The geophysical data on and maps of the Mid-Norden area supplemented with other geological and geophysical data provide valuable tool for analysing the bedrock characteristics in central and northern Fennoscandia. The advantage of the combined maps is that the regional structures and lithology variations can be analyzed across national borders. This is necessary when considering and modelling the large scale tectonic processes that created the Fennoscandian bedrock. An understanding of bedrock evolution is also needed for predicting and modelling the location of ore showings and changes in fracture zones around radioactive waste repositories.

Supply of data and maps

The data and maps (paper and digital PC versions) of the Mid-Norden and Nordkalott areas can be ordered from the Geological Surveys of Norway, Sweden and Finland.

An Internet www page presenting the maps is at the address: http://www.gsf.fi/midnord.

We emphasize that not all the data used for map production are readily available to persons outside the Geological Surveys. In such cases the Surveys are ready to provide consultation assistance with the interpretation and production of special maps.

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INTERNET ONLINE DATABASES PRODUCED BY
THE GEOLOGICAL SURVEY OF FINLAND

by

Caj Kortman

Geological Survey of Finland, P.O. Box 96, FIN-02151 ESPOO, FINLAND
e-mail: caj.kortman@gsf.fi

Key words (GeoRef Thesaurus, AGI): geology, survey organizations, information systems, data bases, Internet

Introduction

The Information Bureau of the Geological Survey of Finland (GSF) maintains a number of reference databases in its information management system (TRIP). In addition to conventional bibliographic references to publications and archival reports, the databases also cover library holdings, museum and drill core samples, and photographic collections, as well as information about ongoing research and factual databases at GSF.

For information professionals the information management system provides an efficient tool for daily routine storage and management of information. The resulting databases are also made available to users for searching and retrieval through user friendly applications.

A standardized approach to the use of index terms has been adopted to facilitate retrieval of information by subject from different databases. At the same time it has been important to ensure technical and conceptual compatibility with other information systems and hence to facilitate the exchange of digital textual information at both national and international levels.

During 1996 some of these databases were made available for public searching on the Internet at the address http://info.gsf.fi/ (Finnish search forms) and a few are also searchable through English search forms at the address http://info.gsf.fi/eng/.

Bibliographic databases on the geology of Finland

FINGE0 is a comprehensive bibliographic database on Finnish geological literature dating from 1971 to present. It covers geoscience literature dealing with Finland, published in Finland, or written by Finnish geologists. The records include index terms (key terms), geographical descriptors and map-sheet numbers. The English index terms are based on the American Geological Institute (AGI) GeoRef Thesaurus, and they are automatically translated into corresponding Finnish terms. This makes it possible for GSF to exchange bibliographic information, which includes index terms, with both the Finnish national library system and also with international geoscience information systems, such as AGI GeoRef. At the end of 1996 the database contained over 13,000 references, of which 53% concerned publications in English and 42% in Finnish. About 800 to 900 records are added annually. The database is updated on a daily basis.

Example of record, reference format:

Example of record, long format:
Unpublished archival material

RAPGEO is a bibliographic database of unpublished reports held in the archives of GSF. The reports date from the end of the 19th century to the present. Of the 3,800 reports almost half concern mineral exploration. The records include Finnish index terms, geographical descriptors, and map sheet numbers.

Example of record, reference format:

Example of record, long format:
ID: 3830
AU: Lindmark, Boris & Koistinen, Esko
TI: Tutkimustyöselostus Valkeakosken kaupungin valtausalueella Hopeavuori 1 (kaivosrekisterinro 5085/1) suoritetuista kultatutkimuksista vuosina 1992-1994. 15 s., 17 l.
SF: OTA
PY: 1996
RN: M06/2114/-96/1/10
CX: kultamalmit, kvartsporfyyri, metavulkaniitit, granodioriitit, geokemialliset menetelmät, geofysikaaliset menetelmät
MS: 2114 10
MM: arseenikisuu, rikkikiisu, magneettikiisu
AA: Au, As
KA: kairattu
CC: 553

GTKMATKAT is a bibliographic database on foreign travel reports by the staff of GSF. It contains 700 references to reports from the years 1990 to 1996.

Example of record:
2nd EEGBS (Environmental and Engineering Geophysical Society) Meeting, Nantes, France, 2.-5.9.1996. 3 s. . 1996, Mattsson, Annina; Vanhala, Heikki

Ongoing research

TREK is a database of ongoing or recently completed research projects at GSF and contains over 200 records. The information includes project titles, project leaders, co-workers, schedules, project numbers, keywords, geographical terms, and abstracts, in both Finnish and English. At the end of 1996 a catalogue of the research projects was published in Finnish and English versions by
extracting the information from the database (Kortman & Aumo 1996).

**Example of record, Finnish version:**

Kittilän-Sodankylän kultatutkimukset
Vastuuhenkilö: Keinänen, Veikko
Muut tutkijat: Härkönen, Ilkka; Rask, Markku; Pankka, Heikki; Pulkkinen, Eelis; Pernu, Teuvo; Kortelainen, Vesa
Hanke: 13213/1996; päätutkimus; perustutkimus; soveltava tutkimus
Päävastuualue: P-SA, raaka-aineet
Kesto: 1996-01-01...1998-12-31
Asiasanat: malmiteos; kultamalmit; metavulkaniitit; rakennuskivi; marmori
Tutkimusalue: Lapin lääni; Kittilä; Sodankylä

**Example of record, English version:**

Gold Studies in the Kittilä-Sodankylä area
Project leader: Keinänen, Veikko
Co-workers: Härkönen, Ilkka; Rask, Markku; Pankka, Heikki; Pulkkinen, Eelis; Pernu, Teuvo; Kortelainen, Vesa
Project code: 13213/1996
Schedule: 1996-01-01...1998-12-31
Keywords: mineral exploration; gold ores; metavolcanic rocks; building stone; marbles
Geographical area: Lappi Province; Kittilä; Sodankylä

**EXPERT** is a register of GSF professionals and their expertise and contains about 300 records.

**Example of record, Finnish version:**

Asiantuntija: Winterhalter Boris
Ammattilaite: Espoo
Asiasanat: miergeologia, merisedimentit, merenpohjan muodot, noduliit, menetelmät
Tutkimusalue: Iätämeri, Suomenlahti, Barentsin meri, Eteläinen jáämeri, Antarktis

**Example of record, English version:**

Name: Winterhalter Boris
Location: Espoo
Speciality: senior scientist
Key words: marine geology, marine sediments, bottom features, nodules, methods

**Library holdings**

**KIRJAT** is the library catalogue covering GSF library holdings since 1992 and contains over 14,000 records. The records include index terms in Finnish, UDC-classification codes and information about the location of the documents (books, maps etc.). The database is updated on a daily basis at the main library in Espoo and also at the branch libraries in Kuopio and Rovaniemi.

**Example of record, short format:**

TAIPALE, Kalle 1996: Levoton maapallo

**Example of record, long format:**

AU: TAIPALE, Kalle
TI: Levoton maapallo
PT: Helsinki
PU: Kirjayhtymä
PY: 1996
PGN: 198 s.
SB: 951-26-4160-7
CX: Maa; geologiset riskitekijät; vulkanismi; maanjäristykset; meteoriti; tuho; paleoklimatologia; ihmisen toiminta; ympäristögeologia; populaarigeologia
CC: 55; 502.5
SI: ES 55; ES 55; ES L; RO 55; KU 55; KU 55

**LEHDET** is a catalogue of periodicals received by the GSF libraries in Espoo, Kuopio and Rovaniemi. It contains about 2,100 records.

**Example of record, short format:**

Mining environmental management . Mining Journal Limited, London

**Example of record, long format:**

TI: Mining environmental management
PT: London
PU: Mining Journal Limited
SS: 0969-4218
CX: kaivostelliit; louhintä; ympäristö
CC: 622, 504
HYL: Mining environmental management
SI: ES 2 (1994) ; RO 1 (1993) -

**Publications and maps issued by GSF**

**GTKJUL** is a register of all printed publications issued by the GSF since 1895. The records include information about publication prices. Forthcoming publications ("in press") are also included in the database.

**Example of record, short format:**

Rantataro, Jyrki 1996: Anthropogenic impact on recent sediment in Jätkäsaari harbour basin, Helsinki, Finland: A comparison with the geochemistry of unpolluted glacial clay

195
Example of record, long format:

AU: Rantataro, Jyrki
TI: Anthropogenic impact on recent sediment in Jätkäsaari harbour basin, Helsinki, Finland: A comparison with the geochemistry of unpollluted glacial clay
SO: Geologian tutkimuskeskus, Tutkimusraportti Geological Survey of Finland, Report of Investigation
PY: 1996
PI: 50 mk

GTKKARTAT is a comprehensive list of all printed maps and map explanations issued by GSF since 1879. It also includes information about maps at scales of 1:20 000 and 1:50 000 which is not included in the bibliographic databases mentioned above.

Example of record, short format:

Väisänen, Ulpu 1995. Ivalo. Maaperäkartta 1: 50 000
MS: 3832 2

Example of record, long format:

AU: Väisänen, Ulpu
TI: Ivalo
SO: Maaperäkartta 1: 50 000
PY: 1995
MS: 3832 2
PI: 50 mk

In addition to the databases available on the Internet, there are also databases for searching and retrieval internally at GSF. These include databases on diamond drill cores, museum specimens, photographs, databases etc., see below:

Online databases produced by the Information Bureau at GSF (number of records at the end of 1996).

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Records</th>
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<td>FINGEO**</td>
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<td>BULLETIN 270*</td>
<td>Geological bibliography of Finland 1934—1970</td>
<td>7 271</td>
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<tr>
<td>BULLETIN 108*</td>
<td>Geological bibliography of Finland 1555—1933</td>
<td>4 312</td>
</tr>
<tr>
<td>RAPGEO*</td>
<td>Unpublished archival reports at GSF 1864—present</td>
<td>3 738</td>
</tr>
<tr>
<td>GTKMATKAT*</td>
<td>Travel reports by GSF staff</td>
<td>694</td>
</tr>
<tr>
<td>TREK**</td>
<td>Ongoing research projects at GSF</td>
<td>236</td>
</tr>
<tr>
<td>EXPERT**</td>
<td>GSF expert register</td>
<td>307</td>
</tr>
<tr>
<td>KIRJAT*</td>
<td>Library holdings at the libraries of GSF 1992—present</td>
<td>14 264</td>
</tr>
<tr>
<td>LEHDET*</td>
<td>Periodicals at the libraries of GSF</td>
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<td>Databases at GSF</td>
<td>37</td>
</tr>
<tr>
<td>VALTAUSRAP</td>
<td>Claim reports</td>
<td>4 177</td>
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<tr>
<td>VANHATKUVAT</td>
<td>Register of old photographs</td>
<td>1 505</td>
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</tbody>
</table>

* and ** = available on Internet at the address http://info.gsf.fi/ (Finnish search forms)
** = also available on Internet with English search forms at the address http://info.gsf.fi/eng/

For users who only wish to know the latest additions to the databases, an electronic version of the news list ("Uutuusluettelo") is available at the address http://info.gsf.fi/info/uutuus/. This service includes information from the following databases. FINGEO, KIRJAT, RAPGEO and GTKMATKAT.

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196

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