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Geoscience for Society
125th Anniversary Volume

Edited by Keijo Nenonen and Pekka A. Nurmi

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Front cover:
Barite crystals ($BaSO_4$) from Korsnäs lead mine in western Finland at a depth of 190 m. Field width 5 cm. Photo: Kari A. Kinnunen.

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PREFACE

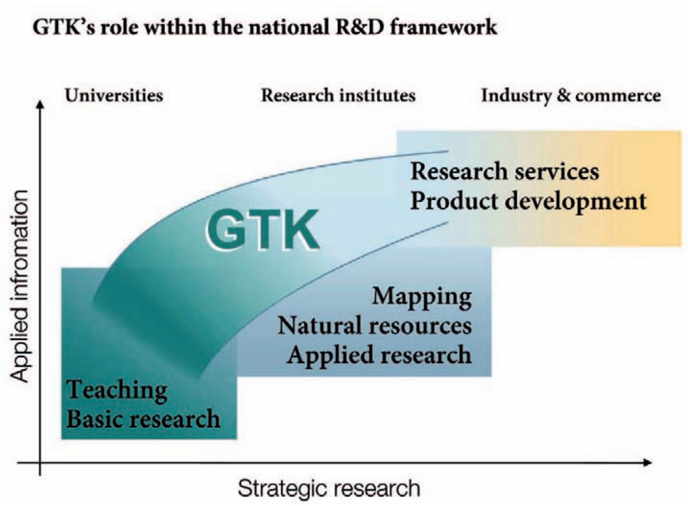
Geoscience has a long and glorious history in Finland (Tanskanen 1986, Haapala 2005). The first geological studies were already performed and academic dissertations written at the Academy of Turku, the first university in Finland founded in 1640. The first Chair in Geology and Mineralogy was established at the University of Helsinki in 1852. During the historical period of the Enlightenment, geoscience received more emphasis and funding, as it could show direct benefits to society and its rulers. The beginning of geological survey activities in Finland was closely connected with the father of Finnish mineralogy, Nils Nordenskiöld, who operated as the General Intendant of the Mining Council during 1823–1855. He was the one who showed initiative and pursued the beginning of geological surveys and exploration funded by the government. His initiatives were fulfilled by founding a geological office to the government's Mining Council in 1870. The work of geologists and surveyors was effective: they mapped much of Southern Finland and made some promising findings of gold and other commodities.

In 1885, Emperor Alexander III approved the suggestion of the Finnish Senate to establish the Geological Commission, which started its operations in 1886 and was renamed the Geological Survey of Finland (GTK) in 1945. Pioneering research by J.J. Sederholm, who led the Geological Commission for 40 years (1893–1933), as well as Wilhelm Ramsay and Pentti Eskola, both professors at the University of Helsinki, were the key to establishing an international reputation for Finnish geoscience. During the past 125 years, GTK has developed as an independent research organization of applied geoscience with the same main objectives to serve the nation with new geological raw materials, and better knowledge of the Earth and its processes for the sustainable growth and well-being of our citizens.

Societal and technological development has had a great impact on geoscience. The turning point was World War II, after which the demand for geological raw materials rapidly rose due to the rebuilding of Europe. We are now living an era of even strongereconomic growth, as the large populations of Asia, South America and Africa are building a better life and well-being for their nations. Modern society requires the use of mineral-based products in the construction and maintenance of housing and other buildings, earth structures, railroads, road networks, power lines, pipelines and other infrastructure. Industrial production and the manufacture of machinery, equipment, vehicles and ICT technology are largely based on the utilisation of mineral-based materials. Mineral fertilisers and agricultural machinery are also vital to food production. The availability of natural resources and resource-based industrial production has become essential to prosperity and well-being in our rapidly changing world.

In parallel with economic growth, environmental problems are increasing, and global change is speeding up. Anthropogenic impacts on the Earth's systems have reached geological dimensions. The demand for geological resources is growing, but at the same time the demand to reduce the environmental impact of the extractive industry is also being pursued. The safe supply and price of energy is becoming a more important factor in mining and metallurgy, as well as in our everyday life. Emission-free energy production, restoring energy for further use, the capture of gaseous emissions and their sequestration in geological structures, and the safe handling of nuclear waste in bedrock present new challenges to our science. We have to develop resource, energy and water efficiency in all our activities. Climate change will lead to an intensification of the global hydrological cycle and will have a major impact on regional water resources. These are all issues where geoscience plays a fundamental role in close association with other sciences and expertise.

Our knowledge of Finnish geology and natural resources has considerably increased during the last few decades. GTK has mapped the bedrock and Quaternary deposits, as well as mineral resources in great detail using modern geological, geochemical and geophysical techniques, so that Finland today has one of the best geological databases in the world. We have recently compiled countrywide datasets of seamless bedrock information at the scale of 1:200,000, and completed low-altitude airborne geophysical (200 m line spacing and 40 m terrain



clearance), regional geochemical (80 000 samples), and reflection seismic surveys at the crustal scale and at high resolution on the main ore-potential formations. Isotopic age determinations have been performed at GTK since the 1960s, and we now have accurate ages for about thousand samples, which is a key to studying the complex evolution of the Finnish Precambrian.

GTK currently plays a vital role in providing geological expertise to the government, the business sector and the wider community. Specific responsibilities include the promotion and implementation of sustainable approaches to the supply and management of minerals, energy and construction materials, and to ensure environmental compliance through monitoring, assessment and remediation programmes. GTK also contributes to a wide range of international geoscience, mapping, mineral resources and environmental monitoring projects, and is active in developing multidisciplinary research programmes with universities, government agencies and stakeholders across related sectors.

GTK has defined in its current strategy to cover three areas of societal impact: (1) mineral resources and raw material supply, (2) energy supply and the environment, and (3) land use and construction, which also form the subsections of this anniversary publication, in addition to a section on geodata management and database development. Our research and development targets are set to meet the demands of societal decision-making and the business sector. Research activities at GTK are currently coordinated through six programmes, each having a five-year duration. The programmes are: (1) mineral potential, (2) eco-efficient mining, (3) energy, (4) marine geology and global change, (5) urban geology, and (6) groundwater and aggregates. GTK's generic development is focused on the development of our services, geoinformation and modelling, data processes and data quality, as well as mineral potential assessment and exploration techniques.

This 125th Anniversary Publication aims at elucidating, through 33 short articles, the current focus of research and development at GTK. In reaching the milestone of 125 years, we can state that our anniversary slogan, "forever young", is justified by the vitality and increasing societal impact of the organization and our research focusing on sustainable development of our society. GTK is currently the centre of geoinformation and applied geoscientific expertise in Finland, and we have very active international co-operation and project export worldwide.

Espoo November 6, 2010

Keijo Nenonen and Pekka A. Nurmi

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1 Research promoting sustainable use of raw materials

An aerial view of the Talvivaara mine, which started production in 2008. It is planned to annually produce 50 000 tons of nickel, 90 000 tons of zinc, 15 000 tons of copper and 1 800 tons of cobalt for the next 50 years. The deposit was discovered by GTK in 1978. (Photo: Talvivaara Mining Company)

1 RESEARCH PROMOTING SUSTAINABLE USE OF RAW MATERIALS

Introduction

An increase in the population, more rapid urbanisation and higher material living standards have resulted in an unprecedented global demand for metals, industrial minerals and rock aggregates. Mineral-based materials, products and structures are used either directly or indirectly in almost every area of our life. New technologies and environmental challenges have still further expanded our need for raw materials and mineral-based products. In addition to an increased need for basic metals, we are becoming increasingly dependent on so-called high-tech metals. These are essential in the manufacture of advanced technological products, including circuit boards, semiconductors, coatings, magnets, mobile phones, computers, home electronics, solar panels, wind power plants and electric cars.

This current era of increased demand for minerals and changing global markets presents new opportunities for the expansion and diversification of mining operations, and for business growth based on innovative developments in refining and processing technologies. Europe is heavily or fully reliant on imports of minerals, so that disruptions in availability and supply can pose a significant risk. Finnish bedrock contains significant known deposits of many metals and minerals, and has considerable potential for the discovery of new resources of critical minerals. In recent years, significant new mines have been opened in Finland, while existing mines have recorded increased production, and many more mining projects are in progress.

Future mining operations will have to be increasingly based on underground operations and the exploitation of deposits having lower mineral concentrations, or which are technically more difficult to process. Responses to these challenges require innovative technological developments throughout the entire extraction and production chain. We would need better exploration methods to particularly identify deep-seated deposits. New processing techniques are needed to process more complex ores, and to respond to the challenges of more resource-efficient mining. Mine closure in an environmentally sound way and post-closure monitoring are basic demands for current mining operations.

The Geological Survey of Finland (GTK) has an important role in the minerals sector. Our data sets and scientific research results on Finnish bedrock, mineral deposits and exploration models are essential for the mining industry. We are actively developing and applying cutting-edge exploration techniques in our ore potential evaluation and research on geological complexes with mineral potential. We are also actively developing the “Green Mining Concept”, which aims at more efficient processes with a reduced environmental impact and footprint.

The eleven papers in this section provide an overview of our research on bedrock and ore geology, and exploration techniques. Our mineral beneficiation studies are described, as well as mining environment studies. Because geological resource extraction contributes extensively to the prosperity of Finnish society, reliable data on geological resources are critical to decision-makers and the business community. The two last papers deal with research on geological resources accounting at GTK and with the economic importance of geological resources.

Pekka A. Nurmi

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METALLIC MINERAL RESOURCES OF FENNOSCANDIA

by
Pasi Eilu

Eilu, P. 2011. Metallic mineral resources of Fennoscandia. *Geological Survey of Finland, Special Paper 49*, 13–21, 2 figures and 3 tables.

The mineral wealth of Fennoscandia is based on its geological evolution, including several episodes producing an extensive range of genetic metal deposit types containing a large variety of exploitable metals. The known and estimated metallic mineral resources in Fennoscandia could cover, at the 2007 consumption level, over 50 years of EU demand for chromium, lithium, niobium, nickel, rare earth elements, tantalum, titanium and vanadium, and 10–30 years of EU demand for iron ore, cobalt, platinum, palladium and uranium. There also are easily exploitable resources of copper, gold, manganese, molybdenum, silver, zinc and zirconium. Hence, the region is a significant future metal supplier and a resource base for the whole of Europe, and especially for the European Union.

Keywords (GeoRef Thesaurus, AGI): mineral resources, metal ores, raw materials, metals, demand, production, European Union, Finland

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INTRODUCTION

The European Union (EU) produces roughly 3% of the metals annually consumed in the world, while it uses 20–30% of the metals globally produced (Brown et al. 2009a, 2009b). For the whole of Europe, both figures are higher, but the ratio between production and consumption largely remains the same: our economies and standard of living are heavily dependent on raw materials produced elsewhere. The future trends seem to show no change from an increasing demand for metals (Tables 1 and 2), but at the same time, exploration for and the development of new mineral resources all over the world is facing increasing competition from other land uses (e.g. Briskey et al. 2007, Commission of the European Communities 2008, Hitzman 2007). In addition, the global minerals market is not completely open, but faces significant hurdles due to national protectionism in the form of regulated and even prohibited export of certain metals, such as platinum, palladium, rare earth elements (REE) and tungsten, from the countries producing a globally significant share of these metals.

Recycling of raw materials could be an effective way to respond to the increasing demand, and most probably will be so in the near future (Brown et al. 2009a, Buchert et al. 2009, Johnson Matthey 2009). However, recent investigations indicate the difficulty of satisfying the growing needs for raw materials solely by increasing recycling. For example, the degree of recycling of precious metals, such as the platinum group metals, is already so high that enhanced recycling cannot be the primary solution for the increasing consumption (Buchert et al. 2009).

In this context, certain parts of Europe are of great importance as both present and future major producers of essential raw materials needed by our society in manufacturing and other industries (e.g. GEODE 2001). Fennoscandia (the Precambrian shield and the Caledonides; Figure 1) is one of these regions: it has a geology similar to other mineral-rich shield areas of the world (e.g. Australia, South Africa, Canada), it has a long tradition of mining and related industries, it also currently has a large number of active mines, it is the sole or the dominant producer of many metals in Europe (Table 1) and will strengthen that position in the near future (Table 2), and the region still has a great potential for new significant mineral discoveries (Eilu et al. 2008, 2009). This is also indicated by the fact that almost half of the present exploration for metals in Europe is taking place in Finland and Sweden (SGU 2009). The metallic mineral resources of Fennoscandia and their significance at the scale of the whole EU are reviewed below.

MAIN ORE DEPOSIT TYPES OF FENNOSCANDIA

Fennoscandia (Figure 1) comprises Norway, Sweden, Finland, and the northwestern Russia (Kola Peninsula and Russian Karelia). The northern and eastern parts are formed by Archaean rocks, and the central, southern and western parts by Proterozoic rocks, with a younging trend in the bedrock towards the southwest. The Archaean and Proterozoic parts form the Fennoscandian shield. The third essential part of Fennoscandia is the Scandinavian Caledonide Mountains (the Caledonides) in the west and north, partially overlying and overprinting the older rocks, but also containing extensive sequences of Palaeozoic rocks. In addition, significant parts of the Kola Peninsula are formed by Devonian intrusions. (Koistinen et al. 2001)

The extensive geological variation of Fennoscandia is equally reflected in the volume and range of types of its mineral deposits. This is a typical feature of all shield areas of the world, such as Western Australia, South Africa, parts of Brazil and Canada, which are all significant metal producers. As expected from the geological context of a Precambrian shield and the Caledonides, Fennoscandia hosts a variety of mineral deposits with significant resources (Figure 1). These include banded iron, mafic to ultramafic intrusion-hosted platinum-palladium, nickel, chromium and vanadium, volcanic-hosted nickel and copper-zinc, orogenic gold, porphyry-type copper-gold, and pegmatite-hosted lithium and tantalum resources. Less common for most of the world are the Kiruna-type iron deposits in northern Sweden, alum shale-hosted uranium-molybdenum-vanadium deposits in Sweden, and the giant peralkaline and carbonatite intrusion-hosted phosphate deposits in the Kola Peninsula region. In addition, Fennoscandia hosts the globally unique Outokumpu copper-cobalt, Talvivaara nickel and Pechenga nickel deposits, which all contain large metal resources. (Weihed et al. 2005, 2008, Fennoscandian Ore Deposit Database 2009, and references therein)

Figure 1. Schematic geological map of Fennoscandia, based on Koistinen et al. (2001), showing the location of major ore deposits.

METALLIC MINE PRODUCTION AND EXPLORATION IN FENNOSCANDIA

Before the industrial revolution, Fennoscandia was already a significant copper and iron producer. Archaeological evidence shows that copper was produced from the Falun mine in the Bergslagen province of Sweden in the 8th century (Eriksson & Qvarfort 1996). During the 16th to 18th centuries, copper and iron mines formed a major basis for the economy of Sweden. During the last 100 years, significant European- and global-scale production of Cu, Ni, Cr and V has taken place in Finland, Cu, Zn and Fe in Sweden, Ti, Cu and Zn in Norway, and Ni, REE, Nb and Ta in the Russian part of the Fennoscandian shield. Another indication of the importance of mining within Fennoscandia is the 412 metal mines that have operated in the region since 1920, and of which 41 are presently active (Fennoscandian Ore Deposit Database 2009). These deposits and their resources provide not just raw materials for the national and European economies, but are also the basis of national mining and metals industries, including companies that presently operate globally but are nevertheless based in Norway, Sweden or Finland. These industries also employ a significant share of the local population in areas with a potentially high degree of unemployment in Northern Europe.

At present, production by European mines is both following the old trends and expanding. In 2007, the Nordic countries (Finland, Norway and Sweden) produced all or nearly all of the Cr, Co, Au, Fe, PGE and Ti, and a significant share of the Cu, Pb, Ni, Ag and Zn mined in the EU (Table 1). Despite this, in 2007 Nordic mines only produced a significant part of the Ti, Cr and Zn consumed by European industries, totalling 31%, 22% and 11%, respectively (Table 1). This reflects the negative raw material balance of the EU (Commission of the European Communities 2008, Brown et al. 2009a).

Table 1. The demand for major and selected minor metals in the world and in the European Union (EU), EU mine production, and the combined Finnish, Norwegian and Swedish mine production, in 2007. Metal tonnages are given in thousands of tonnes. The Fennoscandian production data only includes Finland, Norway and Sweden combined, as no annual production data are available from the Russian part of Fennoscandia. The data are from Euratom Supply Agency (2008), Brown et al. (2009a, 2009b), European Aluminium Association (2009), ICSG (2009), Johnson Matthey (2009), and U.S. Geological Survey (2009).

Metal	World mine production	EU[1] metal demand	EU demand of world production (%)	EU mine production	EU production of EU demand (%)	Fenno-scandian[2] mine production	Fennosc. mine production of EU demand (%)	Fennosc. mine production of EU mine production (%)
Aluminium[3]	38 109	14 000	37	1202	9	0	0	0
Chromite	21 500	2 500	12	556	22	556	22	100
Cobalt	65.5	16	25	0.12	1	0.12	1	100
Copper	15 500	4 053	26	729	18	76.5	2	10
Gold	3.50	1.02	29	0.0112	1	0.0091	1	81
Iron ore[4]	2 043 000	325 422	16	28 266	9	25 344	8	90
Lead	8 085	1 605	20	226	14	63.2	4	28
Lithium	25	6	25	2.19	36	0	0	0
Manganese	12 600	929	7	45	5	0	0	0
Molybdenum	209	85	41	0	0	0	0	0
Nickel	1 660	202	12	31.7	16	3.84	2	12
Niobium[5]	60	nd	nd	0	0	0	0	0
PGE[6]	0.43	0	28	0.001	1	0.001	1	100
REE[7]	128	30	23	0	0	0	0	0
Silver	21.1	5	25	1.71	32	0.34	6	20
Tantalum[5]	0.815	0	35	0	0	0	0	0
Tin	326	84	26	0.041	0	0	0	0
Titanium[8]	4 184	1 440	34	441	31	441	31	100
Tungsten	55	14	25	1.96	15	0	0	0
Uranium	41.3	19	46	1.36	7	0	0	0
Vanadium	56	18	32	0	0	0	0	0
Zinc	10 900	2 268	21	842	37	254	11	30
Zirconium[9]	1 280	290	23	0	0	0	0	0

1) EU includes the EU countries plus Norway in the whole table.
2) Fennoscandia equals Finland + Norway + Sweden in the whole table, because no annual production data exists for the Russian part of the Fennoscandia.
3) EU mine production calculated from bauxite production data assuming 23% Al in bauxite.
4) Iron ore demand = crude steel + pig iron production multiplied by two
5) Niobium and tantalum: a number of countries produce or are assumed to produce Nb and Ta, but that data is not included here, as there is not reliable data available of their production.
6) PGE = platinum + palladium.
7) REE = metal tonnes in rare earth oxides.
8) Titanium as TiO_2. All European production is from Tellnes, Norway.
9) Zirconium as mineral concentrate ($ZrSiO_4$).

A few mines have recently been opened in the region, many existing ones have been or are in the process of increasing production, and a few new ones will be opened by 2012. In Finland, the main new developments include the opening of the Talvivaara nickel and the Suurikuusikko (Kittilä) gold mines (Figure 1), both being the largest in their metal category in Europe. Talvivaara is globally unique in its geological type and in mineral processing. In addition to Ni, it also produces Cu, Co and Zn, and by 2012 possibly also manganese (Mn), and later even uranium. By 2012, the new Kevitsa nickel and Kylylahti cobalt-copper mines are also expected to be in full production, and production of the Kemi Cr mine will have significantly increased. Furthermore, a large phosphate deposit at Sokli may be developed into a mine within a few years.

In Sweden, the major developments include the doubling of production at the huge Aitik Cu mine, a major rise in iron ore production from the Kiruna and Malmberget mines, the opening of a new iron mine at Pajala, reopening of the old Dannemora iron mine, and increasing base metal production at the Skellefte Belt mines. The iron ore project at Pajala also includes processing and future mining operations across the border at Kolari in Finland.

In Norway, the world's largest ilmenite mine, Tellnes, seems to be continuing with stable titanium oxide production (Tables 1 and 2), while the old Bjørnevatn iron mine was reopened in 2009. All the above-mentioned developments are included in the Nordic production data in Table 2. Less clear, due to the lack of available information, is whether there will be changes in metals production in the Russian part of Fennoscandia. Any major changes in production by the very large Pechenga nickel or the Kola Peninsula phosphate-REE-Ta-Nb mines would have a big effect on the total Fennoscandian contribution to European consumption and, for the REE, Nb and Ta, perhaps even for the global supply.

Overall, the planned increases in mine production in Finland and Sweden by 2012 will have the most dramatic effect on the total EU mine production of Cr, Co and Ni, and possibly also of Li and Mn. These changes will significantly reduce the EU dependence on imports of Cr, Co and Ni (compare Tables 1 and 2).

Recent mine developments in Fennoscandia also indicate the production potential of other metals than those listed above, and show that potentially exploitable mineral resources also occur beyond the very large deposits. Examples include the small presently operating gold mines of Jokisivu and Kutemajärvi in southern Finland, the Pampalo gold mine under construction in easternmost Finland, the operating Björkdal and Svartliden gold mines near the Skellefte Belt in northern Sweden, and the plans to open small lithium (± tantalum) and gold mines in central western Finland, at Kälviä. Other such indications are the ongoing nickel exploration at Suomussalmi and Sodankylä in Finland, gold exploration within the Gold Line and uranium exploration in alum shales in Sweden, copper-zinc exploration in central Norway, and gold exploration at Karasjok (Norway) and Kittilä (Finland).

Table 2. Estimates for the metal demand in 2012 in the world and in the European Union (EU), EU mine production, and the combined Finnish, Norwegian and Swedish mine production. Metal tonnages are given in thousands of tonnes; total figures are rounded due to uncertainties in the data. The data are from Euratom Supply Agency (2008), Brown et al. (2009a, 2009b), Buchert et al. (2009), U.S. Geological Survey (2009), SGU (2009), and mining company press releases and company Internet pages.

Metal	World mine production	EU[1] demand	Fenno-scandian mine production[2]	Fennosc. mine production of EU demand (%)	EU mine production	Fennosc. mine production of EU mine production (%)
Aluminium[3]	45 000	16 500	0	0	1400	0
Chromite	25 000	2 900	1000	40	1000	100
Cobalt	72	18	5.4	33	5.4	100
Copper	20 000	5 200	187	5	950	20
Gold	3.50	1.0	0.067	7	0.078	86
Iron ore	2 200 000	350 000	36 900	11	39000	95
Lead	9 000	1 800	74	5	250	30
Lithium	31	7.7	0.75	12	2.7	27
Manganese[4]	13 000	960	30	3	46	65
Molybdenum	220	90	0	0	0	0
Nickel	1 800	220	54	27	85	63
Niobium[5]	75	nd	0	0	0	0
PGE[6]	0.49	0.14	0.002	2	0.002	100
REE[7]	179	42	0	0	0	0
Silver	22	5.6	0.28	5	1.8	16
Tantalum[5]	0.98	0.35	0.0114	4	0.011	100
Tin	375	100	0	0	0.050	0
Titanium[8]	4 800	1 600	440	31	440	100
Tungsten	65	16	0	0	2.3	0
Uranium	42	20	0	0	1.4	0
Vanadium	62	20	0	0	0	0
Zinc	12 000	2 500	330	15	1050	31
Zirconium[9]	2 000	450	0	0	0	0

1) EU includes the EU countries plus Norway in the whole table. EU production and demand 2012 estimated as if their increase is at the same degree as estimated for the world production, except the production further adjusted according to significant increases (from 2007) in planned production in Finland, Norway and Sweden for Cr, Cu, Au, Fe, Ni, PGE, and Zn.
2) Fennoscandia equals Finland + Norway + Sweden in the whole table; the 2012 production estimates are from mining company web pages and press releases; the primary references are available at request.
3) EU mine production calculated from bauxite production data assuming 23% Al in bauxite.
4) Mn production in Fennoscandia is estimated as if Talvivaara would start to produce Mn.
5) Niobium and tantalum: a number of countries produce or are assumed to produce Nb and Ta, but that data is not included here, as there is not reliable data available of their productiion.
6) PGE = platinum + palladium.
7) REE = metal tonnes in rare earth oxides.
8) Titanium as TiO_2. All European production is from Tellnes, Norway.
9) Zirconium as mineral concentrate ($ZrSiO_4$).

KNOWN REMAINING METAL RESOURCES IN FENNOSCANDIA

The Fennoscandian Ore Deposit Database (2009) indicates that very large mineral resources still remain unexploited in the region. Most of these are in the presently active mines and in large unexploited deposits, as summarised in Table 3. If all the known and estimated Fennoscandian mineral resources were put into production, they would cover more than 50 years of 2007 EU consumption of Cr, Li, Ni, REE, Ta, Ti, V, and probably also of Nb, and 10–30 years of consumption of iron ore, Co, PGE, and U (Figure 2). For the rest of the metals discussed here, the situation is challenging. There are large numbers of mines and unexploited deposits of many metals, but the known Cu, Au, Mn, Mo, Ag, Zn and Zr resources could only cover a few years of EU demand or, for Al, Au, Pb, Sn, and W, the resources are quite small compared to EU consumption or even non-existent. Despite this, even the latter two sets of metals include commodities whose production is significant, at least at the regional level, as exemplified by the Suurikuusikko gold mine in Finland and the Zinkgruvan and Skellefte Belt zinc-copper-gold mines in Sweden, belonging to the category of large deposits and providing significant employment to local people.

Table 3. The presently known metallic mineral resources of Fennoscandia (Finland, Norway, Sweden, and NW Russia) in active mines, large closed mines, and in large unexploited deposits. Resources at the end of 2008, according to Fennoscandian Ore Deposit Database (2009) and references therein. All figures are given in thousands of tonnes; total figures are rounded due to uncertainties in especially the category 'potentially large'.

Metal[1]	Active mines, remaining resource	Large closed mines, remaining resource	Large[2] unexploited deposits	Potentially large[2] unexploited deposits	Total
Aluminium	0	0	0	0	0
Chromite	30 990	0	105 800	16 000	153 000
Cobalt	378	26	94	22	520
Copper	8 653	1 142	3 150	2 700	15 700
Gold	0.66	0.026	1.98	0.16	2.8
Iron ore	5 642 700	372 430	2 096 170	674 000	8 790 000
Lead	910	0	0	0	910
Lithium	0	0	1 200	0	1 200
Manganese	3 012	1 079	0	0	4 090
Molybdenum	0	0	190	410	600
Nickel	6 946	703	10 800	5 500	24 000
Niobium	418	0	3 820	650	4 890
PGE	0.049	0.0011	1.7	0.9	2.7
REE	10 313	0	10 200	150	20 700
Silver	12	0.04	0.16	1.4	14
Tantalum	33	0	303	51	387
Tin	0	0	0	5.7	5.7
Titanium	74 862	3 891	236 000	140 000	455 000
Tungsten	0	0	0	0	0
Uranium	0	0	0	350	350
Vanadium	0	89	4 012	2 400	6 500
Zinc	8 458	91	38	0	8 600
Zircon	1 566	0	0	1 260	2 800
N[3]	41	10	52	56	160

1) Metals are given as in Tables 1 and 2.
2) A large deposit is one which contains more than equivalent to 600,000 t copper, as defined by, for example, Lafitte (1984) and Saltikoff et al. (2000). The category 'Potentially large' is used for such cases where the tonnage and/or grade data are of lower quality, but still indicate that the deposit most probably is large.
3) N = number of known deposits.

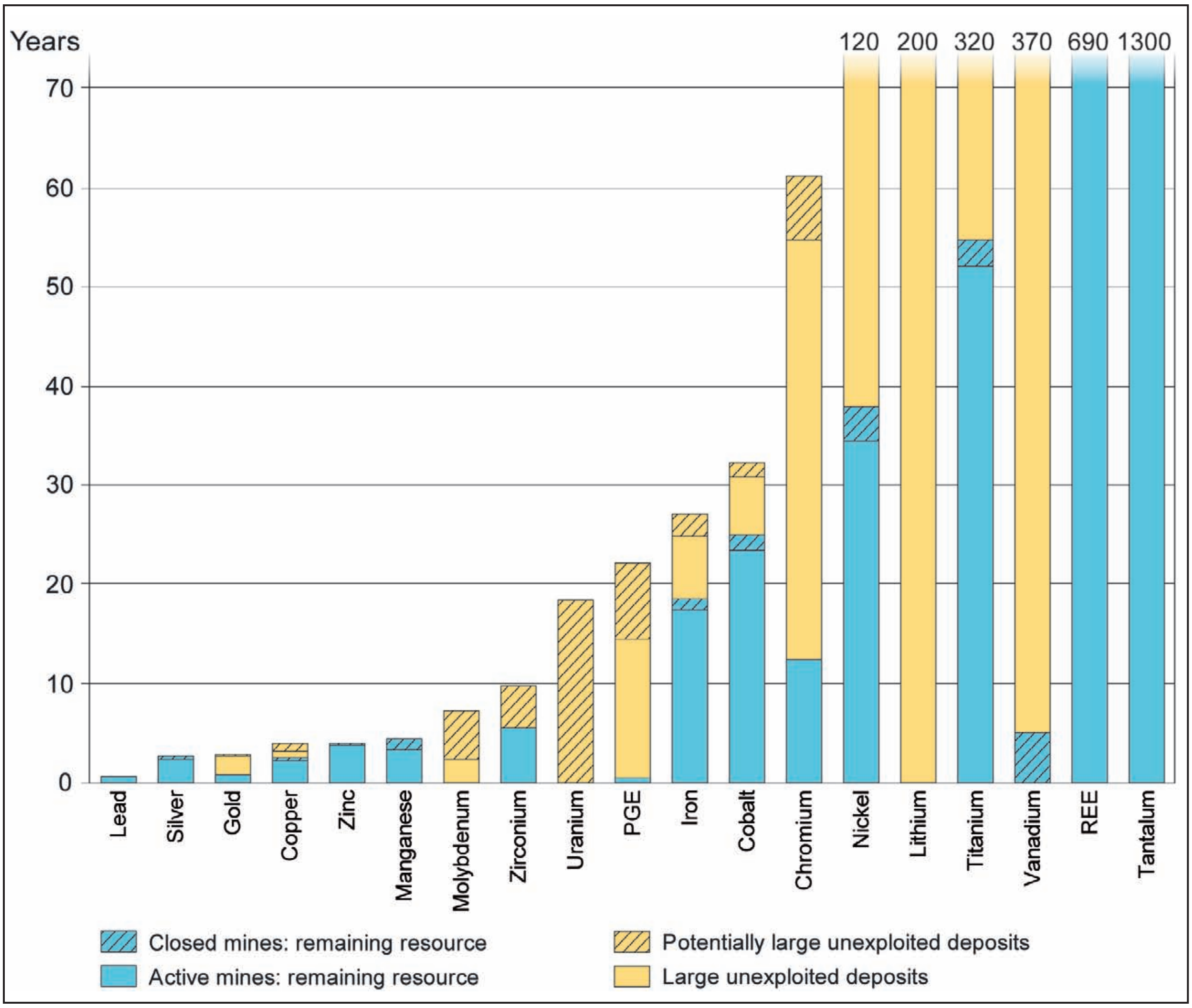

Figure 2. Histogram indicating how many years of EU consumption, at the 2007 level (Table 1), the presently known mineral resources of Fennoscandia (Finland, Norway, Sweden, and NW Russia; Table 3) could potentially cover. Note that aluminium, tin and tungsten are not included, as there are no known resources in these deposit categories in Fennoscandia. Niobium is excluded, as the EU consumption is not known; however, the global data (U.S. Geological Survey 2009) suggest that the Nb resource base of Fennoscandia would probably cover as much of EU consumption as those of Ta and REE.

CONCLUSIONS

Fennoscandia has been, presently is, and in the future seems likely to continue as a significant metal-producing region in Europe. In the global context, only titanium production is at present notably significant, whereas in terms of EU consumption, chromium, cobalt, iron ore, lithium, nickel and zinc production from the Fennoscandian mines is also significant. Fennoscandia also has large resources of a number of metals. The presently known and estimated Cr, Li, Nb(?), Ni, REE, Ta, Ti, and V could potentially cover more than 50 years of EU demand at the 2007 consumption level. Similarly, iron ore, Co, PGE, and U reserves would cover 10–30 years of EU demand if all metals in the presently active mines and unexploited large deposits could be exploited. These figures indicate the importance of Fennoscandian mineral production and metal resources for manufacturing and other industries of the EU and the nations of Fennoscandia. In the future, mining could be even more significant for the national economies of the Nordic countries than it is today. In rural regions of northern and eastern Fennoscandia, with few industrial opportunities, deposits with relatively small resources in the global or European context (e.g. Cu, Au, and Zn) could also be very important, if only such resources could be economically exploited.

The large size and extensive metal range of the mineral resources of Fennoscandia are explained by the complex and very long plate-tectonic evolution of the crust of the Earth in the region. Extensive Precambrian and Caledonian supracrustal and intrusive rocks and Devonian intrusions, formed in major rift and orogenic settings, comprise not only most of the bedrock of Northern Europe but also host all of its mineral resources. These include mineral deposits of both globally common types, such as volcanic-hosted copper-zinc, orogenic gold, and mafic intrusion-hosted nickel and platinum-palladium, but also the unique Talvivaara nickel, Pechenga nickel and Outokumpu copper-cobalt deposit types. These are the ultimate geological reasons why Fennoscandia is and will remain a significant metal supplier for the whole of Europe and especially for the European Union.

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TECTONIC AND METALLOGENIC EVOLUTION OF THE FENNOSCANDIAN SHIELD: KEY QUESTIONS WITH EMPHASIS ON FINLAND

by
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The Fennoscandian Shield is the largest exposed area of Precambrian rocks in Europe and shares many similarities with the ancient shields in Canada, Australia and South Africa, which are all globally significant for their mineral resources. The Fennoscandian Shield is likewise an important metal supplier and a resource base in the European context. We will not aim here at a complete review of the tectonic and metallogenic evolution of the Fennoscandian Shield, but instead focus on some interrelated key aspects and questions concerning Archaean and Palaeoproterozoic evolution, plate boundaries and metallogeny. Tectonic and metallogenic modelling is considered as a framework for understanding ore-forming systems and also as a more detailed conceptual tool needed for mineral exploration.

The description of the geological history of the Shield is divided into Archaean evolution and Palaeoproterozoic rifting and orogenic stages. More data are needed to resolve the accretionary history and metallogenic epochs of the Archaean bedrock in Fennoscandia and to explain its relatively unmineralised nature. One important observation is the apparent lack of pre-2.75 Ga subduction-related rocks, suggesting that appropriate geodynamic environments, for example for orogenic gold, were absent earlier in the Archaean. In contrast, komatiite-hosted nickel, now preserved in volcanic belts, may favour the prevalence of extensional processes unrelated to subduction, at least during earlier stages of evolution

The main Palaeoproterozoic rifting events that affected the Archaean craton commenced with intraplate rifting between 2.50–2.10 Ga, ca. 2.06 Ga drifting and separation of the cratonic components, and 1.95 Ga rifting, ultimately leading to the exhumation of Archaean subcontinental lithospheric mantle. These extensional events were very important metallogenic events, as most of the large chromium, platinum group element, nickel, copper and cobalt resources in Finland are found from these units. Many unresolved questions are still open related to the correlation of these units between different regions, the age of deposition and the nature of ore-forming processes, e.g. in the giant Talvivaara nickel-cobalt-copper-zinc deposit.

Two major Palaeoproterozoic orogens in the Fennoscandian Shield are the Lapland-Kola orogen (1.94–1.86 Ga) and the composite Svecofennian orogen (1.92–1.79 Ga), tentatively divided into four overlapping orogens. Economic ore deposits include volcanogenic massive sulphide, porphyry-type copper-gold, epithermal gold, magnetite-apatite, iron oxide-copper-gold, orogenic nickel-copper and gold deposits in Finland, the most important are the volcanogenic massive sulphide zinc-copper and orogenic gold deposits. Although increasing amounts of new data have allowed us to separate new events and delineate areas with different evolution histories, the complicated and overlapping character of Palaeoproterozoic evolution still remains as an ongoing challenge. This article should not be considered a comprehensive review of the tectonic and metallogenic evolution of the Fennoscandian shield, as it omits many important aspects such as the metallogeny of high-tech metals (Li, Nb, REE etc.), uranium and others. We also have left out, for example, the voluminous rapakivi granites and totally neglected all formations and tectonic features younger than the Palaeoproterozoic.

Keywords (GeoRef Thesaurus, AGI): tectonics, rifting, orogenic belts, metallogeny, Fennoscandian Shield, Paleoproterozoic, Archean, Fennoscandia, Finland

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INTRODUCTION

The Fennoscandian Shield forms the north-westernmost part of the East European Craton and constitutes large parts of Finland, NW Russia, Norway, and Sweden (Figure 1). Within the shield, Archaean crust dominates in the east, Palaeoproterozoic Svecofennian crust in the centre, and Mesoproterozoic rocks are found in the southwest. The Archaean domain has variable amounts of Palaeoproterozoic components, either as accreted terranes or deformed-metamorphosed zones of cover rocks. The Archaean cratonic nucleus of the shield experienced several major Palaeoproterozoic intraplate rifting events between 2.50–2.10 Ga, and c. 2.06 Ga drifting and separation of the cratonic components. The 1.95 Ga Jormua-Outokumpu ancient seafloor (ophiolites) also comprises a unique example of Archaean subcontinental lithospheric mantle. The Palaeoproterozoic era was the most important crust-forming period in the Fennoscandian Shield; the Svecofennian province forms the largest Palaeoproterozoic unit, further divided into sub-units. Younger Meso- and Neoproterozoic crustal growth mainly took place in the western part.

The Fennoscandian Shield is an important metal supplier and a resource base in the European context (Eilu, this volume). Despite hundreds of years of exploration, new deposits are still being found, even close to the surface (< 50 m), and indeed, because of extensive, poorly exposed glaciated terrains, most of the regions are still underexplored. In addition, increasing world demand and prices have turned deposits that were previously sub-economic resources into economically viable reserves. New processing techniques have also made earlier sub-economic deposits become economic ores, e.g. in Talvivaara.

Tectonic and metallogenic models provide a framework for understanding ore-forming systems, and also a more detailed conceptual tool needed for mineral exploration. Crustal and lithospheric boundaries, especially those with preserved rift sequences, are important in focusing ore-bearing fluids to form major deposits, and the nature of boundaries and their tectonic amalgamation history are therefore key elements in large-scale targeting. Knowledge of geological processes and their crustal architecture is essential in understanding ore-forming systems and in carrying out exploration at greater depths.

We have to keep in mind that only fragmented and selective parts of the evolution are preserved, and that with the help of surface observations and a few drillings (normally < 500 m) we can directly observe only << 1% of the crust; all the other interpretations are based on indirect observations. On the other hand, an exceptionally dense coverage of high-quality geophysical (Airo et al., this volume) and geochemical databases in Finland, as well as good geological mapping data combined with voluminous age and isotopical data (Huhma et al., this volume) make the Fennoscandian Shield one of the best-known Precambrian regions in the world. Many of the major ore camps have also been studied in detail by high-resolution seismic methods (Kukkonen et al., this volume).

Although tectonic and metallogenic models for the Fennoscandian Shield have evolved through time (e.g. Hietanen 1975, Gaál & Gorbatschev 1987, Gorbatschev & Bogdanova 1993, Lahtinen et al. 2005, Weihed et al. 2005), many competing models still exist, reflecting the limited amount of direct geological data restricted to the surface or near surface. Consequently, many models are, at least in parts, necessarily rather conceptual in nature, as many alternative interpretations can be presented and do exist. Despite these difficulties, tectonic and metallogenic modelling is useful in creating testable hypotheses to obtain a better understanding of the geological processes that lead to the formation of mineral occurrences. We will briefly discuss here some aspects related to the tectonic and metallogenic modelling of the Fennoscandian Shield, focusing on major ore forming processes during the Archaean and Palaeoproterozoic, especially in Finland. If not otherwise stated, the text refers to the book "Precambrian geology of Finland" by Lehtinen et al. (2005), the article by Weihed et al. (2005) and the Fennoscandian Ore Deposit Database and map (Eilu et al. 2008).

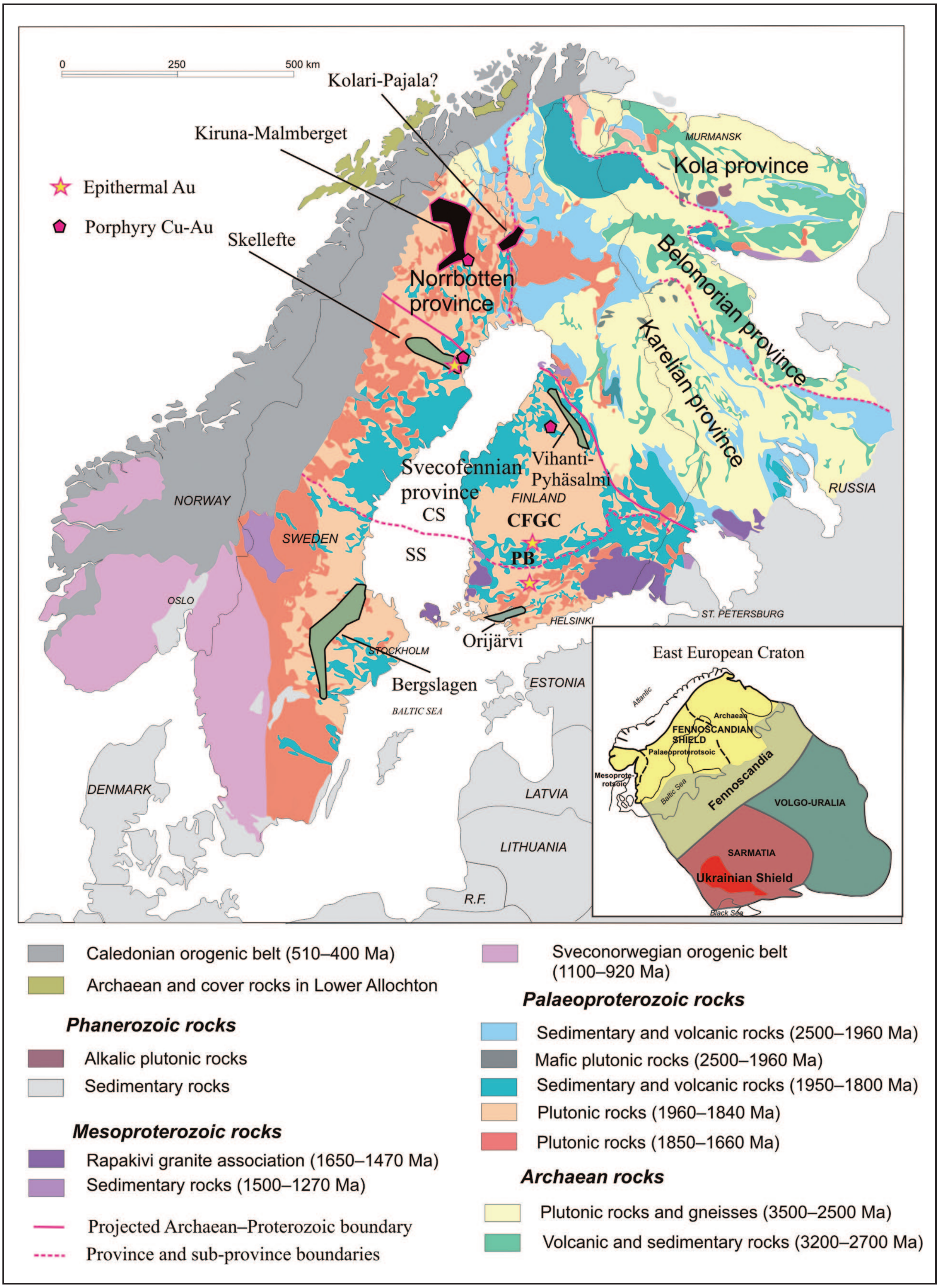

Figure 1. Simplified geological map based on Koistinen et al. (2001) and insert map based on Gorbatschev and Bogdanova (1993). Selected main arc-related metallogenic areas and metal occurrences are indicated (olive green and black). Subareas: CS – Central Svecofennian; SS – Southern Svecofennian. Areas: CFGC – Central Finland Granitoid Complex; PB – Pirkanmaa belt.

ARCHAEAN

The Archaean Earth was different from modern Earth, as the tectonic interactions between segments of the lithosphere and melt-generating mantle processes were affected by secular change caused by the exponential decline of the Earth's radiogenic heat production. The conditions in the world oceans and atmosphere were probably also drastically different from the present ones, primarily because of an anoxic atmosphere. A characteristic feature of the Archaean crust is the occurrence of ultramafic volcanic rocks, komatiites, combined with the overall felsic nature of the crust, dominated by the voluminous occurrence of tonalites, trondjemites and granodiorites (TTG). One possibility for the tectonic evolution in the Archaean is a secular or step-wise change from plume-dominated processes towards more subduction-type processes in continental crust generation. The Neoarchaean ophiolite-like rocks and eclogites in the Belomorian province are possibly examples of the first Phanerozoic-style subduction and collision (Figures 1 and 2; Hölttä et al. 2008).

In Finland, the Archaean can be divided into TTG-type complexes, often migmatitic, and few major supracrustal belts: Oijärvi, Kuhmo-Suomussalmi ja Ilomantsi (Figure 2). The present still rather unevenly distributed isotopic data suggest there are only some small older (> 2.9 Ga) domains within the TTG complexes, which predominantly appear to be 2.7–2.8 Ga in age. However, there is increasing evidence that 2.9–3.2 Ga components within the gneissic complexes may be more common than is currently believed. Only some sporadic mineral occurrences of Mo and Ni have been found in the TTG-dominated complexes. The Oijärvi and Kuhmo-Suomussalmi volcano-sedimentary belts are predominantly c. 2.8 Ga in age and probably formed in within-plate, probably oceanic, environments, whereas the Ilomantsi volcanic-sedimentary belt is younger (c. 2.75 Ga) and shows arc-type characteristics.

Unlike some other Archaean areas, the volcanic belts of the Fennoscandian Shield so far only include a few discovered occurrences of komatiite-hosted nickel-copper sulphides. There are some in the Central Karelian and Vodlozero terranes and one occurrence in the Norrbotten province (Figure 2). No significant volcanogenic massive sulphide deposit is known. A few orogenic gold occurrences have been identified, most of them in the Ilomantsi belt in Finland (Figure 2). The number of economically exploited gold deposits is still very low compared to some other Archaean cratons; c. 5000 known occurrences in Zimbabwe craton, for example. A major period of gold mineralization probably occurred between 2.72 to 2.67 Ga, but Palaeoproterozoic enrichment or a mineralizing event cannot be excluded in some cases. An Archaean carbonatite, intruded in an anorogenic setting at 2.6 Ga, exemplifies the end of Archaean activity in Finland. It hosts a major apatite mine in central Finland.

We still have only vague ideas about what was the main crust-forming mechanism responsible for the growth of the Archaean bedrock in Fennoscandia. Some important open questions are:

- Was there some difference compared to other Archaean segments in the world to explain the relatively unmineralized nature?
- Can these differences be explained by deeper erosion due to stronger Proterozoic reworking?
- Is the Archaean bedrock in Fennoscandia simply underexplored?
- What happened during the Palaeo- and Mesoarchaean?
- Why are the occurrences of these older rocks apparently only sporadic and scattered?
- Are the gneissic tonalite-trondhjemite-granodiorite (TTG) complexes more varied for their age structure than is presently assumed?
- Are there any undiscovered, special metallogenic features related to these older stages?
- One important point is the apparent lack of pre-2.75 Ga subduction-related rocks.

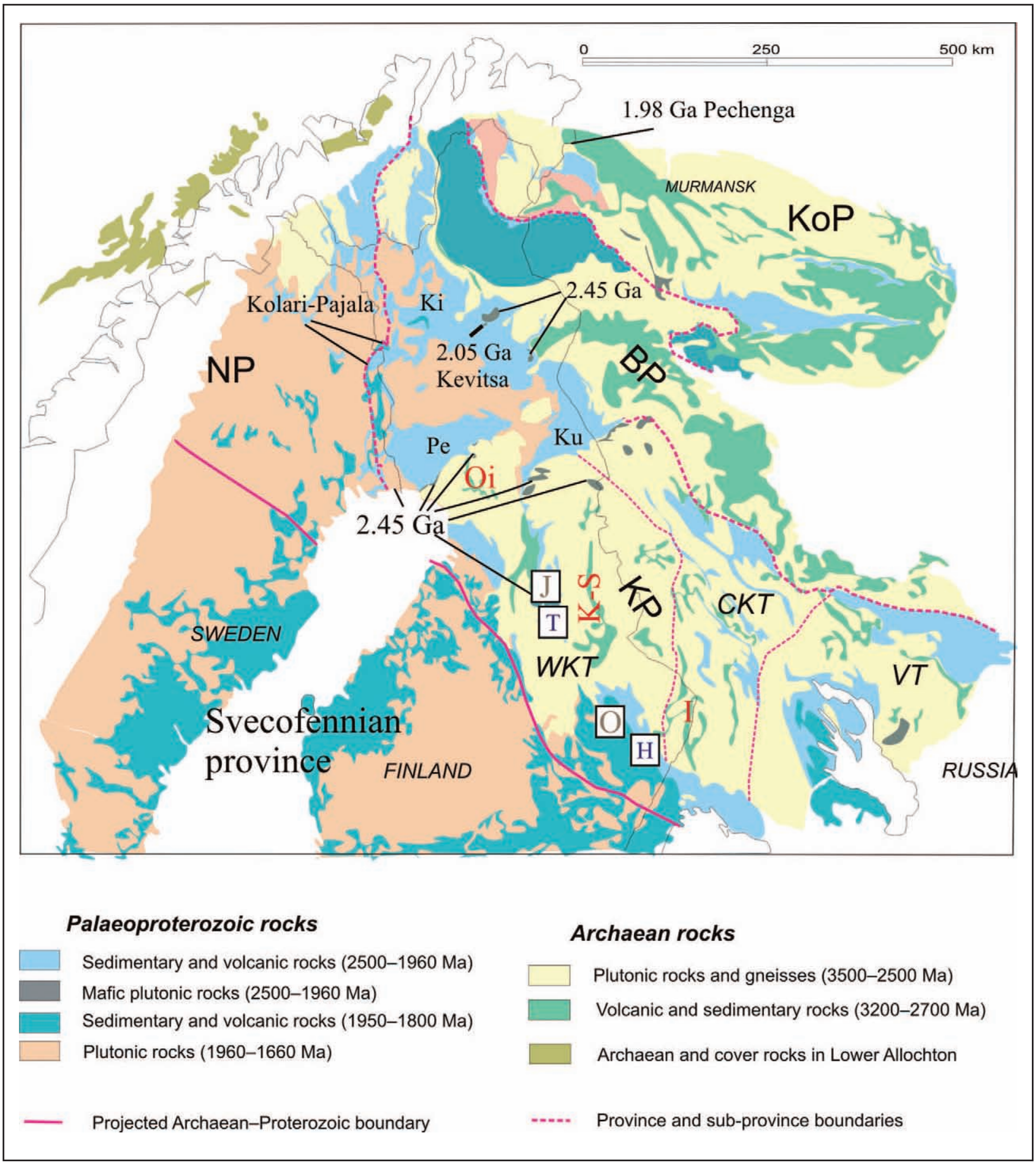

Figure 2. Simplified geological map based on Koistinen et al. (2001) with a focus on Archaean (Hölttä et al. 2008) and Palaeoproterozoic rift-related units. Provinces: NP – Norrbotten province; KP – Karelian province; BP – Belomorian province; KoP – Kola province. Subareas: WKT – Western Karelia terrane; CKT – Central Karelia terrane; VT – Vodlozero terrane. Archaean belts: Oi – Oijärvi; K-S – Kuhmo-Suomussalmi; I – Ilomantsi. Palaeoproterozoic belts: Pe – Peräpohja; Ku – Kuusamo; Ki – Kittilä. Locations: H – Hammaslahti; T – Talvivaara; J – Jormua; O – Outokumpu.

PALAEOPROTEROZOIC RIFTING STAGES

Rifting of the Archaean continent or continents contained in the Fennoscandian shield began in northeastern Fennoscandia and became widespread after the emplacement of 2.50–2.44 Ga, plume-related, layered gabbro-norite intrusions and dyke swarms. These intrusive complexes host major chromium, nickel-copper and platinum group element deposits, including the world-class Kemi chromium mine and Suhanko platinum group element deposits in Finland. The southern branch of c. 2.45 Ga layered intrusions in Finland (Figure 2) seems to have formed a continuous chain, which was later fragmented and transported during younger Palaeoproterozoic movements. Combined with the northern c. 2.45 Ga layered intrusions, these could have formed the edges of a presently west-trending aulacogen. If so, a major question lies in the nature of the boundary between the Norrbotten and Karelian provinces. Does it mark an adjacent continental margin with the proposed aulacogen at 2.45 Ga, or was that margin located more to the west and does the province boundary represent a possible younger event? Presently, we do not know of any 2.45 Ga rocks along the boundary, but of course they could be concealed under younger rocks.

Rifting events at 2.4–2.1 Ga are associated with mostly tholeiitic mafic dykes and sills, sporadic volcanism and typically fluvial to shallow-water sedimentary rocks. It is not clear whether the absence of 2.4–2.1 Ga deep-water sediments in Finland is due to erosional removal or if that period was indeed characterized only by intra-continental rift basins with terrestrial to shallow marine sedimentation and volcanism. Some indications of copper ± gold mineralizations are found in rocks of this time period in the Peräpohja and Kuusamo belts (Figure 2), but it is still somewhat unclear whether synsedimentary processes were important for the ore genesis.

The predominantly psephite-psammite hosted Hammaslahti copper-zinc deposit is possibly related to c. 2.1 Ga rifting, which was associated with tholeiitic volcanism and deep-water sediments. There is still some controversy about its origin; models discuss a syn-genetic exhalative/inhalative origin or ore formation being related to later tectonic and metamorphic processes. The giant black schist-associated Talvivaara nickel-cobalt-copper-zinc deposit also occurs in a Palaeoproterozoic continental rift basin that lacks any intercalated or nearby extruded volcanic rocks. In terms of metal association and ratios, Talvivaara is similar to Phanerozoic black shales with strong redox-controlled metal enrichment, but the age (2.05–1.90 Ga) and ore-forming processes are still uncertain. Moderate concentrations of molybdenum, uranium and vanadium in Talvivaara black shales provide strong evidence that free oxygen already existed in the Earth's atmosphere at c 2.0 Ga. The Hammaslahti and Talvivaara cases are currently being studied by GTK and a plethora of new data will be published in the near future.

Along the present western edge of the Karelian province, 2.05 Ga bimodal felsic-mafic volcanics of alkaline-affinity intercalated with deep-water turbiditic sediments are found. No economic mineralizations have been yet found in this association, but there are some rare earth element–niobium showings in correlative alkaline anorogenic-type granitoids. Close to these alkaline granitoids occurs the c. 2.06 Ga Otanmäki iron-titanium-vanadium deposit in mafic plutonic rocks. The 2.05 Ga Kevitsa mafic intrusion in Lapland (Figure 2) contains platinum group element-rich copper-nickel sulphides, but its relation to the above-discussed alkaline rocks/tectonic event remains to be studied. In addition, 2.05 Ga komatiites and picrites with nickel-copper potential have been found in central Lapland, but their economic significance remains to be proven.

There are still many open questions related to the 2.1–2.0 Ga stage, such as whether the rocks in central Lapland could be correlated with rocks hosting the Talvivaara and Hammaslahti deposits. The regional extent and tectonic significance of the 1.98 Ga bimodal alkaline-tholeiitic magmatism in central Lapland (Hanski et al. 2005) is also an open issue. The Pechenga-type Ni-Cu deposits (Figure 2) are rift-related and also c. 1.98 Ga in age, and it remains open whether they have any relation to the above-mentioned rocks in Finland.

No clear examples of subduction-related magmatism aged between 2.5 and 2.1 Ga has been found in the Fennoscandian Shield. The 2.02 Ga felsic volcanic rocks in Kittilä (Figure 2) occur in association with oceanic island arc-type rocks and are the oldest candidates for Palaeoproterozoic subduction-related rocks in the Fennoscandian Shield. A major problem is how the adjacent within-plate character volcanic rocks are related to the oceanic island arc-type rocks in Kittilä. Do they record continental rifting (Karelian craton), leading to the opening of an ocean in which the arc-type volcanics were erupted? If they are parautochthonous, a correlation with the carbonaceous and sulphidic shales should also be considered. The major problem is the provenance of the Kittilä primitive arc rocks. They are presently located within thrust units that include fragments of serpentinized mantle peridotites, but it is not clear whether they record ocean basin closure close to their present position or represent far-travelled thrust sheets of uncertain provenance. If some of the Kittilä volcanics are arc-related, then why are there no associated volcanogenic massive sulphide deposits, or are they yet to be found?

The Jormua-Outokumpu ophiolites (Figure 2) are a unique example of Archaean subcontinental lithospheric mantle with a thin veneer of 1.95 Ga oceanic crust. A related question still open to debate is their tectonic interpretation; do they record a continental break-up and subsequent formation of a passive margin, or do they represent a rift within an already existing passive margin generated at 2.05 Ga? The associated Outokumpu-type, massive-semimassive copper-cobalt ores have been and still are an important potential source for these metals. Their genesis has recently been revisited in detail (Peltonen et al. 2008). A major practical question is why similar ores have not been found in Jormua, and whether potential Outokumpu-type deposits exist elsewhere in Finland. The ophiolite-like rocks in the Kittilä area could perhaps be considered, but no indications have so far been found.

PALAEOPROTEROZOIC OROGENIC STAGES

The 2.02 Ga volcanic rocks in Kittilä discussed briefly above, 1.98–1.96 Ga arc magmatism in Kola, 1.95 Ga supracrustal rocks and granitoids south of Skellefte, and the 1.93–1.92 Ga island arc rocks in the Savo belt (Figures 1 and 3) are the oldest yet defined Palaeoproterozoic arc rocks. However, the existence has been proposed of still older 2.1–2.0 Ga lithosphere as buried microcontinents in the Svecofennian domain (e.g. Keitele in Figure 3). The main Palaeoproterozoic orogens in the Fennoscandian Shield are the Lapland-Kola orogen (1.94–1.86 Ga) and the composite Svecofennian orogen (1.92–1.79 Ga). The latter has tentatively been divided into four orogens temporally overlapping towards their end phases and named as the Lapland-Savo, Fennian, Svecobaltic and Nordic orogens.

The Lapland-Kola orogen in the north (Figure 3) is a large and wide orogenic root of a mountain belt mainly comprising reworked Archaean crust. It has many similarities to c. 1.9 Ga orogens, such as the Trans-Hudson orogen, which formed due to a collision between two Archean continents, with only a limited amount of juvenile crust preserved. The main open questions are the number of sutures and colliding systems, the amount and nature of the eroded material, and what rock sequences in central Lapland were juxtaposed during the collision. From the metallogenic point of view, this segment seems to be almost barren, but some gold mineralizations have apparently been formed or relocated due to thermal and structural effects

The composite Svecofennian orogen involved the voluminous addition of new crust. It is proposed to comprise 2.1–2.0 Ga microcontinents with unknown prior evolutionary histories, juvenile arcs formed from >2.02 to ~ 1.8 Ga, and Andean-type magmatic additions at 1.89 and 1.8 Ga. One challenge in studying a hot orogen like the composite Svecofennian orogen is to delineate the collisional plate boundaries, or sutures, within the orogen. One possible example of such a suture occurs in the Pirkanmaa belt (Figure 1), which is interpreted as a combination of a fore-arc and an accretionary wedge that was formed at a rifted continental margin. The 1.86–1.85 Ga mature sedimentary rocks (arenites, arkoses and pelites) in southern Finland and central Sweden are problematic, as they record strong chemical weathering in the source area and a non-orogenic, or even cratonic environment. The c. 1.8 Ga NE-SW directed Nordic orogen (Figure 3) crosscutting the E-W and SSW-ENE directed Fennian and Svecobaltic orogens, was formed either due to a continent-continent collision between newly established Fennoscandia and another continent in the south, or as an advancing Andean-type accretionary orogen.

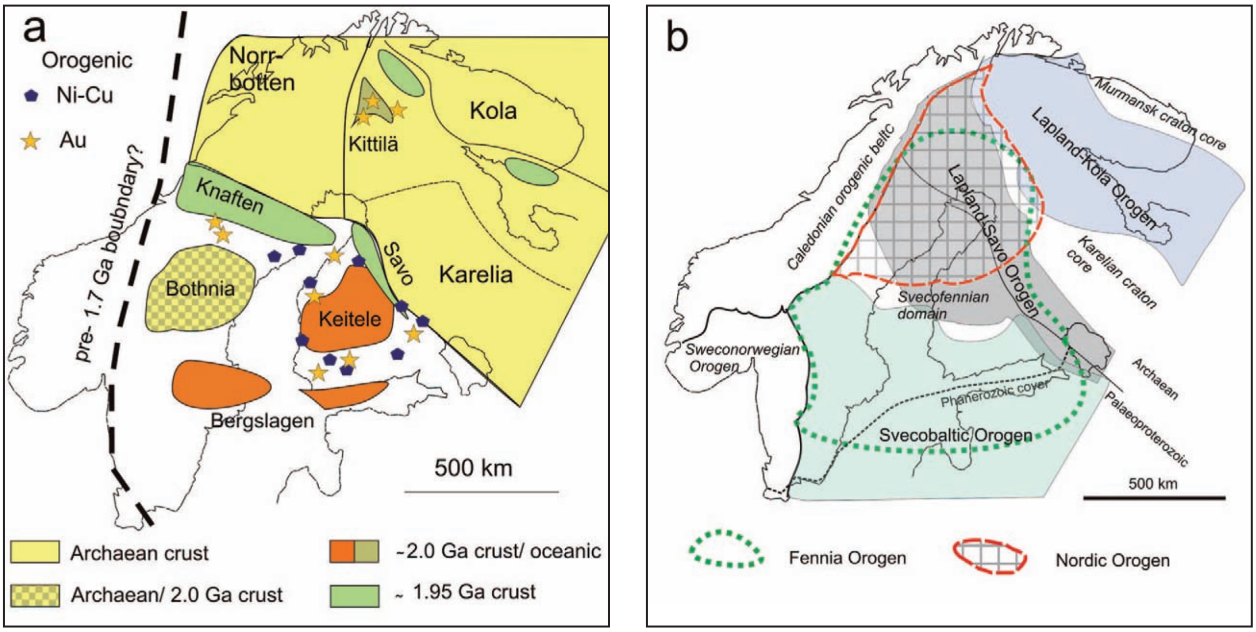

Figure 3. a) Hidden and exposed microcontinental nuclei and arcs older than 1.92 Ga, modified after Lahtinen et al. (2005). Selected Palaeoproterozoic orogenic Ni-Cu and Au occurrences and deposits are shown. b) Major Palaeoproterozoic orogens in Fennoscandia modified after Lahtinen et al. (2009).

Economic ore deposits formed at 1.92–1.80 Ga include volcanogenic massive sulphide, porphyry-type copper–gold, epithermal gold, magnetite-apatite, iron oxide-copper-gold, orogenic nickel-copper and gold deposits. Three identified zones of volcanogenic massive sulphide deposits stand out: Pyhäsalmi-Vihanti, Skellefte and Bergslagen, all with different ages and geodynamic characters. The older (1.92 Ga) Pyhäsalmi-Vihanti-type (Figure 1) deposits occur solely in Finland. The Skellefte-type deposits (c. 1.89 Ga) in Sweden have an inferred continuation to Finland, west of the Pyhäsalmi-Vihanti area, which remains to be verified. It is also not entirely clear whether the Pyhäsalmi and Vihanti-type ores are actually similar in age and genesis. The dominantly calc-silicate and dolomite-hosted Vihanti may be a replacement type deposit and slightly younger.

The Bergslagen area hosts volcanogenic massive sulphide and also iron oxide ± manganese ± apatite deposits. Whereas the Skellefte volcanogenic massive sulphide deposits mainly formed on mature arc crust (compare Figures 1 and 3), the volcanogenic massive sulphide deposits in the Bergslagen–Uusimaa region, similar in age to the Skellefte deposits, formed in an intra-continental, or active continental margin back-arc setting. Such a continental or Andean-type nature perhaps explains the occurrence of magmatic ± hydrothermal magnetite-apatite deposits. Economically very important magnetite-apatite deposits occur in the Kiruna-Malmberget area (Figure 1), where they are linked with a c. 1.89 Ga active continental margin back-arc setting, similar to the situation in the Andes.

The volcanogenic massive sulphide-type deposits are also found in the Orijärvi area in Finland (Figure 1), but it remains open why these are small and why magnetite-apatite deposits are absent from Finland. Few examples of metamorphosed epithermal gold and porphyry copper-gold deposits occur in association with arc-type rocks (Figure 1). It is notable that the large Central Finland Granitoid Complex (Figure 1) contains dominant 1.89–1.88 Ga calc-alkaline to alkaline granitoids and enclaves of subvolcanic and volcanic rocks, and has an active continental margin affinity, but almost no established metallic mineral occurrences of economic interest.

Orogenic nickel-copper deposits in mafi c-ultramafi c intrusions have been identifi ed in two major zones in Finland and one in Sweden, all of which are located in inferred sutures (Figure 3a). It is considered that deep structures along plate boundaries are ideal pathways for primitive mantle-derived magmas to ascend rapidly in the middle crust. In such a situation, major olivine crystallization (taking up nickel) is restrained, favouring nickel precipitation as sulphides. One question is to which plate boundaries some of the deposits in SE Finland and north of Keitele (Hitura nickel-copper) can be linked.

The majority of Palaeoproterozoic gold deposits in Finland are of an orogenic type, and the known occurrences in Finland cluster in Central Lapland (Kittilä) and around the inferred plate boundaries in central and southern Finland (Figure 3a). They seem to have formed syn- to post-peak (dominant) metamorphism, but their timing is somewhat controversial. The largest gold occurrence in Finland, the Suurikuusikko deposit at Kittilä, may be c. 1.9 Ga in age, but the exact age and how much reworking has occurred during younger events remains to be determined. Many of the other orogenic gold deposits and occurrences in Lapland seem to be as young as c. 1.8 Ga in age. The reason for the significant gold prospectivity of central Lapland is still unclear, but the combination of large amounts of mafic volcanic rocks, greenschist facies metamorphism and preferentially multiply reworked old plate boundaries should be explored.

Similar problems of timing are also found in the gold occurrences in central and southern Finland. Most of them are associated with c. 1.89–1.88 Ga synorogenic plutonic rocks and associated shear zones. In many cases, the exact mineralization age is clearly younger, at c. 1.8 Ga, but possibly related to the reactivation of older structures and may locally include remobilization of pre-existing mineralizations and the secondary concentration of precious metals in late-tectonic shear zones (Saalmann et al. 2009). A major question is whether multiple mechanisms led to the enrichment of gold in the first orogenic stage followed by later focusing and upgrading of the gold into a deposit in the second orogenic stage, or if the older structures were acting only as favourable pathways for gold-bearing fluids. Nevertheless, the complicated orogenic evolution (Figure 3b) with several thermal peaks should be taken into account.

Some copper-gold occurrences in NW Finland and northern Sweden have characteristic features similar to the iron oxide copper-gold deposits (IOCG) worldwide. In the broad spectrum of IOCG deposits, the magmatic ± hydrothermal magnetite-apatite deposits form one end member. The most notable examples of these are the giant magnetite-apatite deposits in Kiruna and Malmberget, which were formed at 1.89–1.88 Ga. Numerous epigenetic iron oxide deposits are known, e.g. in Kolari-Pajala (Figure 1), most of which are barren with respect to copper and gold. However, some are overprinted by copper–gold mineralization ± second generation of iron oxides contemporaneous with copper–gold (Niiranen et al. 2007). These features are typical for deposits in known iron oxide copper-gold deposit districts such as Cloncurry, Australia.

In most cases the copper-gold mineralizations in NW Finland and northern Sweden seem to have occurred fairly late, at c. 1.8 Ga, and are often located in reactivated older structures in which the earlier copper–gold-poor magnetite mineralization is hosted. One possible scenario is that they have formed in a far-field back-arc setting to the proposed c. 1.8 Ga Andean-type arc magmatism in the west. A still open question is the nature of the Norrbotten-Karelia boundary at 1.9–1.8 Ga; is it a cryptic suture related to a c. 1.9 Ga collision or the locus of an intra-continental back-arc basin? Another question is the abundant occurrence of c. 1.8 Ga fluid-rich post-collisional subcontinental lithospheric mantle-derived magmas; did they play any role in the derivation of the copper–gold-rich fluids?

CONCLUDING REMARKS

The main aim of this paper has been to present some key aspects and hypotheses and to point out important open questions that we hope could stimulate further studies. Despite a long history of research and enormous progress made during the last decades, the tectonic and metallogenic evolution of the Fennoscandian Shield is far from resolved. Considering the importance of this area as a metal resource base for Europe, future research should also aim at better understanding of the interplay between tectonic processes and mineralization, which is the basis for a more profound evaluation of the Shield's mineral potential. This article should not be considered as a comprehensive review of the tectonic and metallogenic evolution of the Fennoscandian shield, as it omits many important aspects such as the metallogeny of high-tech metals (e.g. Li, Nb, REE), uranium and others.

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ISOTOPE GEOLOGY AND FENNOSCANDIAN LITHOSPHERE EVOLUTION

by
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The isotope laboratory at GTK has contributed enormously to geological research in Finland ever since its inception in the early sixties. The main analytical methods used have been U-Pb, Sm-Nd, Rb-Sr, Pb-Pb and light stable isotopes, and with the recent LA-MC-ICPMS instrument installation, the repertoire is increasing. Isotope research has contributed to many joint projects over a wide range of topics including modelling, mapping, mineral exploration, investigations related to nuclear waste disposal, hydrogeology and GTK consortium mapping projects abroad. Co-operation with universities has been important and isotope geology has had a role in numerous Ph.D. theses in Finland.

Building a full picture of the evolution of a piece of the Earth's crust requires a large amount of radiometric age and isotopic data that can only be supplied by a premiere isotope facility. Examples of the types of information the GTK isotope laboratory has produced include: 1. The oldest rocks so far discovered in Fennoscandia are the 3500 million years old Siurua gneisses, but signs of even older crust are evident in these rocks. 2. The main periods of crustal growth in Finland were related to collisional events at 2.8–2.7 Ga and ca. 1.9 Ga. Yet sediments produced over a wide region during the 1.9 Ga event contain abundant ca. 2.0 Ga zircons, for which there is no obvious source, suggesting that a major block of still unlocated crust must have existed somewhere nearby and supplied abundant detritus to proximal ocean basins ca. 1.9 billion years ago. 3. Before the breakup of the ancient Archean continental core, several pulses of mafic magmatism have been recognized between 2.44 Ga and 2 Ga, and these intrusions have proven to be particularly important as they contain some of the major ore bodies in Finland. These and other important results are briefly described in this paper to illustrate the importance of isotope geology in deciphering the geological history of the Fennoscandian Shield, and Finland in particular.

Keywords (GeoRef Thesaurus, AGI): lithosphere, crust, mantle, rocks, genesis, isotopes, absolute age, Precambrian, Finland

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INTRODUCTION

Radiogenic and stable isotopes are used in the Earth sciences as geochronometers and isotopic tracers to unravel geological and environmental processes. Achievements in isotope geology have had a major role in our understanding of the age and complex history of the 4.5-Ga-old Earth. In Finland, the isotope laboratory at GTK has contributed to this research since the early 1960s, and results obtained have provided the basis for modelling the Precambrian geological history of Finland and the Fennoscandian Shield (e.g. Bedrock Map of Finland, Korsman et al. 1997; Precambrian Geology of Finland, Lehtinen et al. 2005).

Since the laboratory is unique in Finland, extensive co-operation with scientists at GTK, the Universities and other institutions has been the main strategy from the very start. Because of this diversity of collaboration, isotope research has not just focused on a few types of problems, but instead has contributed to a wide range of projects including: modelling, mapping, mineral exploration, investigations related to nuclear waste disposal, hydrogeology and GTK consortium mapping projects abroad (Tanzania, Mozambique, Uganda). The contribution of isotope geology has been significant in numerous Ph.D. theses in Finland.

The final product of the research often is joint publications on a variety of geological subjects (see http://info.gsf.fi/fingeo/fingeo_eng.html). Published age determinations on approximately 1170 samples from Finland are available on the Internet in the GTK Active Map Explorer (http://geomaps2.gtk.fi /activemap/ , choose "published radiometric ages" data layer; also see the data layer description for a list of publications, which number around 220).

The main goal of this paper, after discussing laboratory history and methods, is to show the significance of isotope research in modelling the geological history of Finland and the Fennoscandian Shield. The section discussing the genesis and evolution of the lithosphere in Finland, together with the references, may be considered a compact and fairly comprehensive review of current isotope results on this topic.

HISTORY OF ISOTOPE GEOLOGY AT GTK

The first isotope studies on Finnish rock were already carried out more than fifty years ago, when Olavi Kouvo was as a visiting scientist in the USA. Collaborative work by Kouvo with leading experts in the then newly established field of radiometric age dating employing U-Pb, Th-Pb, Rb-Sr and K-Ar methods produced a fundamental (and at that time, controversial) change in the understanding of the age of the main crustal domains in Finland (Kouvo 1958, Wetherill et al. 1962, Kouvo & Tilton 1966). Upon his return to Finland, Kouvo was invited to establish a laboratory of isotope geology, which he did, at GTK in 1963. In these early days the laboratory built its own mass spectrometers and consumed huge numbers of person-hours hand picking large quantities (in today's terms) of pure mineral concentrates for analysis. It was soon realized that compared to other methods, the uranium-lead isotope system in the mineral zircon provided the most reliable age estimates for rocks, and was thus chosen as the principal tool. Since then, approximately 1600 samples have been analysed using this method.

Another early method utilized in the laboratory, common lead isotopes (mainly from sulphides), has provided significant information for determining the origin of ores and modelling crustal evolution (Vaasjoki 1981, Mänttäri 1995, Halla 2002, Peltonen et al. 2008). The Sm-Nd method was initiated at GTK in 1981 and is used for mineral isochron work and for constraining the long-term chemical evolution of the Earth's crust and mantle (Huhma 1986, Huhma et al. 1990, Rämö 1991). Today, the database consists of more than 2000 analyses. The stable isotope laboratory was established in 1985, and one of the main results has been the discovery of a large positive $\delta^{13}C$ anomaly in 2.2–2.1 Ga old carbonate sediments (Karhu 1993). Subsequently, stable isotopes have been used in hydrogeology (Kortelainen 2007) and studies on late Pleistocene atmospheric evolution (Arppe 2009).

METHODS AND INSTRUMENTATION

Currently, isotope geology at GTK concerns two main research programmes: 1) studies on the age, genesis and evolution of the crust, and 2) isotope hydrogeology. The laboratory employs a staff of 5 scientific and 5 technical persons, and is also frequented by visiting scientists. The conventional methods employed include U-Pb (on zircon, titanite, monazite, baddeleyite, etc.), Pb-Pb (sulphides, feldspars, whole rock), Sm-Nd (whole rock, pyroxene, plagioclase, garnet, etc.), Rb-Sr and stable isotopes (H, C, O). A commercial VG Sector 54 instrument for thermal ionization work has been in operation since 1990. Analyses for isotopic composition of hydrogen, carbon and oxygen are carried out on a Finnigan MAT 251 instrument installed in 1985. Participation in the joint Nordic project NORDSIM since 1995 has yielded outstanding results on deciphering a crustal evolution that is complicated by multiple deformational and metamorphic events. The NORDSIM facility joint operating agreement was recently renewed through 2014 following the successful upgrade of the CAMECA IMS 1270, which now provides a state-of-the-art instrument for the geoscience community.

In 2008, GTK and the Finnish universities established a joint laboratory, the Finnish Isotope Geosciences Laboratory (SIGL by its Finnish acronym), which is located at GTK together with the pre-existing isotope facilities. SIGL has been set up for the analysis of the isotopic composition of a broader range of elements and to have the capability to do this for nearly all types of materials. The lab features a Nu Instruments multiple-collector inductively coupled plasma mass spectrometer (LA-MC-ICPMS) that provides high precision isotopic measurements of elements in samples introduced as solutions (acid-dissolved rocks/minerals or waters) using the desolvating nebulizer or as solids (polished mounts or thin sections) using the New Wave 193 nm deep UV solid-state laser (Figure 1). The advantages of the system are its speed, versatility and extremely low detection limits.

Figure 1. Nu Instruments HR multicollector ICP-MS and New Wave 193ss laser installed at GTK Espoo January 2008.

Present SIGL Capabilities

So far, laser ablation techniques have mainly been applied to in situ U-Pb dating of zircon and monazite from grain mounts (Figure 2) or on thick sections. Hf isotope characterization of the zircon grains has also proven successful (e.g. Rutanen et al. 2010). Measurement of U isotopes from U minerals, e.g. uranophane, to date relatively young events in Finland has been tested with good results, but has so far only been applied to a few samples. Solution work has been concentrated on developing the U-series methodology for soil and carbonate samples. Uranium isotopes, along with Li, Mg, Pb and Sr are now routinely measured from surface and groundwater samples as part of the developing branch of water studies at GTK.

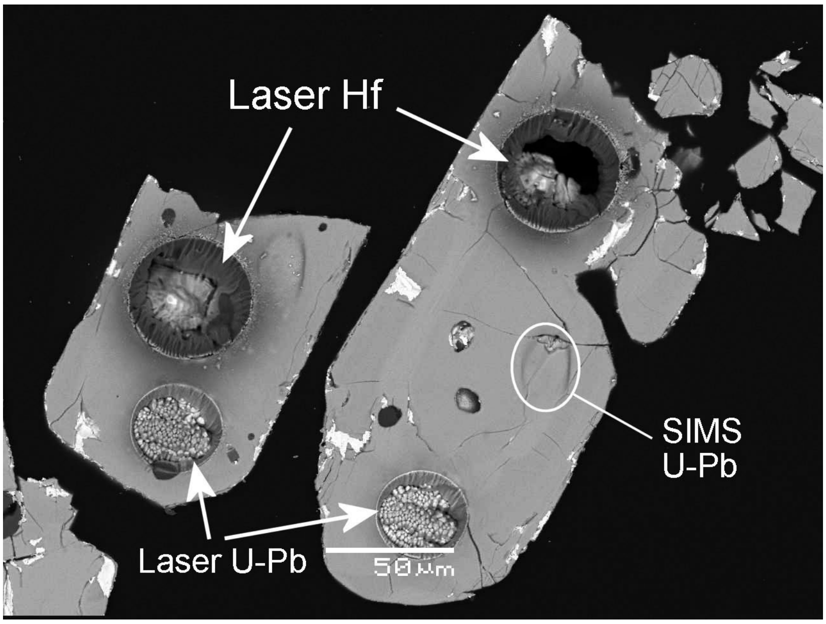

Figure 2. Backscattered electron image of zircon grains with Hf and U-Pb laser pits indicated.

Future Studies

Developments with the laser will concentrate on the capability to perform isotopic studies with high spatial resolution while measuring several isotopic systems on different or even the same minerals within a rock. This work will include U-Pb measurements of less commonly dated minerals, such as perovskite, titanite, baddeleyite, rutile and possibly ilmenite, depending on the U and common Pb content of the target minerals. Also included will be the measurement of Sr and Pb isotopes on spot analyses of feldspars, apatite, carbonates, perovskite and sulphides. In situ analyses of Fe, S and Cu in sulphides will also become increasingly important as the laboratory directs greater effort toward exploration and mining applications. U-series by laser (uranium minerals, apatite, carbonates) will also expand as the need for having the capability to date young events increases (e.g. determining the age of fracture fillings at the nuclear fuel storage facility).

We are convinced that working at a detailed scale with a set of complementary isotopic systems will be one of the most important directions for isotope research in the future. To facilitate the large amount of planned microsampling by laser, a unified coordinate transfer system has been developed that will make use of the powerful combination of mapping of mineral grain positions in rock thick sections by the MLA (Mineral Liberation Analyzer) at GTK Outokumpu, SEM imaging of the interesting grains to document zoning, and then direct isotope measurement by LA-MC-ICPMS. This system will reduce the work required in making preparations for many types of rocks (thick sections versus crushing, separation, hand-picking and mounting) while at the same time retaining spatial information regarding the target mineral-host mineral relationships in the rock. We anticipate this methodology will mark a major advance in understanding processes in crystallizing igneous systems and in systems with ore-bearing fluids.

On the solution side, the list of applications is continuously growing due to the versatility of the instrumentation. U-series solution work will continue to expand, including solutions from soils, carbonates, and other U-containing materials. Some examples of other planned projects include: isotopic analyses of Fe, Cu, Ni, S, for studying mantle-crust interactions and ore forming systems; monitoring the migration of redox sensitive elements (S, Fe, Cu, Zn, Cr, Ni, Mo, Hg) to map paleoenvironmental change and determine anthropogenic sources; Pb bioavailability studies using Pb isotopes as tracers; Sr isotopes of shellfish and mapping Sr inputs (from fertilizer) to closed basins (e.g. Baltic Sea); Si isotopes of foraminifera as a proxy for temperature change recorded in layered lake sediments.

ISOTOPE GEOLOGY AND EVOLUTION OF THE LITHOSPHERE IN FINLAND

The geologic history of the Fennoscandian shield is complex, and extensive collaboration between researchers working in the field and in laboratories is required to fully decipher the geologic record. In these studies isotopic methods play an indispensable role. The main goal of this section of the paper is to illustrate just how large a contribution isotope geology has made, particularly in terms of age dating of rocks. All GTK isotope-related projects have been initiated to study one or more of the following important themes: 1. mantle evolution, 2. crust-mantle interaction, 3. crustal age, origin and evolution and 4. metallogenesis.

The bedrock of Finland forms a part of the ancient Fennoscandian Shield, which is composed of rock units mostly formed between 3.2 and 1.6 billion years ago (Figure 3). This long geological history can be divided into four main periods of geological activity: 1. Archean, 2. Paleoproterozoic evolution preceding the major 1.9 Ga orogeny, 3. rocks related to the Paleoproterozoic 1.9 Ga orogeny, and 4. younger post-orogenic events.

1. Information on ***Archean (> 2.5 Ga)*** isotope systematics of the Fennoscandian Shield has increased significantly in recent years. This includes greenstone belts, paragneisses and granitoids, and involves both U-Pb dating (TIMS, SIMS, LA-ICPMS), and Sm-Nd and some Lu-Hf analyses for evaluating the crustal residence ages. In many of these studies, data from multiple isotopic systems are required in order to be able to look through Proterozoic metamorphic effects, which in some places are pervasive.

These studies have shown that the major crust-forming period in the Archean was ca. 2.8–2.7 Ga, and only a few remnants of older rocks have been preserved (Figure 3). The oldest rocks in the Fennoscandian Shield are ca. 3.5 Ga gneisses in Siurua, Pudasjärvi (Figure 4), where evidence of even older 3.7 Ga crust was obtained from small zircon cores (Figure 3, Mutanen & Huhma 2003, Lauri et al. in press). Signs of 3.5 Ga crust were also found in lower crustal xenoliths from the 0.5–0.6 Ga old kimberlites in Kaavi, eastern Finland (Peltonen et al. 2006). Some xenoliths yielded large ranges of U-Pb zircon ages from 3.5 to 1.8 Ga, but interestingly Proterozoic zircons were distinct grains, and not overgrowths on the Archean zircons.

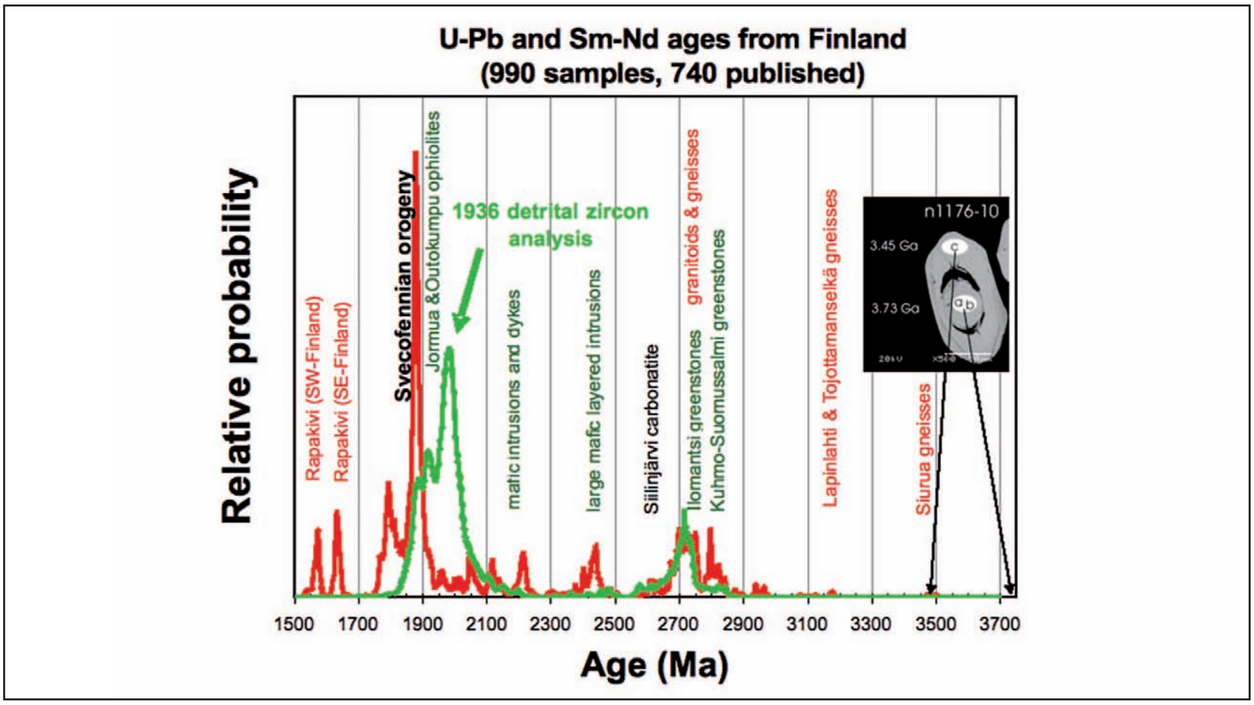

Figure 3. U-Pb and Sm-Nd ages from Finland. The red line shows primary rock ages and is based on results from 990 samples (from which data on 740 are published). The green line shows the age distribution of detrital zircons in Paleoproterozoic metasediments and is based on 1936 U-Pb analyses by SIMS (ca. 1000 published) and LA-MC-ICPMS (unpublished). Also shown is an image of ca. 3.5 Ga zircon from the oldest rock in Finland from Siurua with an older ca. 3.73 Ga core (Mutanen & Huhma 2003).

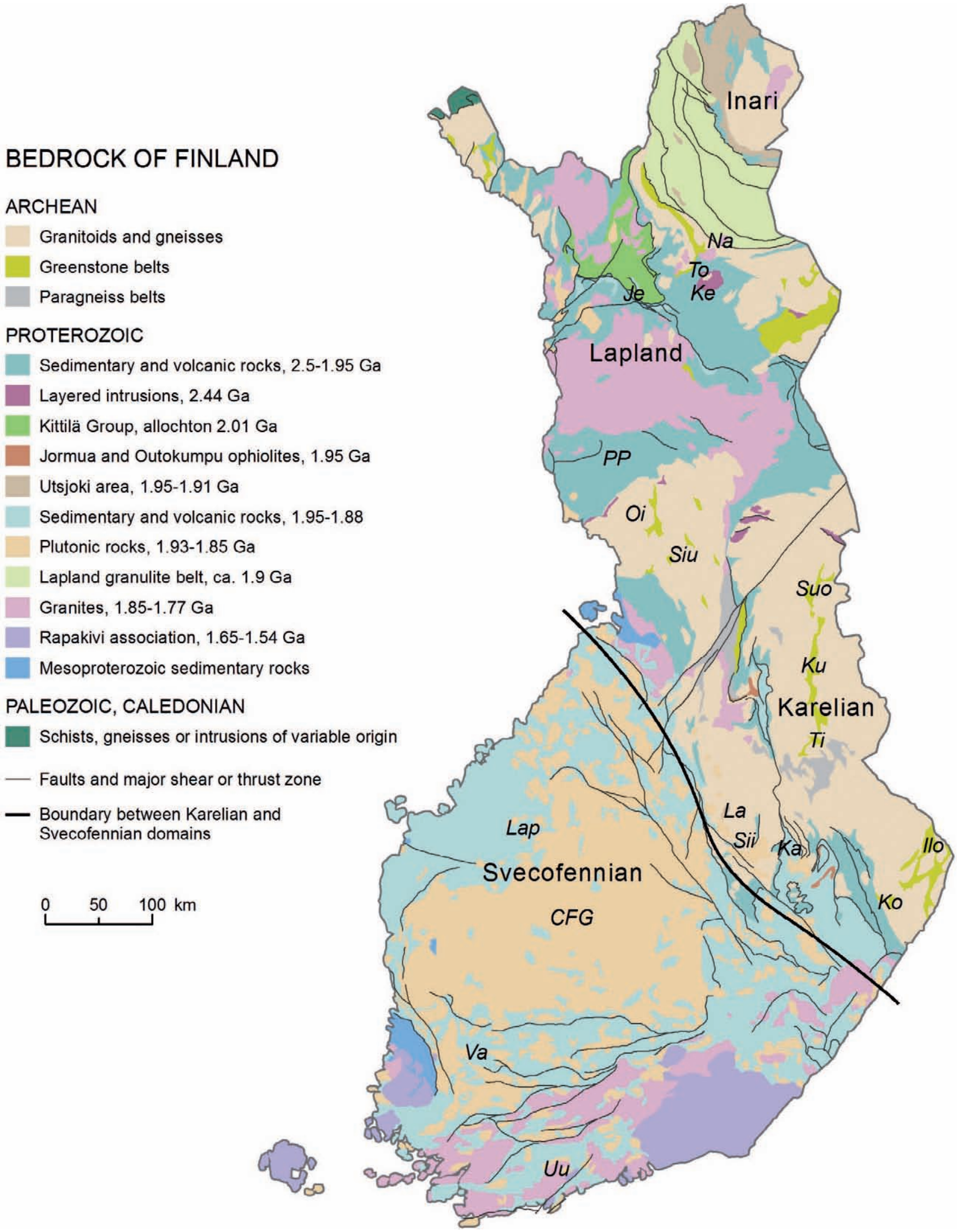

Figure 4. Geological map of Finland, modified from Korsman et al. (1997). Key from North to South: Na = 1.78 Ga Nattanen granite, reworked old crust; To = 3.2 Ga Tojottamanselkä gneiss; Ke = 2.06 Ga Keivitsa mafic intrusion; Je = 2.06 Ga Jeesiörova komatiites; PP = Paleoproterozoic Peräpohja Schist belt; Oi = Archean Oijärvi greenstone belt; Siu = 3.5 Ga Siurua gneisses, oldest crust in the EU; Suo/Ku/Ti/Ilo/Ko = Archean Suomussalmi/Kuhmo/Tipasjärvi/Ilomantsi/Kovero greenstone belt; La = 3.2 Ga Lapinlahti gneisses; Sii = 2.61 Ga Siilinjärvi carbonatite; Ka = 0.5–0.6 Ga Kaavi kimberlites; Lap = 70 Ma Lappajärvi impact crater; CFG = 1.87–1.88 Ga Central Finland granitoid area; Va = Vammala migmatite belt (1.87 Ga metamorphism); Uu = (West) Uusimaa migmatite belt (1.83–1.80 Ga metamorphism).

Most Archean gneisses (TTG) have ages of 2.83–2.78 Ga and 2.76–2.72 Ga, whereas leucogranitoids and leucosomes in migmatites are typically ca. 2.7 Ga (Hyppönen 1983, Käpyaho et al. 2006, 2007, Lauri et al. 2006, Luukkonen 1988, Mikkola et al. submitted, Vaasjoki et al. 1993, 1999*)*. Evidence of high-grade metamorphism at ca. 2.63 Ga is provided by U-Pb data on monazites and zircons as well as Sm-Nd analyses on garnet (Hölttä et al. 2000, Mänttäri & Hölttä 2002*)*.

U-Pb zircon ages from igneous rocks of the greenstone belts give the following results: 1) the Suomussalmi belt contains volcanic fragments of variable ages from 2.94 to 2.82 Ga, 2) the Kuhmo, Tipasjärvi and Oijärvi greenstone belts range from 2.83 to 2.80 Ga, 3) the Ilomantsi belt is predominantly ca. 2.75 Ga whereas 4) the Kovero belt (SW from Ilomantsi), in addition to containing 2.75 Ga material, also contains fragments of ca. 2.87 Ga felsic rocks (Vaasjoki et al 1993, 1999, Huhma et al. in prep*.*). These results suggest that greenstone belts register an extended fragmentary record of geological evolution.

The Sm-Nd results suggest that much of the crust in Kuhmo and Ilomantsi areas is relatively juvenile, whereas further north in Suomussalmi, rocks contain a larger component of older crustal material *(*O'Brien et al. 1993, Käpyaho et al. 2006, Mikkola et al. submitted, Huhma et al. in prep*)*. The oldest Sm-Nd and Lu-Hf model ages of 3.6–3.7 Ga have been obtained from the Siurua gneisses, consistent with their old zircon ages. The paragneisses have been considered as an important component in the Archean crust in Finland. Isotope studies have shown that they are in fact young in the context of Archean evolution. The age of deposition has been constrained close to 2.7 Ga, and much of the detritus was derived from only slightly older crust (Kontinen et al. 2007*)*.

2. The geological record of the pre-orogenic ***Paleoproterozoic (2.5–1.9 Ga)*** evolution is well preserved in parts of the Fennoscandian Shield, especially in Lapland where supracrustal and associated mafic plutonic rocks of this age are abundant. In contrast, the Karelian domain in eastern Finland contains only relatively small remnants of these formations. Isotope research has focused on the following three major topics: 1) the age and characterization of mafic magmatism, which provides information on mantle evolution and crust-mantle interaction; 2) the age, stratigraphy and characterization of supracrustal rocks, particularly in Lapland; and 3) C-isotope excursion in Paleoproterozoic carbonate sediments, which contributes to our knowledge of the evolution of the atmosphere.

Published and unpublished age results on 180 samples from the Karelian domain reveal major mafic igneous activity at 2.44, 2.22, 2.14–2.10 and 2.06 Ga (Figure 3). A few mafic dykes cutting the Archean crust at 2.3 and at 1.96 Ga are also evident. The 2.44 Ga rocks include also minor felsic lithologies and economically important large mafic layered intrusions. In fact, one of the laboratories' globally outstanding achievements was the first U-Pb dates from zircon and baddeleyite in mafic rocks, which were obtained from these 2.44 Ga layered intrusions (Kouvo 1977). Today, several 2.44 Ga intrusions are known throughout the Karelian domain in Northern Finland. An important rock association is the Kittilä Group in Lapland, which consists of ca. 2.015 Ga mafic and minor felsic juvenile rocks considered as an allochthonous ophiolite. In the epsilon-Nd vs. age diagram (Figure 5) these are represented by the (Vesmajärvi Fm) mafic rocks and felsic porphyries, which all have initial Nd isotopic compositions similar to depleted mantle and thus contain no contribution from older crustal material.

Another major volcanic unit in Lapland consists of the (Jeesiörova) komatiites, where in places primary clinopyroxene has survived through all later metamorphic events. Such samples provided the basis for Sm-Nd studies, which have yielded an age of ca. 2.06 Ga and an initial Nd isotopic composition close to depleted mantle (Figure 5). The diagram also shows, for instance, how the material of the 2.44 Ga layered intrusions (Penikat, Koitelainen, Akanvaara) and the 2.06 Ga Keivitsa intrusion are very distinct from coeval depleted mantle and require a large component from Archean LREE enriched lithosphere in their genesis.

A large number of the U-Pb age determinations mentioned above were published in 12 papers in a special volume on Lapland (Vaasjoki 2001), particularly Perttunen & Vaasjoki (2001), Rastas et al. (2001), Räsänen & Huhma (2001), Juopperi & Vaasjoki (2001), Manninen et al. (2001) and Mutanen & Huhma (2001). Other publications, many also containing Sm-Nd results, include those by Alapieti (1982), Huhma et al. (1990), Hanski et al. (1990, 1997, 2001a, 2001b, 2005, 2010), Hanski & Huhma (2005), Lauri & Mänttäri (2002), Lauri et al. (2006), and Niiranen et al. (2005, 2007). A large amount of unpublished results mentioned in Vuollo & Huhma (2005*)* will be published by Huhma et al. (in prep).

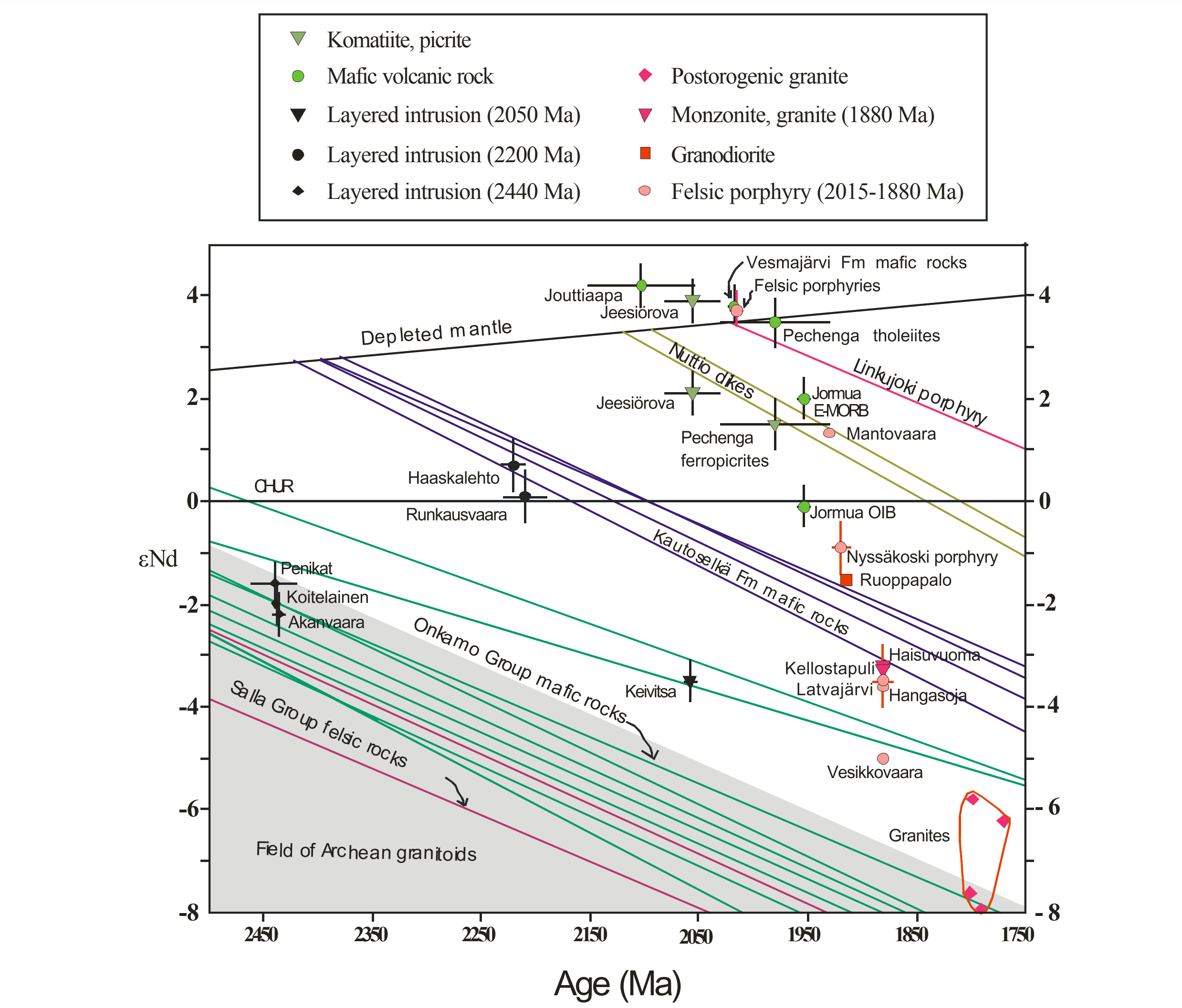

Figure 5. Nd-isotopic evolution diagram for Paleoproterozoic plutonic and volcanic rocks of northern Finland provides an example of the use of ^{147}Sm-^{143}Nd isotope system for studying the genesis of rocks (from Hanski & Huhma 2005, Figure 4.7.). The εNd on the Y-axis denotes the ^{143}Nd/^{144}Nd isotopic composition relative to chondrites (CHUR) and has been calculated from the measured ^{143}Nd/^{144}Nd and ^{147}Sm/^{144}Nd ratios back to Proterozoic time. The ε-values are shown with symbols for rocks that have been dated by U-Pb or Sm-Nd method. Error bars are based on several analyses of each rock association. Evolution lines are shown for metavolcanic rocks lacking direct isotope dating. The main observation to be made from this diagram is that some rocks have origins in depleted mantle (e.g. Jouttiaapa basalts) or have very short crustal prehistories (e.g. 2.015 Ga felsic porphyries), whereas others represent essentially recycled old crustal material (e.g. 1.8 Ga granites). Not all names on the diagram are explained in the text, but may be of interest to some readers; further information is available in Hanski & Huhma (2005). Evolution of depleted upper mantle is after DePaolo (1981). CHUR refers to chondritic uniform reservoir and equals to the evolution of Bulk Earth.

The discovery of a large positive δ^{13}C isotope anomaly in 2.2–2.1 Ga Paleoproterozoic carbonate sedimentary rocks has been one of the important results from the GTK isotope studies (Karhu 1993). Elevated δ^{13}C values up to +10 exist globally and have been explained by an abnormally high rate of organic carbon deposition, which generated a high rate of O_2 production (Karhu 1993, Karhu & Holland 1996). Recently, improved time constraints have been obtained by SIMS dating on zircon in pyroclastic rocks from the Peräpohja Schist Belt, giving an age of 2106 ± 8 Ma (the Hirsimaa Formation). This closely approximates the end of the carbon isotope excursion at a time when the marine δ^{13}C values were at 4–6‰ (Karhu et al. 2007). This is supported by the 2.06 Ga ages obtained from the Pechenga supracrustal rocks overlying the high delta-C carbonate metasediments (NW Russia, Melezhik et al. 2007).

3. The ***Paleoproterozoic orogeny (ca. 1.95–1.8 Ga)*** represents a major crust forming event that contributed to a large part of Fennoscandia and is a significant component globally. Isotope research includes the following topics.

1) Early phases, particularly the (Jormua and Outokumpu) ophiolites.

2) Provenance and age of deposition of the metasediments within Svecofennian, Upper Kalevian and Lapland granulite belt.

3) U-Pb age and origin of igneous rocks, particularly Sm-Nd characterization of the juvenile vs. recycling of older LREE enriched lithospheric (crustal) material in the genesis with emphasis on the Svecofennian and Karelian boundary zone.

4) Timing of tectonic and metamorphic evolution and late igneous phases.

Summarizing all the studies on these topics is beyond the scope of this paper, but a brief summary of a few selected items is included here.

The age of the 1.95 Ga ophiolites is now well constrained and isotopic evidence strongly suggests that the Jormua ophiolite represents a remnant of an Early Proterozoic seafloor that mainly consisted of Archean subcontinental lithospheric mantle (Kontinen 1987, Peltonen et al. 1996, 1998, 2003, 2008).

The bulk of the Svecofennian and Upper Kalevian metasediments were deposited ca. 1.92 Ga ago and are mixtures of predominantly Proterozoic mantle sources with minor Archean components, also shown in the Sm-Nd data (Huhma 1987, Huhma et al. 1991, Claesson et al. 1993, Lahtinen et al. 2002, 2009, 2010, Rutland et al. 2004, Bergman et al. 2008). The isotope characteristics of the migmatitic metapelites of the Lapland granulite belt broadly share these features (Tuisku & Huhma 2006). All these Proterozoic metasediments contain abundant detritus from ca. 2 Ga source rocks, for which there is no known source (Figure 3). Some metasediments also occur in higher stratigraphic levels and are younger than 1.87 Ga.

The oldest rocks in the ***Svecofennian*** domain are ca. 1.93 Ga gneisses and volcanics with initial Nd-epsilon close to +3 and are thus juvenile new crust (Figure 6). The main suites of the mafic and felsic igneous lithologies were formed at 1.90–1.87 Ga ago, and have initial Nd-epsilon values of -1 to +3 (Huhma 1986, Patchett & Kouvo 1986, Lahtinen & Huhma 1997, Vaasjoki & Huhma 1999, Rämö et al. 2001, Vaasjoki et al. 2003, Kurhila et al. 2005, Makkonen & Huhma 2007). This shows that many of these rocks have their ultimate origin in depleted mantle with only a slight input of older crustal material. Lower epsilon values in some rocks suggest the involvement of older crustal material in their genesis. Co-operation with Estonian colleagues has revealed that similar crust continues further south into the Baltic countries under the Paleozoic cover (Puura & Huhma 1993, Puura et al. 2004). Distinct domains within the Svecofennian crust are evident from the lead isotope data on galenas and suggest fundamental variations in source characteristics (Vaasjoki 1981, Huhma 1986). In Northern Finland, the arc-related magmas of the Lapland granulite belt have initial Nd-epsilon close to zero and were intruded into the sediments at 1.92–1.90 Ga ago (Meriläinen 1976, Tuisku & Huhma 2006). Based on Sm-Nd and U-Pb studies it is evident that even more juvenile 1.9 Ga crust exists in the Utsjoki area between the Archean Inari domain and the Lapland granulite belt (Figures 4 and 6, Huhma unpublished).

The contribution of older LREE-enriched lithosphere (crust) in the genesis of 1.9–1.8 Ga rocks is generally high in the ***Karelian*** domain, where some granites may represent largely reworked Archean crust (Figures 5 and 6) (e.g. Huhma 1986, Ruotoistenmäki et al. 2001, Ahtonen et al. 2007, Heilimo et al. 2009).

The isotope studies employing U-Pb on monazite, titanite, zircon and columbite together with Sm-Nd on garnet show that two major high grade metamorphic episodes are evident in the Svecofennian domain, ca. 1.88–1.87 Ga e.g. in the Vammala migmatite belt and ca. 1.83–1.80 Ga further south in the West Uusimaa belt. In the Lapland granulite belt the U-Pb on monazite and zircon together with Sm-Nd on garnet constrain the high-grade metamorphism from peak conditions at ca. 1.9 Ga to subsequent decompression and cooling at 1.87 Ga. The 1.8 Ga event is well shown in many places throughout the Shield by abundant isotopic data, suggesting a major thermal peak and crustal reworking to produce granites. Some mantle-derived mafic rocks were also emplaced at ca. 1.8 Ga ago.

Papers providing isotope data on the timing of these tectonic and metamorphic evolution and late igneous phases include Hopgood et al. (1983), Korsman et al. (1984), Suominen (1991), Kontinen et al. (1992), Mouri et al. (1999, 2005), Alviola et al. (2001), Väisänen et al. (2002), Ehlers et al. (2004), Skyttä et al. (2005, 2006), Skyttä & Mänttäri (2008), Mänttäri et al. (2007), Pajunen et al. (2008a,b), Torvela et al. (2008) and Saalmann et al. (2009).

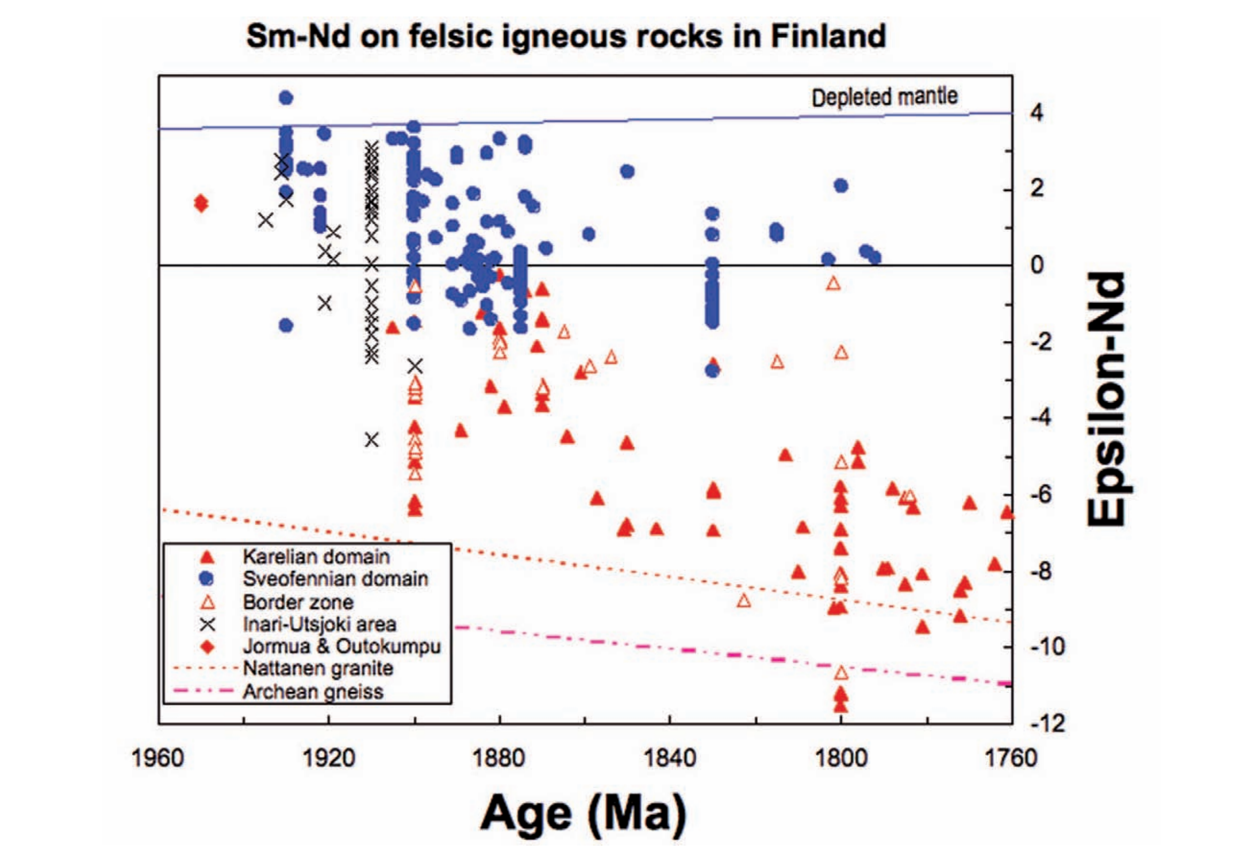

Figure 6. Initial Nd isotopic composition (epsilon-Nd) for 1.76–1.96 Ga felsic igneous rocks in Finland. Ages are U-Pb ages or estimated from the geological context at 1.8 Ga, 1.83 Ga (migmatite belt in S Finland), 1.87 Ga (Central Finland granitoids), 1.9 Ga, and 1.91 Ga (Lapland granulite & Utsjoki area). Note that a slight change in age will not affect the overall picture; see e.g. the evolution line for Nattanen granite or typical Ne-oarchean gneiss. (Data from references in the text and unpublished, n = 270).

4. Isotope studies on the ***post-orogenic crustal lithologies and evolution*** include:

1) rapakivi granites, which consist of two main age groups at 1.64 and 1.57 Ga (Vaasjoki 1977, Rämö 1991, Rämö et al. 1996),
2) 1.26 Ga (postjotnian) dolerites (Suominen 1991) and 1.2 Ga lamproites (O'Brien et al. 2007),
3) 0.5–0.6 Ga kimberlites hosting scientifically important mantle and crustal xenoliths (Peltonen et al. 1999, 2002, 2006, Hölttä et al. 2000b, Peltonen & Mänttäri 2001, O'Brien & Tyni 1999),
4) late veins and shear zones, e.g. ca. 0.4 Ga fluorite-calcite-galena veins (Alm et al. 2005) and fault breccias (Mänttäri et al. 2007), and
5) impact structures (e.g. Lappajärvi at ca. 70 Ma, Mänttäri & Koivisto 2001).

CONCLUSIONS

Since the early 1960s, analyses based on traditional isotope systems such as U-Pb, Sm-Nd, Pb-Pb and $\delta^{13}C$ have been used at GTK to produce geochronological and isotopic database, which provides the cornerstones for building a comprehensive story of the geological history. It may be concluded that the contribution of isotope geology has been enormous for the current understanding of the geological evolution of Finland and the Fennoscandian Shield.

Recent equipment added to the laboratory will continue expanding the existing database. GTK will also focus on the analytical development of non-traditional heavy stable isotopes in a wider field of applications involving mineral exploration, hydrogeology and other environmental issues.

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REFLECTION SEISMICS IN EXPLORATION FOR MINERAL DEPOSITS: INITIAL RESULTS FROM THE HIRE PROJECT

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

Seismic reflection surveys have traditionally been applied in exploring for oil and gas deposits, but currently there is increasing interest in using the method in exploration for mineral deposits in crystalline bedrock areas. This can be attributed to the high resolution provided by the reflection method, which is much better than that of any other conventional geophysical method. In addition, the petrophysical parameters underlying rock reflectivity, i.e., the acoustic impedance, which is a product of rock density and seismic velocity, is closely associated with geological rock properties.

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

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

Keywords (GeoRef Thesaurus, AGI): mineral exploration, metal ores, bedrock, seismic methods, reflection methods, Precambrian, HIRE Project, Finland

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INTRODUCTION

Seismic reflection soundings are widely applied in exploration for oil and gas, but less commonly in mineral exploration in crystalline bedrock areas. The reasons for this have been the traditionally high cost of seismic surveys and the required technologies, as well as logistical difficulties in terrains that are often challenging (topography, soft and wet soils, accessibility, permits, environmental restrictions, mining areas, man-made seismic noise, etc.).

On the other hand, many factors support the use of the method in mineral exploration. One of them is the unprecedentedly high spatial resolution, which surpasses that of any other geophysical surface method. Assuming that sufficient impedance contrasts exist, reflectors with a vertical thickness as thin as 10 m and with horizontal dimensions greater than about 350 m can be directly detected in the uppermost 1–2 km. The resolution does not essentially decrease with depth in the depth range where exploration is concerned (to 1–2 km depth) (Yilmaz 1991).

Massive deposits always have a sufficient impedance contrast with their host rocks, regardless of the host rock type, and are therefore detectable with reflection seismics (Salisbury et al. 2003). Thus, the potential exploratory power of reflection seismics is good, but the detection of massive deposits depends on the dimensions of the target as well as the shape of the body (Bohlen et al. 2003). Reflection seismics can be used as a direct exploration tool, but the small dimensions of deposits in relation to typical seismic wavelengths makes their direct detection quite challenging. On the other hand, reflection seismics can be a very efficient tool in the structural analysis of environments where deposits are already known. In such areas, seismic data also provide a powerful means for 3D modelling with modern visualization software.

In exploration, the application of new methods, or methods that have not previously been applied in an area, usually provides new perspectives on the subsurface, which often results in novel ideas and discoveries. Mineral exploration requires and benefits from new methods and technologies.

Reflection surveys are often more demanding in crystalline than in sedimentary rocks, which can be attributed to the typically smaller contrasts in acoustic impedances between rock types in crystalline bedrock. This sets demanding requirements for the signal-to-noise ratio in hard rock surveys to provide results with a comparable data quality to those from sedimentary rocks. On the other hand, the rapid development of digital signal acquisition and processing in the last 30 years has significantly improved the situation, and at present high-fold, high resolution surveys can be readily carried out and the results processed at a reasonable cost and time. The rapidly improving technological capabilities have gradually changed the situation in favour of applying seismic reflection surveys for mineral exploration and waste disposal site studies (e.g. Green & Mair 1983, Pretorius et al. 1987, Stevenson & Durrheim 1997, Eaton et al. 1997, Goleby et al. 1997, Salisbury and Snyder 2007, Eaton et al. 2003).

In Finland and the neighbouring marine areas, the most extensive seismic reflection surveys have been conducted for crustal-scale studies, namely the BABEL surveys in the Baltic Sea, the Bothnian Sea and the Gulf of Bothnia (Korja & Heikkinen 2005), and the FIRE surveys on land (Kukkonen & Lahtinen 2006). The results of FIRE and the subsequent drilling of a 2.5 km deep hole in Outokumpu into a strong upper crustal reflector (Kukkonen et al. 2006, Heinonen et al. 2009) indicated that host rock environments of mineral deposits could be successfully delineated and traced with reflection seismics.

Early applications of reflection seismics in mineral exploration and mine camp studies in Finland included the reflection and wide-angle surveys across the Outokumpu belt bearing Cu-Co-Zn sulphide deposits (Penttilä 1968), the Sokli carbonatite intrusion hosting phosphorite deposits (Jalkanen et al. 1978, Paarma 1981), the Luikonlahti survey in 1982 (an Outokumpu type sulphide deposit) (P. Heikkinen, pers. comm. 2010), and the survey of the Ylivieska gabbro, a Ni-Cu exploration target (Heikkinen 1984). In addition, we must add here the theoretical discussion and modelling of reflections in the crystalline rock environment and test measurements by Noponen et al. (1977, 1978, 1979). These early applications already demonstrated the possibilities of the method in structural studies of deposit environments, but it took more than 30 years until reflection seismics developed into a technology that could be effectively applied in mineral exploration.

The present paper provides a brief overview of the HIRE (High Resolution Reflection Seismics in Ore Exploration 2007–2010) project, which has been carried out by the Geological Survey of Finland (GTK). The goals of the HIRE project have been to (1) extend reflection surveys to the exploration of the Precambrian crystalline bedrock of Finland, (2) apply 3D visualization and modelling techniques in data interpretation, and (3) improve the structural database of the most important mineral resource provinces in Finland.

The seismic contractor responsible for the field acquisition and basic processing of the data was Vniigeofizika (together with Machinoexport), Moscow, Russia. The Institute of Seismology, University of Helsinki, has been GTK's research partner and subcontractor in the project and responsible for the more detailed post-stack processing of the results. As many of the targets are located in areas of active exploration and/or mining, 12 industrial partners have also participated in the project. The present paper reviews the ongoing project and presents selected results from the HIRE surveys.

HIRE SURVEY TARGETS, ACQUISITION AND DATA PROCESSING

The HIRE surveys have altogether comprised 700 line km of 2D reflection surveys in 16 target areas (Figure 1). The targets have consisted of exploration and mining camps in a very diverse selection of geological environments with Cu, Ni, Cr, PGE, Zn, and Au deposits, most of them economic, as well as the Finnish site for nuclear waste disposal.

Fieldwork was carried out in the 16 target areas in 2007–2008. Typically, a target was covered with a network of connected survey lines, with a total length of lines varying from about 10 km to 90 km per target.

The HIRE surveys have consisted of 2D soundings. Vibroseis sources were applied on lines running on roads, but off-road explosion lines were used in special cases where roads or useful tracks were not available in geologically important locations. The common midpoint (CMP) method with symmetrical split-spread geometry was applied, with asymmetric shooting at the ends of the lines. The number of active recording channels was 402, and the channel interval was 12.5 m. The maximum offset between the source and receivers was 2 502 m in the case of symmetrical geometry, and up to 5 025 m at the ends of lines in asymmetric geometry.

The source point interval was 50 m, but locally, for instance in the proximity of interesting structures, it was reduced to 25 m. Vibrators or small dynamite shots in shallow drill holes were used to generate the seismic source signal. In vibrator work, three (minimum two) 15.4-ton Geosvip vibrators were used as a group. The applied force was about 10 t per vibrator. The sweep was a 16 s linear upsweep with a frequency band of 30–165 Hz, and the total listening time was 22 s. The final correlated signal length was 6 s. The number of sweeps per source point was six. The sweeps were stacked and the stacked data were saved.

Data processing was carried out in three main steps. First, on-site processing was performed by Vniigeofizika at the field base. The first results were mainly used for quality control. Second, basic processing was continued from the field results in the Moscow office of Vniigeofizika. Third, post-stack processing was carried out by the Institute of Seismology of the University of Helsinki (HY-Seismo), starting from the NMO (normal-move-out) stacked sections provided by Vniigeofizika. The post-stack processing included four processing steps: 1) whole trace amplitude equalization, 2) stolt migration with a depth-dependent velocity function, 3) spectral balancing, and 4) depth conversion.

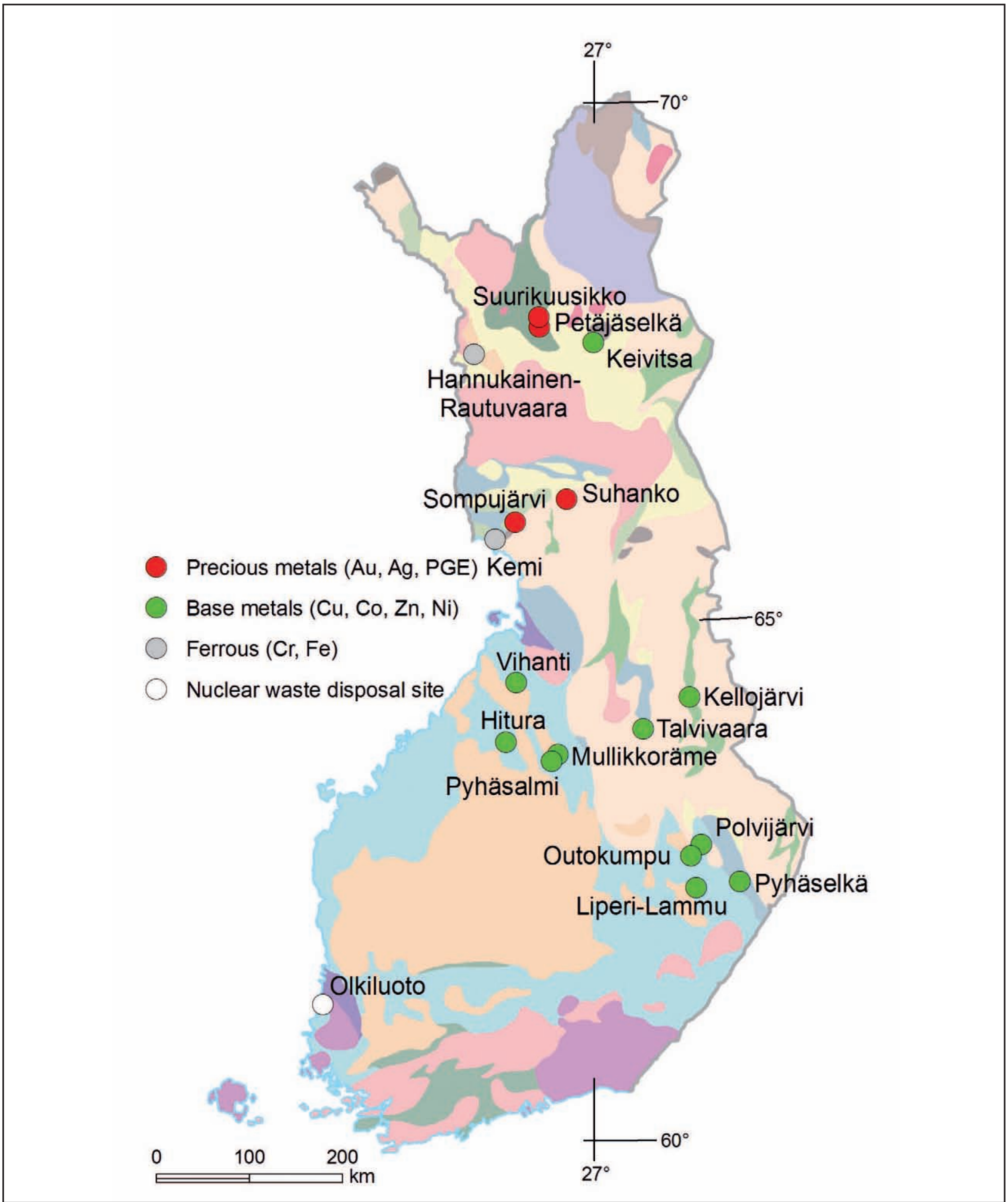

Figure 1. The target areas surveyed in the HIRE project. The targets of Outokumpu and Suhanko were already included in the earlier FIRE project (Kukkonen et al. 2006).

EXAMPLES OF HIRE RESULTS

In the following, we present examples of HIRE results from a few targets.

The Vihanti area of western Finland is well known for its semi-massive Zn-Cu-Pb deposits, which were mined by the company Outokumpu Oy from 1954 to 1992. The deposits are semi-massive sphalerite and pyrite lenses in skarn rock and cordierite gneiss hosted by felsic-intermediate volcanic rocks (Kousa & Luukas 2004). In the Vihanti area, the HIRE survey altogether comprised 84 km of lines, which provided a detailed image of the deep structures of the Lampinsaari and Vilminko formations. One of the Vibroseis lines ran across the Lampinsaari formation. In comparison with the geological cross section of the Vihanti mine, the seismic reflection section revealed a very similar overall structure (Figure 2a and b). The results indicate that the ore-hosting skarn-banded felsic volcanics, cordierite gneisses and mafic volcanic rocks have significant mutual impedance contrasts, but also a distinct contrast against the surrounding intermediate tuffites. This suggests that the host rocks of the deposit could be traced in the subsurface with reflection soundings. The Vihanti HIRE survey has revealed a large number of similar reflectors in the area. Whether they all represent rock types potentially hosting deposits is an open question at the moment, but the results support further exploration in the Vihanti area.

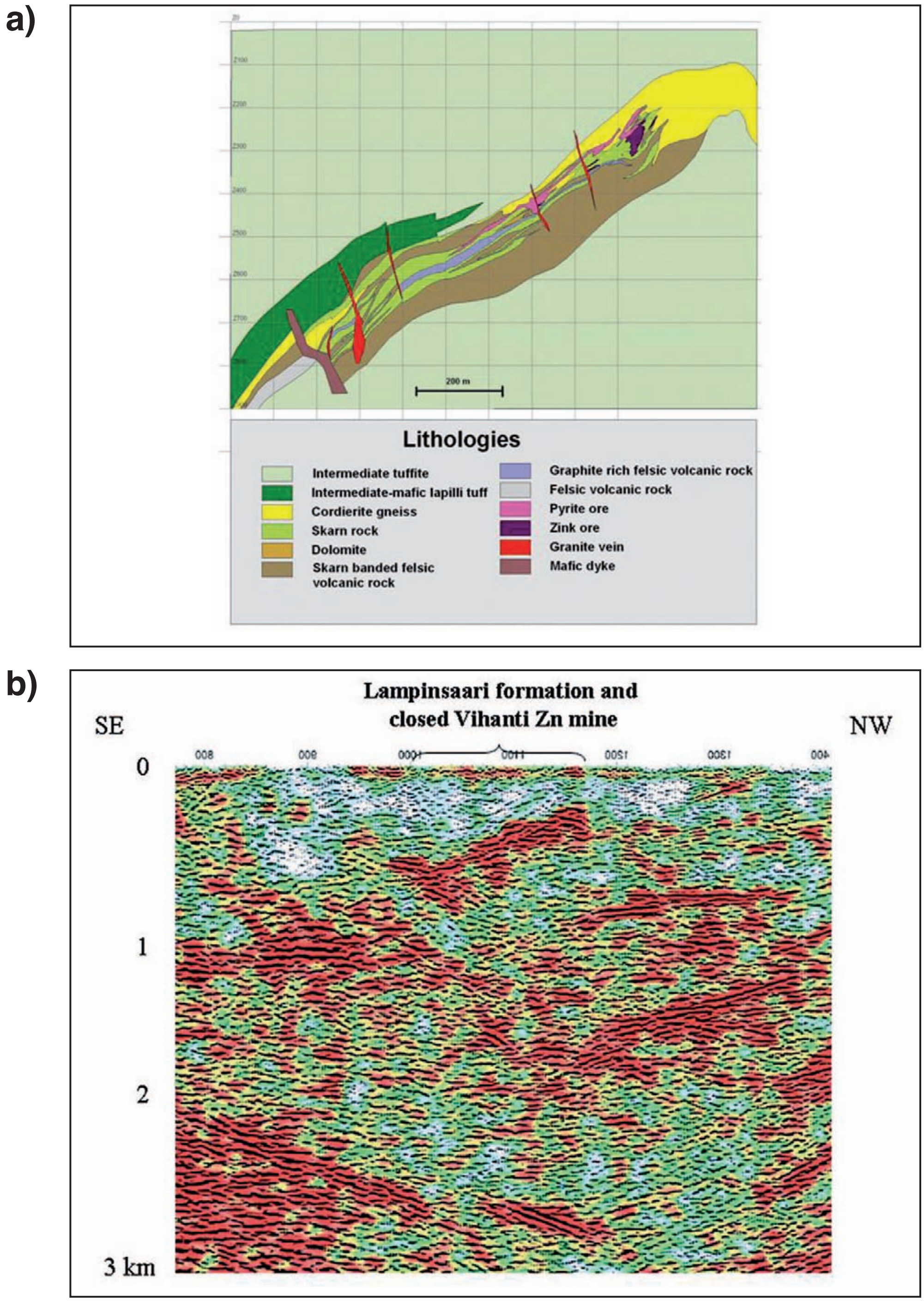

Figure 2. a) Geological cross-section of the Lampinsaari formation from the Vihanti mine (adapted from Kousa & Luukas 2004); b) Detail of a migrated seismic section running across the formation. The horizontal and vertical scales are identical. The section is located about 500 m to the SW from the geological cross-section in Figure 2a.

The Kevitsa ultramafic intrusion in northern Finland (Figure 1) hosts a large low-grade Ni and platinum element (PGE) deposit (Mutanen 1997), which is currently being developed for mining by First Quantum Minerals Ltd (FQM). The HIRE survey was carried out with the explosion method along four connected lines (Kukkonen et al. 2009a). The results revealed the basal contact of the intrusion against strongly reflective metasediments and metavolcanics. The seismic data are in good agreement with gravity models (Figure 3a). The Kevitsa deposit, which consists of fine grain size dissemination of sulphides in ultramafic host rock, also seems to be observable in seismic data (Figure 3b). In addition to these results, the seismic data revealed numerous shear and fracture systems. This has led to a new seismic project in Kevitsa, and a 3D seismic survey was launched in early 2010 by FQM with the aim of generating detailed information on shears, faults and other tectonic structures relevant for the design the Kevitsa open pit.

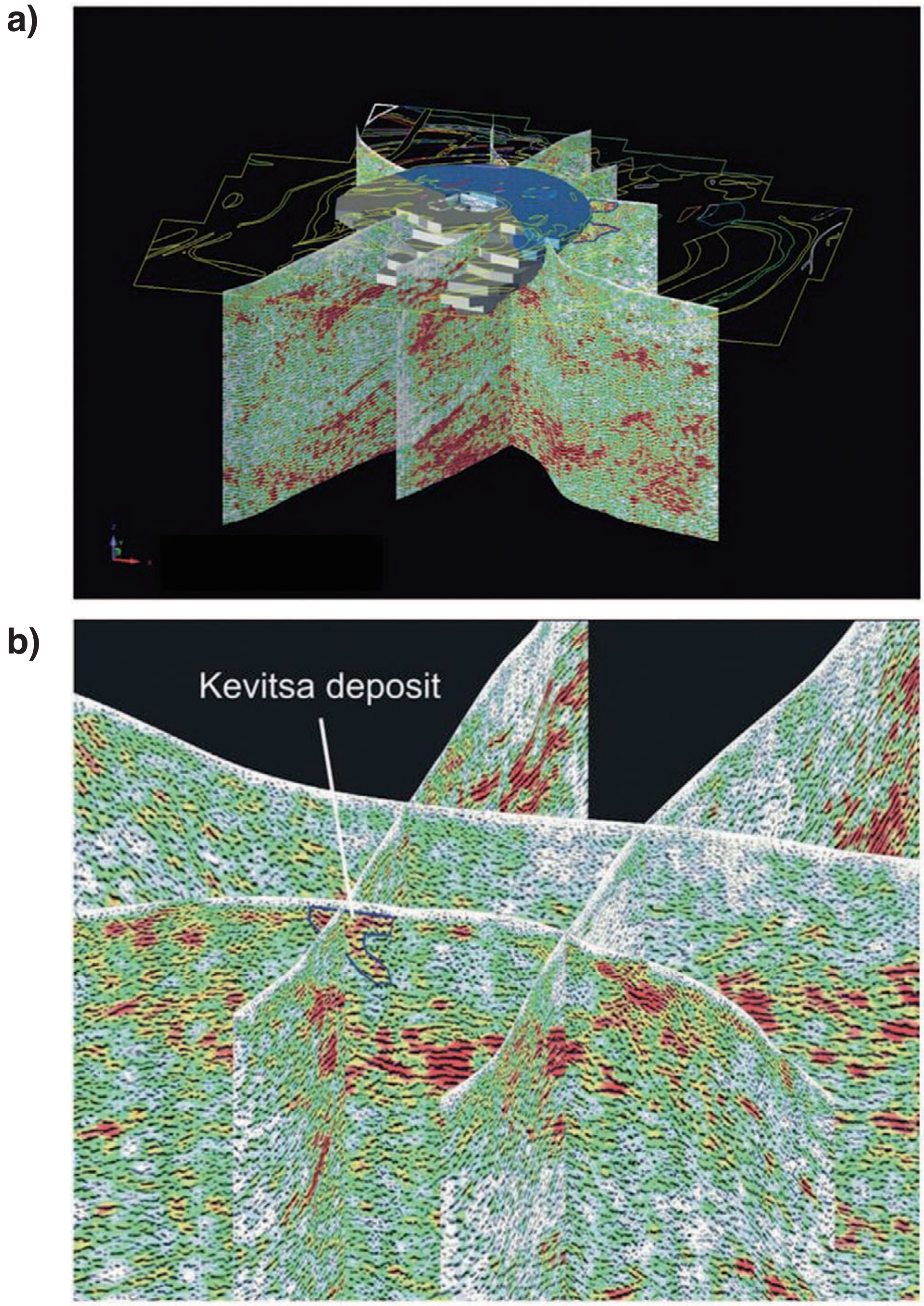

Figure 3. a) 3D presentation of HIRE results in the Kevitsa ultramafic intrusion together with gravity modelling (adapted from Kukkonen et al. 2009a). The seismic sections extend to a depth of 5 km; b) Detail of the Kevitsa HIRE results viewed from the N. The disseminated Ni-PGE Kevitsa deposit appears to be reflective.

The Hannukainen-Rautuvaara area in northern Finland hosts several Fe-oxide-Cu-Au deposits, mostly in clinopyroxene-dominated skarn or albitite (Niiranen et al. 2007). In Hannukainen, one of these deposits was open-pit mined in 1978–1992 by the companies Rautaruukki Oy and Outokumpu Oy. Presently, Northland Exploration Finland Oy holds the exploration claims for the area and is developing the deposits for mining. The overall HIRE survey in the area comprised 80 km of lines, which have revealed an extensive system of potentially ore bearing rocks in the area (Kukkonen et al. 2009b). Here we present only a detail from the SW side of the abandoned Hannukainen open pit (Figure 4). The ores, which are characterized by semi-massive magnetite and weak sulphide dissemination in skarn rock, are seen as very bright reflectors. The uppermost reflector correlates with the layer mined in the Hannukainen open pit and it has also been followed down-dip with drilling to a depth of about 400 m. In addition to this layer, the reflection data show two other strongly reflective layers below the known ore-bearing layer. These reflectors have not yet been drilled, but they may indicate potential target rocks that extend to a depth of at least of 1.5 km beneath the abandoned open pit.

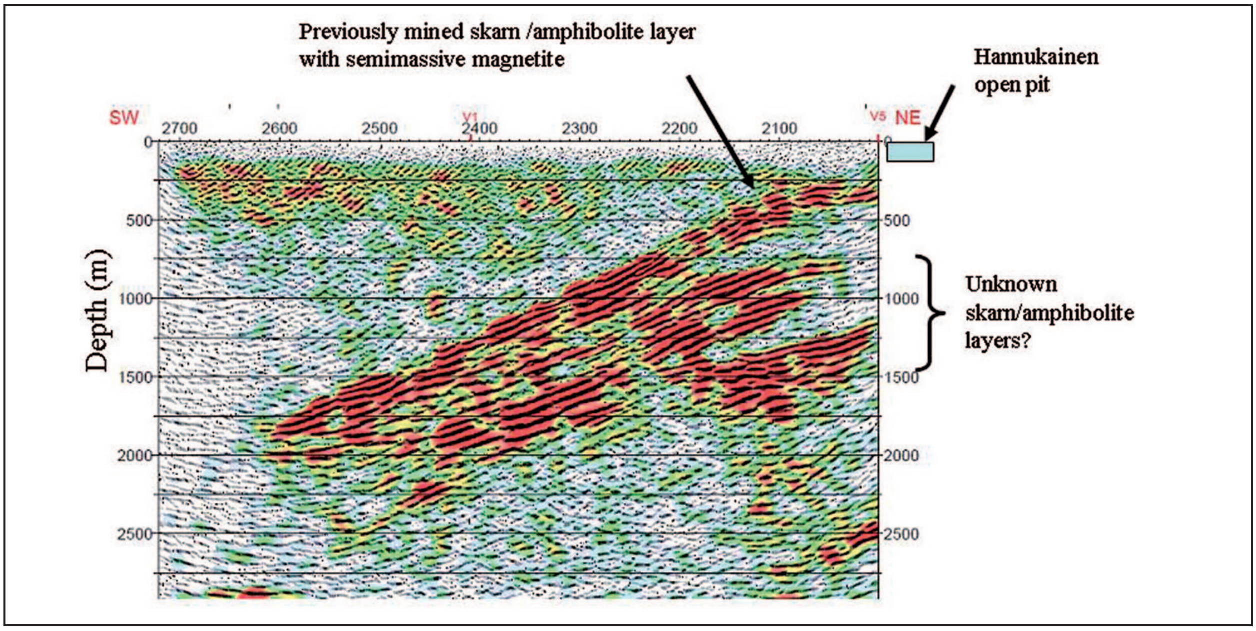

Figure 4. Detail of a migrated section in the Hannukainen Fe-oxide-Cu-Au deposit. The deposits mined in the Hannukainen open pit are associated with the uppermost strongly reflective layer. Beneath this layer, similar bright reflector packages exist.

The final disposal of spent nuclear fuel is being planned in ***Olkiluoto***, western Finland, by the company Posiva Oy. The HIRE survey in Olkiluoto consisted of three lines with a total length of 31 km. As an example, the results from line V1 running from Olkiluoto island (the repository site) to the main continent are illustrated in Figure 5.

The survey in the Olkiluoto area revealed numerous previously unknown structures in the upper crust. On Olkiluoto island, reflectors could be correlated with drill-hole-based data on lithology and brittle fracture zones (Kukkonen et al. 2009c). The main brittle fracture zones detected in drill holes are represented as reflectors in the seismic sections, and several new structures have been interpreted. The most prominent structures observed are subhorizontal strong reflectors, which very probably represent Postjotnian diabase sills intruding both the Svecofennian gneisses and the Mesoproterozoic rapakivi granites. These reflectors can be associated with similar subhorizontal seismic structures recorded in marine seismic transects in the Bothnian Sea (Korja & Heikkinen 2005), and thus they represent a large-scale structure. The Mesoproterozoic rapakivi granites can be distinguished as homogeneous, seismically transparent domains that extend to a depth of at least 4 km. The interpreted rapakivi structures are in a close agreement with gravity modelling results (Kukkonen et al. 2009c).

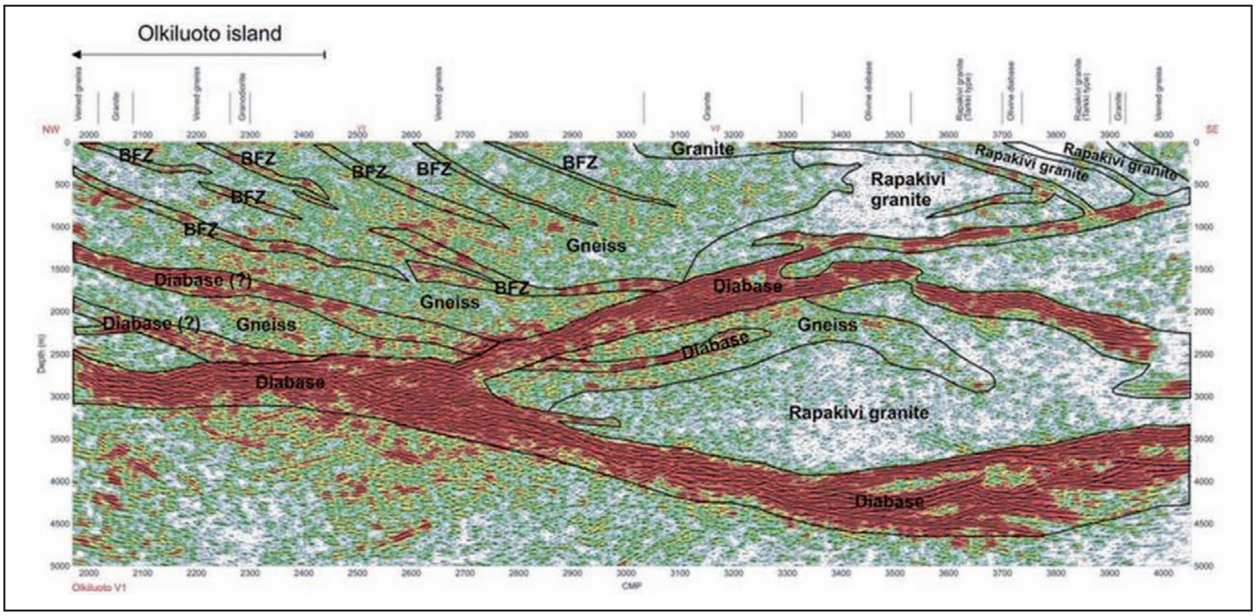

Figure 5. Example of the HIRE results obtained in Olkiluoto, western Finland, where the final disposal of spent nuclear fuel is planned. The NW-SE oriented 10 km long line reveals strong subhorizontal reflectors interpreted as diabase sills and brittle fracture zones dissecting the Paleoproterozoic migmatitic gneiss and Mesoproterozoic rapakivi granite. The more transparent domains are interpreted as rapakivi granite, in agreement with results from gravity modelling (adapted from Kukkonen et al. 2009c).

CONCLUSIONS

The HIRE project has produced detailed 2D seismic reflection data sets from all target areas, comprising fifteen exploration and mining camps and the Finnish nuclear waste disposal site. In this short presentation we have only been able to provide selected examples of the results. Interpretation and modelling of the data are still ongoing, and final conclusions cannot yet be presented. However, previously unknown structures have been revealed in all HIRE targets and our database on the structures of the investigated deposit areas has considerably expanded. Furthermore, previously unknown potential host rocks of deposits have been discovered in several targets. The HIRE results have considerably increased the level of detailed knowledge at previously unexplored depths, and it seems that the ore potential of the study areas may be higher than earlier anticipated. The results support the continued application of seismic reflection surveys in mineral exploration.

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NEW DOWN-HOLE GEOPHYSICAL TECHNIQUES IN THE EXPLORATION OF DEEP ORE DEPOSITS

by
Jarkko Jokinen, Arto Korpisalo and Hannu Hongisto*

Jokinen, J., Korpisalo, A. & Hongisto, H. 2011. New down-hole geophysical techniques in the exploration of deep ore deposits. *Geological Survey of Finland, Special Paper 49*, 59–70, 11 figures and 1 table.

Two new devices for geophysical exploration have recently been developed by the Geological Survey of Finland (GTK). They are both electromagnetic down-hole systems aimed at localizing and studying deep electrically conductive ore deposits and other conductive structures. The GTK-FrEM applies a fixed surface transmitter loop and a movable borehole receiver. This low frequency (330–3189 Hz) technique detects conductors in any direction from the borehole. The GTK-FrEM device uses a memory logger and requires no data transmission via logging cables. A prototype of the logger instrumentation has been successfully tested in exploration work. The EMRE device applies radio wave tomography in cross-borehole surveys for 2D mapping of rock conductivity. The EMRE has a fixed high frequency (312.5–2500 kHz) transmitter in one borehole and movable receiver in other borehole. The processed data are represented as attenuation distribution and apparent conductivity maps between the two boreholes. The EMRE device has been successfully applied in locating good conductors in a sulphide exploration target and in locating poorly conductive fracture zones at a nuclear waste disposal site.

Keywords (GeoRef Thesarus, AGI): geophysical methods, mineral exploration, well-logging, electromagnetic methods, tomography, radio-wave methods

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INTRODUCTION

New exploration methods and equipment are needed, because most of the easily detectable near-surface metallic mineralizations have been already discovered. One possibility is to use geophysical measurements together with drilling to detect potential targets hidden deeper below the ground surface. The use of rapid and cost-effective aerogeophysical methods has increased in prospecting surveys and in pointing out target areas with the greatest potential. At selected target sites, drilling is an exact and essential method, but also a slow and an expensive way to obtain geological information. Moreover, each deep drill hole is an investment that should return the best possible benefit. However, drill holes offer an excellent observation platform to expand the information from the borehole to the surrounding rock volume. In particular, detailed exploration in active mines often requires detailed information on resources possibly hiding between reconnaissance drill holes.

The Geological Survey of Finland (GTK) has developed two new geophysical borehole devices for localizing and studying deep ore deposits. Both new down-hole geophysical techniques apply electromagnetic methods. In the GTK-FrEM device, a large fixed surface transmitter loop generates an electromagnetic field that is detected with a movable borehole receiver. Anomalies in the received secondary field indicate the presence of electrically conductive bodies such as sulphide mineralizations. The GTK-FrEM method is capable of detecting an ore body within a maximum radius of up to 200 m from the borehole. In the EMRE system, the transmitter antenna is fixed in one borehole and receiver antenna is moved in another borehole, building up a bistatic system. Furthermore, varying of the transmitter position allows a tomographic inverse solution of the attenuation of radio waves in cross-borehole space. This radio imaging method (RIM) results in a visual map of the variation in electrical conductivity between two boreholes. The operation distance or borehole separation can be as large as 1000 metres. An internal property of the EMRE device is that it always senses the strongest signal coming from the first Fresnel zone.

Recent technological development in electronics and data processing has opened up new possibilities to improve geophysical logging devices and data processing systems. Exploration techniques can be divided into three separate segments: (i) hardware, (ii) software and (iii) knowledge concerning measurement and interpretation. In the GTK-FrEM system described in the present paper, the instrumentation and data processing programs are new, but the interpretation and most of the measurement know-how are based on exploration traditions at GTK. The first years of the GTK-FrEM project have focused on manufacturing the instrumentation, as well as testing, calibrating and learning to use the system in practice. In the EMRE system, an old device (Russian-based FARA equipment, Redko 2000) has been prepared and is going to be modernized with new electronics resulting in a more modular and functional structure and with a possible additional high frequency option in the near future. Data processing and interpretation are based on existing but also new software. A new combination of instrumentation, cost-effective data processing and know-how has been established at GTK. The EMRE system is in productive use at GTK after three successful field cases. Co-operation with many partners was necessary to achieve progress in both projects presented in this paper.

Before manufacturing the GTK-FrEM device, we had practical experience from two separate frequency domain downhole systems. The SINUS was developed by the USSR Ministry of Geology Research-Production Organization “Rudgeofizika”, St. Petersburg, Russia. The SlimBoris system was developed in the GeoNickel project by IRIS Instruments in co-operation with several partners. Some results obtained with the SlimBoris system have been published in conferences (e.g. Pietilä et al. 2000, Raiche et al. 2003). The GeoNickel project was coordinated by Outokumpu Mining Oy, Finland, and funded by the European Commission under the BRITE/EURAM Programme.

GTK-FREM

The measurement device of the GTK-FrEM has a surface transmitter and a borehole receiver (Figure 1). The transmitter loop lies on a fixed place above or close to the target. The typical side length of the square loop is 500 m. The measurement system has five alternative frequencies varying from 330 to 3189 Hz. When the signal generator supplies a sinusoidal electric current to the loop, a sinusoidal magnetic field generates eddy currents in conductive materials in accordance with the laws of electromagnetic induction (e.g. Parasnis 1986). In electrically resistive host rock, the time-dependent magnetic field has no marked effects, but in an electrically conductive mineralization the eddy currents cause a secondary magnetic field. Inside the receiver, three orthogonal coils are used to detect variations in the magnetic field. The coils measure a combination of the primary and secondary magnetic fields.

Pyhäsalmi Mine Oy is currently mining massive Cu-Zn sulphides and pyrite in Pyhäsalmi, central Finland. The exploration holes at the lower levels of the mine are drilled in sub-horizontal directions outwards from the mine. Traditional electromagnetic logging instrumentation would employ a logging cable between a surface unit and a borehole receiver (Pantze et al. 1986). Because of the logging cable, horizontal holes are very difficult to measure. In co-operation with Pyhäsalmi Mine Oy and J-Embedded Oy, we have developed a solution for the logging of horizontal holes. All necessary electronics is built inside a wireless down-hole probe (diameter 57 mm). The borehole probe is a memory logger that can be pushed into a borehole by a drilling rig at the front of a string of drilling pipes. Logging data from the borehole receiver are loaded onto a computer after uplift and the final results are calculated with data processing software.

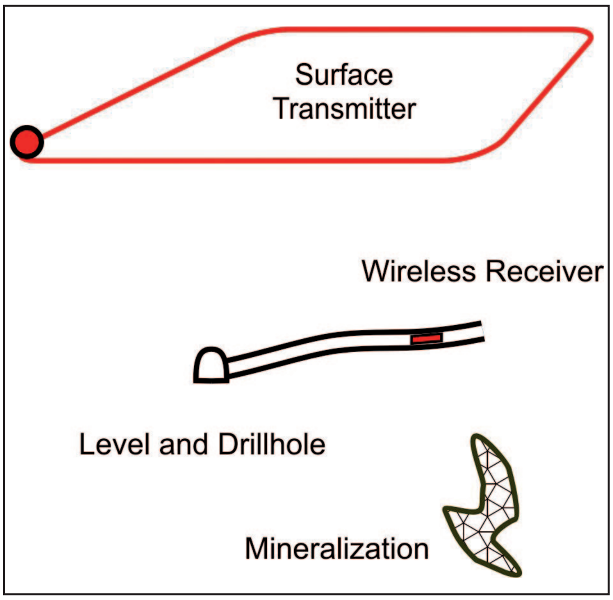

Figure 1. Principle of the GTK-FrEM logging system.

The resultant harmonic magnetic field induces an electromotive force (emf) in the three orthogonal receiver coils. The sinusoidal shape of the emf is recorded by sampling it with a frequency of 22 kHz. The time control of each sample is based on an accurate oscillator in the receiver probe. Another oscillator in the transmitter provides a timing reference for the transmitter current. Parameters of the sine wave functions for the simultaneously recorded sets of receiver and transmitter observations are solved by the Fourier transform. The data record of a single measurement station includes in-phase and quadrature values for each receiver coil. Digital recording of the discrete raw data also gives a possibility to stack and filter the data afterwards.

The principle of the measurement is not new. It directly follows the basic theory of electromagnetism presented in textbooks of geophysics (e.g. Peltoniemi 1988). Comparable measurements can also be carried out with a standard laboratory oscilloscope. The challenges in applying the method are mainly technical. Accurate measurements must be made in slim drill holes with a very slim instrument, under difficult conditions, and large data sets must be recorded.

In order to determine the orientation of the downhole tool, the GTK-FrEM device also measures gravity and magnetic fields with three orthogonal accelerometers and three orthogonal magnetometers, respectively. Rotation, dipping and the azimuth of borehole probe are solved from acceleration and magnetic data. When the probe is kept in a stationary place or is moved at a constant velocity, the deviation in the data is low. When changing the station of the probe, the deviation in the data recorded from the electromagnetic coils and accelerometers is at an elevated level until the probe stands at its new measurement station. Peaks in the accelerometer data are used to count the station number.

An example of the recorded amplitude of the electromagnetic field (red curve) and deviation of the accelerometers (blue curve) is presented in Figure 2. Peaks in the blue curve show exact moments when the drilling rig has started to push (220 s), pushes with almost constant velocity, then stops pushing, when the grip is changed (226–233 s) and the rig pushes again. The recording station interval in the borehole is 3 metres due to the length of the drilling pipes. The next undisturbed transmission pulse of the applied frequency is recorded between 246–248 seconds. Electromagnetic logging results for this depth are solved from samples of this particular 2-second period.

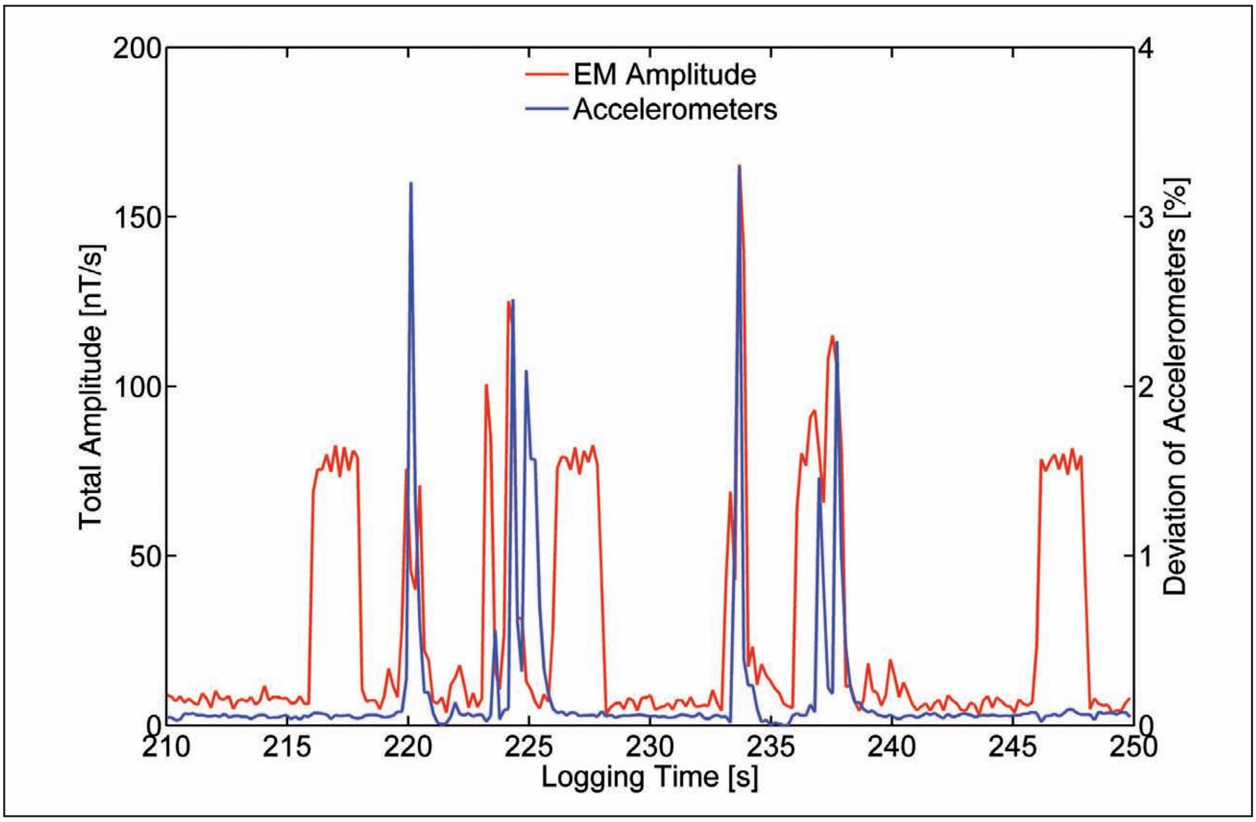

Figure 2. Total amplitude of the electromagnetic field (red) and deviation of the accelerometers (blue) during the time period when the GTK-FrEM down-hole receiver and drilling pipes are pushed 3 metres forward in the borehole.

An example of the final logging results with the new wireless down-hole technique is presented in Figure 3. Results from three orthogonal components with in-phase and quadrature values are combined into one total electromagnetic amplitude profile. The red curve is the result measured at a frequency of 330 Hz and blue curve at 3189 Hz frequency. The profiles in Figure 3 reveal many detailed anomalies caused by conductors close to the borehole, but also larger anomalies caused by extensive structures. One example of a marked anomaly is the minimum at the 700 m station. The borehole penetrates an electrically highly conductive and massive sulphide mineralization that dampens the propagation of the electromagnetic field. The large anomaly at the beginning of borehole R-2232 (blue curve) is caused by the deposit presently being mined behind the borehole.

This new geophysical exploration device is not yet mature enough for operational use, but experience gained in the Pyhäsalmi mine is encouraging. The logging results are repeatable and the logging speed can be almost as fast as new drilling tubes can be pushed into a hole (about 6 m/min), and most importantly, a good correlation between logging results and geology has been achieved. The first prototype of the borehole receiver has shown that EM surveys in sub-horizontal exploration holes are feasible. Development work for thinner (diameter 40 mm) probes, as well as fluent data processing and interpretation is under way.

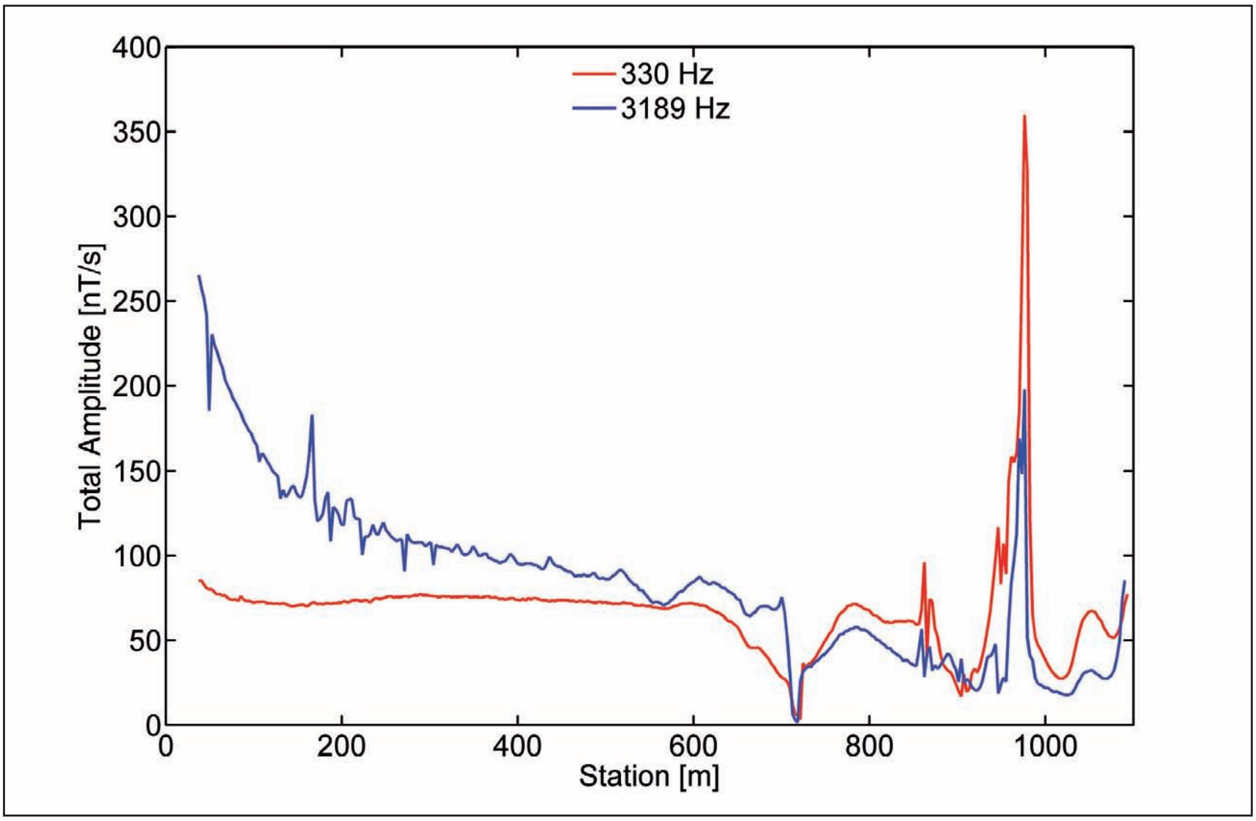

Figure 3. Total amplitude of the electromagnetic field measured in borehole R-2232.

EMRE SYSTEM

The EMRE system is based on the radiowave attenuation between two deep water-filled boreholes (Figure 4). The method is known as the Radio Imaging Method (RIM). A transmitter with four fixed frequencies in one borehole and the continuous movement of the receiver in another borehole makes it possible to recover the attenuation distribution (dB/m) of the rock between the two boreholes. Measurement units are the total electric field component and the relative phase difference between measured and reference signals. The reference signal generated in the transmitter borehole unit is fed through a logging winch cable and ground level reference wire to the receiver unit at the surface for tuning purpose. Measured signals are brought to receiver unit at the surface using a simple idea, i.e. through the receiver winch cable. Technically, the EMRE receiver is established in a manner that does not deviate from a normal radio. Now, the front end of the receiver (RF amplifier) and mixers are situated in the borehole tubes and the normal components (e.g. detector) are situated in the surface box. The armoured winch cable is used to feed the signals to the detector. The measurement or scanning period can be monitored in real time using a portable laptop. The operator can effectively control the measurements, shortening or lengthening the scanning lengths, and thereby increasing the productivity. RIM is a high-resolution technique and especially useful for second-stage exploration, and it is intended to assist with strategic mine planning and large rock building projects. It is based on computerized axial tomography (CT scanning) widely applied, for instance, in medical imaging. RIM differs from CT in both physical scale and scanning geometry characteristics. On a larger physical scale, lower frequencies must be used to achieve sufficient receiver signal levels over practical distances. The spatial resolution in images reconstructed from measured signals may be in metres to tens of metres, while CT images are on a millimetre scale. The measurement geometry is also strongly variable from site to site. Successful measurements have been made in different conditions, with good results at Pyhäsalmi in 2008 (massive sulphide mineralization) and at Olkiluoto in 2009 (possible nuclear waste deposit area).

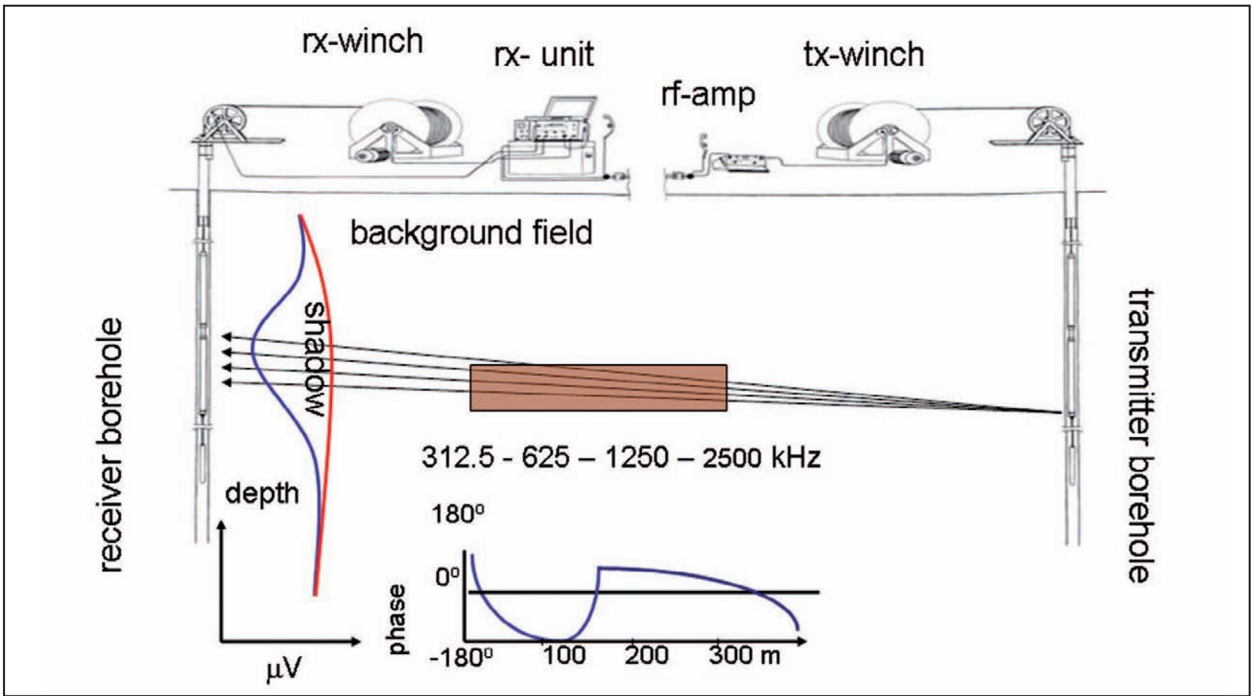

Figure 4. Measurement with the EMRE system (not to scale).

TARGETS

As a frequency domain system, EMRE differs from GPR (ground penetrating radar) in two ways: GPR is a time-domain device and usually works in reflection mode rather than in transmission mode, which is familiar for EMRE. When working in transmission mode, clearly defined boundaries are not necessities. The system was originally developed for disseminated sulphide mineralizations where the rock becomes gradually more conductive towards the centre of the mineralization area (Vogt 2000). During further development of the system at GTK, an additional high frequency of 5 000 kHz is going to be added to the system in order to improve its usefulness, especially in fracture detection within large rock building projects. The massive sulphide mineralization at Pyhäsalmi is a good example for an optimal research area, and it is here that EMRE measurements were carried out with good results in 2008 (Korpisalo & Niemelä 2008). EMRE measurements in both boreholes (section 1) are plotted in the same image (Figure 5). This is a simple way to delineate possible targets in a section. It is evidently clear that the attenuating material must be situated closer to borehole Br2, effectively masking the transmitter in Br2 (dashed lines) and having increasing amplitudes (lines), the transmitter being situated in Br1. The anomaly depth ranges from 150 to 200 metres in a vertical direction. Electric galvanic logging in borehole Br1 (borehole Br1 was common in sections) and EMRE registration in section 3 are compared in Figure 6. As can been seen, EM measurement may have the same distinct and highly localized features as electric logging (350–380 metres), but one has to remember that electric logging senses the close vicinity of the borehole and EMRE signals result from geological formations in the Fresnel zone volume between the boreholes. On the other hand, in upper parts (at ~170 m) electric logging in Br2 (Figure 7) has a strong localized reference to the low resistivity section near borehole but again the effect can be seen in Figure 5 where amplitudes are at diminished level (mainly due to attenuating material near Br2). Furthermore, at a depth of ~400 metres, electric logging corresponds to the low resistivity section in borehole Br1, which can also be weakly seen in EMRE signals in Figure 5 (line) and Figure 6. Thus, radio wave attenuation in rocks corresponds to electrical conductivity, but it is not only the internal material attenuation that increases or decreases the measured signal levels during scanning. The relationship between the antennas and the borehole environment may change greatly from point to point, having its effect (scattering parameter s_{11} which defines the relationship between the input power and the reflected power in the antenna) on signal levels, and is always combined with the material attenuation (Korpisalo 2010a).

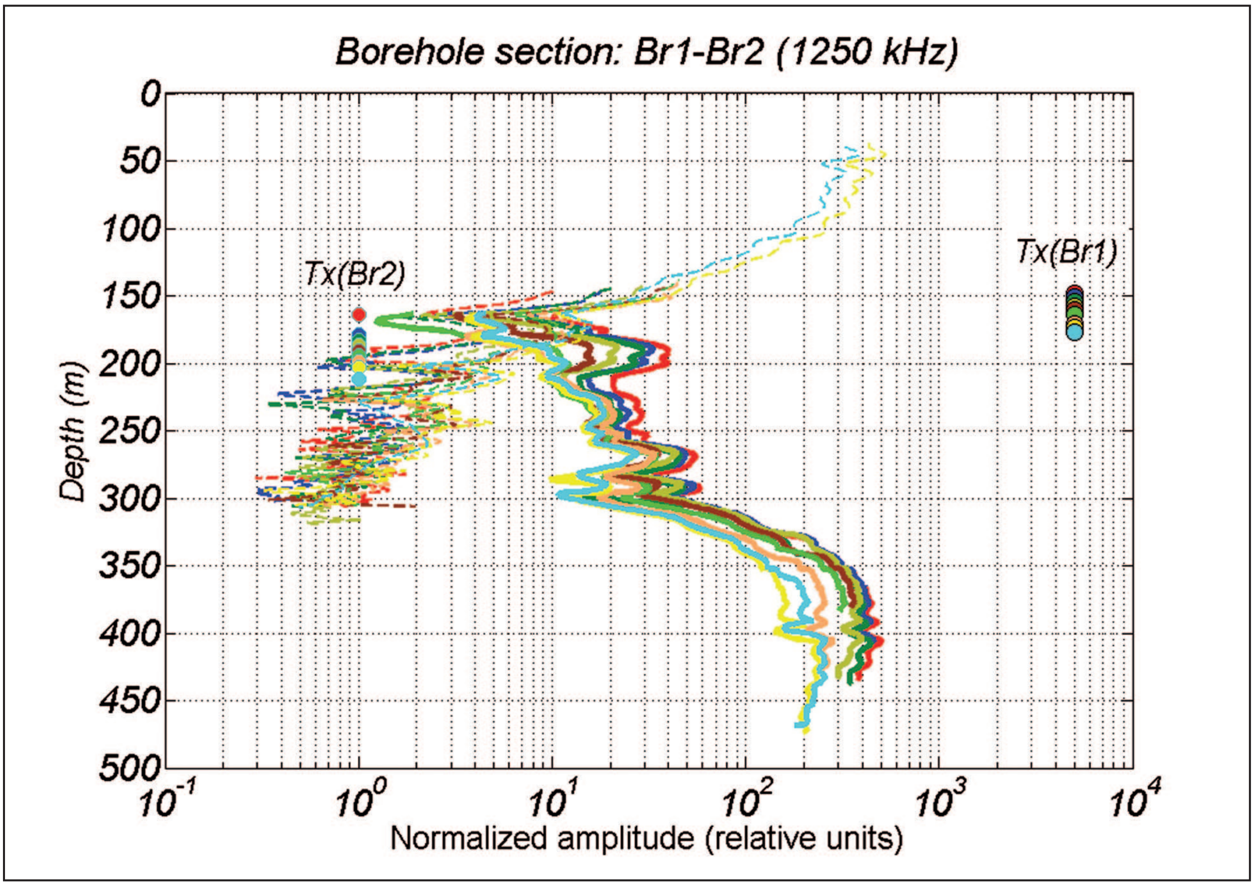

Figure 5. Measured EMRE amplitudes (relative units).

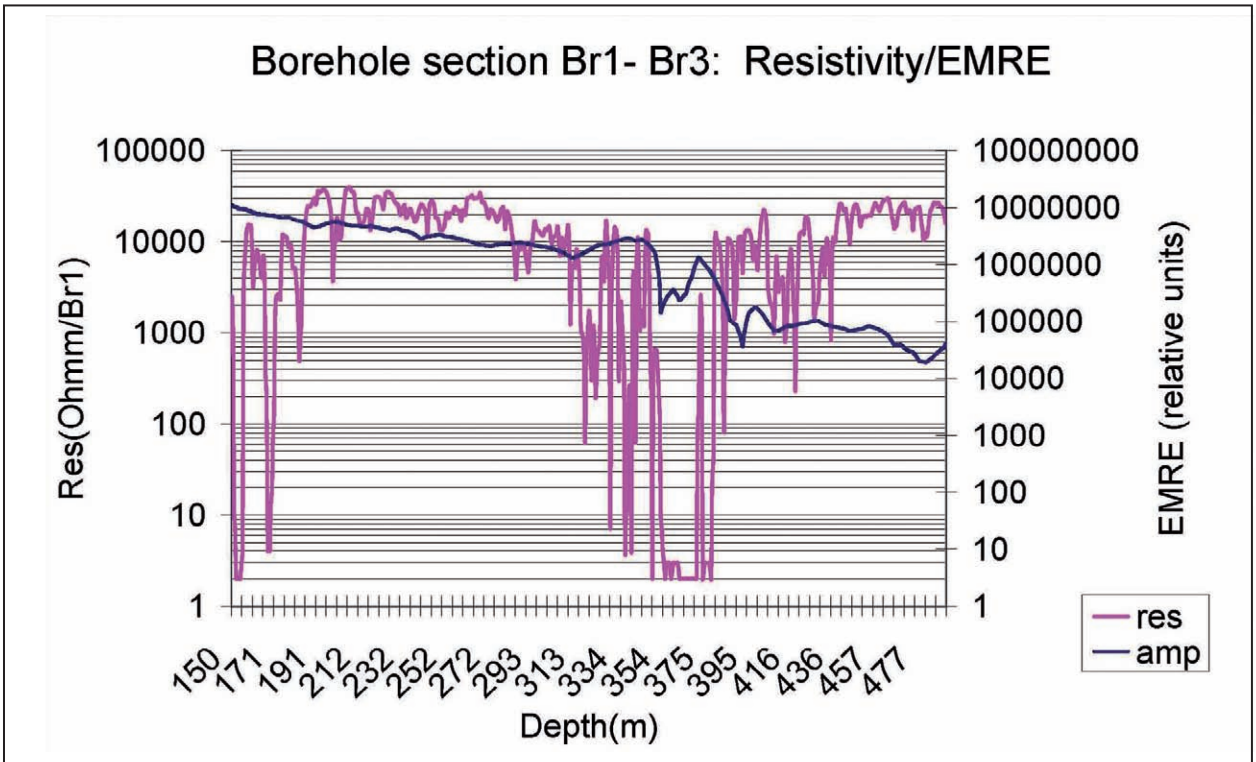

Figure 6. Electric galvanic logging results (Br1) compared with the EMRE signal.

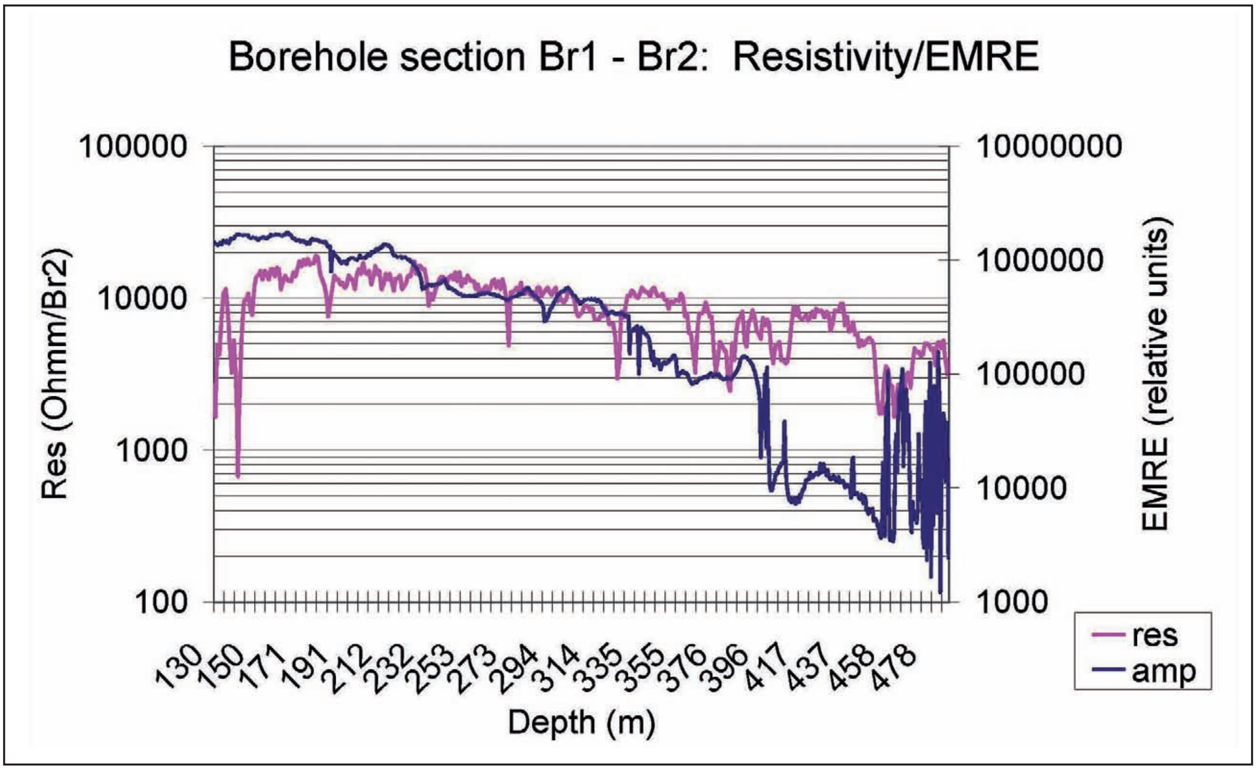

Figure 7. Electric galvanic logging results (Br2) compared with the EMRE signal.

MEASUREMENT

The stationary transmitter itself is connected to the electric dipole and continuously transmits at four measurement frequencies in one borehole, while a mobile receiver senses the electromagnetic energy through a dipole antenna. The use of separate antennas for the transmitter and receiver system can also be referred to as bistatic. Both ZOM (zero offset measurement) and MOM (multi-offset measurement) modes are used. Scanning speeds can be as high as 30 m/min without any disturbance. The scanning length of the receiver can be effectively controlled during measurements. Real-time control also makes it possible to add and remove transmitter positions during the measurement session, increasing the productivity. An internal characteristic of EMRE is that it always senses the strongest signal. It propagates to the receiver through the first Fresnel zone, which is a function of borehole separation and the dominant wave length. Fresnel zone is a prolate ellipsoid obtained by rotating an ellipse (having focus points in transmitter and receiver positions) about its major axis. If there is an attenuating object in this zone (Figure 8), the receiver registers a change (shadow) in the signal level (Figure 4). Borehole separation can be up to 1000 m. Both the amplitudes and the relative phase differences (not the precise travel time measurement) are measured at all frequencies (specifications in Table 1).

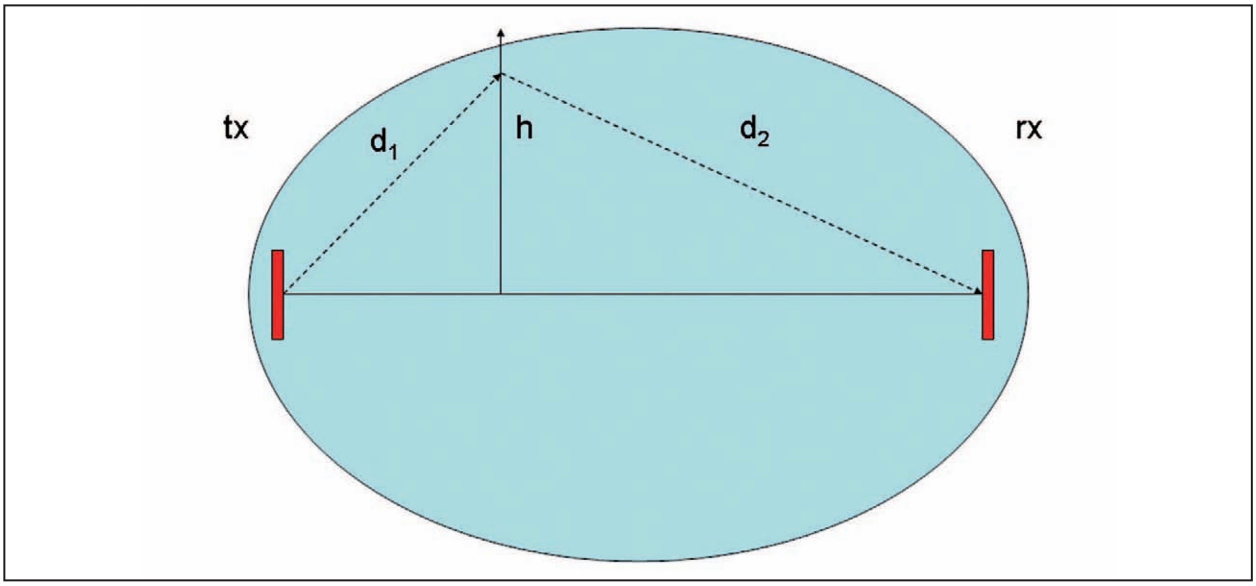

Figure 8. The first Fresnel zone.

Table 1. EMRE device specifications.

Operating frequencies	312.5, 625, 1 250 and 2 500 kHz
Measurement range of voltage	0.5 – 1 000 mV
Measurement range of phase	0 – 360
Maximum transmitter power	2 W
Diameter of borehole modules	36 mm
Winch capacity	1 000 m
Measurement modes	ZOM and MOM
Pressure tolerance	Up to 2 000 m

DATA PROCESSING: INTERPRETATION AND FINAL PRESENTATION

EMRE data processing is carried out in two stages: data editing and interpretation. The data editing stage is often the most time-consuming task in which the data are carefully reviewed. Every transmitter point is displayed in the graphical interface to detect/remove, for instance, possible multipath effects, because interpretation is based on the straight ray assumption. In addition, noisy parts can be cancelled. Before removing any distinct feature from scanning, careful comparison between all frequencies must be carried out, and if the feature is only visible in one frequency it may be acceptable to remove the feature from that frequency. It is also at this stage where the actual xyz coordinates in the borehole are calculated (Korpisalo 2010b).

The second stage is the actual interpretation, where the attenuation values (dB/m) are inverted from the measured data by solving the tomographic equation. As soon as the system matrix is calculated, one has to solve the matrix equation Ax = y to obtain the unknown attenuation values along the ray paths when the straight ray assumption is concerned. Two basic tomographic solving methods are available, namely ART (algebraic reconstruction technique, Kak & Slaney 1988) and SIRT (simultaneous iterative reconstruction technique, Jackson & Tweeton 1996), which are traditional methods. Besides these, effective iterative LSQR (least squares QR method) and CGLS (conjugate gradient method) methods can also be used. As a limited angle method (data coverage seldom >50–60 degrees), new algorithms nowadays already available in medical imaging will soon also be taken into use in geotomography, giving more reliable interpretation results. As the attenuation distribution of the section (Figure 9) is calculated, it can be converted into a conductivity distribution (Figure 10) using a plane wave solution (Zhou et al. 1998). The presented results are from a nuclear waste disposal site in Olkiluoto in 2009 (Korpisalo & Niemelä 2010). The section OL-KR40-OL-KR45 was conic and thus quite challenging for the system. The antenna orientation was occasionally quite disadvantageous and the effect on signals was evident. The conic shape also made it possible to start measurements closer to the air-earth interface, and the single dominant wavelength rule was not used. The functioning of the device and the results with the three lowest measurement frequencies were congruent. However, it was the highest frequency that caused problems. No signals were received, even in the upper parts of the section where the distance between the transmitter and receiver was only about 150 metres. The actual reason for this was not the internal attenuation but the unfavourable functioning of the antenna system in the environment with a frequency of 2500 kHz. Theoretical modelling studies proposed that the scattering parameter s_{11} was below two decibels (<-2 dB), meaning that over 60% of the input power was reflected back to the (transmitter) generator and the rest was transmitted to the environment (Figure 11). Thus, a low efficiency combined with increased attenuation with frequency resulted in low amplitude values (Korpisalo & Niemelä 2010). In Figure 11 both centric and eccentric insulated antennas (ε_{ri}=3) were situated in water-filled boreholes (ρ_{water}=1–500–1000 ohmm, ε_{rw}=81). Rock's resistivity was ρ_{rock}=12500 ohmm and relative permittivity had value of ε_{rr}=20. The maximal functioning levels were reached in 300–1500 kHz band (three lower EMRE frequencies included) s_{11} value being as high as -30 dB when dipole antenna was only 2 mm from the borehole wall (normal situation). The highest EMRE frequency 2500 kHz was situated on a plateau where s_{11} values were in the ineffective levels (< -2dB).

The final presentation was prepared with Geosoft's Oasis montaj processing and mapping software using the EMRE module implemented at GTK, in which a 2D section distribution is transferred to a real 3D borehole environment. When several sections are included in the measurement plan, it is also possible to delineate the targets that may not be situated in the cross section, because the device always senses the strongest signal and it may come as a multipath signal (Fresnel scattering) everywhere inside from the first Fresnel zone (Figure 8).

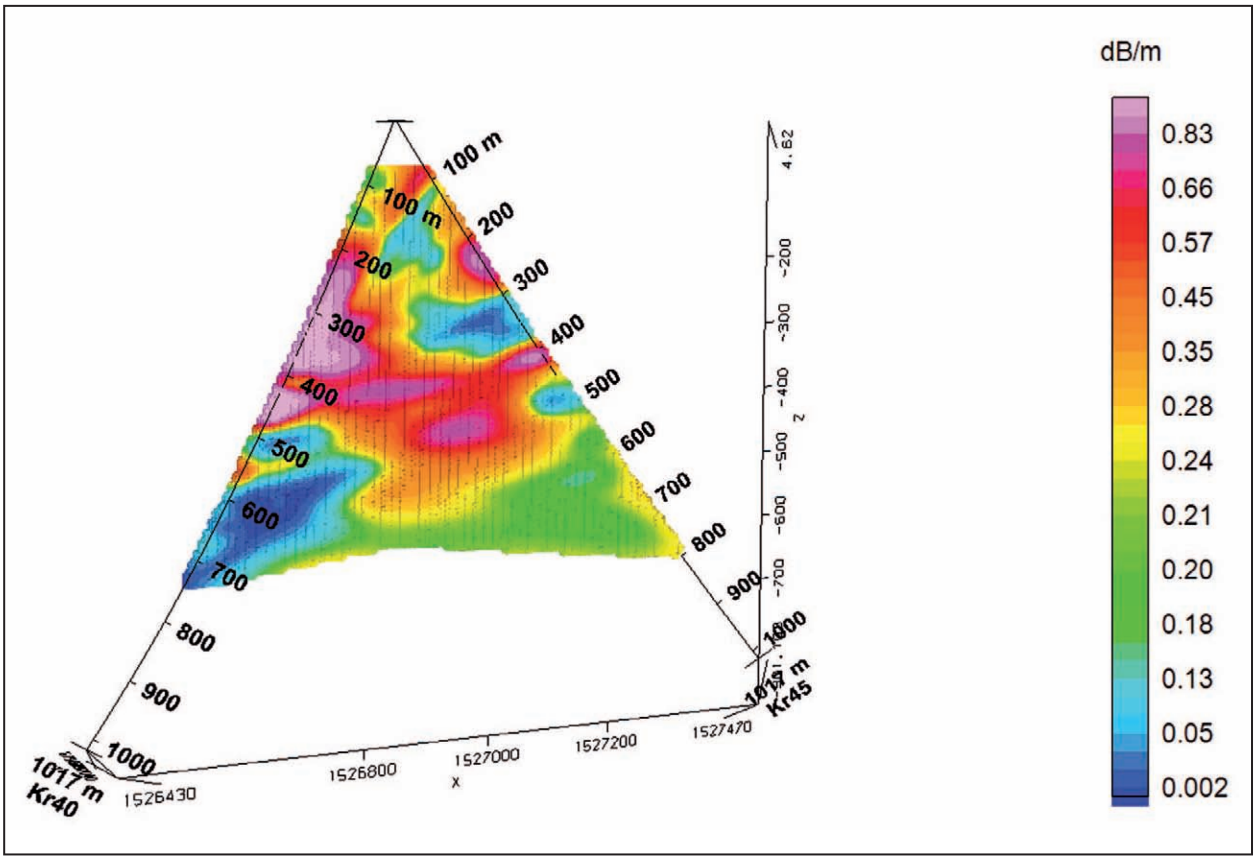

Figure 9. Attenuation distribution of section OL-KR40-OL-KR45 (625 kHz).

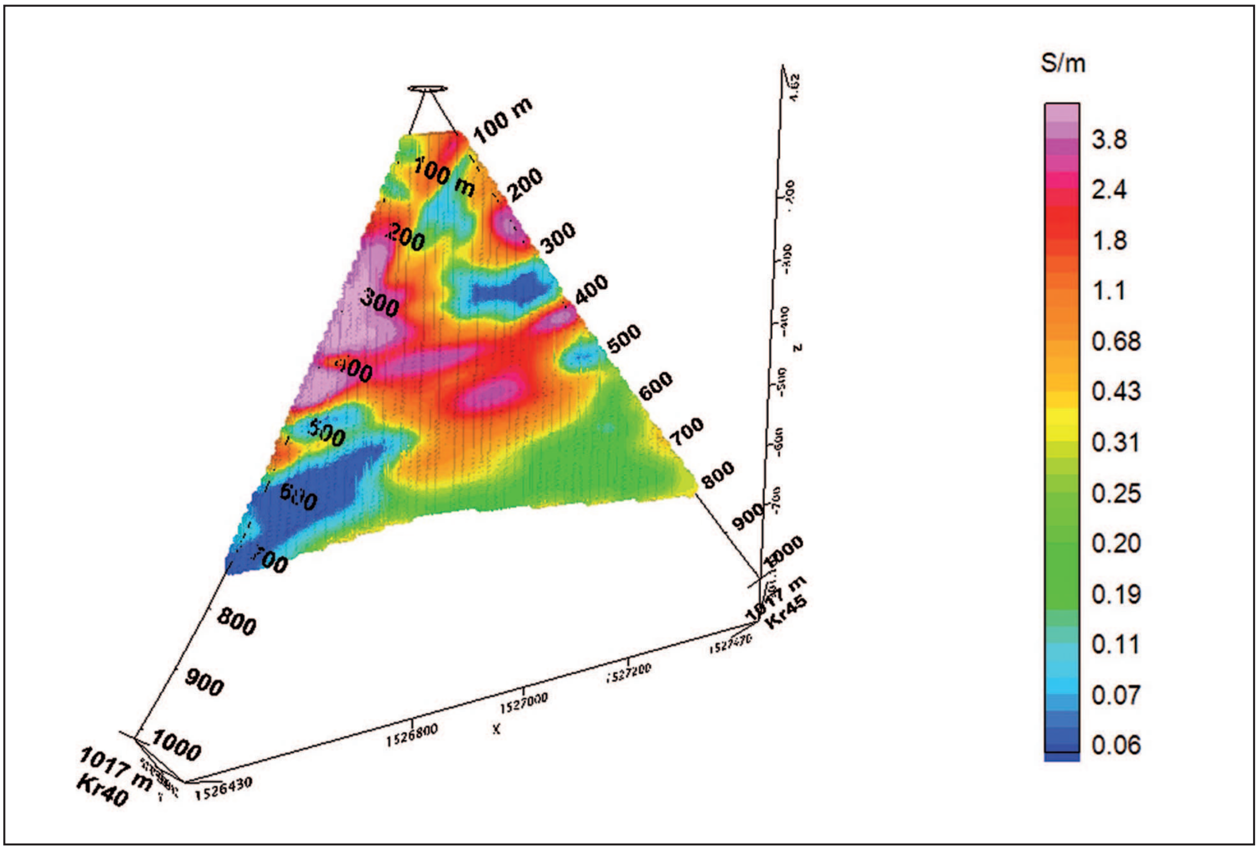

Figure 10. Apparent conductivity of section OL-KR40-OL-KR45 (625 kHz).

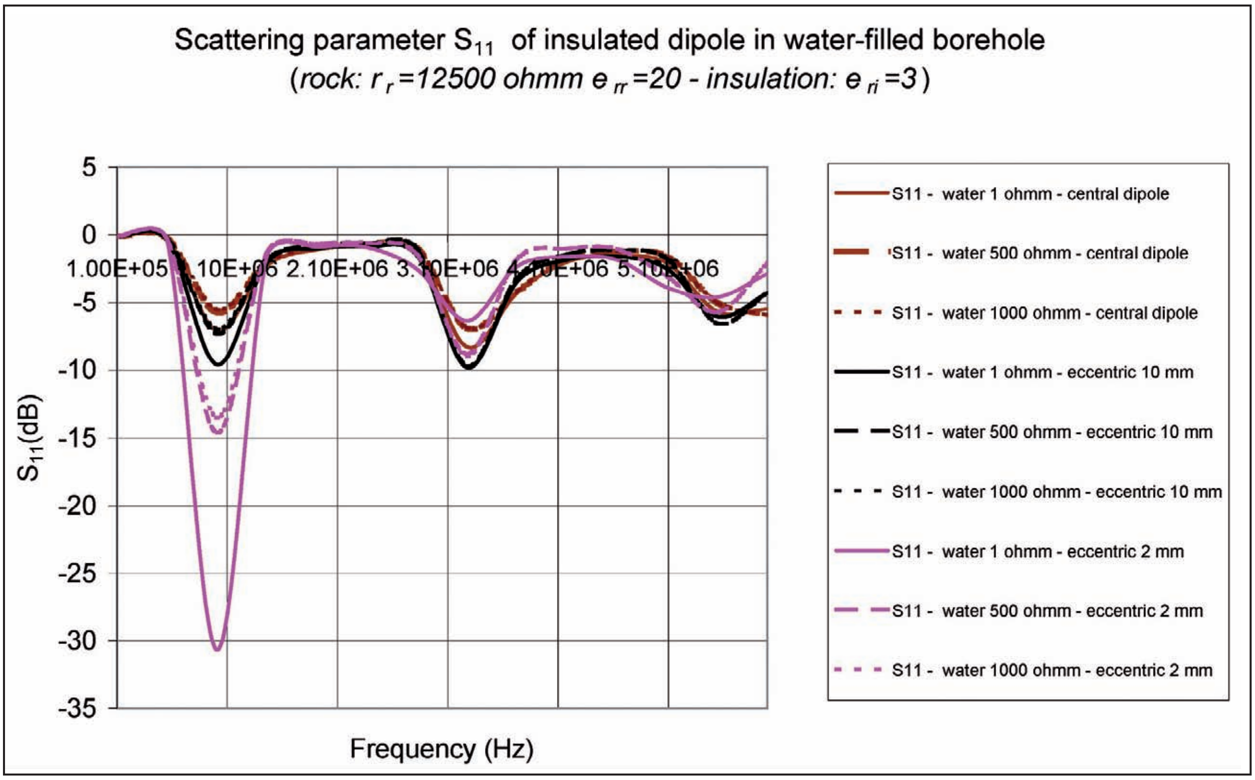

Figure 11. Scattering parameter s_{11} in transmitter antenna.

The EMRE system has been taken in productive use at GTK following the pioneering work at Olkiluoto in 2005 (Korpisalo & Jokinen 2008). Three solved cases in different environments have proven its potential in exploration geophysics. Real-time monitoring makes it possible to follow the scanning in a cost-effective way by shortening and lengthening the scanning during measurement points. The repetition level of the equipment is very good, which can be regarded as one of the characteristic features of a stable device. The system is currently under modernization in order to stabilize and ensure the future functioning and usefulness of the device at GTK.

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MODELLING THE GOLD POTENTIAL OF CENTRAL LAPLAND, NORTHERN FINLAND

by
Vesa Nykänen, Tuomo Karinen, Tero Niiranen and Ilkka Lahti*

Nykänen, V., Karinen, T., Niiranen, T. & Lahti, I. 2011. Modelling the gold potential of Central Lapland, Northern Finland. *Geological Survey of Finland, Special Paper 49*, 71–82, 7 figures.

This paper demonstrates the use of a fuzzy logic spatial modelling technique in mineral prospectivity mapping. We have used structural data derived from 3D modelling of reflection seismic and potential field surveys to further develop the previously published prospectivity mapping results for orogenic gold deposits within the Central Lapland Greenstone Belt, Northern Fennoscandian Shield, Finland. The fuzzy logic technique in GIS provides a flexible tool to test a conceptual exploration model when there is good data coverage within the area of interest. Furthermore, the results of this exploration model testing can be statistically validated if there are a number of known mineral occurrences of the sought mineral deposit type in the study area. In this study, model validation was conducted using the receiver operating characteristics (ROC) technique.

Keywords (GeoRef Thesaurus, AGI): mineral exploration, gold ores, potential deposits, geographic information systems, spatial analysis, fuzzy logic, data integration, Central Lapland Greenstone Belt, Lapland, Finland

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INTRODUCTION

Mineral potential modelling or mineral prospectivity mapping (also known as exploration targeting or mineral potential assessment) can be taken as synonyms of a practice that aims to delineate areas based on their mineral exploration potential. This field of geoscience has increased in popularity, apparently due to the emerging use of the geographical information system (GIS) for mineral exploration in minerals industry. GIS is designed to be used to manage spatially referenced data, which geological, geophysical and geochemical maps and field data particularly are. GIS is typically used as a tool for making maps, maintaining the map databases and for data delivery, but when taking a logical step forward, it can be extensively used as a tool for quantitative analysis of spatially referenced data and for modelling real world phenomena (Bonham-Carter 1994, Pan & Harris 2000, Carranza 2008).

In this study we rank areas within the Central Lapland Greenstone Belt (CLGB) according to their importance in gold exploration. The aim is to illustrate the importance of an exploration model in this process and the flexibility of the spatial modelling technique used. This study is a continuation of previously published work (Nykänen & Raines 2006, Nykänen & Salmirinne 2007, Nykänen & Ojala 2007, Nykänen et al. 2008, Nykänen 2008a, Nykänen 2008b). The inputs for the modelling comprise a selection of digital geoscientific data collected, maintained and distributed by the Geological Survey of Finland (GTK). These data sets are used as spatially referenced layers of evidence in gold prospectivity mapping within the CLGB.

Various mathematical and statistical techniques can be used to recognize patterns in spatial data, thereby making effective use of the annually expanding exploration data. The quantitative analysis of spatially referenced observable reality is also termed spatial data analysis or spatial modelling, in which the spatial distribution of the observations is taken into account in analysis and interpretation. The simplest and/or most common functions or operations for spatial data analysis, which are available in most GIS software, include extraction, buffering, overlay, proximity analysis, shortest path calculation, map algebra and raster analysis.

Many of these operations are used in converting the original geoscience datasets into 'evidence layers' to be used as inputs in the actual spatial modelling, which aims to provide mineral potential assessments. Figure 1 describes a common workflow in a project using GIS for mineral prospectivity mapping as described by Nykänen (2008b). Similar approaches have previously also been introduced by Pan & Harris (2000) and Harris & Sanborn-Barrie (2006). The backbone of a prospectivity mapping exercise in GIS is the implemented exploration model, which defines the characteristics of the deposit type, and thus gives guidelines for selecting the relevant data, especially those data best reflecting measurable or mappable features related to this deposit type. GIS is used to extract or derive the key features from the raw data. These techniques include image processing, interpolation, raster calculation, rescaling, classification or other so-called 'geoprocessing' tasks to prepare the data for the next step, which is the actual data integration part.

GTK has excellent coverage of geological, geophysical and geochemical data over the entire country (see e.g. Salminen 1995, Airo 2005). These digital data provide an almost infinite potential to perform spatial modelling for various geological problems, where mineral exploration is one of the best examples. The most recent additions to the geoscientific data collected by the GTK are the reflection seismic surveys FIRE (Kukkonen & Lahtinen 2006) and HIRE (Kukkonen & Heikkinen 2009). These surveys also resulted in reflection seismic data along the CLGB, thus providing insights into the major structures within our study area. In this study, we use the structures interpreted from the seismic surveys as an evidence layer in a prospectivity model. These and other similar structures are also interpreted within airborne geophysics and are used as input in the modelling.

It is crucial to perform model validation tests for prospectivity maps. There are several techniques for validation. The selection of the validation method depends on the modelling technique used and on the validation data available. A portion of the known mineral occurrences can be excluded from the training set if there are a reasonable number of sites for both training and validation. If the number of training sites is small, then only one deposit at a time can be left out from a training set to perform leave-one-out cross-validation. It is equally important to test the model against the known 'non-deposit sites' or so-called 'true negatives' (as opposed to 'true positives' as deposit sites). This was done in this study by using the receiver operating characteristic (ROC) technique (Fawcett 2006, Zou et al. 2007).

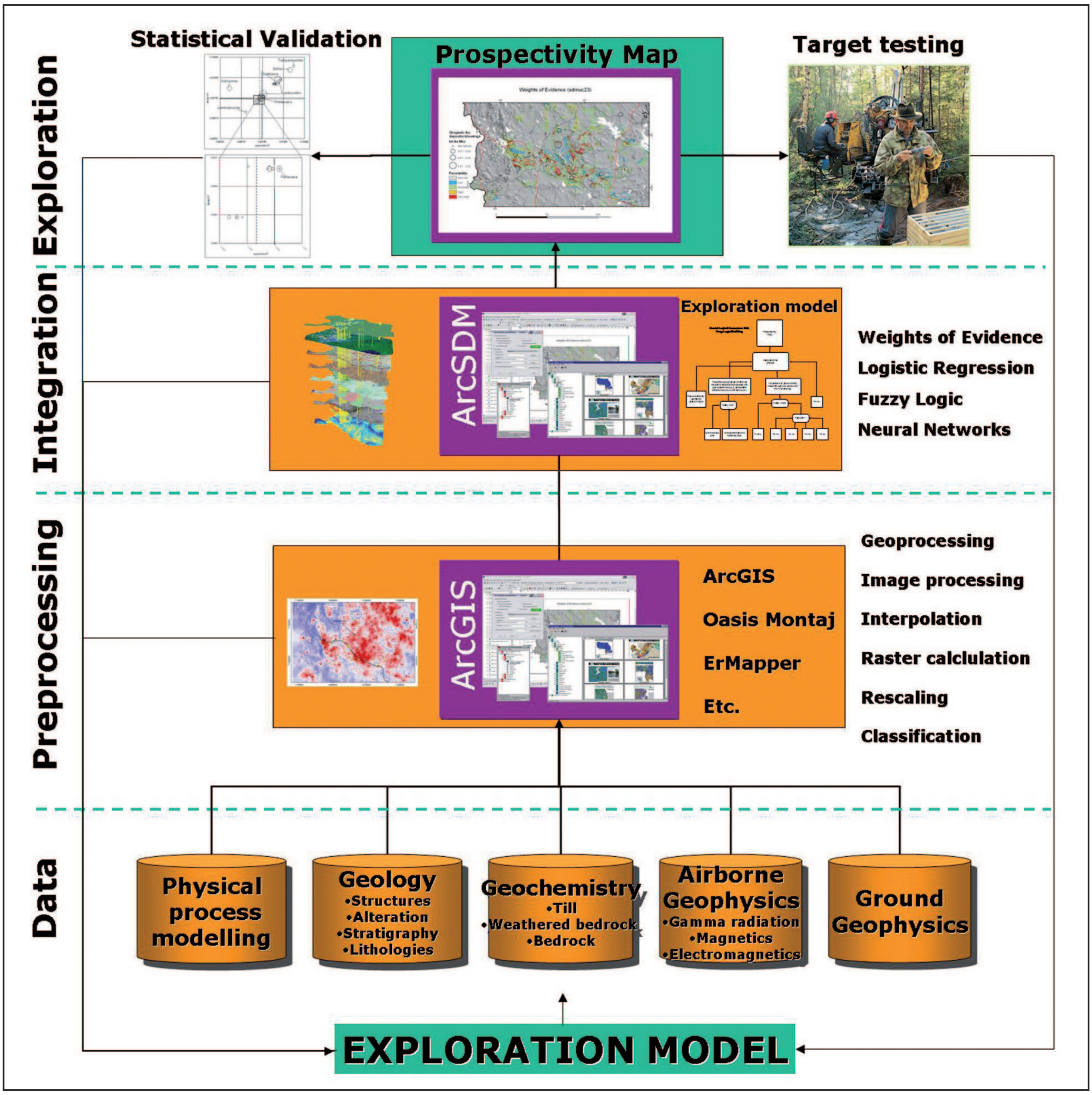


Figure 1. Prospectivity mapping methodology according to Nykänen (2008b).

STUDY AREA

The Central Lapland Greenstone Belt (CLGB) is located in the Northern Fennoscandian Shield, approximately 100 km north of the Arctic Circle (Figure 2). The CLGB consists of Palaeoproterozoic volcanic and sedimentary cover (2.5–1.97 Ga) on the Archaean granite gneiss basement (3.1–2.6 Ga) (Lehtonen et al. 1998, Hanski & Huhma 2005). The Kittilä Group is suggested to be allochthonous (Hanski 1997), whereas the rest of the belt is considered to be autochthonous or parautochthonous (Hanski & Huhma 2005). There are two operating gold mines (Pahtavaara and Kittilä) and one closed gold mine (Saattopora) together with more than 30 drilling-indicated gold occurrences within the CLGB (Eilu 1999, 2007).

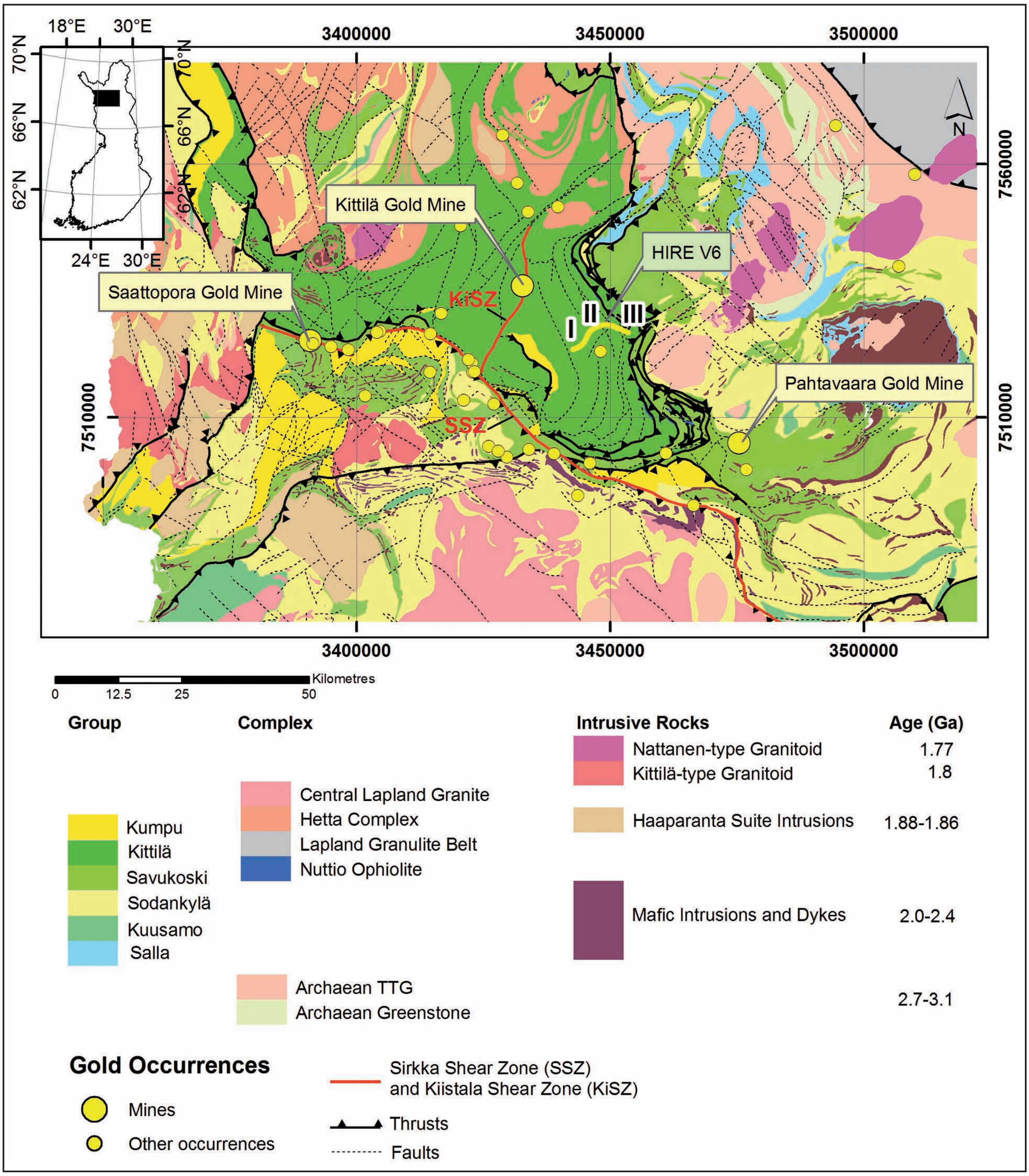


Figure 2. Main stratigraphic units of the study area: Salla Group (intermediate to felsic volcanic rocks), Kuusamo Group (intermediate, mafic and ultramafic volcanic rocks), Sodankylä Group (quartzites and mica schists with minor carbonate rocks and mafic volcanic rocks), Savukoski Group (phyllites, black schists, mafic tuffitic rocks, komatiitic and picritic volcanic rocks), Kittilä Group (mafic volcanic rocks) and Kumpu Group (meta-arkoses, quartzites, polymictic meta-conglomerates, meta-siltstones). The proterozoic succession is underlain by Archaean TTG (tonalitic-trondhjemitic-granodioritic gneisses) and Archaean greenstone (mafic to ultramafic volcanic rocks). Major gold deposits are marked with yellow labels and the reflection seismic survey (yellow line) with a green label. Labels I, II and III refer to locations marked on Figure 3. Geological map modified from Lehtonen et al. 1997.

Orogenic gold occurrences

The orogenic gold deposits are structurally controlled, being located in second- to lower-order shear or fault zones within local compressional to transpressional structures at the time of mineralization (Groves et al. 1998, McCuaig & Kerrich 1998, Goldfarb et al. 2001). The FinGOLD database (Eilu 1999, 2007) includes over 30 drilled gold occurrences with at least one metre of 1 ppm Au within the CLGB. These deposits, classified as orogenic gold type, are frequently spatially related to multistage alteration zones (Eilu et al. 2007). The alteration styles reported are sericite and carbonate alteration in lower-to-middle greenschist facies domains, biotite and carbonate alteration in upper-greenschist to lower-amphibolite facies domains, and biotite alteration and the formation of K-feldspar and calc-silicate minerals in higher metamorphic grade domains (Eilu & Weihed 2005). The breakdown of magnetite and pyrrhotite due to hydrothermal alteration is the most prominent and detectable feature in airborne magnetic-field total intensity maps (Airo 2002).

DATA USED FOR MODELLING

Several tasks need to be completed in GIS to extract the relevant information from the datasets before data integration into prospectivity maps. The common GIS tools are used to apply spatial analytical calculations to the vector GIS layers, such as proximity analysis, density analysis and visibility analysis, or various interpolation methods such as inverse distance weighting, spline or kriging. Furthermore, the resultant grid data might need to be reclassified, generalised or integrated in several ways.

Finland has been completely covered by high-resolution multi-component airborne geophysical surveys flown at 40 m altitude and 200 m line spacing (Airo 2005). In the current study area, the airborne surveys were carried out between 1975 and 2003. Airborne magnetic measurements were carried out using either a proton (1975–1991) or caesium (1992–2003) magnetometers installed on the rear boom of the aircraft. Secular and other magnetic field variations were corrected according to data from a base-station registration. The line data were levelled using an in-house program, and final levelling was performed using tie lines. Airborne electromagnetic (EM) surveys were carried out to map the electrical conductivity structure using either the single- or dual-frequency fixed wing EM equipment. The measured parameters were inphase and quadrature components of both frequencies 3 kHz and 14 kHz. Nykänen & Salmirinne (2007) and Nykänen et al. (2008) used local minima in magnetic field total intensity within a 4 km radius to define alteration zones related to gold mineralization within the greenstone belt. For the current paper we instead used the maxima of the horizontal gradient.

The gravity dataset of the study area has been collected with a point density of one to four observations per square kilometre. Such regional gravity datasets mainly reflect large intrusions, crustal-scale structures, lithological units, faults, and shear zones, particularly those that cause thickening of the greenstone lithologies, which can be associated with gold deposits (Jamieson et al. 1998). Nykänen & Salmirinne (2007) used the horizontal gradient to represent significant rock boundaries. Here, we use the locations of maximum values of gravity gradients that can be obtained using the multiscale edge detection technique (Hornby et al. 1999). By this technique, so-called “gravity worms” are created (Lahti et al. 2010). The edge detection is automatically repeated at different upward continuation levels, which model theoretical surveys performed at different heights above ground level.

Another countrywide dataset, namely the regional till-geochemical survey, was conducted in the 1980s (Salminen 1995) with a sampling density of one sample per 4 km^2. The sampling was performed with a portable percussion drill equipped with a throughflow bit. The majority of the samples were collected as a composite of 3 to 5 sub-samples, from an average depth of 1.5 metres. Within the current study area, part of the sampling was conducted by combining 5 to 10 line samples. The sampled material was chemically unaltered parent till. The samples were dried and the <0.06 mm fraction sieved for analysis. A hot aqua-regia digest was used and Al, Ba, Ca, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Ni, P, Pb, Sc, Sr, Th, Ti, V, Y, Zn and Zr were determined with ICP-AES. In addition, Au, Te and Pd were analysed with graphite furnace AAS (Kontas 1981, Kontas et al. 1990).

The derivatives of the seamless countrywide 1:200 000 scale bedrock map were also used as evidence layers in the modelling (Nykänen et al.

2008). For the model described in the current paper we used the paleostress model defining the favourable dilational sites based on the geometry and the structural interpretations of the bedrock map (Ojala & Nykänen 2007). In particular, the gold deposits are frequently associated with crustal-scale shear zones (Goldfarb et al. 2005) and/or are sited at the boundary between convergent and divergent stress regimes caused by complexities in the geometries of granitoid domes (Groves et al. 2000). This theory was incorporated into the model by using the Sirkka Shear Zone and distance to granite midpoints as evidence (Nykänen et al. 2008). The latter was calculated by first completing a proximity analysis of granitoids within the Kittilä, Savukoski and Sodankylä groups. The mean distance to granitoids within a 2500 m neighbourhood was then subtracted from the original proximity grid, resulting in a grid illustrating the midpoint between the granitoids within the greenstone belt. The midpoint is interpreted as a vector of favourable fluid flow from convergent stress regimes of pure shear between closely spaced granitoids to divergent stress regimes of simple shear within the greenstone belt

A new evidence layer in the previously published models was derived from the 3D modelling of the reflection seismic survey data. The analogies of the interpreted structures were furthermore derived from the airborne magnetics. The following chapter describes the 3D modelling procedure.

REGIONAL 3D MODELLING

Information from the Earth's upper crust is needed to construct a regional geological 3D model. It is important to realize that exploration drilling only penetrates a few hundreds of metres beneath the surface of the Earth, whereas reflection seismic surveys or potential field surveys give information from much greater depths. In the project 'HIRE – Seismic Ore Prospecting 2007–2010', reflection seismic probing was conducted at fifteen potential mineral deposit sites in Finland (Kukkonen & Heikkinen 2009). The project generated reflection seismic data as 2D profile sections for use in further research. The seismic surveys were undertaken in 2007–2008 by the Russian state enterprise VNIIGeofizika with a total of 700 line kilometres of 2D measurements. These surveys were carried out by utilising vibroseismic and explosion seismic methods.

The seismic data used in this study represent the common mid-points (CMP) 4500 and 6700 of HIRE profile V6. This section in the profile is in a large turn, which begins in its westernmost part as NE-oriented and ends in the eastern part as E-oriented. However, there are no significant turning points in this part of the profile. The seismic data are shown as migrated sections in Figure 3, where the lower part includes the interpretation. Locations I, II and III along the profile, as shown in Figure 2, are also indicated in Figure 3.

To keep the interpretation as simple as possible, we have neglected a geological block model and performed the interpretation on the basis of reflective boundaries, as shown in Figure 3b. The only significant interpretation is the division into lithological (blue) and tectonic (red) boundaries. However, we emphasize that the division does not eliminate the possibility that any interpreted boundary could mutually be tectonic and lithological. Our division only shows which of these regimes, tectonic or primary, plays a more significant role in our interpretation.

In our interpretation, the horizontal reflective zones are the lithological boundaries, whilst the moderately dipping and mostly straight reflective zones are the tectonic boundaries. It is noteworthy in our interpretation that while the lithological boundaries are mostly continuous according to their reflections, the tectonic boundaries mark a significant change in the nature of reflective patterns.

At locations I and II, the reflections display a folded structure to the depth of ca. 3000 m and 2000 m, respectively. In this structure, the former area appears to be located in synform, whereas the latter area is in antiform. Within location I, another highly reflective zone appears at the depth of ca. 5000 m, which we interpret as a tectonic boundary. This deeper boundary is planar and moderately westward dipping, and in the area of location II it is already 2000 m below the surface (Figures 3 and 4). It is noteworthy that in its upper part, in between the CMP points 5500 and 5700, this westward dipping boundary is obscured by a gently eastwards dipping, highly reflective array. However, simply on the basis of reflections in this obscured area, one cannot make any definite interpretation of significant cross-cutting relationships, i.e. it is difficult to judge from the seismic data whether the moderately dipping zone of reflections cuts the shallow gently dipping array, or vice versa. Area III of the section displays the most significant highly reflective character, which is obviously due to low-angled and large scale folded bedding planes in the area.

At shallow levels, the reflections appear horizontal, but at deeper levels (> 2000 m) they generally show a low-angled westward dipping structure that eventually meets and becomes cut by the deeper planar and tectonic interpreted boundary mentioned above. In the very eastern part of the section, at the CMP points between 6500 and 6700, there is a pattern in the reflections that indicates a gently eastward dipping planar structure cross-cutting gently westward dipping structures. We interpret this cross-cutting structure as a tectonic boundary.

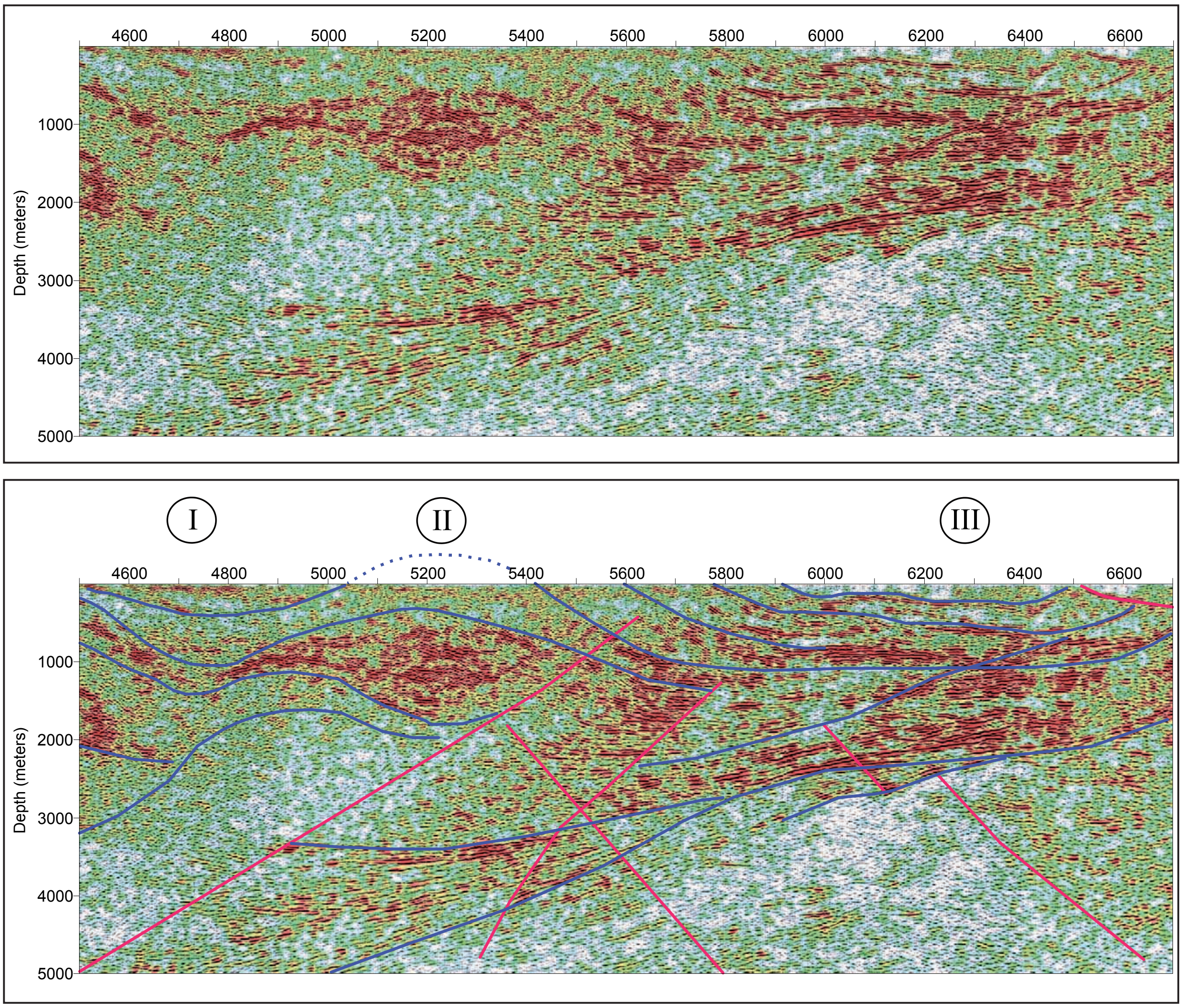


Figure 3. Reflection seismic profile along HIRE V6 from the CMP points 4500 to 6700 (Figure 2). a) Reflectors; b) Reflectors and interpreted structures and boundaries.

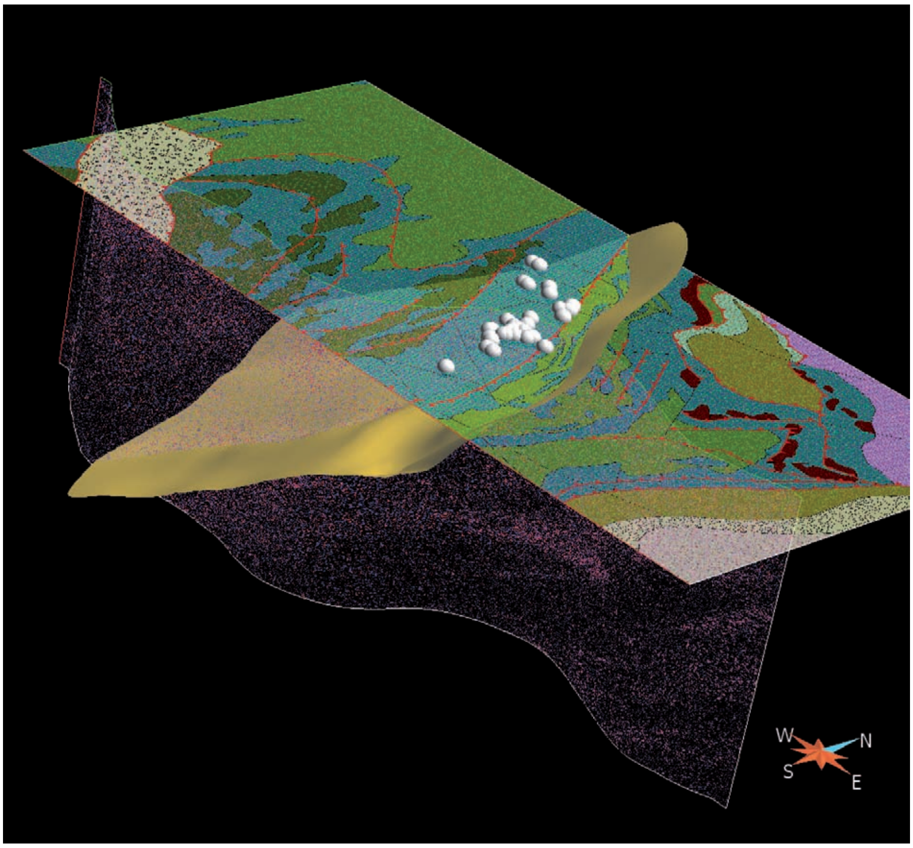


Figure 4. Distribution of drilling sites (with Au > 0.5 ppm) on a gold prospect and interpretation of a major fault/shear structure based on a high resolution reflection seismic survey (Figure 3).

PROSPECTIVITY MAPPING AND MODEL VALIDATION

Many techniques are available for spatial modelling applied to mineral prospectivity mapping, and the selection of a specific technique is often dependent on the data that are available. Bonham-Carter (1994) divides these spatial modelling methods into two main groups based on the data- and then knowledge-driven approach. According to Bonham-Carter (1994), data-driven, or supervised, techniques include weights of evidence, logistic regression and artificial neural networks.

If the occurrences of the deposit type being modelled are lacking, the number of deposits is too low to make valid statistical calculations or if a certain exploration model is tested (as in the current paper), a conceptual (or knowledge-driven) unsupervised approach is applicable. In techniques for conceptual spatial modelling, expert opinions can be used to define thresholds for the favourable map patterns within the given task, e.g. gold prospectivity. According to Carranza (2008), knowledge-driven techniques include applications of fuzzy logic, the evidential belief function, the Dempster-Shafer model and the decision tree approach. We selected the fuzzy logic technique due to its flexible capability to mimic the decision making process of an exploration geologist. The known gold occurrences within the study area were used for model validation.

The first step in prospectivity mapping (Figure 1) is to define an exploration model that will form the basis for the selection of the evidential datasets. The second step is the pre-processing of the selected data and classification of the derived maps into meaningful map patterns, i.e. anomaly maps or evidential maps. In this study, a set of map data was first reclassified into evidence maps and then fuzzified or rescaled from zero to one (from unfavourable to favourable for gold) based on subjective expert opinions. Finally, the rescaled evidential maps were integrated in complex combinations using variable fuzzy operators (Bonham-Carter 1994) to produce a single prospectivity map. The model is documented in a flow-chart describing the data sets and the operators in Figure 5.

The analysis was performed using publicly available SDM (Spatial Data Modeller for ArcView) code (Sawatzky et al. 2009) for the ArcGIS 9.3.1 GIS platform.

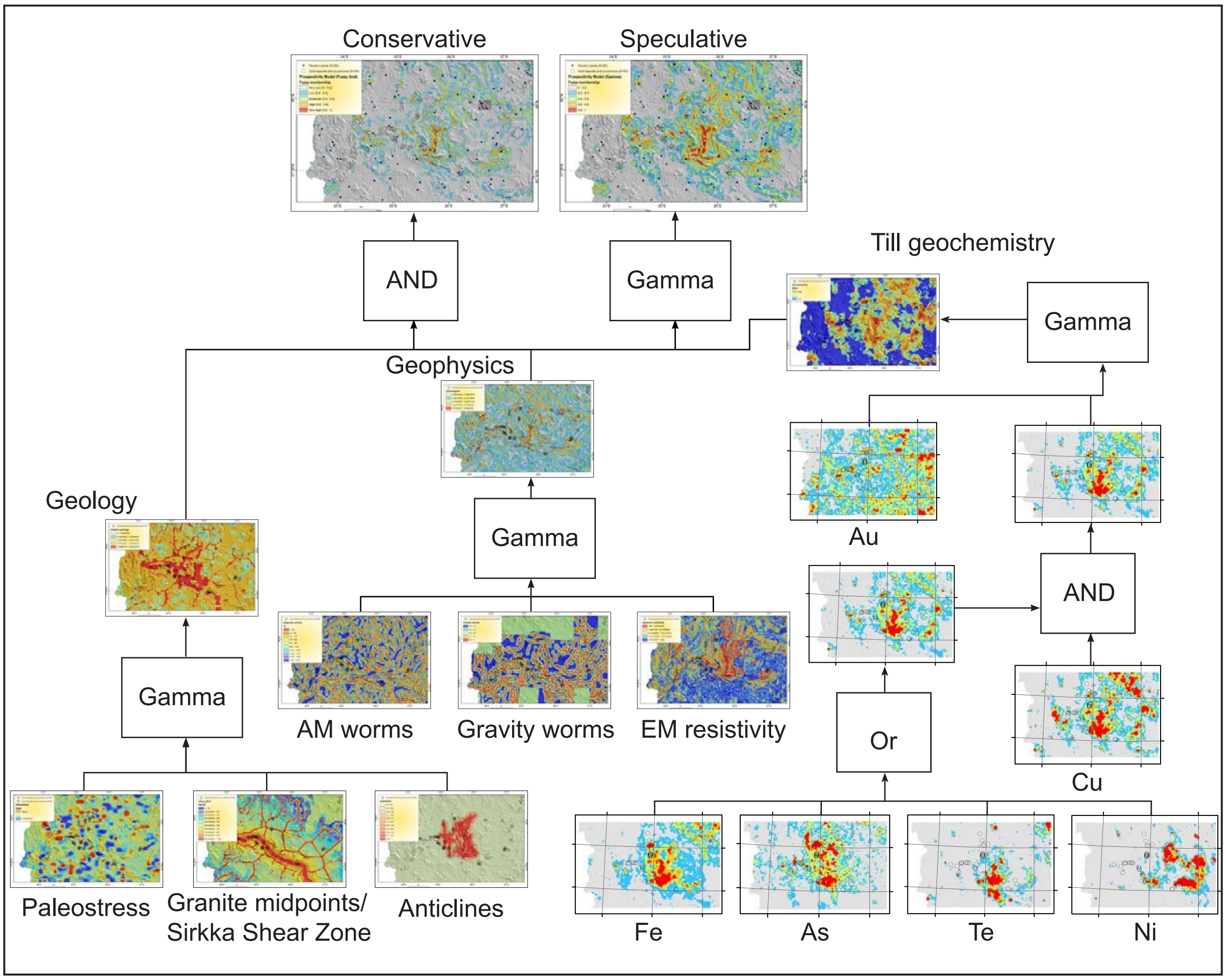
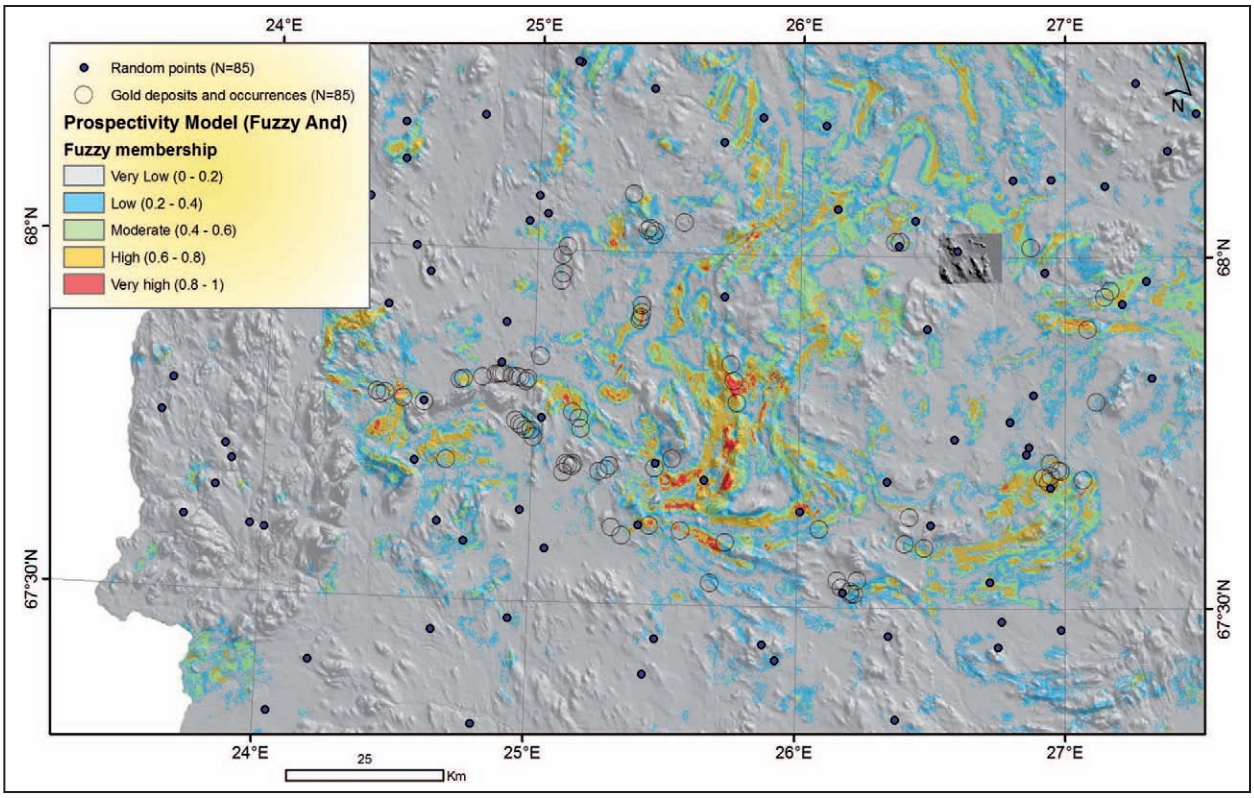


Figure 5. Flow chart describing the data integration network.

To create a fuzzy logic prospectivity model, all the input data were first rescaled to a common scale from zero to one. This was carried out using the so-called fuzzification functions large and small (Sawatzky et al. 2009). Before applying these functions, the data needed to be rescaled to positive numbers. The rescaled datasets were integrated using fuzzy operators (Bonham-Carter 1994) in several steps (Figure 5). A conservative integrated model was created by using a 'Fuzzy AND' minimum operator (Figure 6a), whereas a speculative integrated model was achieved by using a 'Fuzzy Gamma' operator (Figure 6b). The 'Fuzzy Gamma' operator allows for increasive and decreasive combinations of the membership values. The 'Fuzzy OR' operator was used to combine several geochemical datasets to define areas where values of any of the elements used were anomalous.

Visual inspection of the models already indicated that the known Au-deposits occur within the favourable areas defined by the models. We performed an ROC curve validation analysis (Fawcett 2006, Zou et al. 2007) by associating the model pixel values with the deposit sites ('true positive') and with a set of random points ('true negative'). The accuracy of the models can be then assessed in terms of the probability that the model correctly classifies the 'true negative' sites as negative (specificity or true negative rate) and 'true positive' sites as positive (sensitivity or true positive rate). An ROC graph is achieved by plotting sensitivity on the y-axis and (1-specifity) on the x-axis, where the area under the ROC curve (AUC) defines the overall summary of the model accuracy (Figure 7). In this case, the Gamma1 model seemed to perform slightly better than the And1 model, the difference being negligible, however. This validation indicates that both models gave better results than a random sampling would have done. The range of AUC is from 0.0 to 1.0, and a model providing excellent prediction has an AUC higher than 0.9, while a fair model has an AUC between 0.7 and 0.9, and a model is considered as poor when its AUC is below 0.7.



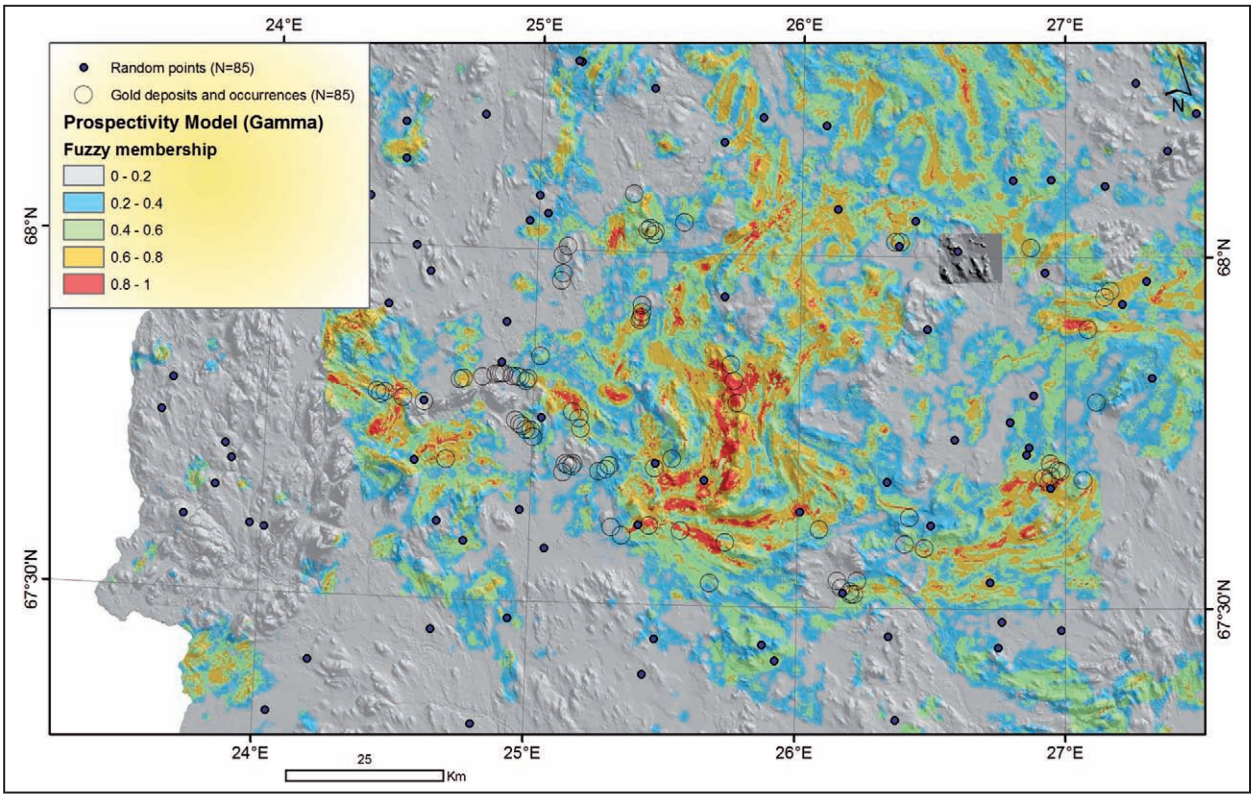


Figure 6. Prospectivity models for orogenic gold deposits using fuzzy logic for integrating data from various sources as described in Figure 5. a) Conservative Fuzzy AND model. b) Speculative Fuzzy Gamma model. Black circles represent the known Au deposits (N = 85), Au occurrences and drilling sites with Au > 1 ppm. Small black dots are randomly generated points used as "*true negative*" sites (N = 85) in ROC curve validation.

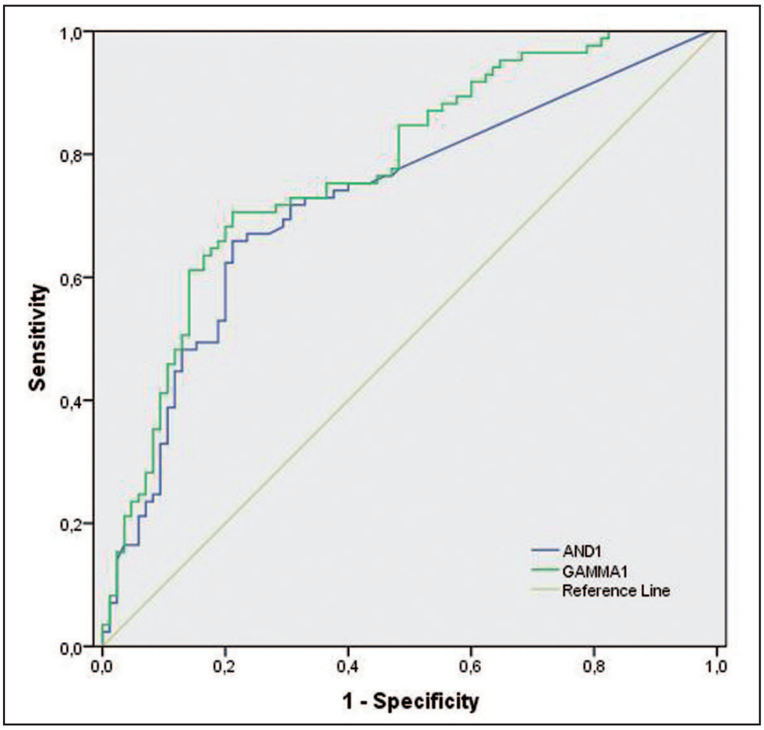


Figure 7. ROC validation curves for the prospectivity models Fuzzy AND1 and Fuzzy Gamma1 calculated using the known Au deposits or occurrences and drilling sites with Au > 1 ppm as "*true positive*" cases (N = 85) and random points as "*true negative*" cases (N = 85). The area under the curve (AUC) for Fuzzy AND1 is 0.73 and for Fuzzy Gamma1 0.78.

CONCLUSIONS

The fuzzy logic technique was used to construct a prospectivity mapping model for orogenic gold deposits within the Central Lapland Greenstone Belt. The resulting models were validated by using, on one hand, the known orogenic gold occurrences as examples of the true positive sites and, on the other hand, a set of random points as examples of the true negative sites. The known deposits were located within the high prospectivity area clearly more often than the random points. This allows us to conclude that the fuzzy logic model describes fairly well the favourability of the orogenic gold deposit type within the study area and highlights potential exploration targets. New, non-conventional geophysical data, such as gravity worms, seismic surveys and their interpretations and derivatives, can be effectively tested by and appended in GIS-based quantitative spatial data analysis.

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EVALUATION AND MODELLING OF NATURAL STONE ROCK QUALITY USING GROUND PENETRATING RADAR (GPR)

by
Hannu Luodes and Heikki Sutinen*

Luodes, H. & Sutinen, H. 2011. Evaluation and modelling of natural stone rock quality using ground penetrating radar (GPR). *Geological Survey of Finland, Special Paper 49*, 83–90, 6 figures.

Ground penetrating radar (GPR) is a rapid method for evaluating the physical structure of bedrock. It reveals the physical discontinuities, like fractures, of the rock mass where the dielectric properties change enough to give a reflection of the radar wave transmitted by the GPR antenna. The method is used in many steps of the evaluation of natural stone quality. It can already be used in the prospecting phase for rapid evaluation of the overall soundness and in more detailed investigation of deposits, as well as in the production planning of quarries to assess the fracture systems. The resolution, depth penetration and detection properties of GPR depend on the antenna frequency used. Lower frequencies give better penetration but less detail, while higher frequencies give better resolution but lower penetration. GPR measurements can be interpreted as single profiles, but can also be used for 3D modelling. Since GPR detects physical discontinuities, good geological knowledge of the site and data from other investigation methods, such as diamond drill cores, is needed in interpreting the features of GPR data.

Keywords (GeoRef Thesaurus, AGI): building stone, evaluation, ground-penetrating radar, measurement, fractures, three-dimensional models

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INTRODUCTION

Ground penetrating radar (GPR) has been extensively used by the Geological Survey of Finland (GTK) since the 1980s. It has become a standard method for peat investigations and soil surveys as well as in the assessment, protection and use of groundwater resources. GPR data are used in interpreting structures, calculating volumes and 3D modelling of different deposits, such as eskers and groundwater areas. In research, GPR has been used, for instance, to determine the dielectric properties of soils. GTK has developed a rapid measurement process combining cross-country vehicle-assisted data collection with accurate RTK GPS positioning suitable for peat and soil surveys. GPR is also utilized in the assessment of fracture systems and the soundness of natural stone deposits.

The prospecting and evaluation process for natural stone consists of several steps (Figure 1). Natural stone deposits are evaluated according to their geological and technical as well as economic and infrastructural characteristics. The texture, structure and colour of the rock are usually assessed with detailed field mapping and sampling. Diamond core drilling and ground penetrating radar (GPR) are used to evaluate the soundness and homogeneity of the rock.

Ground penetrating radar is a widely used method in investigating soil and rock. It is rapid and efficient in the evaluation of, for instance, Quaternary deposits and peat, and also the fracture patterns of rock. The measurement results can be immediately seen and an initial evaluation of the structure of the soil or fracture patterns of the rock can already be carried out in the field. Further measurements can then be planned and performed according to the need. Ground penetrating radar has been used in the evaluation of natural stone deposits around the world.

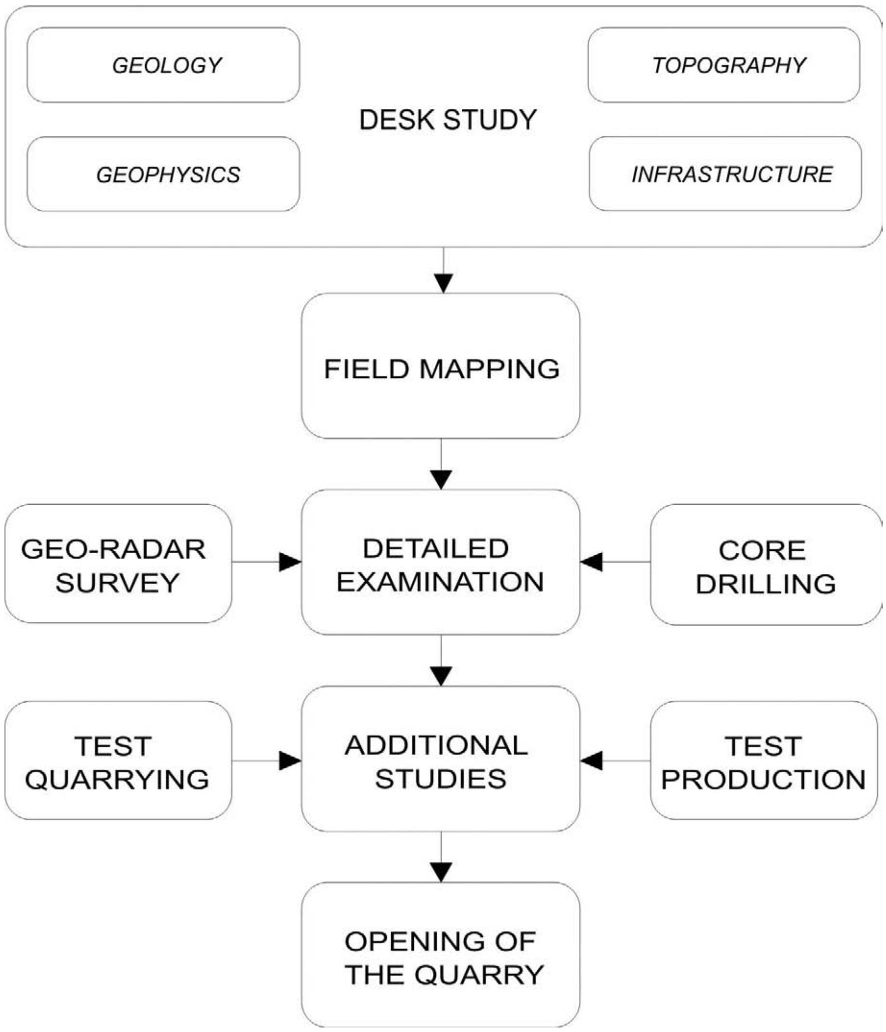

Figure 1. Natural stone evaluation process (Selonen et al. 2000). GPR referred to in the figure as Geo-radar.

THE PRINCIPLES AND INSTRUMENTATION OF GROUND PENETRATING RADAR

Ground penetrating radar is based on the transmission of electromagnetic wave pulses through a medium and observation of the waves reflected back from discontinuities with different dielectric properties (Annan 2004). The frequency and other characteristics of the wave pulse are determined by a transmitting antenna. The location of the discontinuities is calculated from the time taken for the pulse to propagate in the medium from the antenna to the target and back to the receiver.

The resolution and depth penetration of the measurement depends on the frequency and construction of the antenna. The ability to separate targets close to each other depends on the distance between the targets compared to the wavelength of the radar signal. If the space between the targets is much smaller than the wavelength of the radar signal, the reflection may be interpreted as one target instead of two. The depth penetration of the radar signal is correlated with its frequency, since higher frequencies attenuate more than the lower ones. The attenuation is caused by several losses in the measurement process (Daniels 2004). The loss of the transmitted energy is directly proportional to the conductivity of the medium and inversely proportional to the frequency used and the relative dielectric constant of the medium (Reynolds 1997). GPR usually functions better on rocks with a low conductivity and low magnetic permeability, such as granite and granodiorite.

GPR equipment consists of a computer based controlling unit, and an antenna containing a transmitter and receiver. The computer of the control unit has software to control the measurements and to store and process the data coming from the antenna. Some processing, such as filtering, can already be carried out during the measurement, but the final processing of the data is usually done afterwards with specialized software. Antennae are characterised by their frequency range and overall design. In some measurement configurations, the transmitter and receiver are in separate units.

APPLICATIONS OF GROUND PENETRATING RADAR IN NATURAL STONE EVALUATION

GPR is a method for assisting in the evaluation process of natural stone and can be used in several exploration phases. It can be utilized to assist in prospecting as rapid method for checking potential deposits using natural outcrops and small exposures. In particular, measurements at lower frequencies, i.e. <100 MHz, can give necessary information on deeper sections. Rocks that have very few vertical fractures on the surface can sometimes have a well-developed horizontal fracture system that can be difficult to detect from outcrops. A dense horizontal fracture system can prevent the utilization of the deposit by making the surface of the bedrock unusable for production and raising the quarrying costs. GPR measurements can also be performed through a shallow soil cover if it does not consist of conductive soils, like till or clay, with a fine fraction. In the deposit evaluation stage, GPR is systematically used for quality evaluation and detecting fracture systems that can affect the planning of quarrying. GPR is also used in operating quarries to assist in the planning of production. Economical benefits and saving of the material through well-planned quarrying can be achieved by frequently evaluating the natural fractures.

GPR shows physical targets and interfaces that have sufficiently large differences in dielectric properties compared to their environment. This means that the fractures have to be large enough or filled with water or weathering products. Small and tight fractures as well as vertical fractures, giving very weak reflection, may not be detected. Discontinuities of the horizontal fractures can sometimes reveal a vertical fracture by giving a reflection from their intersection. Moreover, the internal structure of the rock can sometimes be interpreted indirectly from GPR measurements. In some migmatitic rocks, the contact between neosome and palaeosome can, due to the competency contrast, be fractured, giving reflections from large-scale folds. In most cases, though, the structural features of GPR data do not coincide with geological boundaries, such as contacts between rock types. Good geological knowledge of the site and data from other investigation methods, such as diamond drill cores, is therefore needed in the interpretation of features from GPR data.

The penetration of the radar wave depends on the dielectric properties of the material. An essential part of GPR measurements is to define the dielectric constant (Er) of the rock. This is needed in interpreting the depth of reflections, since it is directly connected to the velocity of the radar pulse. The Er value of the rock is usually calculated using a known distance between the antenna and a plane that the pulse reflects from, together with the pulse propagation time. The reflection plane can be a horizontal fracture in the rock, observed from a diamond drilling core. The measurement can also be carried out from a stone block in a quarry using the reflection from the block's lower side. More seldom, CMP (common midpoint) or WARR (wide angle reflection and refraction) methods can be used.

Developments in the positioning of measurements from GPS technology have improved the usability of the results. RTK (real time kinematic) GPS positioning, in particular, has enabled the accurate combination of geological mapping and drilling data with GPR measurements, assisting in the evaluation of total quality. Especially, after topographic correction, the interpretations are easier due to the correct angle or dipping of the fractures in the measurement profile.

SINGLE PROFILE MEASUREMENTS

The most common application of GPR data is in detecting horizontal or sub-horizontal fractures, which essentially affect the usability of a natural stone deposit. The detection is relatively easy in unweathered rock having electromagnetic properties favourable for GPR pulse penetration (Figure 2a). The measurement data may also contain hyperbolas, indicating single targets. They can be interpreted, for instance, as traces of vertical fractures, indications of weathering or features related to the rock composition (Figure 2b).

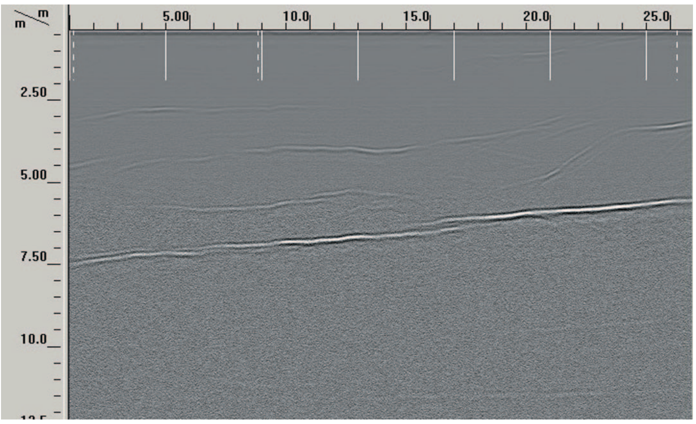

Figure 2a. A sub-horizontal fracture system with continuous reflections.

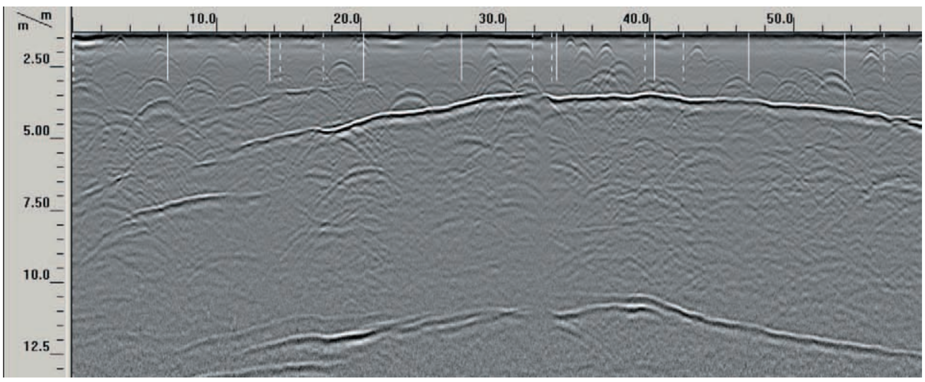

Figure 2b. A sub-horizontal fracture system shown by continuous reflections and single targets indicated by hyperbolas.

The measurements in Figure 2 were performed with a 200 MHz antenna. In Figure 2a, representing homogeneous rapakivi granite, horizontal and sub-horizontal fractures, in particular, are detected as long continuous reflections. From the depth scale it can be seen that the fracture interval is sparse, up to several metres, and the rock is relatively sound. Approximately in the middle of the figure there is a strong reflection passing through the whole length, indicating an open major fracture plane.

In Figure 2b, long continuous reflections are visible in porphyritic granite, indicating fracture planes, together with several single targets. Some of the hyperbolas that are on top of each other are related to sparse sub-vertical fracturing, but based on knowledge of the rock properties, detailed field mapping and diamond core drilling, most of the hyperbolas were interpreted as weathering phenomena in the rock. This weathering is related to sub-horizontal fractures and extends to a depth of up to 10 metres. Long fracture planes can also be seen on the quarry face (Figure 3).

Figure 3. Quarry face of the measurement site in Figure 2b.

MEASUREMENTS WITH HIGH FREQUENCY ANTENNAE

The resolution of GPR data depends on the frequency of the antenna. To demonstrate this, Figures 4a and 4b present measurements from the same profile with antennae of 200 and 900 MHz. The profile represents a weathered rapakivi granite bedrock surface with an intense sub-horizontal open fracture system. The depth penetration of the 200 MHz antenna in these conditions is approximately 11.5 m, while the 900 MHz antenna only penetrates efficiently to a depth of 2.5 m.

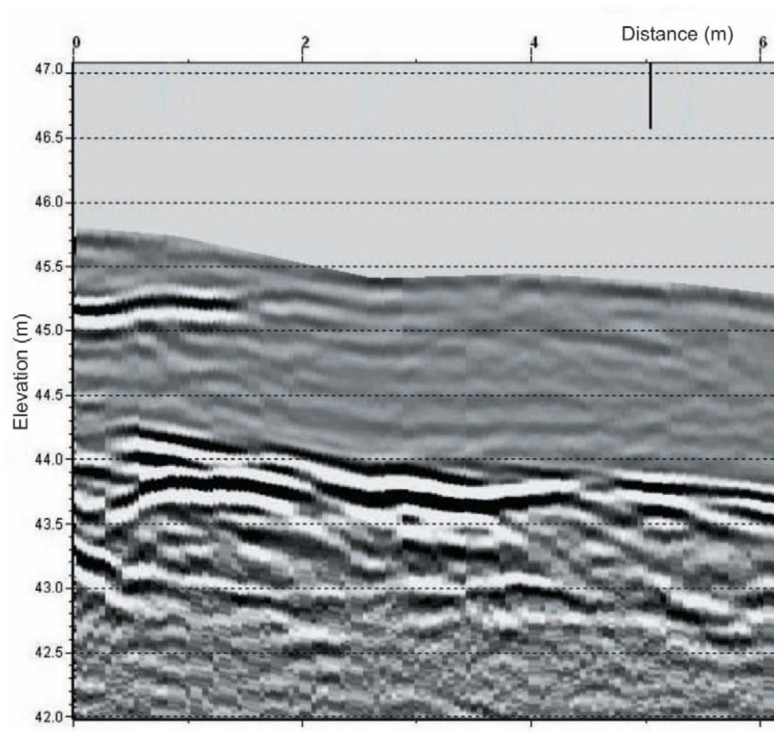

Figure 4a. Measurement with a 200 MHz antenna.

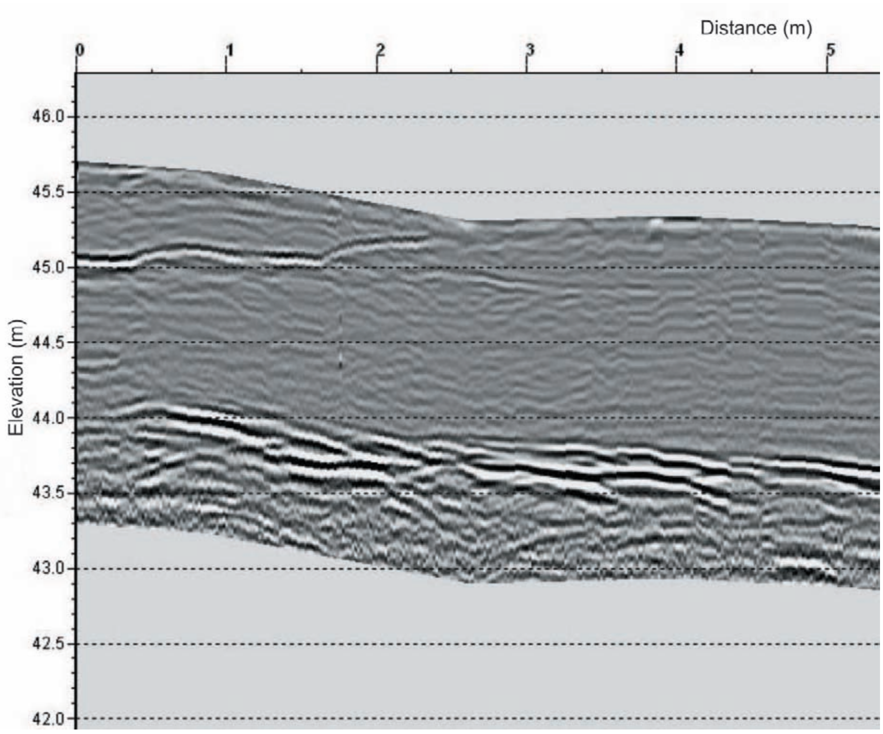

Figure 4b. Measurement with a 900 MHz antenna.

The advantage of the higher frequency antenna is particularly in the detection of weak reflections between the major fracture planes, as can be seen by comparing Figures 4a and 4b. Theoretically, a 900 MHz antenna could detect approximately 4 times smaller objects than a 200 MHz antenna. It is important to distinguish between fractures and sound areas without reflections. In both figures, the highly weathered sub-horizontal fracture system under the depth of approximately 1.5 metres is shown as a wide area of multiple reflections, where the detection of single fractures is difficult. In many cases, the choice of antenna represents a compromise between depth penetration and detection abilities.

3D MODELLING

The rock structure and fracture system can be visualized and interpreted with 3D modelling of GPR data. The modelling data are produced with a dense grid of measurement profiles. The horizontal distance between the profiles is recommended to be less than a quarter of the used wavelength (Grasmueck et al. 2003). With a 200 MHz antenna, the suggested profile distance in granite should be less than 20 cm.

3D modelling was carried out on homogeneous rapakivi granite in south-eastern Finland in 2004. The measurements were performed in an existing quarry on a horizontal quarry bench. A 30 by 30 metre lattice was measured with a 1-m profile interval in perpendicular directions. The aim of the study was to visualize the propagation and continuity of sub-horizontal fracture planes. Rapakivi granite typically has a well developed horizontal or sub-horizontal open fracture system, and the fracture planes are continuous over a large area. Horizontal fractures are cut by sparse vertical fractures that are usually open and also continuous over large areas.

The results can be visualized in parallel profiles (Figure 5a), where the propagation of the fractures can be followed at selected intervals, or in crossing profiles (Figure 5b), where the orientation of the fracture planes can be visualized more easily. The data from the profiles can also be combined and calculated as a block model revealing the internal structure of the rock (Figures 6a and 6b).

The advantage of 3D modelling is the better visual interpretation of the data, although the construction of the model requires a substantial amount of data.

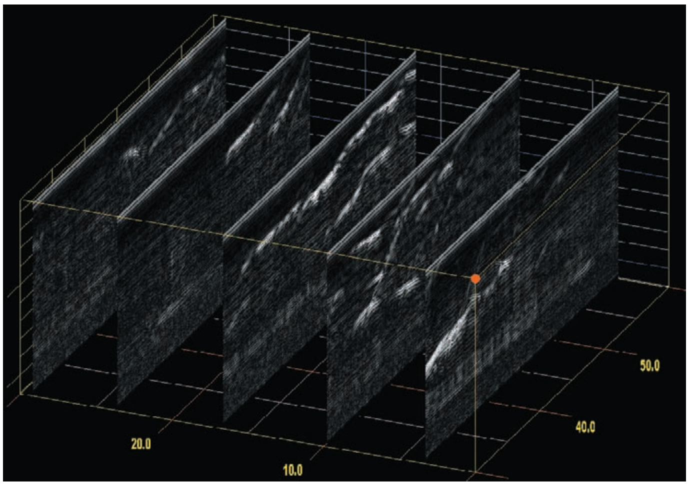

Figure 5a. Parallel profiles.

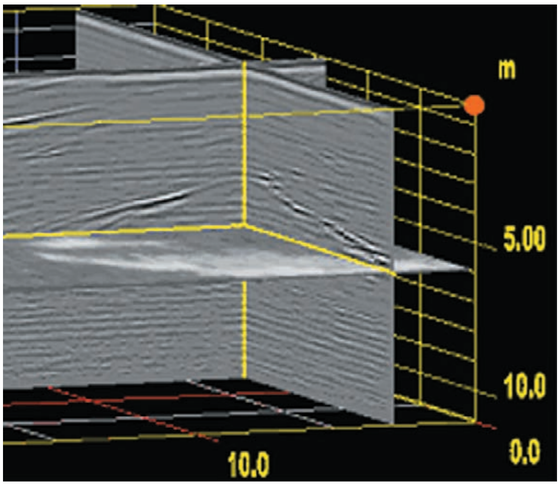

Figure 5b. Crossing profiles.

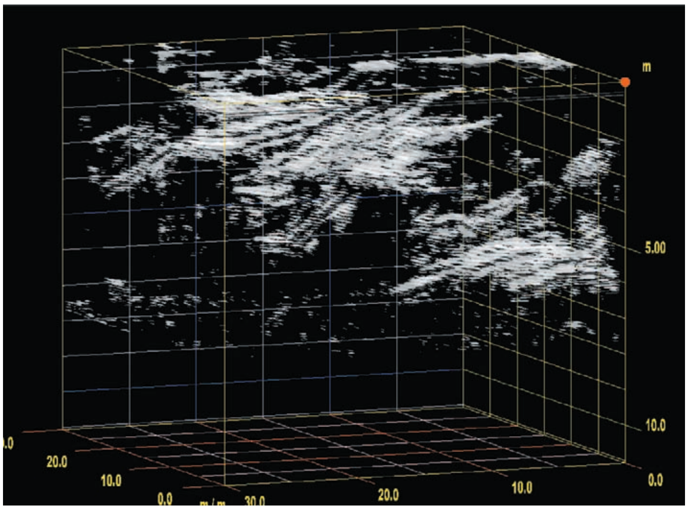

Figure 6a. Data processed to show the peak amplitudes (highlighted), which visualises the propagation of fracture planes.

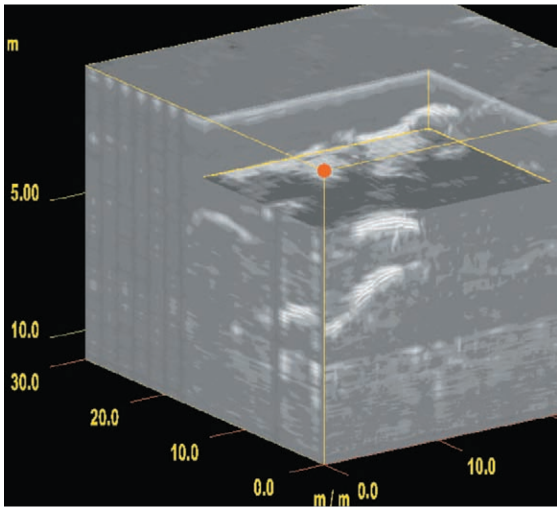

Figure 6b. A block model with data processed a by Hilbert transform.

DISCUSSION

GPR is a modelling technique well suited to the evaluation of natural stone quality. It essentially reveals discontinuities that in most cases are fractures or fracture systems. GPR measurements can be performed in many phases of a quality evaluation, starting from the prospecting phase and continuing to the assistance of operative quarrying. GPR results have to be interpreted in combination with other available data and knowledge of the rock, e.g. diamond drill cores and detailed fracture mapping. Accurate positioning of the measurements enables the linking of the results to the initial measurement environment and the use of the data for geological modelling.

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GEOCHEMISTRY IN THE CHARACTERISATION AND MANAGEMENT OF ENVIRONMENTAL IMPACTS OF SULFIDE MINE SITES

by
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Contaminative drainage from mine sites, and particularly from mine waste deposits, may pose risks to surface waters. Therefore, mine site risk assessment and management require knowledge of the whole series of processes from mine drainage formation to contaminant transport and the eventual ecological effects. This paper summarizes some of the recent studies by the Geological Survey of Finland covering these issues. The studies have included investigations of the mineralogical and geochemical changes in the tailings and variation in tailings effluent quality, the influence of sedimentation dynamics on contaminant distribution in lake sediments, and the use of sediment chemistry and biota to evaluate the environmental impact of the loading. The results demonstrate that even though sulphide oxidation in tailings may already start during the active disposal of tailings, the main impacts of mine drainage on surface waters are typically associated with the post-mining period of AMD generation. This underlines the importance of the proper design and after-care of tailings facilities. In addition, wind-driven bottom currents were observed to have a major influence on the sedimentation dynamics in shallow lakes, which are typical in Finland, and thus also on the contaminant distribution in lakes, further affecting the aquatic impacts of the mine site.

Keywords (GeoRef Thesaurus, AGI): environmental geology, mines, tailings, mine drainage, seepage water, geochemistry, water pollution, lake sediments, diatoms, Arcellacea, Finland

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INTRODUCTION

Low quality mine drainage resulting from mine waste is a world-wide environmental problem causing deterioration of downstream groundwater and surface water systems and affecting aquatic biota. The process largely responsible for the problem is the weathering of sulphide minerals in the sulphide-bearing mine waste, starting once the materials are exposed to atmospheric oxygen and water. The quality of the drainage is, nevertheless, controlled by a series of mineralogical and geochemical reactions in the waste area, and the outcome of these reactions is reflected in the seepage waters surfacing through tailings dams (Blowes et al. 2003, Lottermoser 2007, Heikkinen 2009). The seepage quality further changes due to precipitation and dilution during transport to the receiving water body (Chapman et al. 1983, Räisänen et al. 2005). Ultimately, currents and sedimentation dynamics dictate how the contaminants are distributed in the water body and in its sediments and whether metal-rich layers form that might pose a risk to aquatic life. What is more, the processes and effluent quality, and thus the severity of the impacts, may change with time. Deeper knowledge of all these processes provides tools for risk assessment and risk management at mine sites.

Geochemical methods can be widely applied to support the assessment and management of risks at mine sites. These methods can be used in characterising the nature and spatial distribution of the impacts, and in defining the mechanism of contaminant loading from the mine waste (Blowes & Jambor 1990, Johnson et al. 2000, Heikkinen et al. 2002). In addition, the prevention and mitigation of unwanted impacts are often based on knowledge of geochemical processes (Hedin et al. 1994, DeVos et al. 1999, Räisänen & Juntunen 2004). Combining geochemical studies with investigations on aquatic biota further enables the assessment and delineation of impacts in the receiving water bodies (Cattaneo et al. 2008, Patterson & Kumar 2000, Reinhardt et al. 1998).

This paper summarizes some of the recent investigations carried out at the Geological Survey of Finland (GTK) that have aimed at the characterisation and management of the environmental impacts of sulphide mine sites (Figure 1) using geochemical methods. These studies have covered the factors affecting metal (e.g. Ni, Cu, Zn, Cd, Pb, Co, Fe) release and effluent quality in tailings, the mechanisms controlling heavy metal and metalloid distribution in aquatic sediments and the use of ecological indicators with geochemical data to define the response of aquatic biota to mine drainage. In this paper, implications for the risk management of mine sites are also presented.

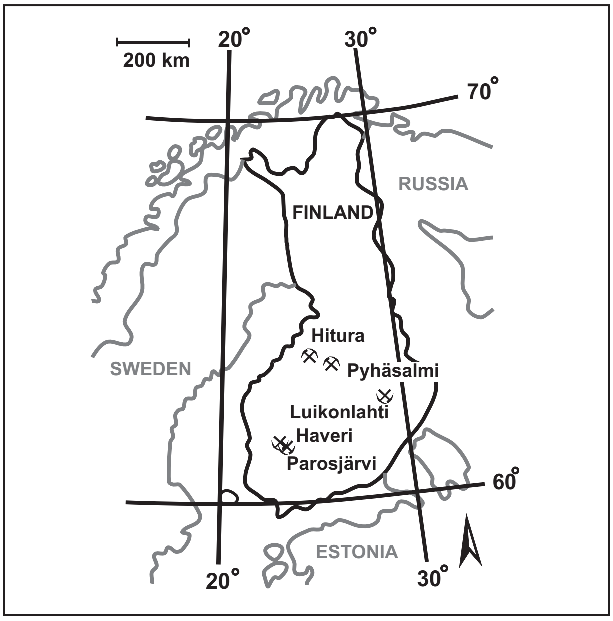

Figure 1. Locations of the mine sites referred to in the paper.

GEOCHEMISTRY OF TAILINGS SOLIDS AND SEEPAGE WATERS – GEOCHEMICAL CONSTRAINTS FOR MITIGATION

Approximately 139 Mt of sulphide-bearing tailings have been deposited at closed, abandoned or active mine sites in Finland as a result of ore processing (GTK's unpublished database of sulphide mine sites). A number of the tailings facilities are located close to lakes or rivers, posing a potential risk to aquatic life if their management fails (see Chapter 4). Knowledge of the geochemical processes and their driving forces in the tailings is a key to finding solutions to prevent the formation of low quality drainage at existing and future mine sites. Recent studies at GTK have applied both mineralogical and geochemical investigations to examine the factors that result in low quality drainage from tailings impoundments (Heikkinen & Räisänen 2008, 2009, Heikkinen 2009).

Influence of tailings material and process chemicals on tailings drainage quality

The primary factor influencing effluent quality in tailings areas is the mineralogical composition of the tailings. This was clearly seen in a study by Heikkinen et al. (2009), in which seepage quality was compared between two types of sulphide mine tailings: low-sulphide tailings from Hitura Ni mine and high-sulphide tailings from Luikonlahti Cu-Zn-Co-Ni mine (Figure 1).

In general, the low-sulphide Hitura tailings, which had a moderate buffering capacity due to the presence of carbonates and Mg silicates, produced circumneutral, net alkaline mine drainage, whereas the effluents from the high-sulphide Luikonlahti tailings (ST), with a low buffering capacity, were mainly acidic (Figure 2a). At Luikonlahti, magnesite tailings (MT) from talc processing covered the sulphide tailings, resulting in neutral seepages from parts of the impoundment (Figure 2a). The metal content of all the seepages was high, but the distribution of the metals followed that of the metal sulphides in the tailings, their susceptibility to weathering and mobility of metals (Hitura: high Ni; Luikonlahti ST: high Zn, Ni, Cu, and Co; Luikonlahti MT: high Ni and As).

The seepage pH and metal content nevertheless varied between the seepage points within a single tailings area due to variation in the intensity of mineral weathering along the seepage flow paths (Heikkinen et al. 2009). For example, flow through the most oxidized, unsaturated sulphide tailings at Luikonlahti produced the most acidic seepages, high in metals, particularly Al and Cu, suggesting advanced weathering of sulphides and also silicates (“Upper seepage”; Figure 2a). In contrast, where the flow path ran through the saturated, unaltered tailings, the seepages were less acidic and mainly contained Zn from relatively easily weathering sulphides (“Toe seepage”, Figure 2a; Heikkinen et al. 2009, cf. Jambor 1994).

In addition to tailings mineralogy, the input of process chemicals markedly influenced the effluent quality. This was seen as higher SO_4^{2-} concentrations in the seepages from the Hitura tailings than from the Luikonlahti site (Figure 2b), despite the higher Fe sulphide content and the more intense sulphide weathering at Luikonlahti. The Fe:SO_4 ratio of the Hitura seepages additionally suggested that the sulphuric acid used in ore processing was a more likely source of SO_4^{2-} than sulphide weathering at Hitura (Figure 2b).

Data on tailings effluent quality are used to design water treatment facilities (Räisänen & Juntunen 2004, Räisänen 2009). The examples from Hitura and Luikonlahti (Heikkinen et al. 2009) illustrate that the goals and designs for treatment typically require case-specific approaches, also taking into account the variability within the site.

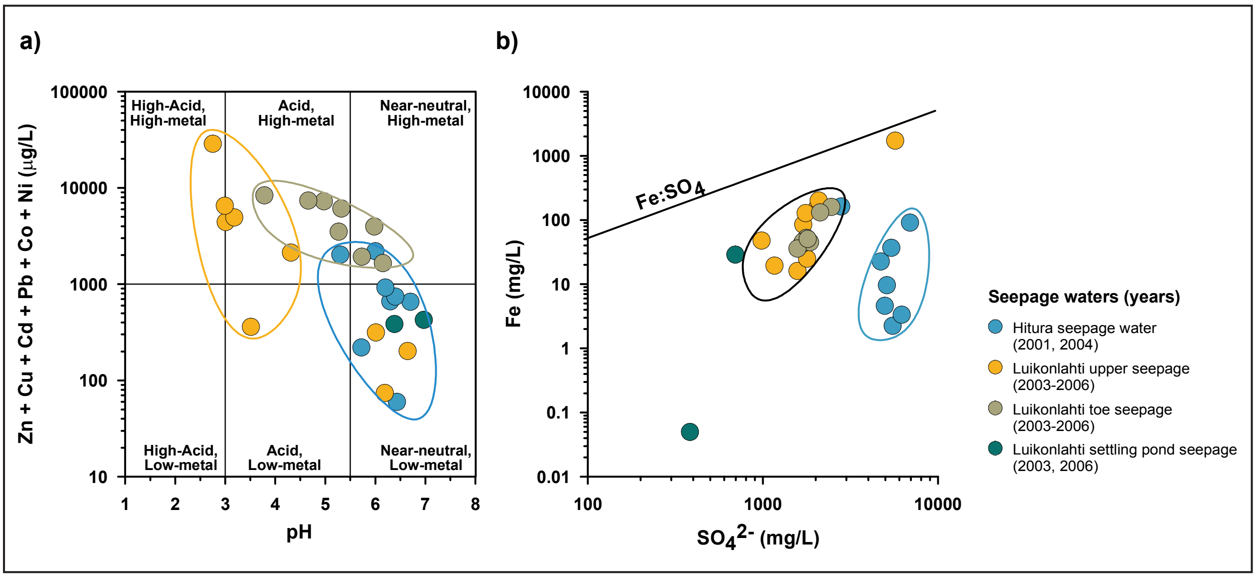

Figure 2. a) Variation in the seepage water quality from neutral to acid mine drainage in the low-sulphide Hitura tailings and the high-sulphide Luikonlahti tailings presented with a Ficklin diagram (Plumlee et al. 1999) showing the sum of dissolved heavy metals (µg/L) plotted against pH; b) Diagram of Fe versus SO_4^{2-} (mg/L) in the Hitura and Luikonlahti seepages. The diagonal black line indicates the Fe:SO_4 ratio produced by pyrrhotite weathering, which is typically one of the primary sources of Fe and SO_4 in tailings effluents.

Influence of tailings design and disposal technique on the formation of mine drainage from tailings impoundments

As described above, the presence of sulphide minerals in the tailings is a challenge for the storage of mining waste. However, the design of the impoundment and the disposal technique ultimately determine whether the sulphide minerals are exposed to weathering and whether mine drainage starts to form. These factors were examined at the Hitura and Luikonlahti tailings impoundments using a 3D approach that employed selective extractions and pH measurements, together with visual observations and mineralogical knowledge, to assess the progress and spatial distribution of weathering in active tailings areas (Heikkinen & Räisänen 2009, Heikkinen 2009).

The 3D study showed that sulphide oxidation with subsequent metal release may occur in the unsaturated border zones close to the earthen dams and at the tailings surface in active impoundments, despite the continuous operations (Heikkinen & Räisänen 2009). The latter was particularly so if there had been a delay in the burial of fresh Fe sulphide-rich tailings, for example due to a shift in the discharge point or a temporal cessation of disposal. In the Hitura low-sulphide tailings, oxidation had commenced in the unsaturated shallow tailings when the tailings were left uncovered after disposal had ceased.

The metals released in sulphide oxidation were largely retained in the shallow tailings by secondary precipitates (e.g. Fe oxyhydroxides) that had formed as a result of the oxidation (Heikkinen & Räisänen 2008, 2009). At Hitura, this mechanism effectively prevented the downward transport of metals in the circum-neutral conditions. At Luikonlahti, however, sulphide oxidation had resulted in such acidic conditions that metals were no longer retained in the precipitates. In fact, at Luikonlahti the oxidized layers are potential sources of metals if pH-Eh conditions change.

Based on the study, means to prevent sulphide oxidation need to be addressed in planning tailings dams and tailings disposal (Heikkinen 2009). One option is to keep sulphide-rich tailings saturated in all phases of disposal, if possible.

Variation in the quality of tailings effluents over time

The retardation of sulphide oxidation in tailings over time may change the drainage quality in the long-term (Alakangas et al. 2010). The metal content and pH of tailings effluents may also vary in the short-term, both seasonally and annually, due to local hydrological conditions, setting constraints for water treatment design. For example, seasonal variation in water quality, such as changes in the pH and sulphate concentration, has been observed to control trace metal adsorption on secondary precipitates (Kumpulainen et al. 2007). At the Luikonlahti mine site, the quality of tailings seepage waters was monitored 2–3 times per year from May 2003 to May 2007 (years 2003–2006; Heikkinen et al. 2009). The results of the monitoring revealed marked fluctuations in pH and metal content between seasons and sampling years (Figure 3). Overall, the lowest concentrations of metals occurred in late June, after the discharge peak due to snow-melt and spring rains, whereas the highest concentrations were measured prior to this event. The magnitude of the fluctuations was clearly influenced by the length of the flow path in the tailings, as the variation was more distinct at the seepage point located in the upper section of the tailings dam ("Upper seepage") than at the monitoring point at the toe of the dam ("Toe seepage"; Figure 3).

In addition, the Luikonlahti case showed that changes in the impoundment structure may cause additional variation in the seepage water chemistry (Heikkinen et al. 2009, Räisänen 2009). At Luikonlahti, the increase of the thickness of the alkaline magnesite tailings during the monitoring period, at the end of the mining operations, was observed to reduce the metal content and increase the pH value of the seepages (Figure 3). Furthermore, seepage waters changed from net acidic to net alkaline. According to Räisänen (2009), the decrease in the metal content in the upper and toe seepages varied from 40% to 99%, depending on the metal and seepage point.

This variation poses challenges both for the monitoring programme and the water treatment design. To estimate the annual load and to dimension the water treatment design, frequent monitoring of the seasonal and annual fluctuations is needed. However, based on the Luikonlahti example, the final decision of the treatment system design may only be made after finalizing the closure of the tailings impoundment (Heikkinen 2009).

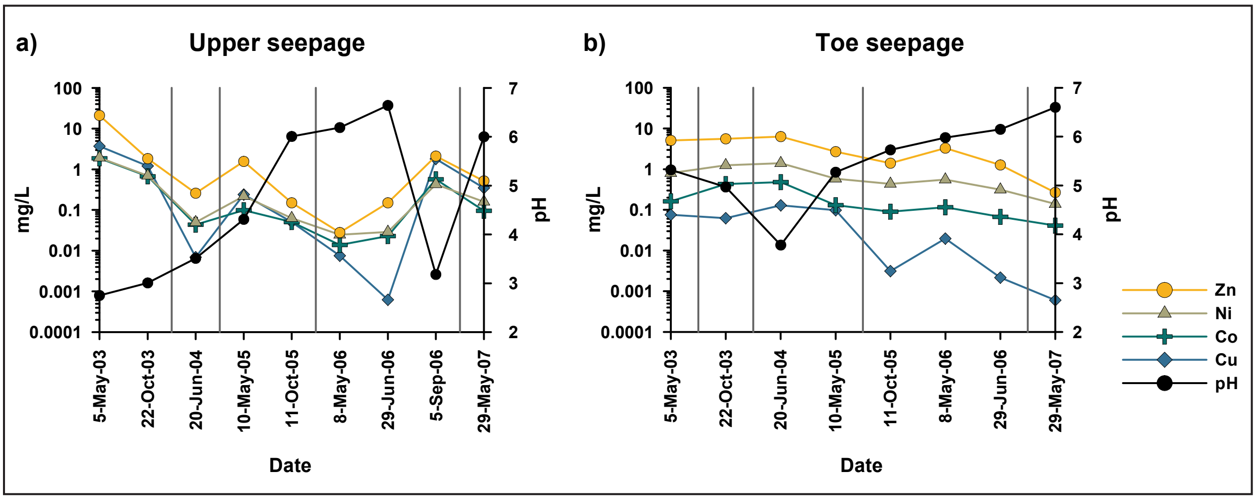

Figure 3. Diagram showing an example of the effect of local hydrological conditions and structural changes in the tailings impoundment seen in the metal concentrations (mg/L) and pH in the Luikonlahti tailings seepage waters between May 2003 and May 2007. a) 'Upper seepage' from the upper section of the tailings dam and b) 'toe seepage' from the toe of the dam. (Modified after Heikkinen et al. 2009).

INFLUENCE OF SEDIMENTATION DYNAMICS ON CONTAMINANT DISTRIBUTION IN MINE-IMPACTED LAKES

In Finland, potential contaminants from a mine site often end up in a lake basin. Understanding the transport and accumulation of the contaminants in lake basins is essential in assessing the risks to aquatic systems from mine sites. In general, the main hypothesis is that gravitative particulate settling or geochemical focusing causes the transport and accumulation of contaminants towards the deepest parts of the basin (Håkansson & Jansson 1983, Rowan et al. 1992, Schaller & Wehrli 1997, Lindström et al. 1999). This type of sediment focusing is manifested in deep lakes, but the hypothesis needs re-evaluation in shallow lakes, where wind-driven bottom currents become dominant in the sedimentation dynamics.

In Finland, the mean depth of lakes is only 6 m and the wind-driven bottom currents may thus significantly affect the sedimentation dynamics and the accumulation of contaminants. Therefore, this type of information is valuable, for instance, in the risk assessment of mine sites with potential contaminative drainage to lakes. The question is topical in Finland, which has the greatest continuous lake area in Europe, and better tools are thus needed for environmental monitoring to evaluate contaminant transport and accumulation in the lake basins.

Case study from Lake Pyhäjärvi

Lake Pyhäjärvi in Western Finland has received effluents from the Pyhäsalmi Zn-Cu mine (Figure 1). The effect of the wind-driven bottom currents on the sedimentation dynamics and metal accumulation in the lake was studied. Lake Pyhäjärvi represents an average lake in Finland in terms of depth (D_{mean} = 6.6 m, D_{max} = 27 m, A = 126 km^2). The study consisted of two parts: 1) estimation of the spatial distribution of gyttja deposits in the basin by means of echo soundings (survey line distance 70–130 m), and 2) analysis of element concentrations in the top sediment (< 10 cm, 1-cm slices).

Interpolation data on gyttja thickness, which was interpreted from echo sounding profiles, were combined with bathymetric data into a single map (Figure 4). According to the 2D (Figure 5) and 3D figures, transport/erosion areas occur in the deepest parts of the lake basin (> 20 m), whereas gyttja mainly accumulates in the flanking area (at 10–20 m depth) of the deep. The inverse relationship observed between accumulation and basin depth contradicted the simple sediment focusing hypothesis, which means that factors other than gravitative particulate settling should be taken into account. The dune-like morphology of the gyttja accumulations and longitudinal erosion areas with respect to the basin deep refers to the action of wind-driven bottom currents. The bottom currents have been most effective in the main lake basin of Lake Pyhäjärvi, but their impact on sedimentation seems to have been less efficient in the Kirkkoselkä basin, near the mine, because of the shorter fetch (Figure 6a and b).

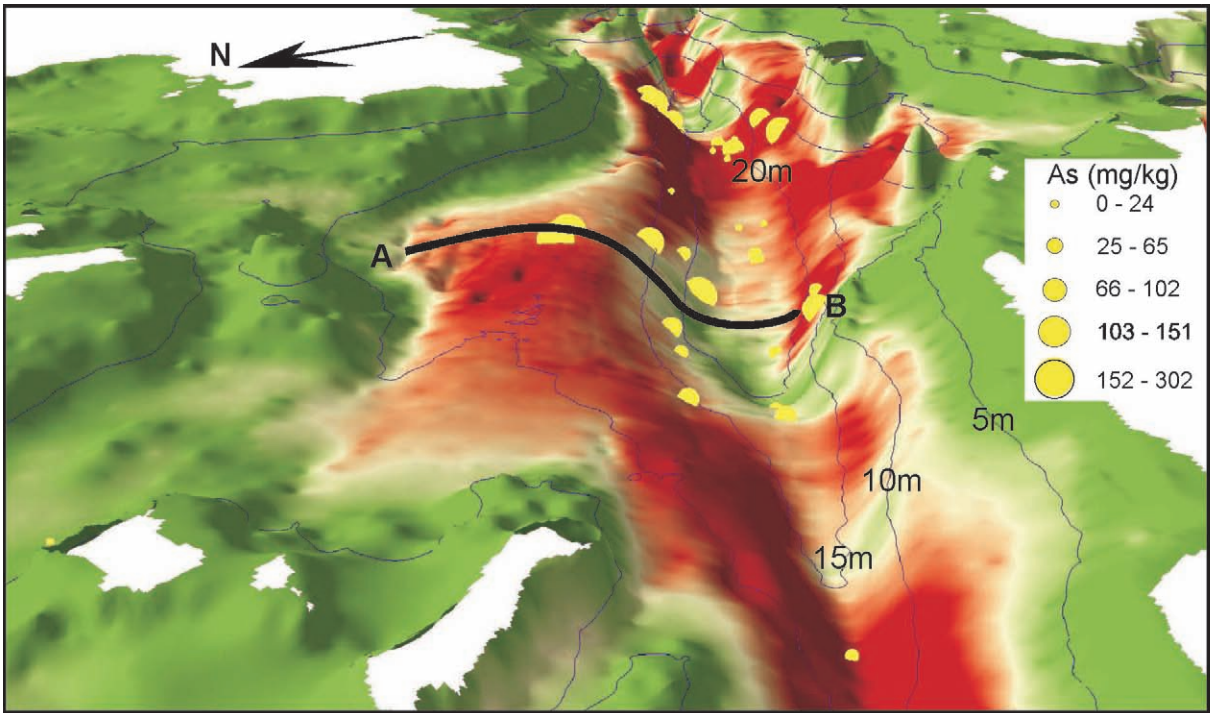

Figure 4. Diagram showing the relationship between maximum As concentrations (yellow circles) in the top sediment profile (< 10 cm; see Figure 6b) and sediment dynamics in the central part of Lake Pyhäjärvi. Sediment thickness is presented in a 3D view with 35 times vertical exaggeration. The green colour indicates erosion areas and red accumulation areas (cf. Figure 6a). Line A-B shows the cross section of the echo soundings presented in Figure 5. Basemap © National Land Survey of Finland, licence no. MML/VIR/TIPA/217/10.

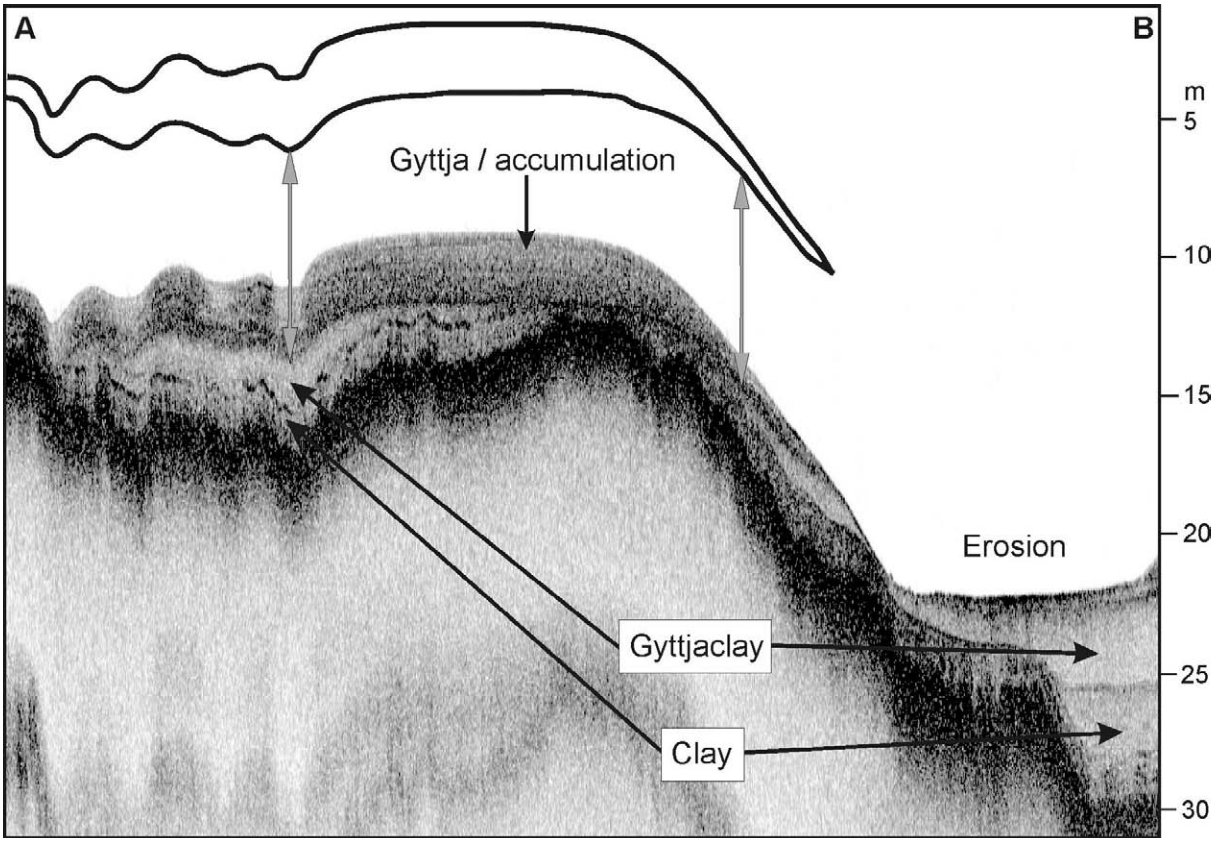

Figure 5. Cross section of the echo soundings of sediment thickness in the central part of Lake Pyhäjärvi (location is presented in Figure 4) showing the accumulation and erosion zones. The accumulation area is located at 10–15 m depth, whereas the erosion zone is at > 20 m depth.

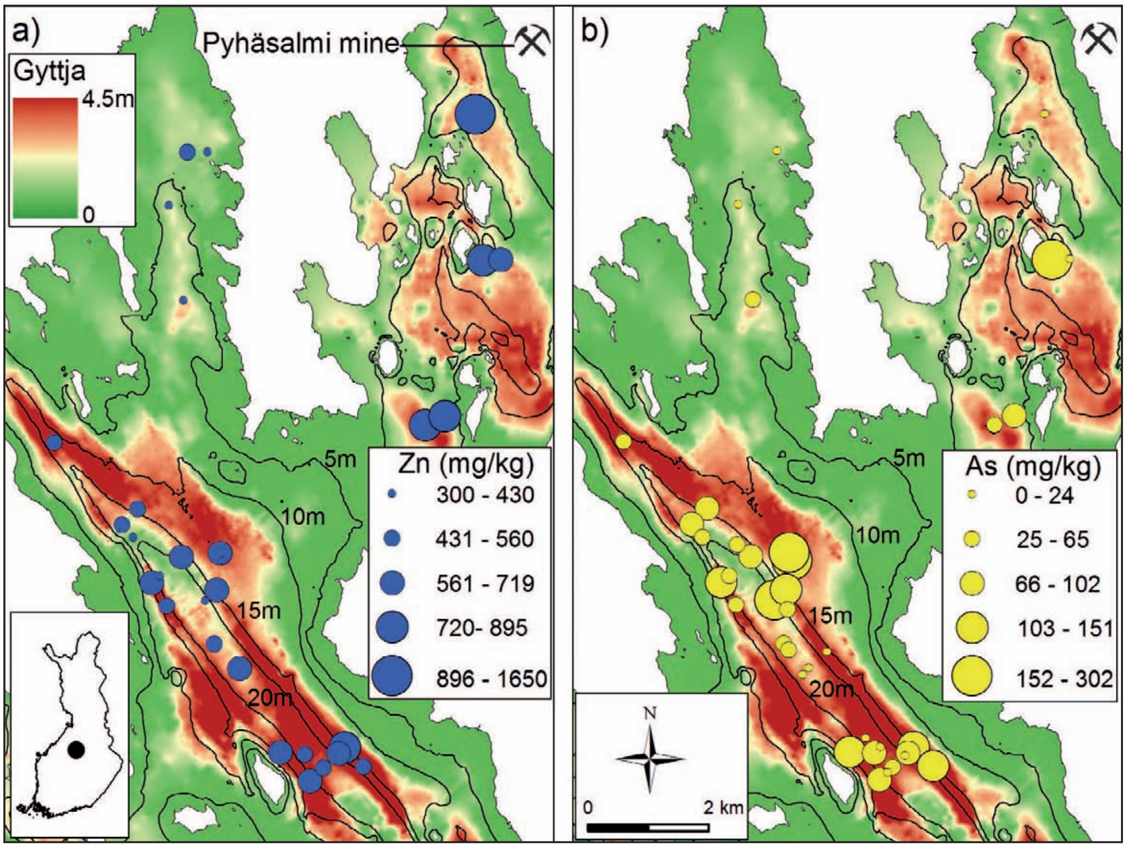

Figure 6. The spatial distribution of a) maximum Zn concentrations and b) maximum As concentrations in the top sediment profile (< 10 cm) of Lake Pyhäjärvi. The outfall of the lake is NW from the Pyhäsalmi mine. The thickness of the gyttja layer is expressed as a coloured surface and water depth as contours. Basemap © National Land Survey of Finland, licence no. MML/VIR/TIPA/217/10.

The greatest Zn concentrations in Lake Pyhäjärvi occur in the vicinity of the Pyhäsalmi mine (Figure 6a), but the bottom currents have spread the Zn-bearing sediments throughout the lake. On the other hand, the distribution of As seems to be dependent on the internal processes of the basin, because the greatest As concentrations occur in the central part of the lake, where the sedimentation driven by bottom currents has been strongest at the depth of 10–15 m (Figures 4 and 6b). The high As concentrations in Pyhäjärvi can probably be linked to the properties of the catchment area, because As concentrations in the Pyhäjärvi and Kolima catchments and lake sediments are typically high (Lahermo et al. 1996, Mäkinen 2004).

The example from Lake Pyhäjärvi shows that sedimentation dynamics should be taken into account in mine site risk assessment to evaluate the spreading of potential contaminants in aquatic environments. In particular, the selection of sediment sampling points should be based on knowledge of the sedimentation dynamics in the basin, because the deepest parts of the lake may be a focus of erosion rather than accumulation. If the sampling is systematically directed to the deepest parts of the lake without knowledge of the accumulation or erosion systematics, the results may give a distorted picture of the drifting and accumulation of contaminants in the basin.

CHARACTERISATION OF THE AQUATIC IMPACTS OF SULPHIDE MINE SITES BASED ON SEDIMENT CHEMISTRY AND AQUATIC BIOTA

Once the formation of metal-rich mine drainage, its transport in the watershed, and distribution in lake basins has been examined, the possible ecological effects should be investigated. Finnish mines rarely cause mine drainage that could result in acute ecological effects in surface waters, but the accumulation of metals in sediments may lead to concentrations that exceed the threshold effect concentrations. Aquatic impacts may, therefore, occur in the sediments rather than in water. In addition, the archival nature of sediments, i.e. the preservation of information on past environmental conditions in old sediment layers, is valuable for studies on mine sites. Geochemical studies of sediments are therefore essential in the characterisation and management of the aquatic impacts of mines in Finland.

Sediment-derived information on background or reference conditions is especially important for mine site research. Observations of changes in biota in conjunction with geochemical measurements are essential, because ecological effects may be suppressed in mining environments even if metal concentrations increase. Such a lack of ecological effects may be due to the adaptation of species to locally elevated background (natural) concentrations or alternatively to low metal bioavailability (Chapman 1996). Various numerical methods are available to relate the ecological signals to geochemical data and to study the statistical significance of the co-variation (e.g. Legendre & Legendre 1998). Furthermore, sediment-derived local background data can be used as a reference in assessing and identifying possible mining-related changes. Otherwise, natural gradients or changes caused by factors unrelated to mining may be mistaken for mine water impacts.

Two main groups of ecological indicators in sediments have been utilized in the recent mine impact studies at GTK: siliceous diatom algae and testate amoebae (Kihlman & Kauppila 2010). Together, they span a range of habitats within the aquatic system, providing a complementary view of the ecological impacts. Both groups are abundant and preserve well in sediments, have a ubiquitous occurrence, are sensitive to environmental gradients, and show assemblage shifts with environmental pressures. While diatoms live in several habitats in a water body, testate amoebae are often locally derived and live in the uppermost few millimetres of the sediment, providing a high temporal and spatial resolution for studies on profundal conditions. Ecological analyses are combined with chemical determinations employing different leaches and the relationships between biota and these geochemical proxy records are then studied with the aid of suitable numerical methods.

Spatial and temporal delineation of the environmental effects of sulphide mine sites

Results from recent GTK sediment studies at mine sites support the observations from tailings areas that the nature and intensity of metal releases from mines varies considerably over time, as does the pH of the effluents (Kauppila et al. 2006, Kihlman & Kauppila 2009a). The changes are related to both the phase of mining operations and the degree of weathering in the waste materials. The resulting ecological effects also depend on the characteristics of the mine drainage at any given time (Figure 7; Kihlman & Kauppila 2010). Similarly, the spatial extent of both the chemical and ecological changes in sediments may change over time (Kihlman & Kauppila 2009b).

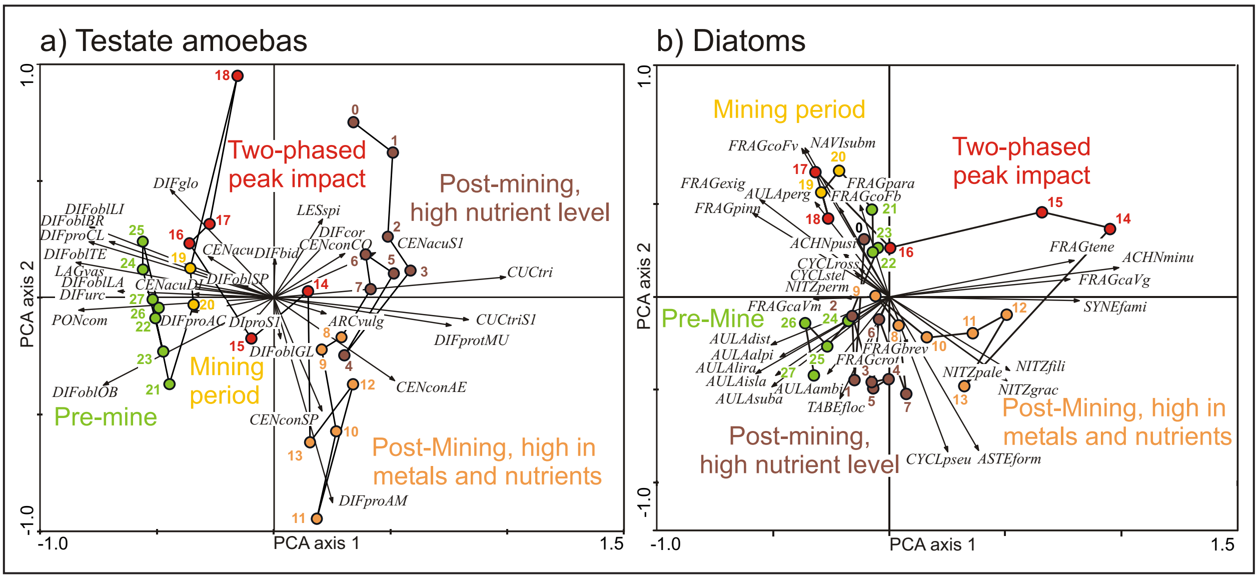

Figure 7. A principal components analysis (PCA) ordination plot summarizing the temporal evolution of mine impact seen in the species assemblages of a) testate amoebas and b) diatoms. Different types of mine drainage result in distinct species compositions. Sediment core from Lake Kirkkojärvi, Haveri.

At the Luikonlahti Cu-Zn-Co-Ni mine, the onset of the mine and the actual mining activities had only minor effects on the sediment geochemistry and assemblages of testate amoebae (Kihlman & Kauppila 2009a). However, the situation changed after the closure of the mine due to the onset of acid mine drainage (AMD). This led to the peaking of metal concentrations in the sediment and major ecological changes. In the most recent sediments, faunal shifts reflected the change towards more neutral drainage that resulted from the switch to talc production at the mill, as described above. A similar pattern of temporal changes in the composition of mine waters and ecological consequences was also observed in the study on the closed Cu-Au mine of Haveri in Ylöjärvi (Figure 1; Kihlman & Kauppila 2010), where short-term peaks in sediment metal concentrations with contemporaneous ecological shifts were detected and dated to the post-mining period (Figure 7). The recent study of the Pyhäsalmi Zn-Cu mine showed that the management actions have reduced metal loading and the associated ecological effects since the peak loading phase in the 1970–80s, and the mine effluents presently consist largely of Ca and SO_4^{2-} (Kihlman & Kauppila 2009b).

Geochemical methods also have been used in the spatial delineation of mine effects. At Haveri, metals and the associated ecological effects on testate amoebae have spread widely in the lake basin, while in Luikonlahti the ecologically relevant impact was limited to the Petkellahti bay area. Outside the bay, ecological changes were almost undetectable (Figure 8, right panel). On the other hand, a spatial gradient was also observed in the natural assemblages from the pre-mine samples in Luikonlahti (species favouring certain habitats). Sediment studies are often the only means of obtaining this type of pre-mining information that should be taken into account when investigating mining impacts. At Pyhäsalmi, the spatial extent of the major mine impact has been rather limited, even in the peak loading phase, although metals have spread widely in the lake basin at less extreme concentrations.

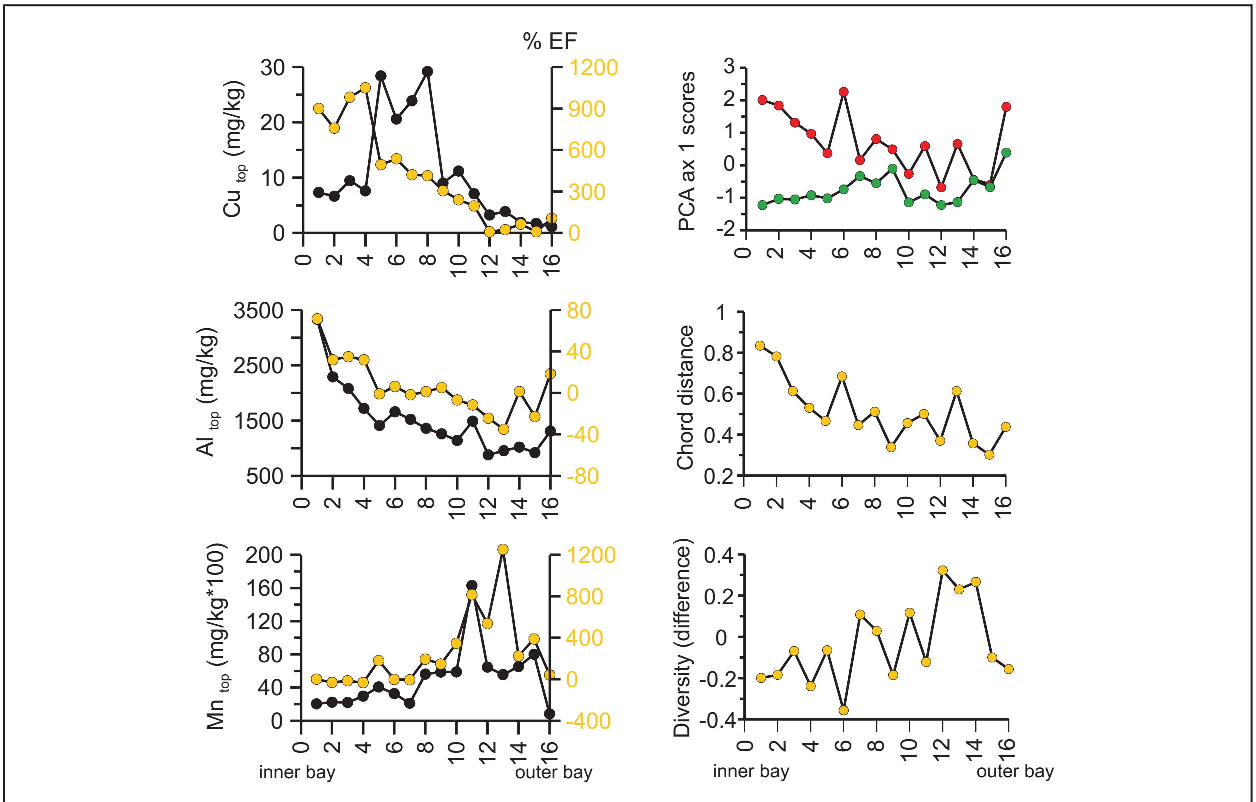

Figure 8. Selected geochemical gradients in the top sediments of the Petkellahti Bay at Luikonlahti (left) and the associated pre- to post-disturbance shifts in sediment testate amoeba assemblages (right). EF = top-bottom enrichment factors. Green dots = pre-disturbance PCA Axis 1 scores, red dots = post-disturbance scores. Mine waters enter the lake in the inner bay.

Separating the effects of different environmental stressors

In most cases, other stressors besides those caused by mining are present that could affect the biota in aquatic systems. Even in the most remote areas, atmospheric deposition and climatic shifts have changed biotic assemblages. Detecting the actual mine impact can be quite challenging if the signals of other environmental factors such as nutrient enrichment and sedimentation conditions dominate.

In a study on the Hitura Ni mine (1970–2009), the sediment record from a heavily modified fluvial lake was analyzed to investigate the possible effects of the mine on the Kalajoki River (Kauppila 2006). The results clearly showed that the lake environment and diatom assemblages had profoundly changed in 1979, when the water level of the lake was increased by 1.5 m and the then extensive macrophyte stands were cut. Due to these hydrological management actions, the early effects of the mine could not be studied and the pre-disturbance sediments were no longer valid as reference samples. Instead, the period of decreasing metal and nutrient loading after 1979 was investigated. Both metals and nutrients had a statistically significant effect on diatom algae, even though metal and phosphorus concentrations in sediments had not decreased. These effects were statistically independent of each other, an example of a case where the effects of different stressors could be separated.

In certain cases, different stressors cause similar ecological effects. This is not surprising, because opportunistic taxa often thrive in various stressed environments. In studies on the aquatic impacts of the Haveri Cu-Au and Parosjärvi W-Mo-As mines, metal contamination resulted in ecological changes characteristic of nutrient enrichment in the recipient lakes (Parviainen et al. 2006, Kihlman & Kauppila 2010). At Haveri, these stressed diatom assemblages showed a poor fit to the phosphorus gradient, and at Parosjärvi the diatom species having the highest correlations with sediment [As] were those with high phosphorus optima in the inference model.

In studies on the Luikonlahti mine, the effects of many environmental stressors were recognized (Kauppila et al. 2006, Kihlman & Kauppila 2009a). Spatial gradients in the surface sediments suggested the impact of several environmental variables, such as those reflecting the overall geochemical conditions (e.g. S, Fe, redox conditions) or an increase in inputs of organic matter and nutrients. However, Al was the only factor that was significantly associated with the horizontal species gradient in the bay, referring to a decrease in pH resulting from AMD, the direct toxic effects of Al, or smothering of sediment biota by Al precipitates.

Do reference sites exist in mine-impacted lakes?

Recent sediment studies in mining environments have highlighted both the importance of local reference data and the difficulties in determining suitable reference samples and sites. A vast array of environmental gradients that are completely unrelated to mining may cause spatial and temporal gradients in biotic assemblages. These should be separated from the actual mine water impacts.

For example, in the studies on Luikonlahti (Kihlman & Kauppila 2009a) and Pyhäsalmi (Kihlman & Kauppila 2009b), sediment characteristics and the associated assemblages of testate amoebae of the suggested remote reference sites were fundamentally divergent from the pre-mining subsamples of the impacted areas. At Haveri (Kihlman & Kauppila 2010), the suggested reference site, chosen to represent the independent effect of eutrophication, turned out to be contaminated by mine-derived metals, despite the upstream location. In addition, the different water depth at the reference site caused some fundamental differences between the faunal assemblages of these sites, even before the mine impact.

Studying lake recovery from mine loading

Sediment studies can also be employed to examine the recovery of a lake from mine water loading, because of the temporal record sediments provide. In the Lake Pidisjärvi example from the Hitura mine, decreasing Ni loading from the mine was correlated with changes in diatom assemblages, even though sediment metal concentrations had not decreased (Kauppila 2006). The assemblages still differed markedly from the pre-mining samples, to a large degree because of the drastic modifications made to the lake basin in 1979, and it is unrealistic to expect that the species compositions will ever approach these earlier assemblages.

In the Haveri case, both diatoms and testate amoebae showed signs of recovery after the peak metal loading phase (Figure 7; Kihlman & Kauppila 2010). However, a simultaneous change in the trophic status of the lake has also affected the biotic assemblages, changing the assemblages towards a different direction, independent of the mine impact.

CONCLUSIONS

Recent mine site environmental investigations at GTK have focused on the mechanisms controlling mine drainage formation in tailings areas, factors affecting the distribution of metals in receiving lake basins, and the impacts of mine drainage on surface water bodies. These studies have provided several insights into the problem, including the following:

- Tailings effluent quality is site-specific, and may show seasonal and annual variation due to local hydrological conditions, but also due to changes in material disposal. This variation should be taken into account in designing tailings water treatment.
- Sulphide oxidation in tailings areas may already start during active disposal, particularly in the border zones of the impoundment and if there is a delay in the burial of high-sulphide tailings. This requires special attention in the planning of tailings facilities and disposal.
- In shallow lakes, wind-driven bottom currents may control sedimentation and also the distribution of mine-derived metals in the sediments.
- The nature of the ecological effects of mine drainage varies in relation to changes in effluent characteristics through different phases of mine operation.
- Major impacts of mine drainage on surface waters are often transient and date to the post-mining period of AMD generation; most of the mining impacts can thus be avoided by diligent remediation of tailings facilities.
- In most cases, other stressors besides mine drainage have affected aquatic biota near mine sites.
- Sediment studies often provide the only means of taking the pre-mining conditions and natural gradients into account when examining the environmental effects of mines.

These studies have shown that mine site risk assessment clearly benefits from this type of a multidisciplinary approach.

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NEW MINERAL PROCESSING APPLICATIONS AT GTK

by
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The GTK Mineral Processing Laboratory is specialized in working closely with mining companies, equipment suppliers and engineering offices to ensure correct process dimensioning for new beneficiation plants. It offers a unique platform for the development and testing of energy-saving, low-environmental-impact crushing, grinding and concentration processes. The laboratory is equipped to develop mineral processing methods anywhere along the beneficiation chain from mineralogical analysis to dealing with process waste. Moreover, testing of promising methods can readily be ramped up from bench-scale to pilot-scale.

The applicability of mineral processing in environmental remediation and recycling has been demonstrated on numerous occasions.

Keywords (GeoRef Thesaurus, AGI): metal ores, beneficiation, methods, applications, recycling, slag, soil pollution, remediation, Finland

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INTRODUCTION

The Mineral Processing Laboratory started in the town of Outokumpu under the name of VTT (Technical Research Centre of Finland) in 1981, having belonged to the same organization since the 1940s. The laboratory was transferred from VTT to GTK in 2004, and continued its activity in the same premises that were built in 1988 (Figure 1).

The Mineral Processing Laboratory and pilot plant facilities are unique in the world in terms of scale and variety. The main task of the Mineral Processing Laboratory is to conduct ore beneficiation studies for mining companies when assessing ore deposits and drawing up profitability calculations, starting from laboratory testing and extending all the way to campaigns at the pilot plant. The research activities also include detailed mineralogical studies for ores and process samples as well as chemical analyses.

GTK has carried out process development for numerous ore types over the years. In the past few years, research has especially focused on the processing of nickel, gold, iron, phosphate and platinum (PGM) ores. A full research chain, including mineralogical work, bench-scale tests and a pilot campaign, can be undertaken at GTK's premises for the client's ore evaluation projects. The pilot plant fulfils the requirements for testing the workability of a complete continuous beneficiation process. A properly conducted pilot campaign is the most reliable way of assessing the commercial exploitability of a mineral deposit. Moreover, as a part of the client's feasibility study, basic engineering can be conducted at GTK for the planned processing plant with a fixed throughput, including the equipment sizing, cost estimation and preliminary layout design. The required data for engineering purposes are collected during bench-scale and pilot-plant testing.

In addition to metal containing ores and industrial minerals, mineral processing methods can be also used in other kinds of applications where eco-efficient processing methods are needed. In the past few years, GTK has successfully utilized these methods in new research areas, such as the recycling of slags and by-products from metallurgical processes and the remediation of contaminated soils.

At GTK, eco-efficient processing methods for primary and secondary materials of various types are developed in close cooperation with other research institutes and beneficiaries.

Figure 1. The Mineral Processing Laboratory of GTK in Outokumpu.

MINERAL PROCESSING

Mineral processing unit operations are easily adapted as flexible combinations for various materials and applications. Flowsheet development and testing of different variables is first carried out on a laboratory scale. After the best procedure has been developed, it can be tested as a continuous process on a larger scale in a minipilot or pilot plant.

The minipilot is a small, continuously operated facility installed in a transportable container that can be run on a continuous basis with a feed capacity 20–50 kg/h. An ore sample of 1 to 2 tons, composed of drill cores, can be used as the feed material. More versatile equipment can be found at the pilot plant, operating with a capacity of 1 to 5 tons per hour. The ore sample needed for a pilot run is normally 100–300 tons. The versatility and high degree of automation and instrumentation makes the pilot plant of GTK one of the leading facilities of its kind in the world (Figure 2).

The methods of characterization of ores and other materials are also investigated at GTK, as described in the following.

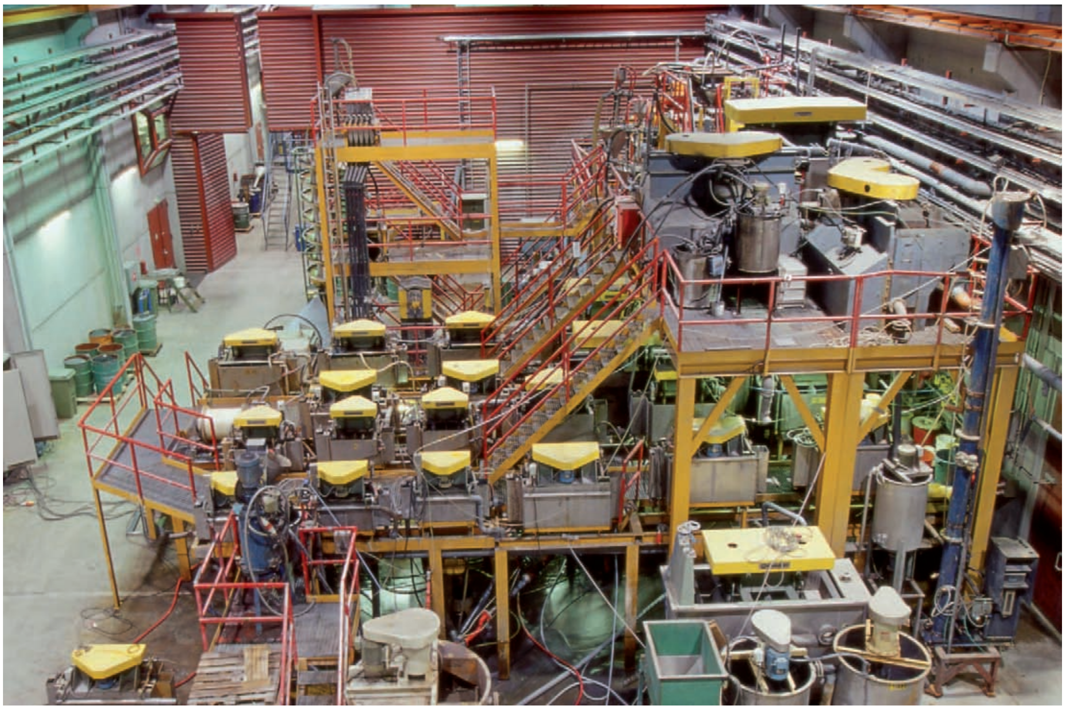

Figure 2. View of the flotation section of pilot plant.

Characterization

The first step in the process development of a new material is detailed chemical and mineralogical characterization, which provides initial data and thus a starting point for beneficiation testing. The most frequently used analytical methods are X-ray fluorescence spectroscopy and atomic absorption spectroscopy for quantitative elemental analysis, fire assay for analyzing precious metals and inductively coupled plasma emission mass spectrometry (ICP-MS) for analyzing elements from liquid samples.

Mineralogical characterization is an essential tool in developing beneficiation methods for various ores. Knowledge of the mineralogy (e.g. phases, occurrence, grain size, liberation, association) in the ore feed, concentrates and process tailings enables the development of a suitable process method in each case. At GTK's Mineral Processing Laboratory, the main equipment for mineralogical characterization is the Mineral Liberation Analyzer (MLA) (Figure 3). The MLA consists of a standard modern scanning electron microscope (SEM) with an energy dispersive X-ray analyzer and a software package. The on-line program of the MLA software controls the SEM, captures images from the sample, performs the necessary image processing and acquires EDS X-ray spectra unattended. In addition to MLA, optical microscopes, X-ray diffraction and an electron microprobe are used in mineralogical studies.

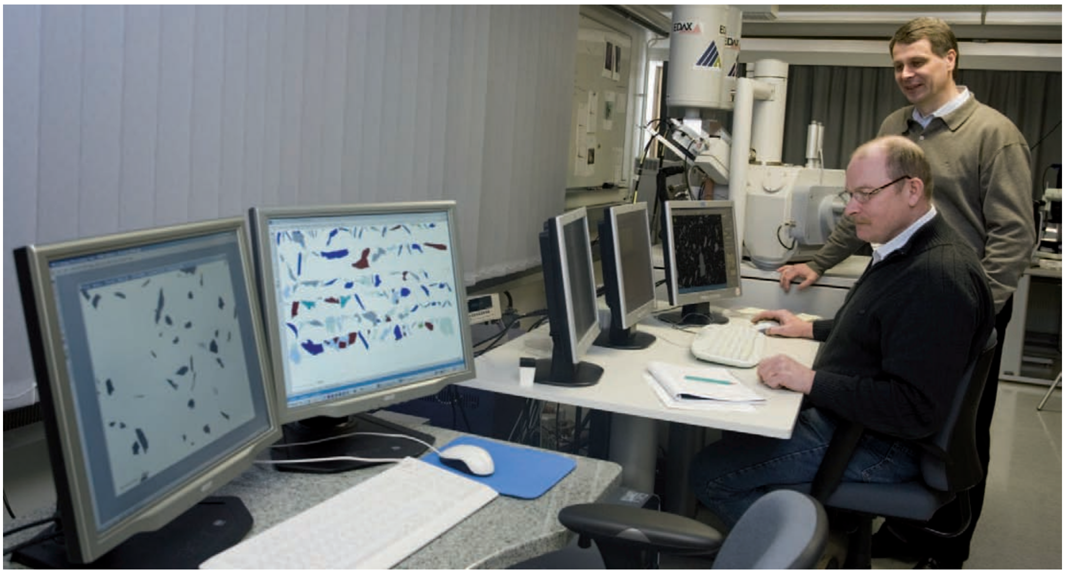

Figure 3. MLA is a modern tool for mineralogical characterization. Photo: Pekka Turtiainen.

Comminution

Comminution (crushing and grinding) is one of the most demanding phases of mineral technology because the selection of an appropriate crushing and grinding method is a prerequisite for a successful separation process. The investment and operating costs of comminution constitute a major part of the total beneficiation costs, and the study of this subprocess before process design is thus absolutely necessary. The first stage of a comminution study is to define the energy consumption for a new sample as well as the degree of liberation of valuable minerals to determine the correct grind size.

Several crushing and grinding methods can be used in comminution studies: metal medium and autogenous grinding with their applications. The optimum grind size is first determined by laboratory tests, after which the various grinding methods and flowsheets can be examined in a continuously operated pilot circuit.

Beneficiation methods

The main beneficiation methods are flotation, gravity and heavy media separation, and magnetic separation. Hydrometallurgical methods (leaching) can also be used to complement or replace beneficiation in certain applications. In addition to conventional leaching, bioleaching has become a potential recovery method for metals during the past few decades.

Gravity and heavy medium separation are used when separating minerals with different specific gravities. Gold ores are typical examples for which gravity separation is used. Other examples include chromite and diamonds. The methods are also used for several precious metal and sulphide ores in combination with flotation, as well as in a variety of recycling processes as an auxiliary method. Laboratory studies can be conducted with small shaking tables or centrifugal concentrators. The pilot plant is equipped with several types of spiral separators, a full-scale shaking table and a Knelson concentrator (representing one type of centrifugal concentrator). Pneumatic separators can be used for dry process applications. The basics of heavy media separation can be examined at the laboratory scale with an Erickson cone. In a pilot plant, a drum separator for pebble-size materials and a dynamic Dyna Whirlpool separator for fine-grained materials are available.

Magnetic separation is used when separating minerals with different magnetic properties. It is commonly used in iron ore beneficiation, but is often also applied for other ores as one stage of a combined process with flotation or gravity methods. The development of neodymium magnets used in permanent magnet separators as well as super conducting and other high-gradient electromagnetic applications have opened up new application opportunities for the magnetic separation of various materials. Magnetic field intensities up to 2 Tesla are possible to achieve with the separators of GTK.

Flotation is the most common beneficiation method used for metal-containing ores and industrial minerals. It is a process used to separate minerals, suspended in water, by attaching them to gas bubbles to enable selective recovery by levitation of the target minerals. Flotation utilizes differences in physico-chemical surface properties of various minerals. In addition to minerals, flotation can be used in the treatment of recycled materials, the remediation of contaminated soil, de-inking of paper, and water treatment. The research possibilities at GTK extend from batch tests in the laboratory (Figure 4) to continuously operated large-scale campaigns at the pilot plant. The study of a new ore sample or other material starts with laboratory testing on a sample size of up to a couple of hundred kilograms. The first step in simulating a continuous flotation process is the minipilot, in which sample sizes are typically 0.5–2 tons. A pilot-scale test run provides an opportunity to extensively study different kinds of beneficiation flowsheets, as well as to use various types of methods and equipment. The required sample size is typically some hundreds of tons. The pilot plant is also equipped with a continuously operated on-line analyzer, as well as extensive instrumentation and automation for control and adjustment of the flotation circuit.

Figure 4. Flotation test going on in the laboratory. Photo: Pentti Koponen.

Hydrometallurgy, such as pressure oxidation and leaching, may be applied for minerals that respond poorly in beneficiation or for concentrates or tailings of the beneficiation process. Hydrometallurgical research at GTK covers cyanide leaching of gold from ores and concentrates, various types of acid leaching methods for ores and slags, as well as pressure leaching. Hydrometallurgical studies at GTK are mainly conducted as batch tests, but continuous larger scale research is also possible.

Bioleaching is a promising technique that can commercially provide lower capital costs, low energy, and a more environmentally friendly method for metal recovery than traditional extraction techniques. Bioleaching utilizes microorganisms and their metabolic products to transform solid compounds into a soluble and extractable form. For example, gold, copper, nickel and zinc can be leached from low grade ores as a result of bacterial activity. One of the targets of bioprocess research is to improve understanding of the key factors in bioleaching. The research methods at GTK involve the whole process of bioleaching, from small-scale shake flask tests to pilot scale column test work, starting from the cultivation of microbial cultures for bioleaching and ending with an optimized bioleaching process in which valuable metals are recovered (Figure 5).

Figure 5. Bioleaching column in the backyard of GTK Mineral Processing Laboratory. In this test, 110 tons of ore was packed in a 9-metre-high column. Photo: Pentti Koponen.

An example of current and future research to support process development

Process chemistry research at GTK focuses on identifying and monitoring physicochemical interactions in beneficiation processes. Electrochemical and surface chemical phenomena in different process stages (such as grinding, flotation, and leaching) may have a major impact on the process conditions and beneficiation results. In order to optimize processes it is essential to have good knowledge of the chemistry and a possibility to determine and measure certain chemical effects.

For example, galvanic interactions in mild steel grinding take place between iron from the grinding media and sulphide minerals. This may have strong effects on the upgrading of sulphide minerals. The amount of interaction can be determined by utilizing certain electrochemical measurements and leaching methods, thus influencing the process optimization.

Time-of-flight secondary ion mass spectrometry (ToF-SIMS) is a highly sensitive technique for surface analysis. It identifies all the elements and can be used for determining the composition, possible contaminants and also the depth profile of the studied material. GTK has a desk-sized ToF-SIMS instrument, which is an essential tool, for instance, for measuring traces of organic reagents on minerals and the oxidation level of a mineral at a selected point.

The aim is to combine process chemical methods such as ToF-SIMS with mineralogical characterization methods in order to create a comprehensive combined procedure to support process development for ores and by-products.

Case study: Kevitsa

The Kevitsa nickel-copper-PGM ore deposit in Sodankylä, northern Finland, is one of the examples that GTK has extensively studied during the last three decades. The deposit was originally discovered and drilled by GTK via its exploration programmes in the 1980s, and this work continued between 1990 and 1994. Initial mineral processing tests were also conducted at that time by the laboratory of VTT (later the Mineral Processing Laboratory of GTK).

After GTK's basic work, the Finnish mining and metal company Outokumpu continued the exploration in the 1990s and expanded the resource to 234 million tons at a 0.26% nickel cut-off grade. The company also studied the processing of the ore, but the results were not sufficiently satisfactory to lead to further interest in utilizing the deposit. Major corporate restructuring also affected the decisions within the company. Thus, Outokumpu handed Kevitsa back to the Finnish government.

A private junior company, Scandinavian Gold Prospecting, acquired the Kevitsa property from the Finnish government in 2000. The company, under its later name Scandinavian Minerals, started cooperation with the Mineral Processing Laboratory of GTK in 2004.

The metallurgical tests at GTK started with mineralogical and bench-scale studies, followed by continuous closed-circuit flotation tests at the minipilot facility. Extensive pilot-plant tests were realized in four campaigns during 2006–2008 (Figure 6).

From the very beginning of the recent test work, GTK applied the selective flotation scheme, in which separate copper and nickel concentrates were produced. It was found that making two separate concentrates would offer much better economy than the flotation of a single bulk concentrate.

The real challenge was to develop a process that yields smelter-grade concentrates with good recoveries of both copper and nickel. Through careful studies to optimise the flotation conditions, GTK succeeded in developing a grinding/flotation process capable of yielding both high grades and recoveries of the main metals. Added value in concentrates is obtained from platinum, palladium, gold and cobalt.

Following the last pilot run in 2008, the work of GTK with the Kevitsa ore has continued with the study of basic process conditions such as electrochemistry, which plays an essential role in flotation. In addition, detailed information on PGM mineralogy has been acquired by extensive mineralogical investigations.

Kevitsa Mining Oy, a later subsidiary of Scandinavian Minerals, was purchased in 2008 by First Quantum Minerals (FQM), a Canadian mining company. FQM has continued the development of the Kevitsa property and is on the way to opening a mine, which is targeted to go on stream in mid-2012. In 2009, the mineral reserves were estimated at 107 million tonnes grading 0.296% nickel and 0.418% copper (with surplus benefits from PGMs, gold and cobalt). The estimated mine life would be over 20 years and the expected workforce approximately 200 during commercial production.

In addition to the main beneficiaries, such as the mining company and the surrounding society, the opening of a large-scale mine in Kevitsa will also mean the realization of expectations for GTK, which has a long history of exploration and metallurgical testing of this significant deposit over many decades.

Figure 6. The operation of pilot plant is monitored and controlled in the control room. Photo: Joonas Hukkanen.

UTILIZATION OF MINERAL PROCESSING METHODS IN RECYCLING AND ENVIRONMENTAL RESEARCH

GTK has successfully applied methods used in mineral processing for different kinds of materials. The methods are applied for the processing of large amounts of materials, and it is reasonable to extend their use to other areas where they can be effectively exploited, such as the separation of metals from industrial slags and bullets from old shooting ranges. The applicability of mineral processing methods in recycling and environmental research has been tested over the years. Examples include metallurgical slags, such as copper from smelter slag and aluminium from tetrapacs, the separation of metals and plastics from electronic scrap, and deinking of paper. Some of the application areas are described in the following. To gain a better idea, processing methods for bottom ash from municipal solid waste incineration and for soil from shooting ranges are described in more detail.

Slags

Bottom ash from municipal solid waste incineration (MSWI)

New kinds of slags and ashes need to be managed in Finland, as waste incineration has nowadays become more common. The treatment and disposal of these residues significantly affects the operating costs of a waste incineration plant, and if disposed without utilisation, the slags and ashes will burden landfills. Meanwhile, there are a number of ongoing national and EU-level development initiatives in Finland to enhance the reuse of waste materials. One example is bottom ash from municipal solid waste incineration (MSWI), from which new reused material suitable for earth construction purposes can be developed. Bottom ash is a heterogeneous mixture of slag containing varying proportions of glass and metal residues. During the incineration process the elements with a high boiling temperature remain in the bottom ash, while more volatile elements with low boiling temperatures end up in the air pollution control residues. The main chemical components of bottom ash are the oxides of silicon and aluminium. Other constituents include alkaline and alkaline earth compounds, chlorides, sulphates, ferrous and non-ferrous metals and their compounds, and unburned organics. Non-incinerated material represents 1–5 wt-% of bottom ash. As a result of rapid cooling, vitreous material is formed. Various metal or metal alloy particles are found in the ash, such as small pieces of pure iron or bronze. The reuse of bottom ash requires the development of suitable upgrading processes, as it is not a suitable material for reuse as such. In the upgrading process of waste materials, various process technologies commonly used in ore beneficiation can be applied. The value of the upgraded product is based on the content and market price of metals.

In practice, physical processing, i.e. the removal of ferrous and non-ferrous metals, is usually needed to produce a better quality bottom ash. Commonly used physical techniques include size, density, magnetic and electrostatic separation. Magnetic separation has already been used for the recovery of ferrous metals from bottom ash for a long time, and eddy current separation has recently also been applied for the recovery of non-ferrous metals.

The aim of the study at GTK was to develop a suitable combination process for separating valuable metals from Finnish MSWI slag and generate an end product that fulfils the requirements set for earth construction material. In addition to the above-mentioned techniques, flotation and bioleaching were tested as potential separation methods for non-ferrous metals. As with ores, slag was characterized chemically and mineralogically before processing. The main mineralogical characterization method was MLA. The method gave valuable and illustrative information on different phases in slags, which assisted in the development of the separation process.

The studied sample was first divided into different size fractions to facilitate further treatment. Non-ferrous and ferrous particles were separated by magnetic separation. In addition to more traditional eddy current and gravity separation methods, flotation was tested for nonferrous material. The combination of grinding and sieving seems an interesting option to recover almost pure metal concentrates prior to flotation. For fine non-ferrous material, flotation seems to be an adequate process for recovering copper.

The use of bioleaching for slags

While bioleaching has traditionally been used in the treatment of sulphide minerals, in particular, a recent project has concerned the development of bioleaching techniques for use with metal-containing wastes. Bioleaching was tested as a potential method to separate metals from fine fractions and agglomerates in MSWI slag (Figure 7). The bacterial mix used in the tests was a similar kind of strain to that used in the bioleaching of base metals from ore, for example at the Talvivaara nickel mine. Slag samples were leached for 6 months and the metal content in solution was analysed four times during that period. Based on the results, metals - especially copper, aluminium and zinc - were leached with a good level of recovery. The results were extremely encouraging and bioleaching is currently being applied in a project on the processing of several types of industrial slags.

The optimisation and successful upscaling of processing methods requires a comprehensive understanding of the material properties of the bottom ash in question. In addition to conventional physical separation technologies, bioleaching appears to work especially for the recovery of aluminium and copper from coarse bottom ash fractions, whereas flotation is suitable for copper recovery from fines. The results support the integration of bioleaching and different physical processing techniques in bottom ash upgrading in order to enhance the metal recovery and improve the final product quality.

Figure 7. Bioleaching is tested for extracting metals from slag materials. Photo: Joonas Hukkanen.

Remediation of contaminated soils

Both the economic value of free land and the risk to human health caused by pollutants has created a strong growth in the remediation of contaminated land. Remediation methods that produce clean soils and exploitable concentrates separated from them will meet the demands of sustainable development and are forward-looking technologies for the future.

Shooting range areas. Mineral processing techniques can be applied in the remediation of shooting range soils. The studied soils, originating from several old shooting ranges, were heavily contaminated by lead- and copper-containing bullets and lead pellets, as well as their disintegrated fine-grained weathering products. Lead and copper in the soil samples mainly occurred as coarse particles and could be easily mechanically recovered by combining wet sieving with heavy medium separation (Figure 8) and consecutive gravity concentration stages. It is possible to reduce the residual metal content of the final remediated soil enough for it to be readily deposited in its original location. The transportation of large amounts of soil is thus avoided. The high grade metal concentrate separated from the soil enables effective recycling of metals. The cleaning of soil and recovery of metals at the same time makes the treatment more economical compared to traditional methods. In the test work carried out, 83–90% of total lead and 91–99% of total copper was recovered from the soil as a concentrate containing ca. 95% metals.

The metallurgical treatment was tested at GTK for the metal concentrate obtained from a pilot plant campaign in which 230 tons of material from the impact berm of a shooting range was remediated. By a simple melting method, lead and copper were separated by heating the concentrate above 400 ºC, whereby lead was melted while copper remained solid. The purity of the copper fraction was 94% and that of the lead fraction 98%, although the melting tests were only preliminary.

The fine soil fraction contains 5–17% of the total lead, mainly as fine-grained carbonaceous weathering products such as hydrocerussite, $Pb_3(CO_3)_2(OH)_2$, and cerussite, $PbCO_3$, and 1–3% of the total copper. Due to the higher solubility of lead carbonates and the high surface area of these particles, they form a significant source of contamination for the environment. The corresponding compounds of altered copper are azurite, $Cu_3(CO_3)_2(OH)_2$, and malachite $Cu_2(CO_3)(OH)_2$; the weathering process is stopped on the surface of Cu particle. The weathering process causes the lead of the bullets, after shooting into the berm, to begin transforming into the above-mentioned secondary lead compounds. The weathering process is continuous and goes through the whole lead grain. Complex-forming leaching was used to recover the lead and copper from the fine soil fractions with recoveries of 95–98%. By combining the mechanical and leaching processes, lead and copper recoveries of up to 99.9% can be achieved.

Concentration with a shaking table is commonly used for this type of raw material. Specific coarse flotation is a particularly useful method to recover altered compounds. Coarse flotation (Figure 9) enables the recovery of coarser particles than normal flotation. The fine lead particles are often covered by the product of carbonaceous weathering, which makes them amenable to recovery by flotation. The development of techniques is continuing at GTK.

Sawmill areas. In addition to shooting ranges, the remediation of soil from old sawmill areas containing dioxins and furans has been tested at GTK. The aim of the study was similar to the case of the shooting range soils, i.e. to develop a process by which the contaminated soils can be remediated so they are pure enough to be reused. The samples studied were collected from a typical old sawmill area.

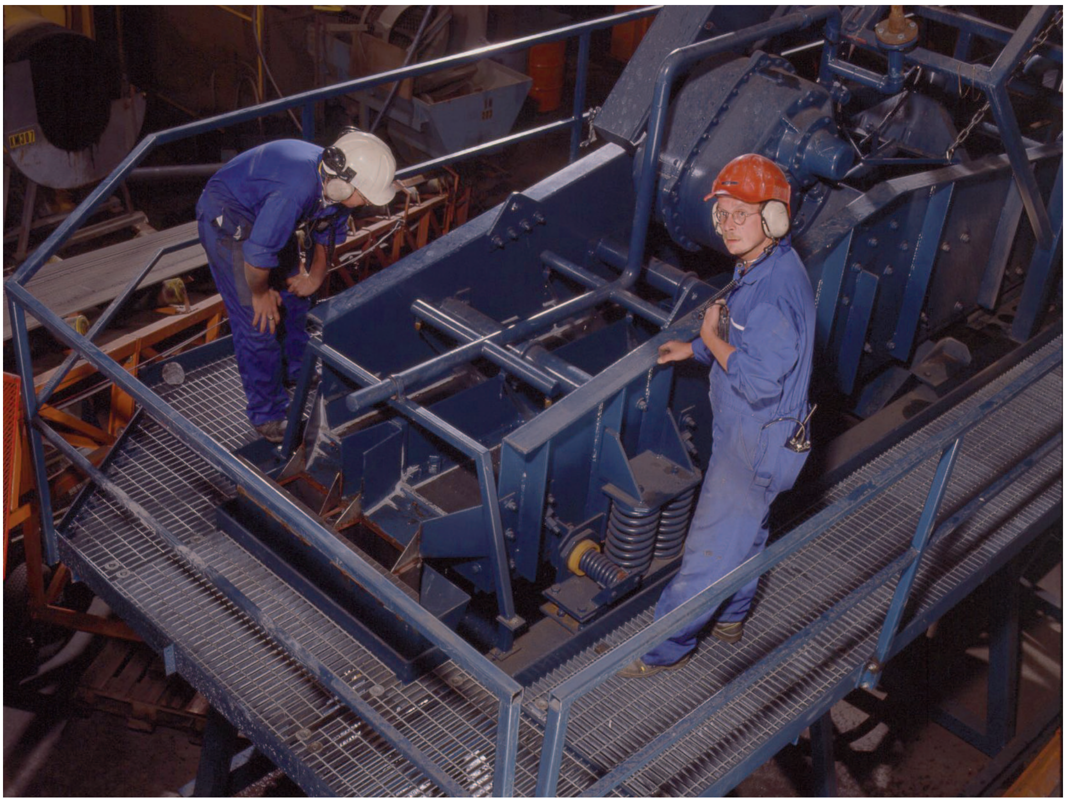

Figure 8. Heavy medium separator in pilot plant.

Figure 9. Flotation of coarse particles with the Skim-Air cell in pilot plant. Photo: Joonas Hukkanen.

The process used had two main steps. Firstly, the pollutants were released from mineral surfaces by attrition using a laboratory wet grinding mill or ultrasound in wet conditions. Secondly, the released pollutants were separated from the soil, e.g. by using classification methods for separating the fines with pollutants. The fines were treated by burning. Dioxin and furan levels in the coarse material proved to be low enough for further processing.

Oil contaminated land. A preliminary study to test the applicability of mineral processing techniques to remediate soils contaminated by diesel oil revealed that mineral processing methods are indeed applicable. The studied unit processes were gravity separation (heavy media), grinding and flotation. The studied materials were two soil samples from petrol station areas. The oil concentrations of the samples were high, ca. 10 000 ppm, and the oils were extensively degraded in both samples. A combination of scrubbing and heavy media separation yielded rather good separation of oil from the contaminated soil. The applied processing method was shown to be economical; the highest costs originated from transportation. The results of the study were promising.

CONCLUSIONS

The strength of GTK's Mineral Processing Laboratory lies in its ability to conduct a full research chain for the client's ore beneficiation project: mineralogical studies, bench-scale test work and pilot-plant campaigns can be undertaken in the same premises. Versatile facilities in laboratories and the pilot plant offer a possibility to develop tailor-made processes for any ore type or flowsheet. The research group can also offer its expertise in the basic engineering of commercial processing plants.

Numerous ores of various types from Finland and abroad have been studied during the more than 60-year history of the Mineral Processing Laboratory. Experience has shown that ore deposits that were previously considered unprofitable can be made exploitable via intensive research and development of the beneficiation process. Such deposits in Finland, whose exploitation has recently started or are promising for commercial mining in the near future, include nickel, gold, iron, phosphate and PGM ores. The processing of these and many other ores was studied by GTK's Mineral Processing Laboratory before they came publicly known.

As conventional mineral processing methods have been developed to treat large amounts of materials, their application is not limited to the separation of valuable minerals from ores. During the past decade, GTK has successfully utilized the same methods in new research areas, such as the recycling of slags and by-products from metallurgical processes and the remediation of contaminated soils. The treatment of these materials can have two-fold targets: the recovery of metals as valuable products and the cleaning of the main bulk material to fulfil environmental requirements for deposition or later use as landfill or in earth construction.

The future challenges of GTK's Mineral Processing Laboratory are likely to be in the further development of beneficiation technology for low grade ores: the recovery of metals should be performed effectively and at the same time the processing must meet the requirements of sustainability and eco-efficiency. The application of processing methods for recycling and cleaning of various materials will also have a significant role in future research.

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GEOLOGICAL RESOURCE ACCOUNTING AND ASSOCIATED RESEARCH

by
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Vuori, S., Aatos, S. & Tuusjärvi, M. 2011. Geological resource accounting and associated research. *Geological Survey of Finland, Special Paper 49*, 115–120, 2 figures.

The secure supply and use of geological resources has become an increasingly acknowledged subject in global discourse, not least due the strong emergence of developing countries and climate change. The path of global development has also set new challenges for the geoscientific community. The Geological Survey of Finland (GTK) has a long history and strong expertise in working with the utilization of geological resources. This background provides a good basis for promoting the sustainable use of these resources, which has also been recognized in our strategic future planning. One of the lines of work that supports sustainability is geological resource accounting. This topic is in fact a group of activities at GTK that include actual accounting as well as research associated with sustainability issues. In general, accounting consists of account development and web-based accounting services for different geological materials, including secondary raw materials, whereas research has focused on life cycles and material flows. Here, we report the current state of the art of geological resource accounting development and associated research at GTK.

Keywords (GeoRef Thesaurus, AGI): mineral resources, secondary raw materials, accounting, life cycle assessment, Finland

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INTRODUCTION

Geological resources form an essential foundation of society in many respects. The globally increasing demand for geological resources has brought sustainability issues connected with resource use higher on the agenda of international discourse. Population growth, rising living standards and urbanization are also likely to sustain the growing demand for resources in the future. The anticipated path of development will require increasing commitment from the geo-scientific community and nations to find criteria and solutions for the sustainable use of these resources.

The Geological Survey of Finland (GTK) has been actively following its global and local operational environment in order to revise and keep strategic focuses up-to-date to respond to the recognized and anticipated challenges. As a government agency, GTK has a key role in providing geological information and expertise to government and industry that is associated with the supply and management of geological resources in Finland. One of the strategic goals of GTK is to promote novel technologies for sustainable development, which supports our primary aspiration to foster sustainable growth and welfare via geological knowledge.

As a consequence of the strategic goals, a number of research lines and projects have been established at GTK. One group of research and development activities that is close to sustainability issues is executed under term of accounting. This line of work includes actual accounting and the development of accounting concepts, as well as research that assesses the performance of the mineral industry. In general, the organization of work can be regarded as matrix that combines accounting and research, which brings marked synergy for account and research development (Figure 1). Accounting and associated research are further discussed in the following chapters.

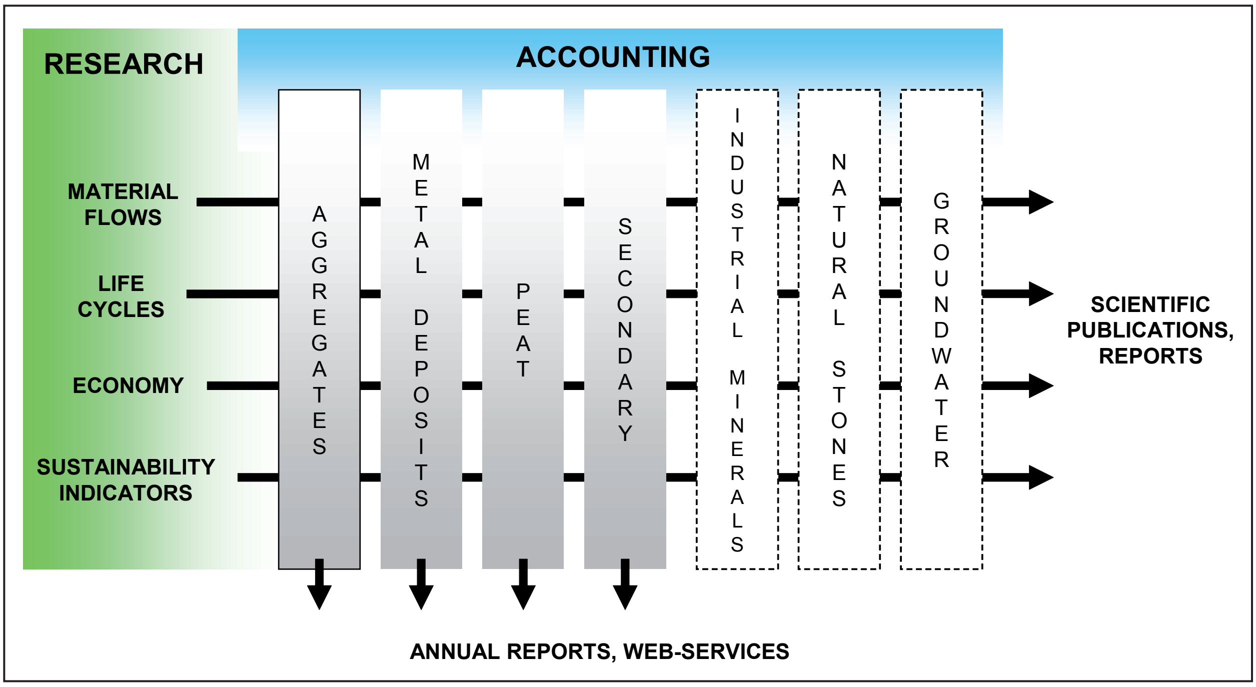

Figure 1. The combined development of accounting and research. Information that is yielded by accounting can be utilized as input data in research. From among the account web services, the one for aggregates is already available. Current development is especially being carried out with peat, metal deposits, and natural and secondary aggregates. Research has focused on material flows, life cycles and economic issues. During progress in research and accounting, sustainability indicators will also be considered.

ACCOUNTING

National geological survey organizations have a key role in geological resource accounting, as they administer substantial amounts of geological information. The combination of geological knowledge of the location, quantity and quality of resources with data on extraction provides the foundation for resource accounting. In Finland, geological resource extraction is under the jurisdiction of the Ministry of the Environment (peat, groundwater, soil and bedrock) and the Ministry of Employment and the Economy (industrial minerals and rocks, metallic ores and soapstones). In both cases, administrative data collection is chiefly focused on the utilized masses or volumes, whereas information on the resources is collected by GTK. In addition to web services, we annually publish a report of investigation that summarizes the annual extraction and production of geological resources (e.g. Vuori et al. 2008a, Tuusjärvi et al. 2009).

Existing aggregate accounting service (Kitti)

During the last decade, considerable effort has been put into creating a web-based service for aggregates by GTK, the Ministry of the Environment, the Finnish Environment Institute, the Uusimaa and West Finland Regional Environment Centres, the City of Hyvinkää and INFRA ry. This work has focused on the Uusimaa region, which is crucial to the aggregate supply of the growing urban capital area. Furthermore, Uusimaa is one of the most densely populated areas in Finland, which sets the requirement to coordinate the supply of extractable aggregate resources with other forms of land use, groundwater resources and environmental perspectives.

The developed web service provides information on the location of aggregate resources in addition to information on extraction permits, permit areas and extraction (see the accounting service http://www.geo.fi/en/kitti/). Furthermore, soil and nature protection areas have been included in the service, in addition to a geographical base map. The actual accounting, i.e. the change in the remaining aggregate resources, is a result of merging the data on extraction and monitoring collected by authorities in accordance with the Land Extraction Act and GTK's data on aggregate resources.

Account development

The key aspect of developing an integrated geological resource accounting system is to define the accounting concepts for each selected material flow that form the core process of an individual account. At present, the core processes under development include peat and natural and secondary aggregates, in addition to natural and anthropogenic sources of metals. The concepts are being developed in collaboration with national authorities, international geological research organizations and industrial operators.

The next phase in accounting system development after the conceptual planning phase focuses on the design and construction of a public, web-based data service and user interfaces for distributed databases managed jointly by GTK, which is offering the resource data and spatial web services, and by environmental permitting authorities delivering the extraction data, as in the case of aggregates.

RESEARCH

Accounting associated research that is currently being carried out at GTK can be divided into three fields: 1) secondary raw materials, 2) material flows and life cycles, and 3) economic assessments. The first two are described below, whereas the focus of economic research is discussed in detail in an article by O. Holmijoki (this volume).

Secondary raw materials

An objective for the near future is to promote data collection development concerning natural and anthropogenic secondary raw materials as a part of geological natural resource accounting. In this context the former can be regarded to be discharged non-harmful soil or rock matter whereas the term anthropogenic refers to e.g. metal-bearing mineral wastes that are generated by industrial processes. In parallel with account development for secondary raw materials, the inventory and assessment methods for these secondary mineral resources are being redeveloped, which aims to facilitate better access to the resources and promote sustainability in geological resource utilisation.

The focus of our research is the development of methods demonstrating the environmental acceptability of secondary raw materials (Luodes et al. 2008), exploration method development for secondary mineral resources used in green technologies (Teir et al. 2006), and GIS data and database development for secondary geological natural resources in collaboration with international research and industrial partners, as well as domestic authorities. Another field of research is the management of natural and mineral waste aggregates (e.g. Vuori et al. 2008b). As these aggregates are low cost but high density materials, transport distance is a significant factor from an economic and environmental point of view. Research in this field is currently also being carried out to provide GIS-based tools for better collaboration between land use planners and industry in order to optimize the material flows of primary and secondary aggregates. Research and development with secondary raw materials is also aimed at supporting the objectives of the EU and national waste and product legislation, as well as sustainable raw material policies.

Life cycles and material flows

The Finnish metal industry is almost entirely dependent on imported raw materials. Although metal mining is estimated to grow considerably in Finland, the dependence on imports will also probably remain high in the future. The promotion of sustainability requires tools for objective assessment of the overall impacts (environmental, societal or economic) of metal production. A high volume of imports sets challenges for assessments due to the limited possibilities to access foreign mine production data and associated environmental information. For this reason, one of the research focuses is to promote the better applicability of methods such as life cycle assessment (LCA) and material flow analysis (MFA) to the minerals industry, based on the enhanced use of geological expertise on resources as well as mining and concentration processes. Knowledge and data on the deposits can be used to circumvent some of the current challenges in assessment work. The most recent research outcome is the development of an impact allocation method for multi-metal mining (Tuusjärvi et al. 2010). The new method promotes methodological homogeneity between LCA studies associated with production in metal mining.

CONCLUSIONS

Information on geological resources and their use is important for many aspects of society. Accurate data on the location, volumes and characteristics of geological resources can help to steer regional development planning, or can be applied to boost the profitability of primary industries. Research on secondary raw materials, material flows and life cycles can help the mineral industry to mitigate its environmental impacts. Furthermore, research can also provide a variety of other types of information to the industry, which is most apparent in the case of economic assessments (see Holmijoki, this volume). The combination of accounting and associated research ultimately aims to promote sustainable management of natural resources via decision support (Figure 2).

Considering our target setting, we are currently focusing our research and development on the following key areas of interest: research on the possibilities to have GIS-based analyses integrated with resource accounting and its web services; the development of an annual geological resource use publication so that it would also include assessments on the sustainability of resource use. From an economic point of view, the combination of geological resource accounting with monetary flows in preparing scenarios is considered to be interesting. Work with secondary raw materials will be one of the key areas of our research, in addition to promoting new ways of using geological knowledge in material flow and life cycle assessments that focus on the mineral industries. A topic that is also under consideration is research on the possibility to integrate spatially referenced data with statistical data in order to develop novel sustainability indicators. Finally, we also recognize a growing need to provide more support for communication concerning the sustainability issues of the minerals industry to the wider public.

ACKNOWLEDGEMENTS

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Supplementary information on the web:

Geological maps and material provided by the Geological Survey of Finland
http://www.geo.fi/en/

The Finnish aggregates accounting service managed by the Geological Survey of Finland
http://www.geo.fi/en/kitti/

Webpage of the Geological resource accounting research programme
http://en.gtk.fi/research2/program/accounting/

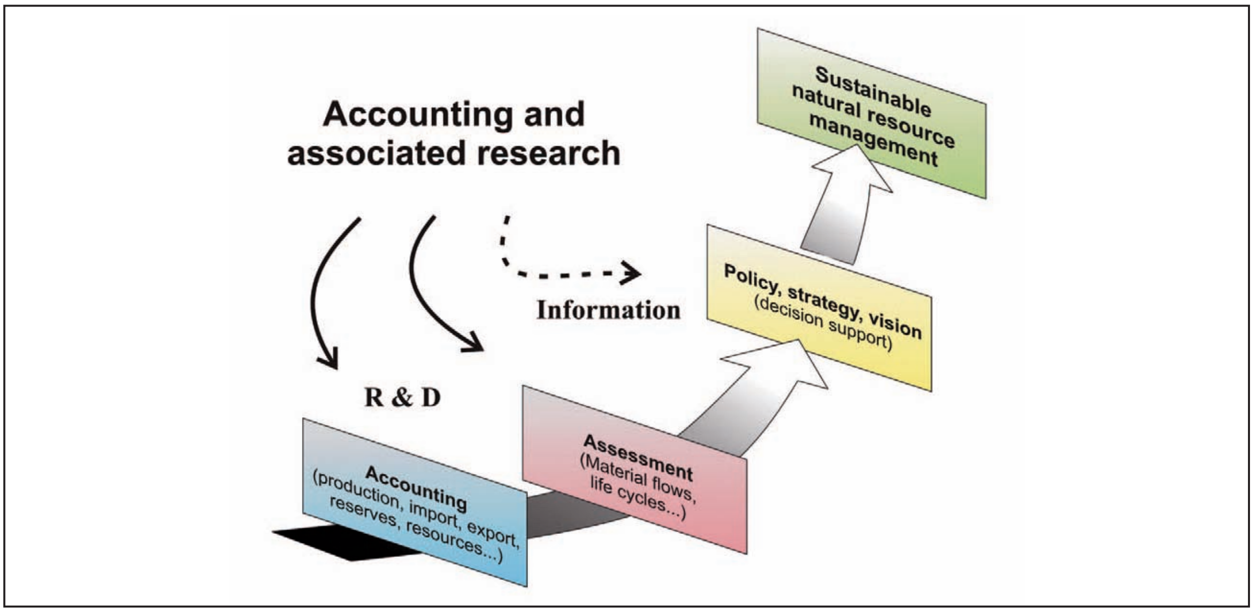

Figure 2. The primary goal of accounting and assessment work, which includes research on secondary raw materials, material flows and life cycles and economic issues, is to provide objective and high-quality information for decision support. Balanced recognition of the economic, environmental and social impacts of resource use combined with good judgment in decision making can ultimately lead towards sustainable natural resource management.

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Geoscience for Society
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THE IMPORTANCE OF GEOLOGICAL NATURAL RESOURCES TO THE ECONOMY OF FINLAND

by
Olavi Holmijoki

Holmijoki, O. 2011. The importance of geological natural resources to the economy of Finland. *Geological Survey of Finland, Special Paper 49*, 121–128, 5 figures and 1 table.

In assessing the importance of geological natural resources to Finland's economy, statistics for the national economy, the industrial economy and foreign trade were used along with supply and use tables analysing the structure of the national economy. To examine the economic cause-effect relationships, impact analyses based on input-output theory were used.

Mining and quarrying's share of the country's total value of production has been less than 0.5% for the years 2000–2008. In recent years, domestic production in the mining of metal ores has been clearly growing. Geological natural resources' share of the country's total imports was around 13% in 2008. Crude petroleum and natural gas as well as metal ores and concentrates accounted for a significant share of the value of imports. Due to low levels of export, domestic production is in practice dependent on the economic situation of domestic consumer industries.

As measured by their financial value, mining and quarrying products were used most in the refining of petroleum, secondly in the processing of metals and thirdly in energy production. All three industries are strongly dependent on imports. Mining and quarrying products were most widely used in the manufacture of chemicals and chemical products. When the indirect impacts of consumer industries are taken into account, the importance of construction to the mining and quarrying industries grows substantially.

In the 2005 operating environment, the changes in production volume in the extraction of peat and in construction raised GDP and employment most effectively. The same industries increased imports the least. Manufacture of petroleum products and processing of metals raised GDP the least. The same industries increased imports the most, and also their impact on employment was weak.

The price changes in the mining and quarrying product classes cause greater pressure for price changes in product markets than the price changes in the product categories for the consumer-industry main products. This is natural because the mining and quarrying products are at the beginning of the processing chain.

The national economy approach presented in this article provides information about geological natural resources for both political decision-making and corporate strategic decision-making.

Keywords (GeoRef Thesaurus, AGI): mining industry, mineral resources, mining, production, import, export, consumption, economic impact, Finland

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OPERATING ENVIRONMENT OF THE NATIONAL ECONOMY

The use of geological natural resources can be seen in many ways in the environment built by man for himself. Metal ores and concentrates are used to produce factories, means of transport and consumer goods. Peat and fossil fuels are used as sources of energy. Industrial minerals are important raw materials in the chemical industry. Gravel, sand and stone are used in buildings and in creating infrastructures.

The objective of sustainable usage of geological natural resources requires us to take account of economic, ecological and social perspectives at both national and international levels. The national economic approach presented in this article enables consideration of the aforementioned perspectives at the same time.

The operating environment of the national economy is the supply table and the use table at basic prices with its additional segments for labour usage (Figure 1). The structure of the supply and use tables follows the European System of Accounts (ESA 1995). Economic activity was divided into industry classes in accordance with the NACE Rev. 1.1 / TOL2002 classification, and economic interaction was divided into product categories in accordance with the CPA2002 classification.

The supply and use tables represent the years 1995–2006 at a general national economic level. Economic activity for the whole country was divided into 59 industry classes (table 1), and economic interaction was divided into 59 domestic and foreign product catogiries. These industries and product classes comprise industries and product categories for mining and quarrying as well as industries and product categories for the corresponding consumer industries.

The information included in the supply and use tables is presented using national economic concepts. Industrial output – or more specifically market output at basic price – refers to the commercial value of goods and services at the factory gate supplied by the industry itself during the financial period. When intermediate consumption of products at the purchasers' price, i.e. goods and services bought from outside, is deducted from the industry output, added value is obtained at the basic price. The added value accurately indicates the share of GDP provided by the industry. When the compensation of employees is deducted from the added value, a key parameter corresponding to gross margin for the business economy is obtained.

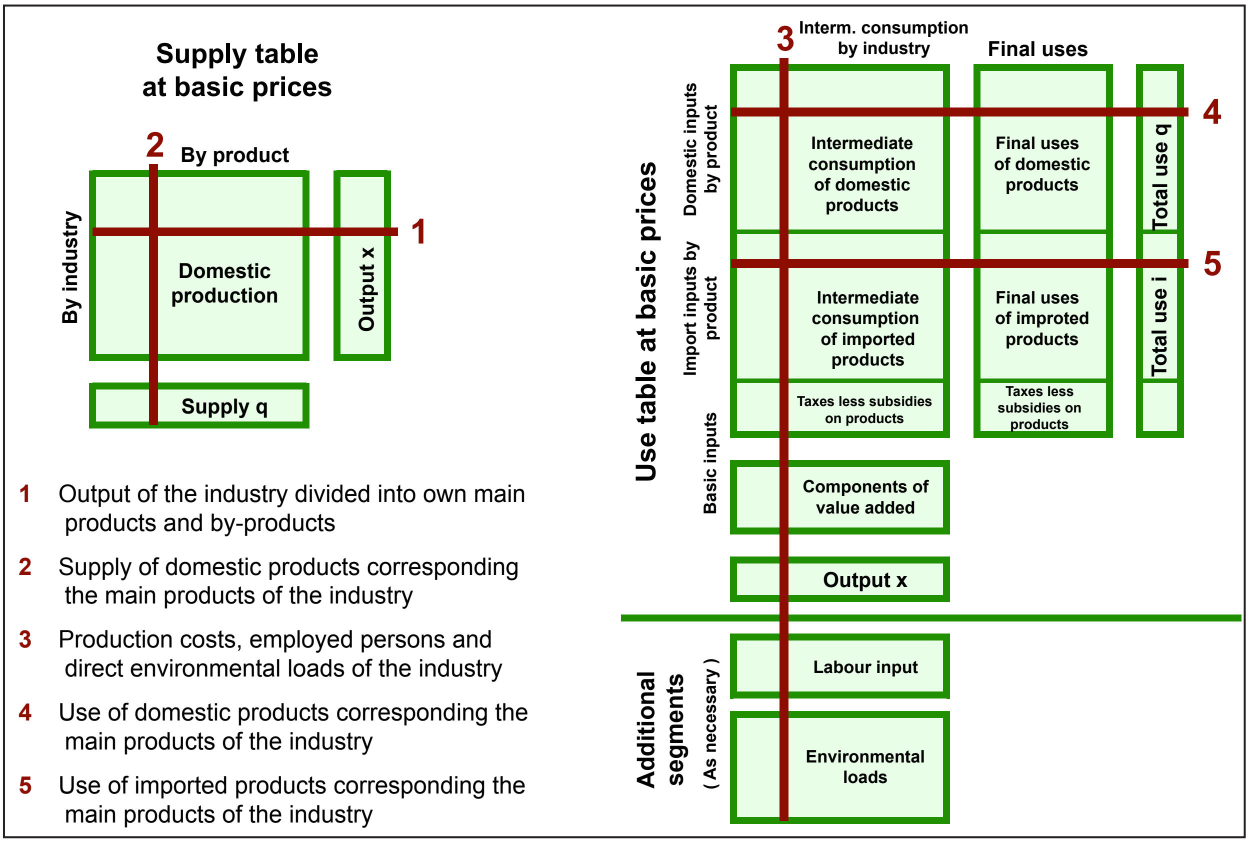

Figure 1. Operating environment of the national economy. Enterprises are divided into establishments, and the establishments are positioned in the operating-environment tables according to the main product of the establishment. An industry is represented by the sum of the economic activities of the establishments manufacturing the same main product. Additional segments can be added to the use table at basic prices as needed, for example labour usage and environmental loads by industry. With the help of additional segments, it is possible to analyse the effects of economic activity, for example, on employment or on emissions causing climate warming.

Table 1. Industries in the operating environment at the general level of the national economy. Domestic production by industry in 2006. The mining and quarrying industries are represented by codes 10, 11, 12, 13 and 14. The corresponding consumer industries are represented by codes 40, 23, 27, 21, 24, 26 and 45. Source: Statistics Finland – supply and use tables for the national economy.

Code	Industries (NACE Rev 1.1 / TOL2002)	Output m€	Value added m€	Gross margin m€	Emplyed 1000 persons
01	Agriculture, hunting and related service activities	4,123	1,196	686	99.0
02	Forestry, logging and related service activities	3,357	2,187	1,786	21.7
05	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing	163	96	82	2.1
10	**Mining of coal and lignite; extraction of peat**	**400**	**139**	**87**	**2.3**
11	**Extraction of crude petroleum and natural gas; incidental service activities**	**0**	**0**	**0**	**0.0**
12	**Mining of uranium and thorium ores**	**0**	**0**	**0**	**0.0**
13	**Mining of metal ores**	**208**	**126**	**96**	**0.6**
14	**Other mining and quarrying**	**835**	**243**	**124**	**3.5**
15	Manufacture of food products and beverages	9,078	2,276	815	38.7
16	Manufacture of tobacco products	0	0	0	0.0
17	Manufacture of textiles	684	281	96	6.5
18	Manufacture of wearing apparel; dressing and dyeing of fur	437	179	62	6.0
19	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear	207	85	29	2.4
20	Manufacture of wood and of products of wood and cork, except furniture	6,419	1,530	532	30.5
21	**Manufacture of pulp, paper and paper products**	**14,608**	**3,917**	**2,105**	**31.3**
22	Publishing, printing and reproduction of recorded media	4,551	1,885	661	31.9
23	**Manufacture of coke, refined petroleum products and nuclear fuels**	**7,168**	**744**	**609**	**2.5**
24	**Manufacture of chemicals and chemical products**	**7,135**	**2,058**	**1,153**	**18.0**
25	Manufacture of rubber and plastic products	2,967	1,085	442	16.2
26	**Manufacture of other non-metallic mineral products**	**2,988**	**1,183**	**504**	**17.3**
27	**Manufacture of basic metals**	**11,633**	**2,297**	**1,434**	**16.6**
28	Manufacture of fabricated metal products, except machinery and equipment	6,656	2,584	875	48.5
29	Manufacture of machinery and equipment n.e.c.	14,463	4,279	1,390	66.1
30	Manufacture of office machinery and computers	92	27	12	0.4
31	Manufacture of electrical machinery and apparatus n.e.c.	3,861	1,256	568	16.2
32	Manufacture of radio, television and communication equipment and apparatus	17,534	6,306	4,130	35.5
33	Manufacture of medical, precision and optical instruments, watches and clocks	2,067	846	308	12.1
34	Manufacture of motor vehicles, trailers and semi-trailers	1,833	390	105	7.4
35	Manufacture of other transport equipment	2,526	688	120	14.6
36	Manufacture of furniture; manufacturing n.e.c.	1,798	618	166	16.6
37	Recycling	424	112	73	1.0
40	**Electricity, gas, steam and hot water supply**	**6,105**	**3,061**	**2,363**	**13.4**
41	Collection, purification and distribution of water	446	291	202	2.5
45	**Construction**	**25,911**	**9,746**	**4,087**	**172.4**
50	Sale, maintenance and repair of motor vehicles; sales of automotive fuel	5,135	2,636	1,203	55.6
51	Wholesale trade and commission trade, except of motor vehicles and motorcycles	15,235	6,539	2,605	96.7
52	Retail trade, except of motor vehicles; repair of personal and household goods	9,304	4,971	1,691	160.2
55	Hotels and restaurants	5,636	2,392	756	77.9
60	Land transport; transport via pipelines	7,874	3,984	1,764	85.6
61	Water transport	2,219	887	436	10.2
62	Air transport	2,135	712	401	5.1
63	Supporting and auxiliary transport activities; activities of travel agencies	8,849	3,154	1,903	30.3
64	Post and telecommunications	7,884	2,962	1,509	45.0
65	Financial intermediation, except insurance and pension funding	4,727	2,959	1,545	27.9
66	Insurance and pension funding, except compulsory social security	1,608	817	359	9.2
67	Activities auxiliary to financial intermediation	1,023	424	246	3.5
70	Real estate activities	24,085	15,947	14,818	39.4
71	Renting of machinery and equipment without operator and of personal and household goods	1,099	504	367	5.0
72	Computer and related activities	5,938	3,108	824	50.9
73	Research and development	1,264	740	75	14.8
74	Other business activities	13,251	7,421	2,035	161.0
75	Public administration and defence; compulsory social security	13,293	7,110	831	174.7
80	Education	9,722	6,923	652	161.1
85	Health and social work	18,250	12,423	1,483	341.2
90	Sewage and refuse disposal, sanitation and similar activities	1,364	618	379	7.2
91	Activities of membership organisation n.e.c.	2,687	1,493	160	41.0
92	Recreational, cultural and sporting activities	4,832	2,451	825	51.8
93	Other service activities	1,072	647	448	15.7
95	Private households with employed persons	124	124	0	8.4
	Total economy in 2006	**329,287**	**143,657**	**63,017**	**2,433.2**

GEOLOGICAL NATURAL RESOURCES IN THE OPERATING ENVIRONMENT OF THE NATIONAL ECONOMY

The extraction of geological natural resources, i.e. the mining and quarrying industries, is represented by Figure 2 with key parameters for the industrial economy and national economy. The product markets are represented by Figure 3.

Mining and quarrying's share of output, GDP and employment for the whole country has been modest. The share of output was 0.35–0.45% for the years 2000–2008, while it was at its highest (0.5%) at the start of the 1980s. At their height, mining and quarrying employed 10,000 people at the start of the 1980s, but the number of employees fell to 5,500 by the mid 1990s. In recent years, the number of employees has been rising thanks to heavy investment in the mining of metal ores.

The importance of mining and quarrying to the regions of Northern and Eastern Finland is significantly greater than to the country as a whole.

The value of domestic production of products obtained from mining and quarrying (product class C according to the CPA2002 standard classification) was around m€ 1,470 for 2006 (the most recent data available), i.e. around 0.4% of the country's total domestic production value. The value of imports for product class C in the same year was around m€ 8,120, and in 2008 it was more than m€ 9,500. Crude petroleum and natural gas along with metal ores and concentrates accounted for a significant share of the value of imports. Product class C accounted for 13% of the country's imports in 2008.

In recent years, the value of imports and, at the same time, domestic consumption has been clearly growing. Due to low export levels, domestic production is in practice dependent on the economic situation of the domestic consumer industries. At the same time, domestic production has to compete with imported products for market share.

Domestic consumption is divided into intermediate consumption, final consumption expenditure and gross capital formation, when expressed using concepts of national accounting. In the mining and quarrying product categories, domestic consumption means in practice intermediate consumption, i.e. domestic product markets between enterprises.

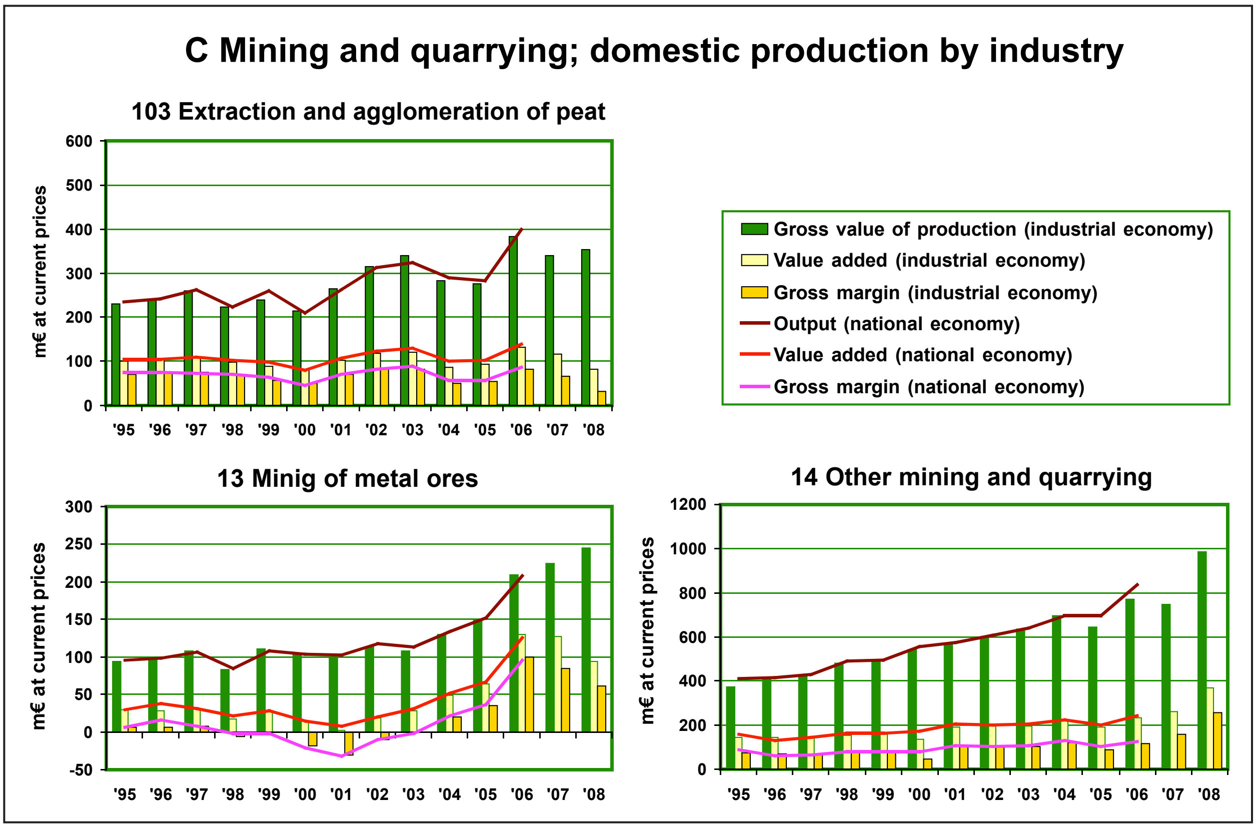

Figure 2. Output, added value and gross margin for the national economy for the years 1995–2006, and gross production value, value added and gross margin for the industrial economy for the years 1995–2008 in the mining and quarrying industries 103, 13 and 14 (according to the NACE Rev. 1.1 / TOL2002 standard classification). Sources: Statistics Finland, 1) regional and industrial statistics on manufacturing, 2) supply and use tables for the national economy.

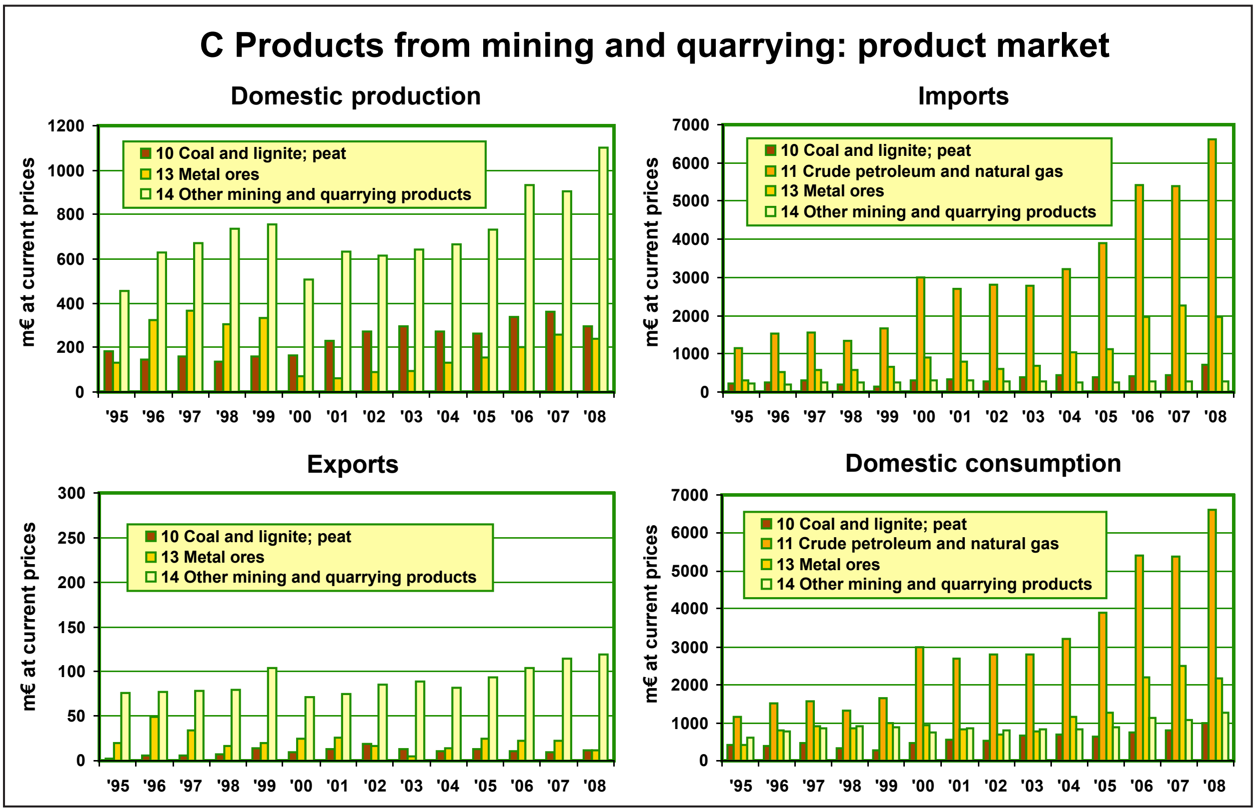

Figure 3. The market for products obtained from mining and quarrying for the years 1995–2008 in product categories 10, 11, 13 and 14 (according to the CPA2002 standard classification). The author has estimated the values for domestic production for the years 2007 and 2008. Domestic consumption is domestic production plus imports minus exports. Sources: 1) Statistics Finland, supply and use tables for the national economy, 2) The Finnish National Board of Customs.

The mining and quarrying products used directly for the years 1995–2008 by the customer industries for domestic and foreign products in mining and quarrying – domestic plus imports – are represented by Figure 3. Even though domestic production goes almost entirely into intermediate consumption, the share of domestic products, in product category 14 alone, of domestic consumption of products is greater than the imported products' share. As measured by monetary value, mining and quarrying products were used most in the refining of petroleum, secondly in the processing of metals and thirdly in energy production. All three industries strongly depend on imports. Mining and quarrying products were most widely used in the manufacture of chemicals and chemical products. When the indirect impacts of customer industries are taken into account, the importance of construction to the mining and quarrying industries grows substantially.

ANALYSIS OF THE ECONOMIC IMPACTS

The impact of the mining and quarrying industries and their customer industries on Finland's national economy has been studied via impact analyses of basic changes in volume and in price derived from input-output theory for the national economy. A basic volume change refers to a market situation where the industry increases the output of its own main products and by-products so that the industry's direct annual production value rises by m€ 10. A basic price change refers to a market situation where the market price for a domestic product increases so that the product's direct annual supply value rises by m€ 10. The impact analyses have been carried out in a use table at basic prices representing the operating environment.

The impact analyses of basic volume and price changes can be carried out for all industry classes in the operating environment and for all domestic and foreign product categories. All key stages of the processing chain can be analysed with the precision desired. The precision of the analysis depends on the division of the industry and product classification used in the operating environment. The impact analysis for basic volume changes proceeds backwards along the processing chain. The impact analysis for basic price changes proceeds forwards along the processing chain. When the same impact analyses are made in several operating environments representing different years, information about the current key cause-effect relationships and their changes in the whole processing chain are obtained.

As a result of the impact analysis, the total impacts of a basic volume change or price change, i.e. the direct and indirect effects on all the industry classes and product categories in the operating environment, are obtained. The generalising and combining of basic changes enables the forecasting and optimisation of situations arising in product markets regarding, for example, impacts on employment, degree of processing or environmental impacts.

A summary of the impact analyses of m€ 10 basic volume changes in the mining and quarrying industries (103 Extraction and agglomeration of peat, 13 Mining of metal ores and 14 Other mining and quarrying) and in seven consumer industries is presented in Figures 4a and 4b. In Figures 4a and 4b, the total impacts are ordered according to their magnitude in the year 2005.

The total impacts of basic volume changes on industry output and domestic production varied in the 2005 operating environment between 1.20 and 1.98 times the basic output change. Domestic production was increased most effectively by extraction and agglomeration of peat and least by manufacture of petroleum products. The size of the impacts was determined to a large extent by how large the value of domestic purchases was in relation to the value of industrial production. In the time-series comparison, the total impacts of metal-ore mining have varied the most.

In the 2005 operating environment, the changes in production volume for the industries 103 Extraction and agglomeration of peat and 45 Construction raised GDP and employment most effectively. The same industries increased imports the least. Manufacture of petroleum products and processing of metals raised GDP the least. The same industries increased imports the most, and also their impact on employment was weak.

When the years 1995, 2000 and 2005 are compared with one another, the impact on employment has changed the most. The trend is clearly downward in all the industries. Even though the total impacts of a basic volume change on GDP remained unchanged relative to the basic change (for example Construction, Extraction and agglomeration of peat in Figure 4a), the impacts on employment diminished when calculated per basic change. The decrease in the impact on employment is explained by a growth in work productivity. The work productivity in extractive industries has increased by automation, larger production units and due to the increased competition in the markets.

The manufacture of petroleum products and the processing of metals were in practice completely dependent on foreign mining and quarrying products. The production of energy required, in addition to the use of peat, significant imports of coal, crude petroleum and natural gas.

As a proportion of output, the industry that processed domestic mining and quarrying products the most is industry 26, which includes the manufacture of glass, engineering ceramics, cement, concrete, concrete products and stone products. The economic importance of paper manufacture and construction to mining and quarrying is based on the high volumes in these industries.

The summary of impact analyses of m€ 10 basic price changes in the product categories 103 Peat, 13 Metal ores and 14 Other mining and quarrying products and in the product categories for the consumer-industry main products is presented in Figure 5. The total impacts of an basic price change on industrial output and domestic production varied in the 2005 operating environment between 1.35–3.15 times the basic price change. Price-change pressures in domestic production were caused the most by the price change for peat and were caused the least by construction work. The size of the impacts was determined to a large extent by how large a part of domestic production of the product class went into intermediate consumption. In the time-series comparison, price-change pressures caused by metal ores varied the most.

Price-change pressures caused by the mining and quarrying product classes were greater than the price-change pressures caused by the product classes for consumer-industry main products. This is natural because the mining and quarrying products are at the beginning of the processing chain. In a similar way, construction work, or more correctly construction on building sites, is at the end of the processing chain, so the price changes for construction are not transferred as such into domestic production. The financing of construction and its impact on the prices of domestic products is not included in the calculations.

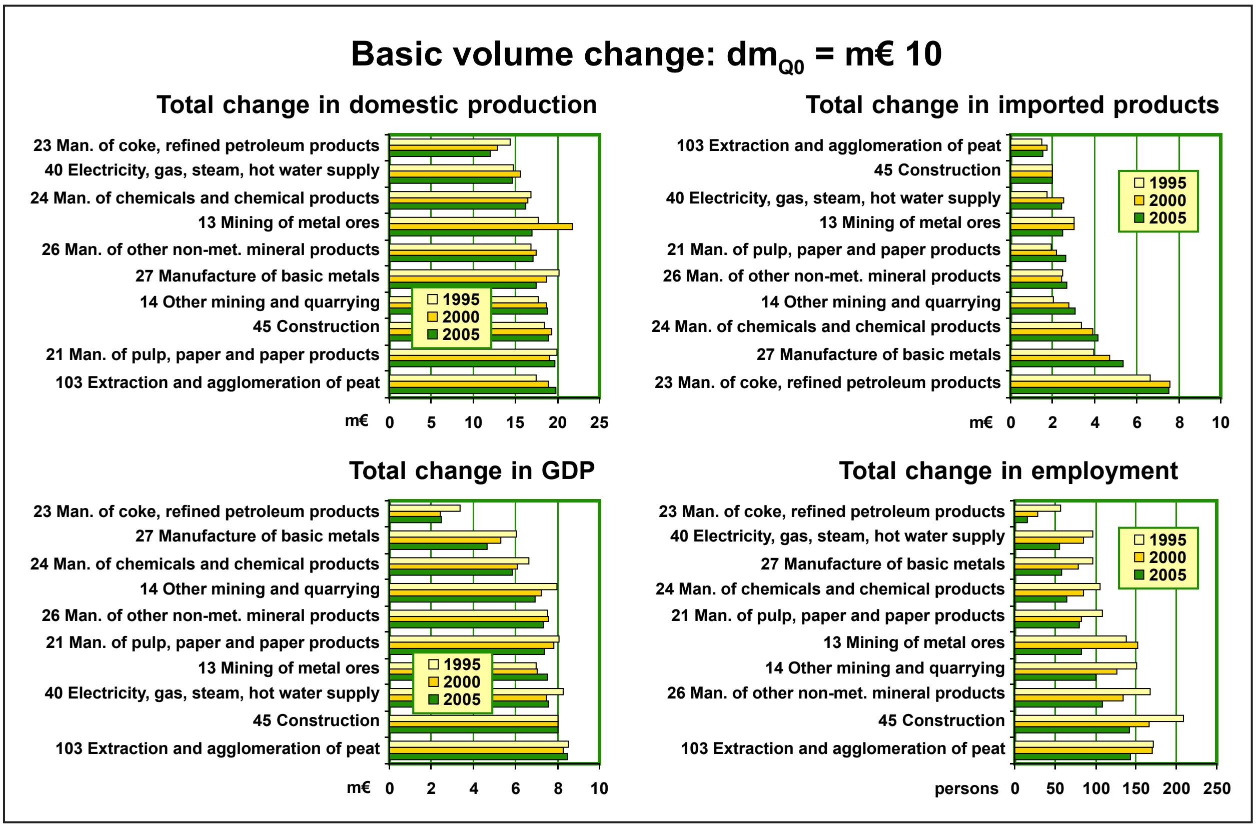

Figure 4a. Summary of the total impacts of a m€ 10 basic volume change on domestic production, imports, GDP and employment for the years 1995, 2000 and 2005. The total impacts for the industries are ordered according to their magnitude in the year 2005.

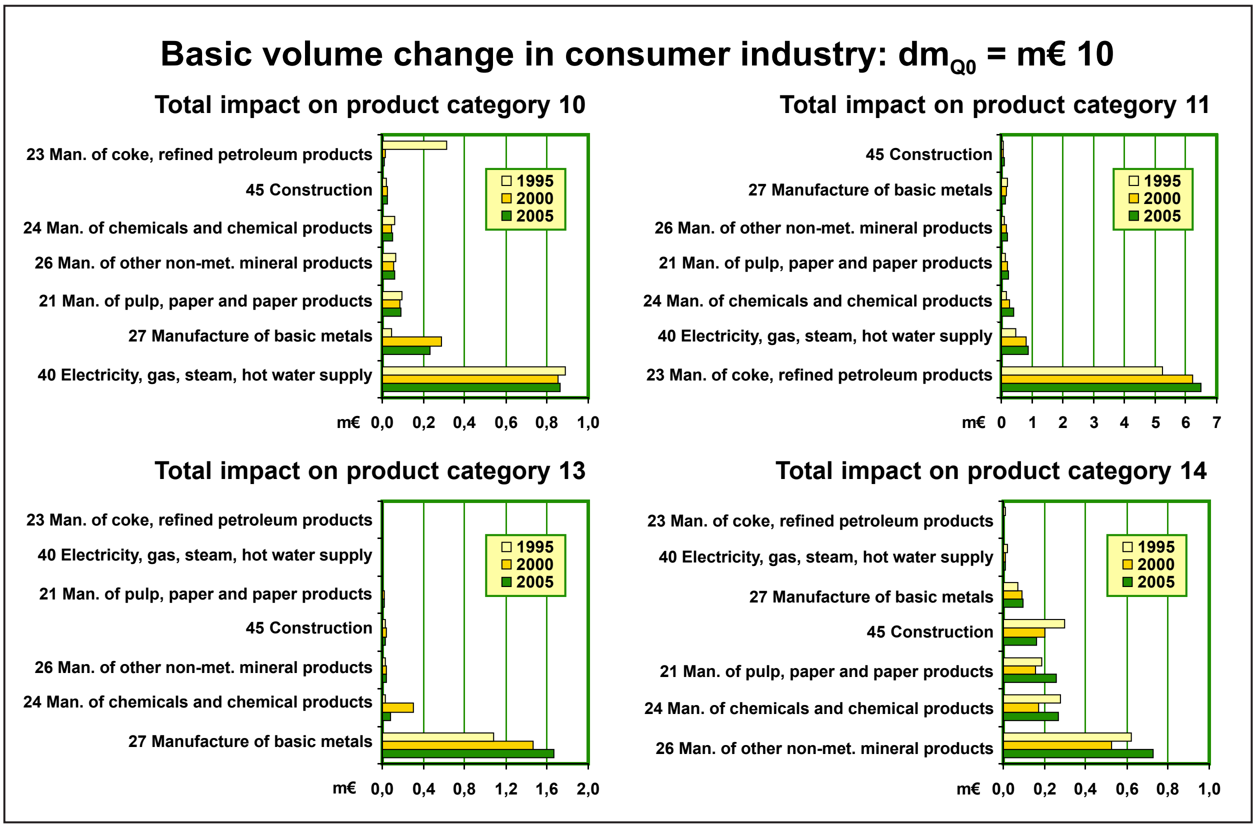

Figure 4b. Summary of the total impacts of a m€ 10 basic volume change in the mining and quarrying customer industries on the mining and quarrying product classes 10, 11, 13 and 14 (total of domestic and imports) for the years 1995, 2000 and 2005. The total impacts for the industries are ordered according to their magnitude in the year 2005.

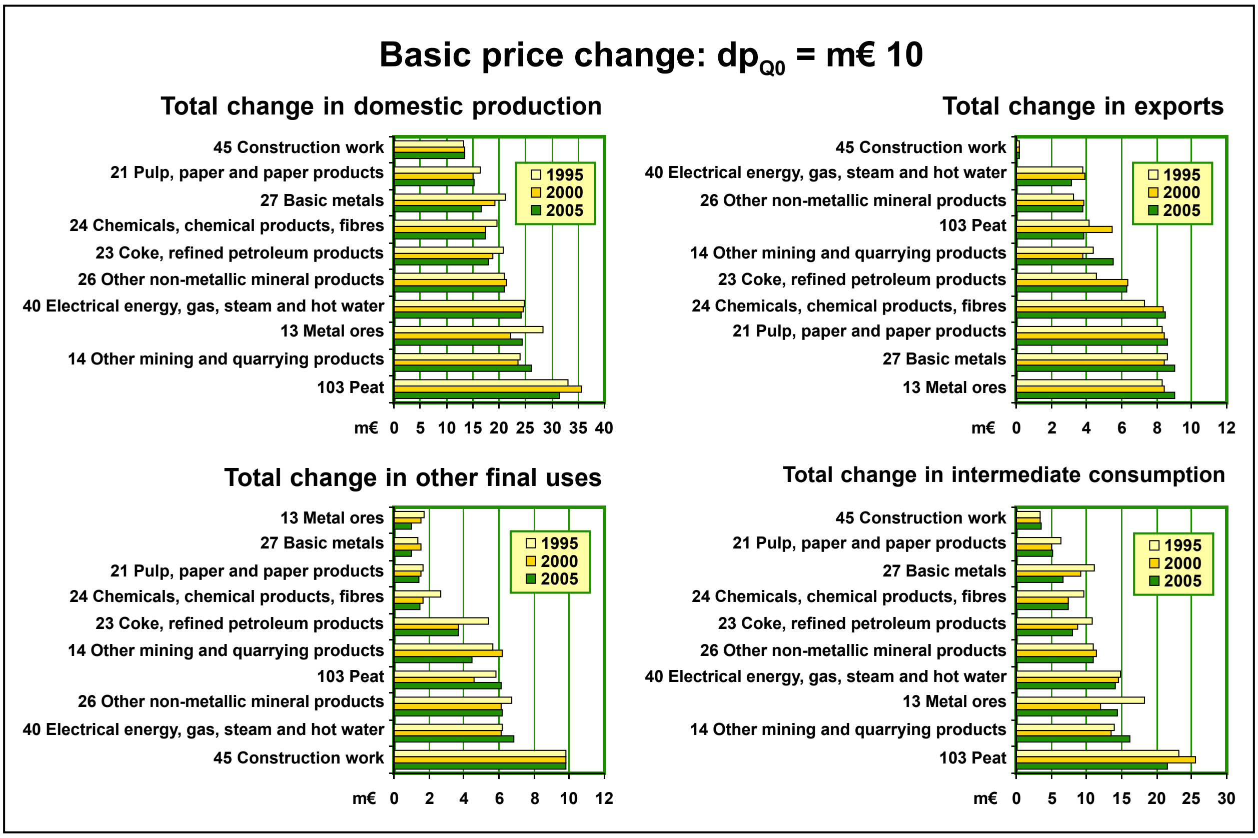

Figure 5. Summary of the total impacts of a m€ 10 basic price change in the domestic product category on domestic production, exports, other final uses and intermediate consumption for the years 1995, 2000 and 2005. In the calculation, only the prices of the domestic products were changed. The total impacts for the product categories are ordered according to their magnitude in the year 2005.

FROM THE OPERATING ENVIRONMENT OF THE NATIONAL ECONOMY TO THE BUSINESS ENVIRONMENT

The national economic study above is transferrable to the corporate level, because the operating environment tables are suitable for corporate business-environment structure modelling. An enterprise "only" needs to know how to position its own establishments and products, its customers and product suppliers in the industry classes and product categories of the operating environment tables. The business environment of an enterprise is a combination of inspection levels of the macro- and microeconomy. The result is numerical data describing the "business as usual" state of the whole national economy, for the year selected, at the industry and product classification level chosen by the enterprise in the supply and use table at basic prices. At the general level of the national economy, numerical data relating to Finland is available for every year from 1995 onwards.

An enterprise operating in the EU area may in practice concentrate directly, in the modelling of its business environment and the provision of numerical data, on industries and product categories of interest to it, because general numerical data at the national economic level is available for all the established EU countries from 1995 onwards. This enables the examination of an enterprise's operations anywhere in the EU. Import and export link the countries being examined to each other.

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2 Research for the energy sector

The use of geoenergy is rapidly growing. GTK models the geoenergy capacity of bedrock for larger building projects. (Photo: Maarit Nousiainen, GTK)

2 RESEARCH FOR THE ENERGY SECTOR

Introduction

As a northern country, Finland is more dependent than average on a constant and safe supply of energy, especially during the cold season. Our metal and paper industry uses abundant amounts of energy compared with other nations in the EU. One half (49%) of our total energy supply goes to industry and some 21% to the heating of domestic and public buildings. Traffic accounts for only 17% of the total energy use.

Finnish public energy policy rests on three fundamental elements: energy, economy and the environment. The most important factor in the energy policy influencing the current operating environment is international cooperation with the aim of reducing greenhouse gas emissions.

In accordance with the public energy policy, GTK's energy research has provided energy-related information as part of Finland's efforts to reduce its dependence on imported fuels and lower the impact of energy production on climate change. Organized around the themes of geoenergy, bioenergy and nuclear power, GTK has sought to apply basic research findings to commercially viable applications.

Finland is one of the first nations that have already made a decision to store used nuclear fuel and waste in the hard crystalline bedrock as a final solution. Here, GTK has acted as an independent expert to develop geodata, particularly on the ultimate placing of the nuclear waste and the evaluation of proposed nuclear power plant sites. In the area of nuclear waste management, the emphasis is on bedrock modelling, studies on filler materials and the chemistry and dispersion of groundwater.

Finland does not have oil reserves, any coal, lignite or natural gas. Our only slowly renewable (subfossil) energy recourse is peat. One third of our land area is covered with shallow peat deposits, which GTK surveys and evaluates. Peat biomass studies pursue two objectives. Testing efforts focus on the cost-effective utilization of peat areas, along with the development of geophysical applications in peat mire mapping and the use of peat as a raw material in the production of biodiesel fuels. The sustainable level of the peat harvesting and environmentally acceptable areas for peat utilization are currently hot topics of environmental debate.

Following the good example of our neighbour, Sweden, Finland has pursued the use of shallow geoenergy, which is basically solar energy that has been stored in the surface part of the ground up to a depth of a few hundred metres. Here, GTK has focused on the development of ways to assess potential shallow geoenergy resources. Joint development projects with companies and other research organizations and service providers on commercial geoenergy applications are emphasised. GTK has carried out extensive work on ground-source heating and cooling at the district level and for large targets such as shopping centres, office buildings, hotels and public buildings.

Finland's geology does not give much possibility to store CO_2 in our hard and crystalline bedrock, as there is not enough pore space. However, GTK has examined the possibilities for carbon dioxide capture and sequestration in geological structures in the Baltic periphery, as well as new innovations in mineralogy and carbonisation. The development of original solutions is emphasized with a view to the emerging international demand for CO_2 capture and sequestration.

Keijo Nenonen

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GEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS IN THE SELECTION AND CHARACTERIZATION OF THE DISPOSAL SITE FOR HIGH-LEVEL NUCLEAR WASTE IN FINLAND

by
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Two power companies, Teollisuuden Voima Oy (TVO) and Fortum Power and Heat Oy, are preparing for the final disposal of spent nuclear fuel deep in the Finnish bedrock. In the initial phase of the site selection process in the late 1970s and early 1980s, the Geological Survey of Finland (GTK) examined the general bedrock factors that would have to be taken into account in connection with final disposal with reference to the international guidelines adapted to Finnish conditions. On the basis of extensive basic research data, it was concluded that it is possible to find a potential disposal site that fulfils the geological safety criteria. In the subsequent site selection survey covering the whole of Finland, carried out by GTK in 1983–1985, 101 potential investigation areas were discovered. Eventually, five areas were selected by TVO for preliminary site investigations: Romuvaara and Veitsivaara in the Archaean basement complex, Kivetty and Syyry in the Proterozoic granitoid area, and Olkiluoto (TVO's NPP site) in the Proterozoic migmatite area. The preliminary site investigations at the selected sites in 1987–1992 comprised deep drillings together with geological, geophysical, hydrogeological and hydrogeochemical investigations. A conceptual geological bedrock model was constructed for each site, including lithology, fracturing, fracture zones and hydrogeological conditions. On the basis of preliminary site investigations, TVO selected Romuvaara, Kivetty and Olkiluoto for detailed site investigations to be carried out during 1993–2000. After the feasibility studies, the island of Hästholmen, where Fortum's Loviisa nuclear power plant is located, was added to the list of potential disposal sites. In the detailed site investigations, additional data on bedrock were gathered, the previous conceptual geological, hydrogeological and hydrogeochemical models were complemented, the rock mechanical properties of the bedrock were examined, and the constructability and the overall suitability of the sites for final disposal in terms of technical and safety aspects was evaluated. After the detailed site investigations, the nuclear waste management company Posiva Oy (jointly owned by TVO and Fortum) proposed Olkiluoto as the site of the final disposal facility. In December 2000, the Government made a decision in principle in favour of the project, and in May 2001, the Parliament ratified the Government's policy decision by 159 votes to 3.

The geological and geophysical investigations at Olkiluoto have resulted in a 3D geological model of the site. The geological model serves as basic background data and a geometrical framework for the models of rock mechanics, hydrogeology and hydrogeochemistry. All these various disciplines have been integrated in Olkiluoto Site Description reports to produce a coherent picture of the site. An underground rock characterisation facility, ONKALO, is currently under construction at Olkiluoto. The aim of ONKALO is to study the bedrock at the final disposal depth for the planning of the repository and for safety assessment, and to test the disposal techniques in real deep-seated conditions. Eventually, it will be part of the repository.

Keywords (GeoRef Thesaurus, AGI): radioactive waste, underground disposal, site exploration, bedrock, geophysical methods, three-dimensional models

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INTRODUCTION

Currently, there are two nuclear power plants in Finland, each having two reactors: Loviisa NPP owned by Fortum Power and Heat Oy and Olkiluoto NPP owned by Teollisuuden Voima Oy (TVO). A third reactor is under construction at Olkiluoto and will be operational in 2012. The present total production is about 2 700 MW, which covers 26% of the electricity consumption in Finland.

The Nuclear Energy Act states that any nuclear waste generated in Finland shall be treated and disposed of in Finland, and no nuclear waste from other countries shall be imported into Finland. Consequently, the power companies, TVO and Fortum, are preparing for the final disposal of the spent nuclear fuel deep in the Finnish bedrock. The nuclear power companies are responsible for practical preparations, research and the final disposal of nuclear waste. In 1995, they established a joint company, Posiva Oy, to take care of the implementation of the nuclear waste management. The Finnish authorities (Ministry of Employment and the Economy and Radiation and Nuclear Safety Authority, STUK) are responsible for the principles governing nuclear waste management, safety criteria and for ensuring that legislation is complied with. Funds for nuclear waste management are collected in advance in the price of nuclear electricity.

The spent fuel from the nuclear reactors is high level radioactive waste. Although its activity rapidly decreases after use, its careful isolation from the living environment is vital. Final disposal in a deep geological repository has been chosen in many countries, including Finland, because it has been considered to be less risky than disposal in interim storages on or near the surface. The bedrock serves as a natural barrier and changes in the conditions of the bedrock are very small and slow compared with the surface conditions. In addition to the crystalline bedrock, for example in Finland and Sweden, salt, clay and tuffaceous formations have been internationally studied.

The Finnish Radiation and Nuclear Safety Authority, STUK, has set requirements related to the host rock for the disposal of spent fuel. These requirements are presented in the YVL Guide 8.4 (STUK 2001). This guide will soon be replaced by the guide STUK-YVL E.5. In the following, the regulatory requirements are presented according to the YVL Guide 8.4. The guide requires that the host rock characteristics are such that they act as a natural barrier and that they are favourable with respect to the long-term performance of engineered barriers. "*Such conditions in the host rock as are of importance to long-term safety shall be stable or predictable up to at least several thousands of years. The range of geological changes which occur thereafter due to e.g. the large scale climate changes, shall be estimable and be considered in the determination of the performance targets for the barriers.*" Features indicating unsuitability of the site are as follows: "*proximity of exploitable natural resources, abnormally high stresses, predictable anomalously high seismic or tectonic activity and exceptionally adverse groundwater characteristics, such as lack of reducing buffering capacity, and high concentrations of substances which might substantially impair the performance of barriers.*" Regarding the host rock, special emphasis should be placed on geological structures. The guide YVL 8.4 (STUK 2001) states "*the structures of the host rock of importance to groundwater flow, rock movements or other factors relevant to long-term safety, shall be defined and classified. The waste canisters shall be emplaced in the repository so that adequate distance remains to such major structures of the host rock which might constitute fast transport pathways for the disposed radioactive substances or otherwise impair the performance of barriers.*"

The final disposal plans in Finland and Sweden are based on the KBS-3 concept developed by Swedish Nuclear Fuel and Waste Management Co (SKB). The basic principle of the concept is to isolate the nuclear waste from living nature or people by using multiple natural and engineered release barriers (Figure 1). The spent nuclear fuel is sealed in copper canisters with a framework of nodular cast iron. Each canister is emplaced in vertical holes in the repository tunnels and then surrounded by bentonite clay (expands when absorbs water). Finally, all the tunnels are sealed with bentonite clay, crushed rock and concrete plugs.

The amount of spent fuel for final disposal will be 6 500 tU, assuming that 5 units are in operation for 60 years. Before final disposal in the geological repository, the spent fuel will be stored under water in the interim stores at the power plant sites for ca. 40 years to reduce the level of radioactivity. Low and intermediate level waste generated in operating and servicing a nuclear power plant has been disposed in shallow repositories since 1992 in Olkiluoto and 1997 in Loviisa.

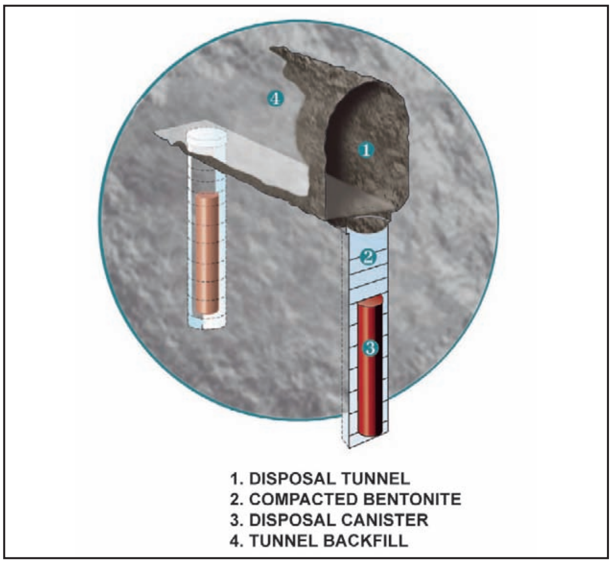

Figure 1. KBS-3 concept for the final disposal of nuclear waste. Figure courtesy of Posiva Oy.

Nuclear waste disposal studies are ongoing in many nuclear power-producing countries, but only in Finland and Sweden has the final disposal site already been selected. The spent nuclear fuel from the Finnish nuclear reactors will be disposed of deep (ca. 400 m) in the bedrock at the Olkiluoto site, where the NPP of TVO is located. Geological Survey of Finland (GTK) has been closely involved in all phases of the site selection process as a consultant for TVO and Posiva. The aim of this paper is to briefly describe the process that has led to the selection of the Olkiluoto site, and to describe the geological and geophysical investigations conducted during the site selection studies, without presenting detailed results. In the final section, the ongoing geological and geophysical investigations at Olkiluoto are briefly discussed.

SITE SELECTION PROCESS

Site selection survey

The first studies on the properties of Finnish bedrock related to the final disposal of nuclear waste were conducted by GTK in the late 1970s and early 1980s. In the initial phase, general bedrock factors were examined with reference to the international guidelines (OECD/NEA 1977) adapted to Finnish conditions (Niini et al. 1982). The structure of the bedrock of Finland was also described (Vuorela & Hakkarainen 1982). On the basis of extensive basic research data, it was concluded that it is possible to find a potential disposal site that fulfils the geological safety criteria, although additional long-term investigations are needed. In terms of international requirements for a nuclear waste disposal site, such as stability, compactness, low hydraulic conductivity and a good sorption capacity, the Finnish crystalline bedrock is generally very good. A disadvantage is the fracturing of the bedrock. Since the only way that the nuclear waste could reach the ground surface from deep disposal is through water flowing in the fractures and fracture zones, the localisation of the water-conductive fractures and fracture zones is important. On the other hand, not all the fractures are water-conductive, and studies have proven that fracturing and water conductivity decreases with depth.

The principles for a research programme for the selection of a disposal site were set in 1982 (Äikäs & Laine 1982). In 1983, the Finnish Government made a decision in principle regarding the aims and timetable for the selection of the final disposal site. The general principle is that the site should be selected by the year 2000 as a result of a stepwise programme of bedrock investigations, involving three stages tied to the following timetable (Teollisuuden Voima Oy 1992a):

- 1983–1985 selection of potentially suitable sites for preliminary investigations;
- 1986–1992 preliminary site investigations at a few candidate sites selected from the above sites;
- 1993–2000 detailed site investigations at a small number of the above sites, thought to be the most suitable on the basis of the preliminary investigations.

The selection of the final disposal site in 2000 was to be followed by a site confirmation phase lasting approximately ten years, so that the construction of the repository could start in 2010 and final disposal in 2020.

The basis of the site selection survey, carried out by GTK in 1983–1985 (Salmi et al. 1985), was the block mosaic structural model of the bedrock, in which fracture zones of different sizes border the bedrock blocks large enough for a disposal site (Figure 2). The basic idea was that possible future bedrock movements and groundwater flow will be concentrated into existing fracture zones, whereas the bedrock blocks in between will remain intact.

The progression of the site selection survey is presented in Figure 2. The nationwide screening resulted in 327 large (100–200 km^2) regional bedrock blocks or target areas surrounded by possible fracture zones obtained from the interpretation of satellite images, aerial photos, topographic maps, and geological and aerogeophysical maps. The main geological criteria in the evaluation of potential areas were the topography, stability of the bedrock, homogeneity of the area, rock type, fracturing, ore potentiality and number of outcrops (Salmi et al. 1985). After the complementary geological studies and evaluation of environmental factors, 62 target areas remained. Inside these large bedrock blocks, 134 potential investigation areas, measuring 5–10 km^2, were identified. After the geological classification, including the field checking, and evaluation of environmental factors, 101 potential areas remained. These areas were classified into four categories on the basis of their suitability for further studies. After the evaluation by authorities, 85 potential investigation areas were left. In addition to this survey, a separate feasibility study of the island of Olkiluoto and its surroundings was carried out (Hakkarainen 1985, Kuivamäki & Vuorela 1985), because of its special position as the location of a nuclear power plant. From these areas, TVO selected five areas in different geological environments for preliminary site investigations: Romuvaara and Veitsivaara in the Archaean basement complex, Kivetty and Syyry in the Proterozoic granitoid area and Olkiluoto in the Proterozoic migmatite area (Figure 2).

Preliminary site investigations

The preliminary site investigations at the five selected sites, carried out in 1987–1992, were aimed at determining the structural setting of each site, the distribution of rock types within them, the location and the geometry of the fracture zones and the hydrogeological conditions of the sites, including the hydraulic parameters of the fracture zones. The purpose of the investigations was to gather a sufficient amount of comparable data from each site, through which the bedrock structure and the groundwater conditions could be modelled and evaluated in terms of the safety of waste disposal, and which would enable the further selection of sites for detailed site investigations. The goal was not to find the bedrock with the “best possible qualities”, but to identify places where the requirements for safe disposal are sufficiently fulfilled, including chemically stable conditions, a small amount of groundwater and slow groundwater flow, and good retardation properties of the bedrock (Teollisuuden Voima Oy 1992a). The investigations were largely focused on the groundwater conditions, fracturing and the overall structure of the bedrock.

The investigations comprised deep drillings together with geological, geophysical, hydrogeological and hydrogeochemical investigations (Teollisuuden Voima Oy 1992a). Six deep drillholes with a depth of 500–1000 m were drilled at each site. The geological investigations consisted of field mappings and drillhole investigations and included determination of the rock types both areally and at depth, mapping of fractures, fracture minerals and fracture zones, defining of the petrographical and geochemical properties of the rock types and minerals, and a study of the ductile deformation history. The state of stress in the rock mass was measured in the drillholes and its significance was evaluated.

The geophysical investigations comprised measurements from an aircraft, on the ground surface and in the drillholes. The airborne surveys were carried out using magnetic, electromagnetic and radiometric methods. The applied ground methods included systematic profiling with VLF or HLEM as well as magnetic measurements at three sites. Additional ground surveys, depending on the conditions and needs at each site, included seismic refraction and gravimetric surveys, electrical and electromagnetic soundings and horizontal seismic profiling (HSP). Two categories of geophysical methods for drillholes were used, based on their investigation volume. A set of standard methods, imaging only the drillhole wall or its immediate surroundings included magnetic, electric (normal array or Wenner), radiometric γ–γ, natural γ, neutron-neutron, seismic P-wave velocity and hole calliper. These surveys provide a detailed image of the lithology and fracturing along the drillholes. The drillhole applications imaging a larger volume around the drillholes comprise vertical seismic profiling (VSP) and drillhole radar (single-hole profiling and VRP) (Teollisuuden Voima Oy 1992a).

In the hydrogeological investigations, the conductivity, hydraulic head and the hydraulic connections of the groundwater were mapped and measured. Hydrogeochemical investigations included determination of the chemical composition of the groundwater and its variation areally and at depth, and studies on the residence times, origin and the development of its composition.

On the basis of all these investigations, a conceptual geological bedrock model was constructed for each site, including lithology, fracturing, fracture zones and hydrogeological conditions, the main emphasis being on localizing fracture zones and description of their properties, especially hydraulic conductivity (see e.g. Saksa et al. 1992, Saksa et al. 1993). In the modelling of the fracture zones, an approach was adopted that the fracture zones are planar and that the structural properties continue linearly from one point to another. Modelling of the geometry of the fracture zones was largely based on geophysical data. The conceptual bedrock model was then used as a basis for the conceptual groundwater flow models.

On the basis of preliminary site investigations, TVO selected Romuvaara, Kivetty and Olkiluoto for detailed site investigations during 1993–2000, and the selection was approved by the authorities. The reasons for selecting these three sites were that there were less uncertainties in the bedrock models and the explorability of these sites was considered more favourable than that of the two other sites (Teollisuuden Voima Oy 1992b).

Until 1996, the spent fuel from Fortum's Loviisa NPP was transported to the Soviet Union and later to Russia for disposal. However, after the Nuclear Energy Act forbade the return of spent fuel, the spent fuel from the Loviisa plant has also had to be disposed of in Finland. In 1997, following the feasibility studies in 1995–1996, Posiva added the island of Hästholmen, where the Loviisa NPP is located, to the list of potential disposal sites (Posiva Oy 1996). The same investigation programme that was carried out at other sites was done also there.

A complementary investigation programme on the potentiality of the basic rock types for final disposal was carried out in 1991–1993. The study included an inventory of the basic plutonic and volcanic rocks in Finland and an evaluation of their properties. The conclusion was that the properties of these rock types are not more favourable than of those in the felsic rock types within the selected sites (Teollisuuden Voima Oy 1993). Moreover, the large basic rock formations often contain ore mineralizations, making future human intrusion possible.

Detailed site investigations

The aim of the detailed site investigations in 1993–2000 was to gather additional data on bedrock, verify and complement the conceptual geological, hydrogeological and hydrogeochemical models constructed in the preliminary site investigations, evaluate the rock mechanical properties of the bedrock and evaluate the constructability and the overall suitability of the sites for final disposal in terms of technical and safety aspects (Anttila et al. 1999a–d). The investigations included the drilling of four to six additional drillholes and petrographical and geochemical investigations of the drill core samples. Studies of fracture minerals were carried out. Geological investigations also included the excavation and mapping of two investigation trenches with a length of 150–400 m at each site to obtain more bedrock and fracture data in areas with no outcrops. Groundwater sampling continued and hydraulic conductivities and hydraulic heads were measured in packed-off drillhole sections. A new Posiva flowmeter for difference flow and transverse flow measurements was used in the drillholes. To investigate the current movements of the bedrock, each site was equipped with an integrated GPS monitoring system.

The geophysical surveys focused on drillholes and their immediate surroundings, with a goal to enhance the precision and supplement the bedrock data. Fracturing was studied with different drillhole wall scanning methods, such as a borehole-TV, dipmeter and acoustic televiewer. Larger volumes around the drillholes were surveyed by drillhole radar with a directional antenna and by VSP with a 3-component geophone system and an improved processing and interpretation technique. Furthermore, the mise-à-la-masse method was applied to correlate the fracture zones between drillholes and from drillholes to the ground surface. From the ground surface, electromagnetic soundings were carried out to map the distribution of deep saline groundwater and the location of electrically conductive fracture zones.

Modelling during the detailed site investigations mainly focused on the characterization of the water-conductive fracture zones and on the interpretation of their geometry (see Saksa et al. 1998). As in the case of preliminary site investigations, the connection of the fracture zones from one drillhole to another and from the surface to the drillhole was based on the assumption of the planar continuity of the fracture zones. The bedrock model was constructed using the geological ROCK-CAD modelling system. Summaries of the investigations during the detailed site investigations have been presented by Anttila et al. (1999a, 1999b, 1999c, 1999d).

On the basis of the preliminary and detailed site investigations, Posiva proposed Olkiluoto as the site for the final disposal facility. In December 2000, the Government made a decision in principle in favour of the project, and in May 2001, the Parliament ratified the Government's policy decision by 159 votes to 3. From then on, the investigations have solely been focused on Olkiluoto.

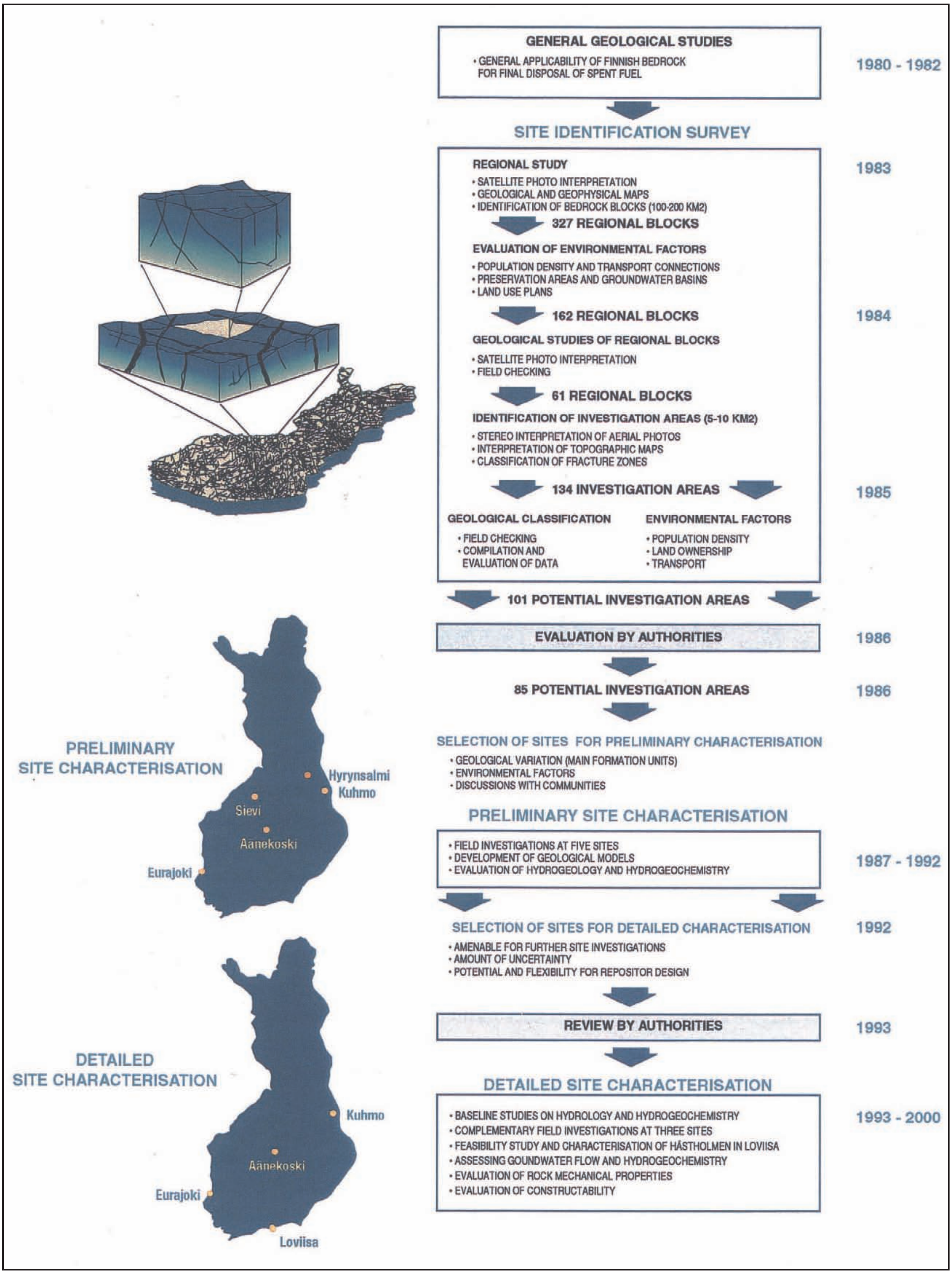

Figure 2. Flow chart of the site selection process (Anttila et al. 1999a–d).

SITE CONFIRMATION PHASE

The geological and geophysical studies at Olkiluoto already started in the early 1980s in connection with the planning of the repository for low- and intermediate-level waste (Äikäs 1986). The repository was constructed in the late 1980s and commenced operation in 1992. Since the beginning of the preliminary site investigations in 1988, geological mapping of the outcrops has been carried out on several occasions, consisting of mapping of lithologies, of structures of the ductile deformation (foliation, fold axis, axial planes, lineation), and of structures of brittle deformation (fractures and brittle deformation zones). Since Olkiluoto Island is poorly exposed, with the area of the mapped outcrops representing only ca. 4% of the total area, outcrop mappings have been supplemented by detailed mapping of 16 excavated and cleaned investigation trenches (Figure 3) in areas with few or no outcrops (for references, see Aaltonen et al. 2010). A total of ca. 18 000 tectonic measurements have been made, both on outcrops and in the investigation trenches. During the mappings, the rock types were determined macroscopically from the exposed outcrop surface. At the same time, samples were taken for further microscopic, geochemical and petrophysical analysis of the rock types.

Figure 3. Excavation and mapping of an investigation trench at Olkiluoto. Photo: Ismo Aaltonen, Posiva Oy.

There are currently 53 deep drillholes, which, with the exception of four drillholes, all are inclined. The lengths of the drillholes vary from 125 to 1 050 metres. The drill cores were first logged onsite (see Aaltonen et al. 2010 for references) and later in detail, including petrographic, litogeochemical and petrographic investigations of the drill core samples (see the list of reports in Aaltonen et al. 2010) The petrographic and litogeochemical studies of ca. 250 core samples have been summarised by Kärki & Paulamäki (2006).

Basic structural data on both ductile and brittle deformations have been gathered from the drillholes. Small-scale fold axes, axial planes and lineations have also been observed. In general, OPTV drillhole images and WellCAD software have been used for foliation orientation measurements, and in some cases also for measurements from the oriented core. In the drillholes, a total of ca. 20 000 observations and measurements have been conducted on ductile elements.

So far, ca. 66 500 fractures have been mapped and characterised from the drill cores. All fractures that carry imprints of tectonic movements, i.e. slickensides, were studied in order to obtain characteristics of the fracture surfaces such as shape, indicative traces of movement, orientation and kinematics (fault vector direction, direction of slip). A total of ca. 2000 fault plane and fault vector directions have been measured. On the basis of fault vector orientation, the fractures were classified into groups, the members of which have a possibility to originate from one, single event of faulting.

In addition to the study of slickenside fractures, the sections of increased fracturing have been mapped and subdivided into brittle joint zone intersections and brittle fault zone intersections, according to the classification procedure for deformation zone intersections at Olkiluoto (Milnes et al. 2007). Brittle joint zone intersections are composed of fractures that do not show visible traces of movement, whereas in brittle fault zone intersections, faulting and cataclastic features are obvious, although in some cases they may show only a few slickensided fractures. Rock type, fracture types, orientation of fractures and fracture sets, the relation of fractures to ductile features (foliation, shearing), cataclastic features, breccias, and fault gouges have been observed in each brittle fault zone and joint zone intersection. All these fracture data have played a key role in preparing the brittle deformation model of the site.

During the Site Confirmation Phase, a wide range of geophysical applications were used at Olkiluoto, including a supplementary airborne survey with 50 m line spacing (Figure 4) (Leväniemi 2008, Kurimo 2009), as well as ground and drillhole surveying. A summary of the investigations with the original references is presented in Aaltonen et al. (2010).

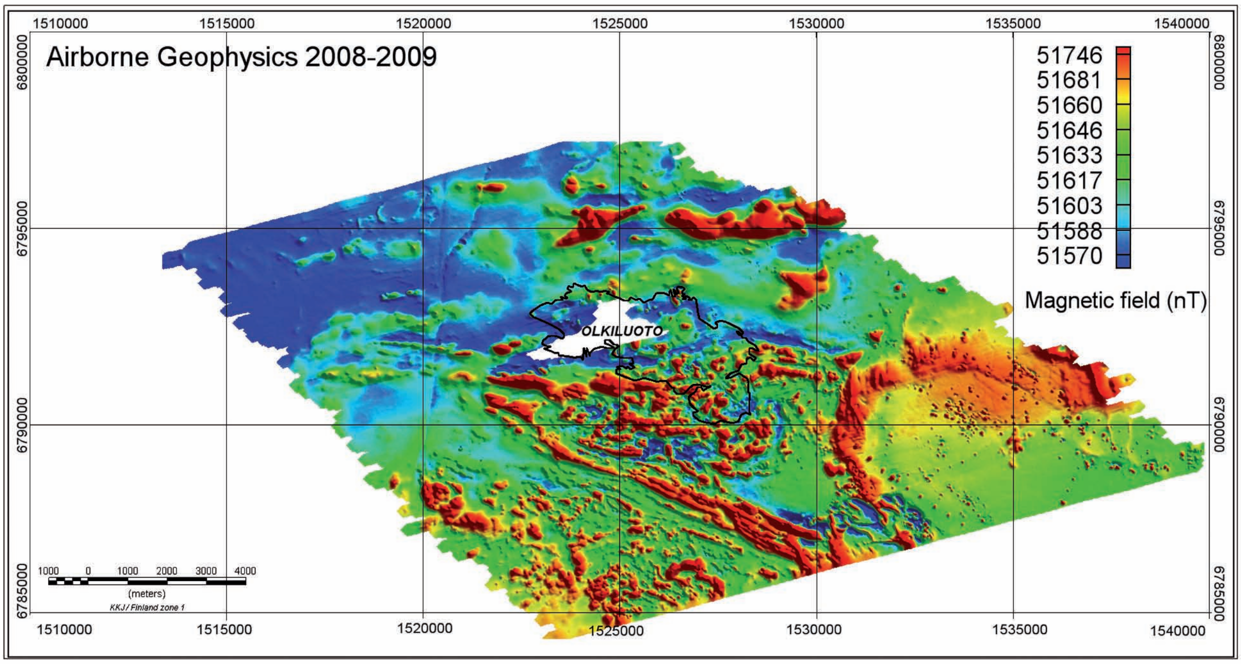

Figure 4. Aeromagnetic map of the Olkiluoto area, total field (Kurimo 2009).

Geophysical ground surveys have comprised magnetic and horizontal-loop EM measurements, supplemented by measurements in the south-eastern area. Furthermore, seismic refraction soundings have been carried out in several separate campaigns. Ground penetrating radar soundings and interpretations have been conducted along three investigation trenches as well as in the eastern part of the area to study, e.g., possible postglacial faults. Supplementary SAMPO Gefinex wide-band electromagnetic soundings were carried out at Olkiluoto in 2002, 2004 and 2007. The data have been used for mapping deep saline groundwaters, but they also provide information on sulphide minerals and possible deformation zones related to sulphide-rich locations. A 3D seismic pilot study was carried out in the central part of Olkiluoto in 2006 (Juhlin & Cosma 2007). As a follow-up to the work carried out in 2006, a new 3D seismic survey was conducted in 2007, focusing on the eastern part of the site (Cosma et al. 2008). In 2008, additional seismic information was gathered from Olkiluoto and its surroundings, when three HIRE vibroseismic lines, totalling 31.1 km, were surveyed along the nearby roads (Kukkonen et al. 2010). The HIRE results revealed a number of previously unknown features deep in the bedrock of Olkiluoto (Figure 5). The most important result is the occurrence of very strong subhorizontal or gently dipping reflectors at a depth of 2–3 km, typically 500–1000 m thick and very continuous laterally. These reflectors are most probably related to 1 270–1 250 Ma old olivine diabase dyke swarms or sills, widely occurring east and northeast of Olkiluoto. The HIRE results also revealed a number of moderately or gently dipping reflectors, partly supporting the existence of known deformation zones. Some reflectors have provided totally new information on the geometry of probable deformation zones.

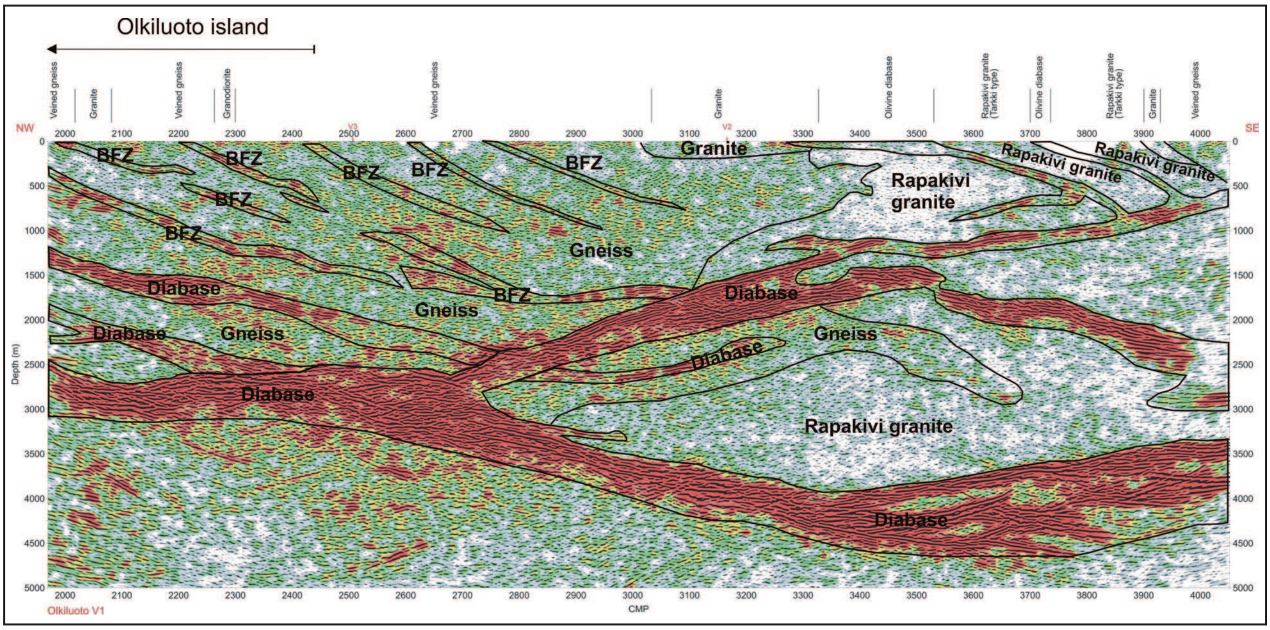

Figure 5. Migrated NMO section of HIRE line V1 and its interpretation (Kukkonen et al. 2010). BFZ = brittle fault zone.

Single-hole geophysical loggings have been systematically conducted in all available drillholes, a process already initiated during the preliminary site investigations. In most cases, the data gathered have comprise different acoustic (full waveform + tube-wave registration), radiometric (natural gamma radiation, gamma-gamma density, neutron-neutron), electrical (long normal, short normal/wenner, single-point resistance), magnetic, thermal and caliper data, as well as optical imaging of the drillhole wall. The acoustic, radiometric, and electric parameters have mainly been used in determining the locations of the deformation zones (however, sulphides have a strong effect on electrical measurements). The magnetic data have mainly been used in locating ferrimagnetic, pyrrhotite-rich sections.

The spectral gamma method has been used in mapping alteration zones, but the results also seem to have a strong petrological correlation. Mise-à-la-masse surveys have been used in mapping fracture zones, but they also give information on sulphide minerals and possible deformation zones related to sulphide-rich locations (Ahokas & Paananen 2010). VSP surveys have been carried out in 14 drillholes starting from 1990. Furthermore, some horizontal seismic profiling (HSP) and crosshole surveys, as well as Walkaway Vertical Seismic Profiling (WVSP), have been carried out. Electromagnetic FARA radiowave imaging has been performed in Olkiluoto between drillholes OL-KR4 and OL-KR10, and between drillholes OL-KR40 and OL-KR45 (Korpisalo et al. 2008, Korpisalo & Niemelä 2010).

The geological and geophysical investigations have resulted in a 3D geological model of the Olkiluoto site. The geological model consists of four sub-models: a lithological model, a ductile deformation model, a brittle deformation model and an alteration model (Paulamäki et al. 2006, Mattila et al. 2008, Aaltonen et al. 2010). The lithological model presents the general lithological properties of definite rock volumes or units that can be defined on the basis the migmatite structures, textures and modal compositions. The model aims to describe the spatial distribution of genetically related bedrock units that have sufficiently constant properties. The ductile deformation model describes the products of polyphasic ductile deformation, which defines the geometrical properties of lithological units presented in the lithological model. Moreover, structures of ductile deformation are important precursors for subsequent brittle deformation. The brittle deformation model describes the products of multiple phases of brittle deformation, fault zones and other fractures. The model shows the localities and orientations of specific brittle fault structures and aims to illustrate all significant fractures created by the long-term evolution of brittle deformation. The aim of the alteration model is to present the shapes, volumes and types of altered bedrock, and it includes products of retrograde metamorphism, hydrothermal alteration and subsequent low-temperature weathering, which have affected the lithological units. Due to these processes, the physical properties of altered rocks may be drastically different compared to those of primary, fresh rocks. Thus, the degree and type of alteration are important parameters in the evaluation of, for instance, the mechanical strength of the rocks.

This subdivision is artificial and made just for convenience of description, because all these submodels are more or less connected to each other. The geological model serves as basic background data and a geometrical framework for the models of rock mechanics (Hudson et al. 2008), hydrogeology (Vaittinen et al. 2009) and hydrogeochemistry (Posiva Oy 2009) (Figure 6). All these various disciplines have been integrated in the Olkiluoto Site Description reports (Andersson et al. 2007, Posiva Oy 2009) to produce a coherent picture of the site. The next Olkiluoto Site Description report, which will be published in 2011, will be the final one to combine all site knowledge and understanding for the construction licence application.

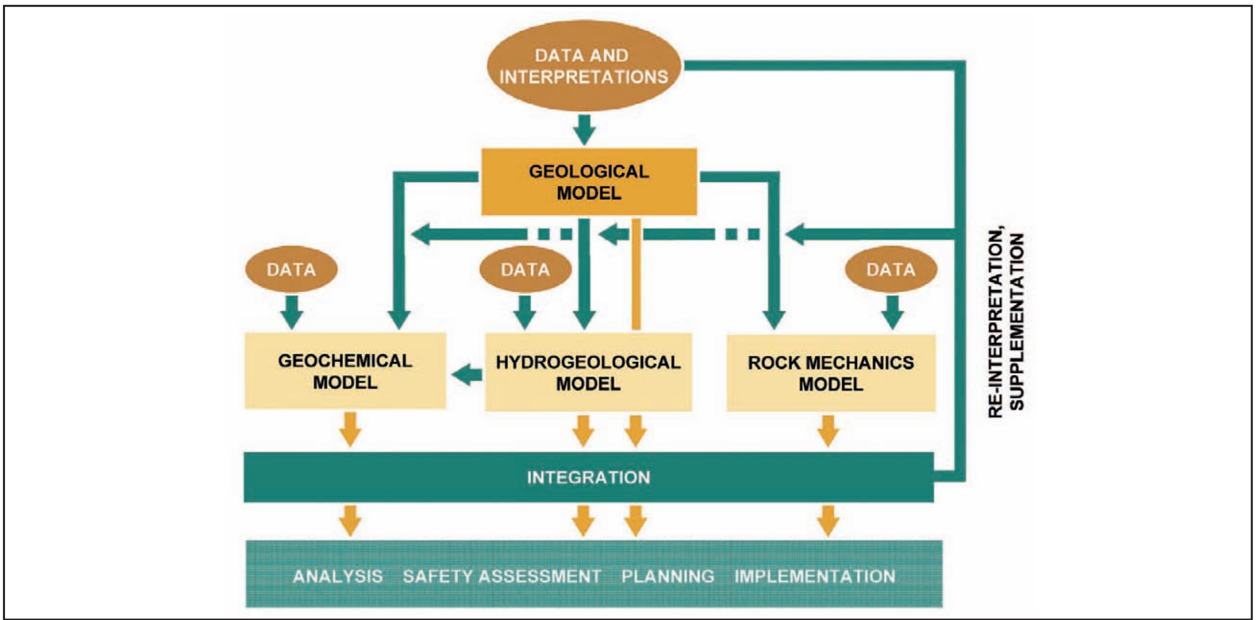

Figure 6. Flow chart of the interaction between geological model and other disciplines. Figure courtesy of Posiva Oy.

An underground rock characterisation facility, ONKALO, currently under construction at Olkiluoto, is an important part of the site investigations. When completed in 2010, ONKALO will be composed of an access tunnel, approximately 5.5 km in length, to the depth of 520 m, ventilation shafts and exploratory tunnels, the main characterisation level being at the depth of 420 m (Figure 7). Excavation of the ONKALO access tunnel started in September 2004 and in January 2010 it had reached a length of ca. 4 100 metres, corresponding to a depth of ca. 390 metres below sea level. The purpose of ONKALO is to study the bedrock of the site at the final disposal depth for the planning of the repository and for safety assessment, and to test the disposal techniques in real deep-seated conditions (Posiva Oy 2003). Eventually, it will be part of the repository.

Geological mapping of the ONKALO tunnel has been performed systematically in increments of 5 meters, corresponding to the length of one excavation round. The geological mapping is divided into three phases: round mapping, systematic mapping and supplementary studies (Engström & Kemppainen 2008). The purpose of the round mapping, performed soon after each quarrying round, is to obtain geological data for the geotechnical estimation of the rock mass. The mapping includes observations of the main rock type, main fracture orientations, and parameters for rock mechanical Q-classification. Systematic mapping, performed tens to hundreds of metres behind the ongoing quarrying area, includes, in addition to detailed fracture mapping, observations of rock types and structures of ductile deformation (foliation, fold axis, axial planes, lineation). Supplementary studies include the identification of long, tunnel cross-cutting fractures and deformation zone intersections (both brittle and ductile), and the mapping of water leakage.

The results of the geological mapping of the ONKALO tunnel are reported as geological outcomes, each covering a section of the tunnel ranging from 150 to 400 meters in length. The outcomes of the tunnel survey have been used in the construction of the geological models. The currently reported outcomes correspond to tunnel section 0- 990 m (Nordbäck et al. 2008).

One important activity using the Olkiluoto site models is to predict the properties of the bedrock that will be encountered during the construction of the ONKALO tunnel. Furthermore, these predictions will be compared with the outcome following the mapping of the tunnel. The results of these so-called *prediction-outcome* studies (Andersson et al. 2005) will be then utilised for the revision and development of the site descriptive models and applied modelling methodologies.

Twelve pilot drillholes have been drilled and five more will be drilled in selected tunnel sections before the excavation in order to verify the bedrock properties and, especially, to locate the water-conducting brittle deformation zones. The studies performed in the pilot holes include geology, geophysics, hydrogeology and hydrogeochemistry. Long-term research is going on in the characterisation niches, i.e., short tunnels proceeding from the main access tunnel. In the niches, the properties of the surrounding rock are being investigated and hydrogeological and hydrogeochemical conditions monitored. Long characterisation drillholes will be drilled from the niches to the final disposal depth.

Posiva has set up the Rock Suitability Criteria (RSC) programme to develop a classification scheme both to be applied to the repository layout design and to define suitable rock volumes for the deposition hole. The classification scheme considers both long-term safety and engineering aspects. The practical criteria, based on current site data and models, are defined for different stages, including the repository, panel, tunnel and deposition hole stages (Hellä et al. 2009). The RSC programme is responsible for defining the host rock requirements and setting up a procedure for *in situ* verification that these requirements are met.

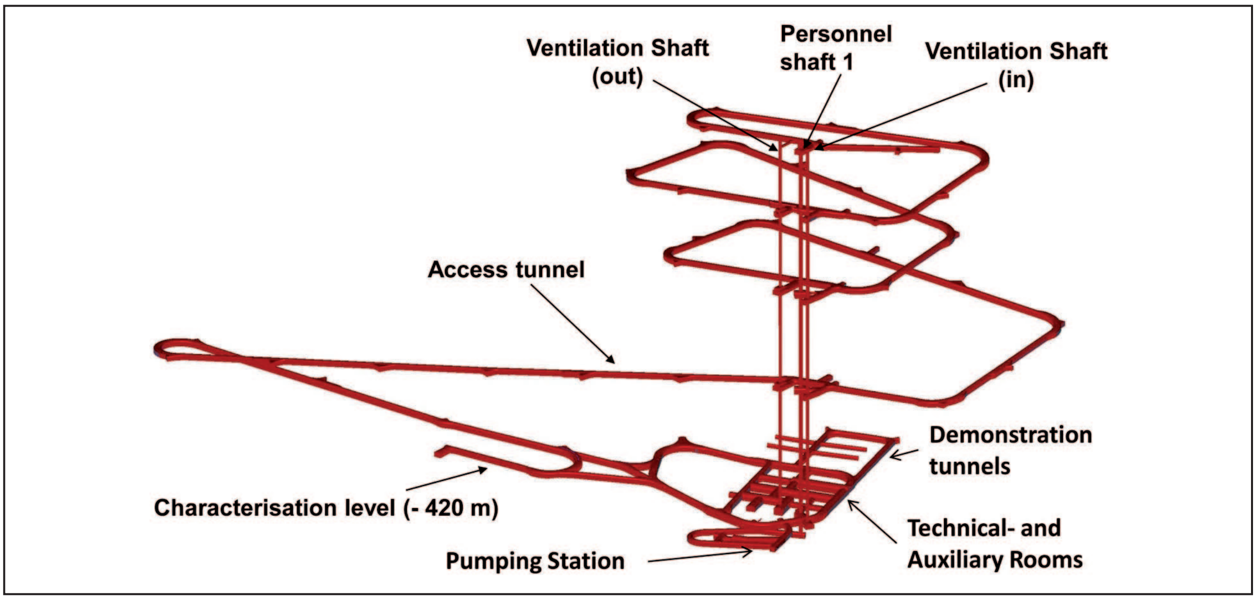

Figure 7. ONKALO layout. Figure courtesy of Posiva Oy.

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GEOLOGICAL SAFETY ASPECTS OF NUCLEAR WASTE DISPOSAL IN FINLAND

by
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The management of nuclear waste from Finnish power companies is based on the final geological disposal of encapsulated spent fuel at a depth of several hundreds of metres in the crystalline bedrock. Permission for the licence requires that the safety of disposal is demonstrated in a safety case showing that processes, events and future scenarios possibly affecting the performance of the deep repository are appropriately understood. Many of the safety-related issues are geological in nature. The Precambrian bedrock of Finland has a long history, even if compared with the time span considered for nuclear waste disposal, but the northern location calls for a detailed study of the processes related to Quaternary glaciations. This was manifested in an extensive international permafrost study in northern Canada, coordinated by GTK. Hydrogeology and the common existence of saline waters deep in the bedrock have also been targets of extensive studies, because water chemistry affects the chemical stability of the repository near-field, as well as radionuclide transport. The Palmottu natural analogue study was one of the international high-priority natural analogue studies in which transport phenomena were explored in a natural geological system. Currently, deep biosphere processes are being investigated in support of the safety of nuclear waste disposal.

Keywords (GeoRef Thesaurus, AGI): radioactive waste, underground disposal, bedrock, safety, natural analogs, radioactive isotopes, hydrochemistry, permafrost, biosphere, Finland

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INTRODUCTION

Energy production in Finland is based on a variety of sources, ranging from purely renewable bio-energy to imported fossil carbon and hydrocarbon resources. Nuclear power has been a substantial component of the energy source selection during the last three decades, providing a continuous supply of carbon-neutral base energy for society. However, the permission for and introduction of nuclear power plants included the requirement for safe management of radioactive wastes produced by the nuclear power industry. Geological disposal in the Finnish bedrock remained the most realistic option after the 1994 amendment to the Finnish Nuclear Energy Act, stipulating that radioactive wastes must not cross Finnish borders.

Operative responsibility for nuclear waste management in Finland lies with the nuclear energy industry, while the regulatory authorities and other decision makers also use independent information from different research organisations. The Geological Survey of Finland (GTK) has been one of the major actors in supporting the development of a safe geological disposal concept since the first power plant started operation in 1977. Site selection and site investigation studies (Paulamäki et al., this volume) have directly supported the operative programme of the power and waste management companies, while research conducted by means of public sector funding has focused more on general aspects of the long-term safety of geological disposal in crystalline rock. Originally, public sector financing was mainly based on annual governmental grants from the Ministry of Trade and Industry, and research on contracts with the Radiation and Nuclear Safety Authority of Finland (STUK), but since 1987 centralised research programmes have been organised (e.g. Rasilainen 2006). The current national research programme for nuclear waste management (KYT2010) will be completed by the end of 2010. An important aspect of the current and future public sector research programmes is also to educate and transmit knowledge to future generations.

The nuclear waste disposal concept planned to be applied in Finland is in principle the same as the Swedish KBS-3 solution, which relies on the protection provided by technical barriers (copper-iron canisters, bentonite buffers), the isolating and transport-resistant characteristics of the low-porosity Precambrian crystalline rock and on the stable geological conditions of the Fennoscandian Shield. The safety and performance of the multi-barrier disposal system is a subject of continuous evaluation, manifested in a series of reports by nuclear power producers and the waste management organisation Posiva Oy (e.g. Vieno & Nordman 1999 and references therein). The next major step in the progress of nuclear waste management in Finland is the construction licence application, including the safety case documentation. The safety case requires scientific and technical understanding of the geological and geochemical features, events and processes around a deep geological repository on a time scale of hundreds of thousands of years in the future.

GENERAL STABILITY OF CONTINENTAL CRYSTALLINE BEDROCK

The bedrock planned for nuclear waste disposal in Finland was formed in the Palaeoproterozoic Svecofennian orogeny about 1800 million years (1.8 Ga) ago. During the Mesoproterozoic rifting, evidently related to the Svekonorwegian orogeny (1.25–0.9 Ga ago), plate tectonic forces moved the Fennoscandian Shield as a part of the Baltica plate from the mid-latitudes towards the South Pole. Mesoproterozoic sedimentary rocks, cut by younger diabases, are preserved in depressions in and around the Bothnian bay. The accumulation of sediments caused an additional load to the bedrock, while later Neoproterozoic weathering and erosion had the opposite effect. Remnants of kaolinitized crust indicating strong weathering in low-latitude tropical conditions are occasionally preserved in the Finnish bedrock. In addition to the continuous plate tectonic horizontal movements and collision of plates, as well as the vertical tectonic load variation due to sedimentation and erosion, continents have been subjected to the repeated accumulation and melting of continental ice. The most severe glaciation in the geological history of the Earth may have been the Neoproterozoic "Snowball Earth" about 600–800 million years ago, when the Baltica continent situated in southern mid-latitudes was covered by a kilometres-thick ice layer (Hyde et al. 2000).

In the Tertiary, the opening of the North Atlantic and collision of the African and Eurasian plates gradually settled the continents in their present position. Widening of the Atlantic along the mid-oceanic ridge is an on-going process affecting the present stress conditions of the Fennoscandian shield. Tertiary tectonic uplift has raised the Caledonian mountains by more than one kilometre, also affecting the topography of Finnish Lapland.

The time scale considered in the context of nuclear waste management is short compared to that of the geological history of the Fennoscandian shield. Consequently, the geological history of the last period, the Quaternary, including the time of extensive, repeated glaciations of the Fennoscandian Shield, has been in focus when evaluating the stability of the bedrock at time scales of 0.5 million years and less. The last glaciation terminated about 10 000 years ago, but the effect of the released ice load can be still observed as crustal uplift, which has also caused movement in some bedrock faults. Postglacial bedrock movements have been investigated at GTK since the 1980s (Ojala et al. 2004 and references therein). They were observed to be old fault zones that were reactivated soon after the deglaciation, and the movement may have been accompanied by marked seismic events. Earthquakes are the most evident manifestations of the currently occurring bedrock deformation. However, in Fennoscandia, the seismic activity is very low and is concentrated offshore near the coastline of southern and central parts of Norway.

RADIONUCLIDE TRANSPORT AND RETARDATION PHENOMENA IN CRYSTALLINE ROCK: NATURAL ANALOGUES

The Palmottu uranium deposit in southwestern Finland was the target of an extensive natural analogue study that began in 1987 as a national co-operative research project between different organizations (Ahonen et al. 2004 and references therein). Between 1996–2000, the study grew into a large EU-supported international research project (Blomqvist et al. 2000). The ultimate goal of the Palmottu study was a quantitative description of the radionuclide transport processes in the bedrock. Migration phenomena were investigated at both the process level (sorption, matrix diffusion, colloids and microbes) and the integrated modelling level utilizing data on the flow field, hydrogeochemistry and other transport-related processes.

Data from Palmottu were also used in studying the use of natural safety indicators in the safety assessment of nuclear waste (Kaija et al. 2003). The objective of this IAEA-coordinated project was to contribute to safety assessment by means of additional safety indications derived from natural systems. Palmottu was also one of the high-priority natural analogue studies in the EU-financed NAnet project (Miller et al. 2006), with the aim to promote the usability of natural analogues for the safety case of nuclear waste disposal.

The Palmottu project resulted in a detailed structural, hydrogeological and hydrogeochemical model of the site, and in an inventory of uranium transport during geological history. About one percent of uranium in the bedrock was estimated to be in secondary oxidized phases in the fractures, whereas the uranium mass in the biosphere above, including surficial waters, lake sediment and peat deposits, was two more orders of magnitude lower. Uranium concentrations in the biosphere around the Palmottu deposit do not clearly differ from the Finnish average, indicating that the contribution of the uranium deposit to the surficial uranium may have been very small. Representative Eh, pH and chemical composition data were obtained by long-term pumping of water from fracture zones isolated by packers in several boreholes. The results demonstrated the insolubility of uranium in reducing (anoxic) waters at depths of 250 m and more. Another important outcome was the spatial heterogeneity in water composition between different fractures. For example, waters evidently having an isotopic signal from the last glaciation could be detected (Figure 1). All this points out that the movement, mixing and transport of uranium by water in fractured crystalline rock is strongly restricted.

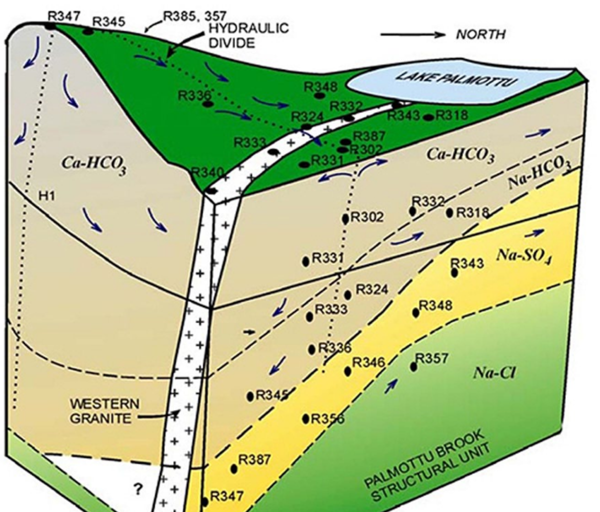

Figure 1. Conceptual hydrogeological model of Palmottu. Groundwater flow directions are indicated by arrows, depth extension is about 350 m. (Blomqvist et al. 2000).

HYDROGEOCHEMICAL CONDITIONS DEEP IN THE BEDROCK

Water in bedrock fractures has an important role in the safety of nuclear waste disposal. Chemical stabilities of the near-field technical barriers (bentonite buffer and copper canisters) are dependent on the physicochemical properties of water around the repository. Groundwater chemistry also affects the transport of radionuclides possibly released in the bedrock.

A systematic study of groundwaters deep in the bedrock started at GTK in the mid-1980s, and the existence of saline waters at variable depths all around the country was soon observed. In addition to dissolved ions (mainly Ca, Na, Cl), the existence of dissolved gases (mainly methane and nitrogen) in saline waters was verified (Nurmi et al. 1988). The results indicated that the total salinity of water typically increases with increasing depth in drill holes.

Later on, sampling techniques were improved by taking advantage of packer equipment, which allows the pumping of water samples from isolated fracture zones. A light-weight packer device was developed at GTK (Laaksoharju et al. 1995), while cooperation with the Swedish nuclear waste management organisation SKB offered the possibility to use a more advanced sampler and mobile laboratory within the Palmottu and Hyrkkölä natural analogue projects (Ahonen et al. 2004, Marcos et al. 1999). The reduction-oxidation potential (denoted as Eh, on a hydrogen scale) of a groundwater-rock system is a parameter of special importance for repository safety assessment, but the determination of Eh from natural waters has proven to be far from straightforward, requiring long-term pumping and monitoring of the water obtained from isolated bedrock fractures. Due to the availability of advanced monitoring techniques, extensive redox studies could be carried out in the uranium-bearing environment of Palmottu (Ahonen et al. 1994, Cera et al. 2002).

The age and evolution of deep saline waters is still a matter of controversy, and different types of isotope techniques have been applied to unravel the question. As water is a medium interacting with its surroundings, an unequivocal answer can seldom be obtained. As an example, carbon-14 age determination may indicate an age older than the detection limit, but it can be argued that water-rock interaction allows water to receive dissolved carbon from the surrounding old carbon sources (e.g. fracture calcites). The concept of “residence time” applies to water within the hydrological cycle, but deep saline waters often show stable isotope (^{2}H, ^{18}O) compositions outside the range of meteoric waters (Blomqvist 1999). On the other hand, bedrock groundwaters also show a wide range of stable isotope compositions, indicating variable temperatures of precipitation, including signal of past ice ages. An interesting example from the Lupin mine in Arctic Canada was reported by Stotler et al. 2009: Based on the stable isotope composition, water sampled below the present permafrost was precipitated in cold conditions, and the ^{14}C age of bicarbonate indicated the precipitation time of the last glacial maximum, whereas ^{14}C of dissolved methane was below the detection limit in the same water.

ICE AGE SCENARIO: PERMAFROST STUDIES

One of the factors arousing interest in studying the effects of past glaciations was that bedrock groundwaters at several sampling sites in Finland seem to contain an isotopically anomalous component, which was interpreted to be due to the infiltration of glacial waters (Blomqvist 1999). Glacial meltwaters intruding into the bedrock are oxic and diluted in dissolved components, thus potentially affecting the hydrogeochemical conditions around a deep geological repository. On the other hand, evidence from the last glaciation suggests that southern parts of Finland were not continuously covered by continental ice, but subarctic tundra conditions prevailed, allowing the freezing of water in the bedrock to possibly propagate to depths of several hundreds of metres into the bedrock. Consequently, the effects of permafrost deep in the bedrock should be understood with respect to the nuclear waste repository, which will possibly be subjected to similar conditions in the future.

In order to promote scientific understanding of permafrost and its role in repository safety, the international Permafrost project was initiated by the Geological Survey of Finland together with the nuclear waste management companies Posiva Oy (Finland), SKB (Sweden), Nirex (UK), and Ontario Power Generation (Canada) in 2001 (Ruskeeniemi et al. 2002, 2004, Stotler et al. 2009). Lupin gold mine in Nunavut, Canada was selected as the target site of the study. The Lupin gold deposit is situated in the Precambrian crystalline shield area in an area of continuous permafrost that extends to a depth of about 500 m (Figure 2). Several important uncertainties relating to the potential effects of permafrost on the safety of nuclear waste disposal were studied within the project.

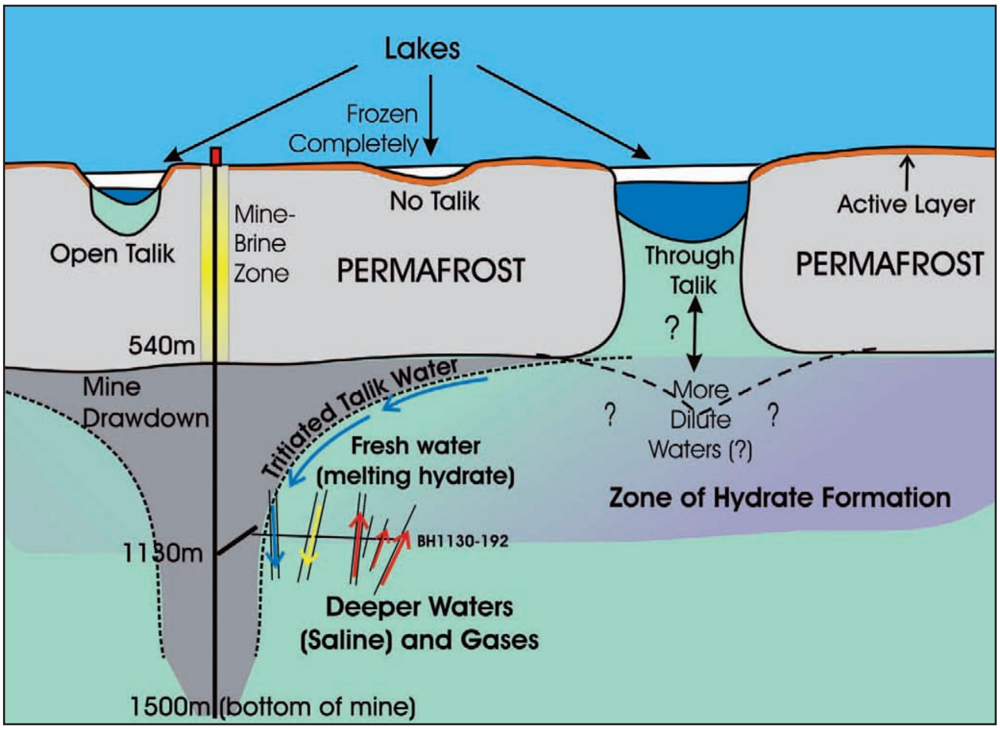

Figure 2. Conceptual hydrogeologic model of the Lupin area (modified from Stotler et al. 2009).

In situ studies at the Lupin mine did not indicate any phenomena related to bedrock stability that would be a result of the lowering of the bedrock temperature below zero. Low-porosity crystalline rock appears dry, even below the permafrost, whereas water-producing boreholes were met at the depth of 890 m and below. It was postulated that dissolved components in groundwater may segregate when water in the bedrock freezes, forming a separate saline fluid phase (cryopeg). However, the drilling of two new research boreholes through the base of the permafrost did not indicate the existence of any saline zone below the permafrost.

Major lakes keep the bedrock surface temperature above zero, which implies that the bedrock below the lakes remains unfrozen and may act as a possible flow path (talik). The Lupin mine is situated very close to Lake Contwoyto. Hydrogeological observations in the mine were considered as a tool to reveal possible hydraulic connections through the talik from the lake to the deep parts of the mine below the permafrost. Several boreholes below the permafrost at the depths of 890 m and 1130 m were plugged by expandable packers and were equipped with pressure gauges and valves for water sampling (Figure 3). Pressure monitoring over a three-year period indicated that the longest boreholes, i.e., those most probably reaching undisturbed conditions, have the highest hydraulic heads, whereas shorter holes were evidently affected by draining due to the pumping of water from the mine. None of the boreholes indicated a hydraulic connection with the lake. An important observation was that the highest measured hydraulic head values were parallel with the permafrost boundary at 540 m. This water level may be representative of the undisturbed, indigenous conditions below the permafrost in crystalline rock, i.e. when the propagation of the permafrost boundary ceases, the hydraulic head of water entrapped below the permafrost may level off on a regional scale. In other words, completely frozen bedrock may act as a rigid roof above the “normal” water-saturated rock, which would thus not be affected by the “cryostatic” pressure above.

Theoretically, low temperature high pressure conditions may facilitate the freezing of dissolved methane trapped below the permafrost. Consequently, a solid methane-water mixture (clathrate or "methane ice") may form during cold climate periods, whereas increasing bedrock temperatures would result in the dissolution of methane in water. Water samples obtained from the deep sub-permafrost boreholes at Lupin mine contained dissolved gases in abundance, up to about 0.5 L gas per 1 L of water (NPT). As observed at other study sites within crystalline rock, dissolved gas predominantly consist of methane and nitrogen. Small amounts of ethane (< 2 %) and other longer chain dissolved carbohydrates were also detected.

Figure 3. Groundwater sampling from a drillhole at 1130 m depth. Photo: Timo Ruskeeniemi.

DEEP LIFE: EXISTENCE AND EFFECTS

New data and observations are continuously being produced indicating that there is a deep biosphere within the Earth's crust down to depths where temperatures are less than ~120 ºC. However, present and ancient biogeochemical processes in the Precambrian crystalline bedrock terrains such as the Fennoscandian Shield are not yet well understood. Challenges have been encountered both in representative microbial sampling of the deep bedrock (down to more than 1000 metres) and the methods available to study the microbiological diversity and ecology of this extreme habitat of life. The existence of microbial communities in the deep crystalline bedrock has been verified in several studies (e.g. Hallbeck & Pedersen 2008), but the origin, diversity, dynamics and energetics of these deep subsurface microbial communities still remain largely unresolved.

Currently, the 2516 metres deep Outokumpu research borehole, administered by GTK, is a major target of the deep biosphere research in Finland. Borehole water has been sampled by a tube sampler to the depth of about 2400 metres. Water in the borehole is saline, with the highest total dissolved salinities being about 47 g/L near the bottom of the borehole. Dissolved gases, predominantly methane and nitrogen, are abundant (about 900 mL gas in 1000 mL of water). Repeated sampling of the borehole water has verified the existence of microbes in the water, in amounts of about 10^4 cells/mL. A biogeochemical study of the possible interactions between water, gases and microbes is utilizing various isotopic techniques, whereas molecular biological methods are being used to examine the diversity and metabolism of the deep-dwelling microbes.

Deep life studies on the Outokumpu deep borehole have partially been supported by the Finnish research programme for nuclear waste management (KYT2010), and the outcomes of the research are primarily aimed to provide a better understanding of the deep biosphere processes in support of the safety of nuclear waste disposal.

DISCUSSION

In the course of its long geological history, the Fennoscandian bedrock has been continuously subjected to changing tectonic stress fields due to the collision of continents and loading/unloading events related to the changing sediment and ice sheet cover, causing vertical movements. This has resulted in the mosaic-like block structure of the bedrock, where fracture zones surround more or less intact blocks of different sizes. The old block structure currently existing is considered stable, and fracture zones mainly dissipate the stress due to tectonic forces and glacial-induced uplift of the crust. In addition, the continental crust has always been subjected to daily "Earth tide" movement due to the gravitational effects of the moon and other bodies in the solar system. It is well justified to consider the Fennoscandian Shield as a geologically stable environment.

Due to the northern position, Finnish bedrock may experience glacial conditions in the future in the same way as it has in the past. Consequently, the effects of periglacial conditions on the bedrock were investigated at the Lupin mine in northern Canada, where permafrost presently extents down to the depth of the planned Finnish nuclear waste repository. A thorough study of the conditions below the permafrost did not indicate any major, clearly permafrost-induced effects on the hydrogeology or bedrock stability.

Hydrogeological and hydrogeochemical conditions around a geological repository are important determinants of the stability of an engineered barrier system consisting of waste containers enveloped by a bentonite buffer in deposition holes. The salinity of water at the repository depth is an indication of stagnation and the lack of connection of deep waters with the near-surface hydrological cycle. However, the possible negative effects of salinity on the stability of the engineered barriers must be critically evaluated.

One of the fundamental aspects of deep geological disposal is the multibarrier principle: If the technical barriers fail, bedrock will provide the next barrier against radionuclide migration to the biosphere. In the safety assessment of the high-level nuclear waste repository, radionuclide transport and retention processes in rock are conceptualized and finally expressed as numerical models that simulate the transport and dispersion of harmful compounds. This methodology allows a quantitative estimation of the radioactive dose rate received by the biosphere in the worst case. However, "hard numbers" required to describe the behaviour of the bedrock-groundwater system always include uncertainty. Hydrogeological parameters defining the movement of water are typically site-specific, whereas the parameters related to water-rock interaction (sorption, matrix diffusion etc.) can be studied, for instance, in laboratory-type experiments on geological materials at different scales from drill cores to underground laboratories. Natural analogues are a major geoscientific source of information supporting the understanding and demonstration of transport processes in natural systems. Natural analogues utilize an inverse approach: results of a long-term process are observed in natural systems and compared with the results obtained by predictive modelling. Neither of these approaches may be considered sufficient alone, but as a combination they constitute a composite argument supporting the safety case. The safety case of nuclear waste disposal is based on multiple lines of evidence, which together provide information to show that the effects of a particular phenomenon and all coupled phenomena together are understood well enough to make decisions. For the geological disposal of nuclear waste, understanding of the bedrock processes – from bedrock stability to biogeochemistry – is of special importance.

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ENERGY POTENTIAL OF FINNISH PEATLANDS

by
Kimmo Virtanen[1] and Samu Valpola[2]

Virtanen, K. & Valpola, S. 2011. Energy potential of Finnish peatlands. *Geological Survey of Finland, Special Paper 49*, 153–161, 7 figures.

One-third of the Finnish land area is covered by mires and peat. GTK has investigated 2.0 million ha of the 9.3 million ha area covered by mires in Finland.

According to the EU Commission, the broadly-based Finnish energy economy, with various energy sources, is the best in the EU. As a fuel, peat fulfils the goals of the EU energy policy in Finland well: it is local, its availability is good and the price is stable. The use of peat also enhances national security. At present, peat is used in around one hundred larger applications that co-generate electricity and heat.

In Finland, the development of mires has led to several mire complex types and three main types: raised bogs in Southern Finland, aapa mires in Ostrobothnia and Lapland, and palsa mires in Northern Lapland. Peat layers are deepest in southern Finland and partly in the southern Finnish Lake area, the Region of North Karelia and in the area of central Lapland. The mean depth of geological mires is 1.41 m and the thickest drilled peat is 12.3 m.

According to peat investigations, the national peat reserve totals 69.3 billion m3 in situ (peatlands larger than 20 hectares). The dry solids of peat are estimated at 6.3 billion tones. Sphagnum peat accounts for 54% and Carex peat for 45% of feasible peat reserves.

Peatlands that are technically suitable for the peat industry cover a total area of 1.2 million ha and contain 29.6 billion m3 of peat in situ. Slightly humified peat suitable for horticultural and environmental use totals 5.9 billion m3 in situ. The energy peat reserve is 23.7 billion m3 in situ and its energy content is 12 800 TWh.

Keywords (GeoRef Thesaurus, AGI): energy sources, peat deposits, mires, peat, fuel peat, reserves, Finland

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INTRODUCTION

The Geological Survey of Finland (GTK) studies and maps peat reserves in Finland in a focused manner. Peat research has been conducted at GTK ever since it was established 125 years ago. GTK's oldest peat studies were connected to a report on the natural history of mires and geological soil mapping.

One-third of the Finnish land area is covered by mires and peat. GTK has investigated 2.0 million ha of the 9.3 million ha area covered by mires in Finland. The study material comprises about one million study points and 15 000 single peatland basins from which geological peat data have been collected. In Finland, there are some 100 000 peatland units (single basins), of which 33 700 exceed 20 hectares. Based on this data, the present study assesses the peat resources of Finland and their exploitability (Figure 1).

According to the EU Commission, the broadly-based Finnish energy economy, with various energy sources, is the best in the EU. In the Finnish energy economy, peat is used to replace imported fossil fuels. Two-thirds of the energy consumed in Finland has been generated with imported fuels. In Finland, peat is classified as a slowly renewable biomass fuel. According to EU legislation, peat as a fuel is a part of the emission trading system, and its calculatory carbon dioxide emissions are based on combustion only. As a fuel, peat fulfils the goals of the EU energy policy in Finland well: it is local, the availability of peat is good, and the price is competitive and stable. The use of peat also enhances the national security of supply, as it can be stockpiled for several years when compared to rapidly renewable and disintegrating biofuels such as timber and wood chip material. At present, peat is used in around one hundred larger applications. The biggest of these are located in the inland cities, which have integrative co-generation of electricity and heat, mainly using peat.

Nowadays, the mapping and inventory of peat reserves in Finland is done not only to provide information on the reserves of peat for energy generation, but also to pinpoint raw materials related to the other uses of peat. In Finland, peat is mainly used in energy generation or in horticulture. Energy peat accounts more than 90% of the total peat production, and so-called white peat, used as a horticultural peat and litter material in animal husbandry, for around 7–8%. A smaller amount of peat is used in municipal sludge and biowaste composting plants and as biofilters, as an oil-absorbent, an insulating material, in textiles, and in balneology.

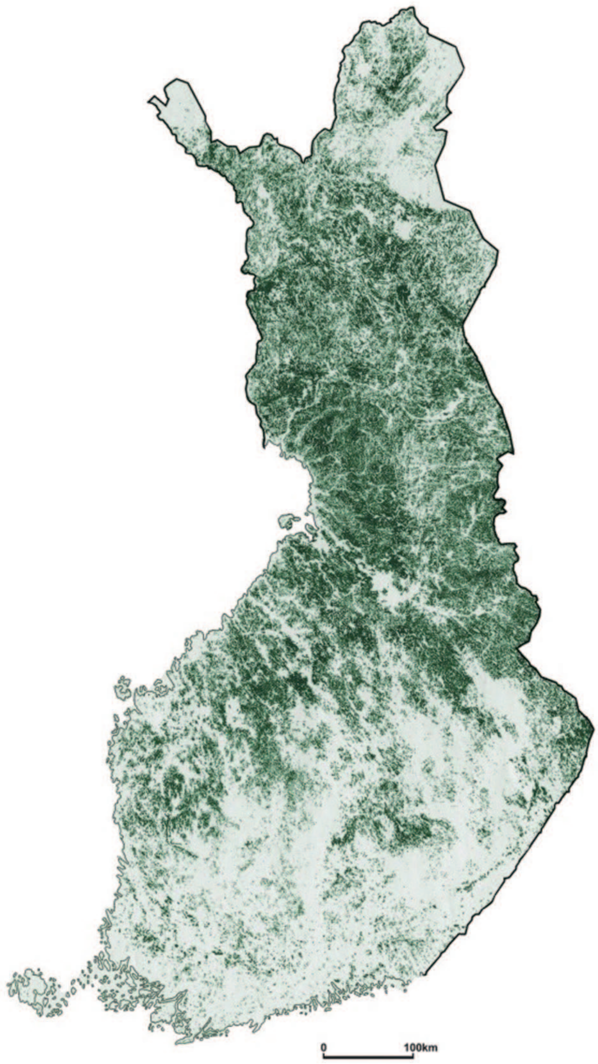

Figure 1. Peatlands in Finland.

STUDY METHODS

The whole area of Finland has been mapped by low altitude aero geophysical methods from a flight altitude of approx 30 m and a flight line spacing of 200 m. Field studies are planned using the accordingly obtained aerial gamma radiation data and maps as base data. The gamma data can be used to locate different peat deposits, and to differentiate peat deposits with regard to the depth of the peat layer in them. Furthermore, the suitability for *in situ* field investigation can be determined.

In field observations, the stratigraphy of peat layers and topography of the mire, including vegetation and the site type, are determined. Through coring, peat samples are macroscopically studied for their botanical origin (*Carex, Sphagnum, Bryales, Phragmites, Equisetum* etc.), and the degree of humification according to von Post's ten-point scale (Figure 2). The organic sediments below the peat and the mineral sediments at the bottom of the basin are also determined. Laboratory samples are taken from locations that as far as possible represent the usable peat layer of the site. Laboratory samples are taken with a sampler designed for coring volumetric peat samples, enabling accurate estimates of the energy content of the peat deposit. Nowadays, ground penetrating radar (GPR) is often used to complement the data on the thickness of the peat (Figure 3). GPR is also used in studies concerning the margin areas of basins, in estimating the remaining peat in production areas or in groundwater geological studies related to peat production. The elevation of peat layer surfaces has traditionally been measured by optical levelling, but GTK is currently introducing airborne laser scanning data provided by the National Land Survey of Finland. This substantially improves the quality of peat data.

GTK has used a relatively sparse survey map in the basic peatland inventory. On the basis of this inventory, the characteristics of the peat types for different modes of utilisation, such as energy generation or horticulture, are established. Similarly, the size of the areas suitable for peat production, the estimated amount of peat and the energy content are determined. Additionally, the environmental impact of starting peat production is assessed.

The information accumulated from the mapping of peat reserves has been used to form a national peat database at GTK, which is accessed when formulating various summaries for different local, regional or even nationwide purposes.

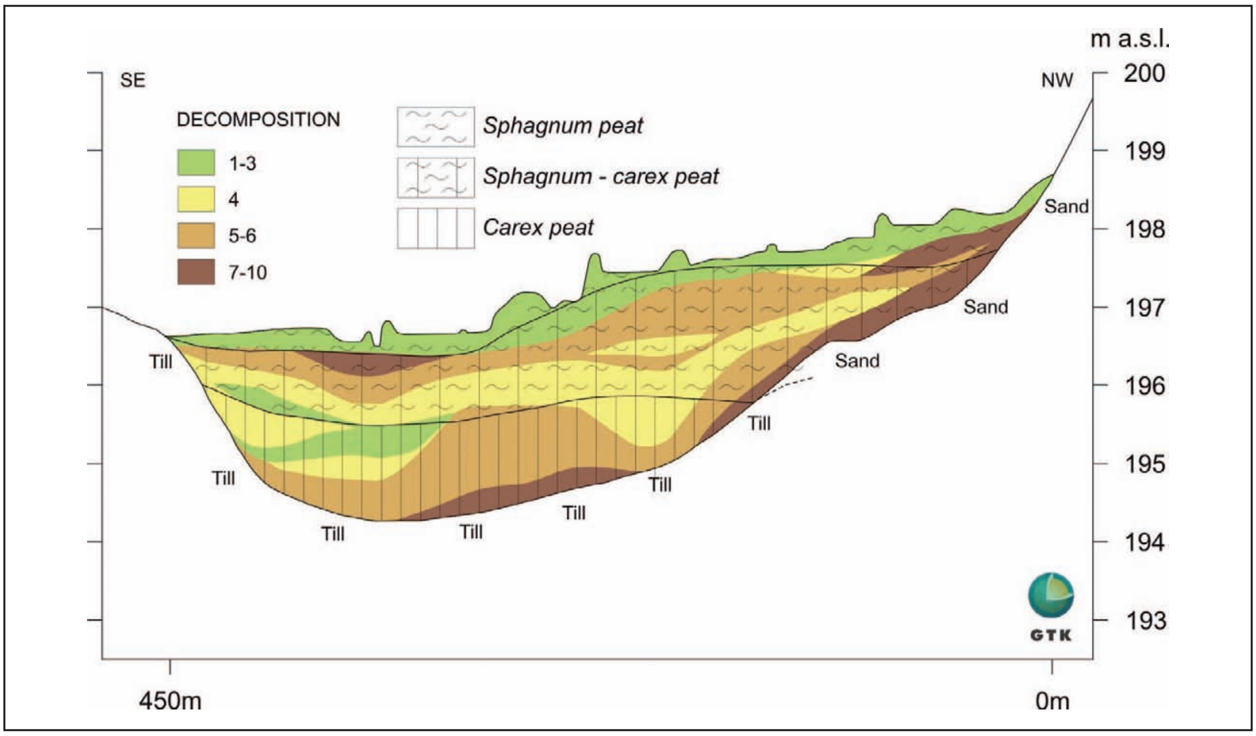

Figure 2. Peatland cross-section; peat types and degree of peat decomposition.

Figure 3. A modern light-weight ground penetrating radar (GPR) in operation and a GPR profile (below). Photo: Samu Valpola.

PEAT RESOURCES

Peat layers consist of the remains of ancient plants. Long ago, the plants in question formed mire plant communities, i.e. mire site types, and they in turn formed mire complex types. In Finland, the development of mires has led to several mire complex types and three main types: raised bogs in Southern Finland, Lake Finland and along the coast of Ostrobothnia; aapa mires in the region of Suomenselkä, North Ostrobothnia and Lapland; and palsa mires, where the core of the palsa hummock is frozen throughout the year, in Northern Lapland (Figure 4).

Raised bogs typically have a thick and poorly-decomposed *Sphagnum* moss-dominated peat layer, which may often also include the remains of hare's-tail cottongrass (*Eriophorum)*, deer grass (*Trichophorum)* and rannoch-rush (*Scheutzeria)*, along with *nanolignids* (the remains of dwarf shrubs). Thin decomposed layers are further typically found inside poorly-decomposed peat.

The peat strata of aapa mires are characterised by the variability of the peat types. The most common peat types occurring in aapa mires are dominated by *Carex* grass, with additional factors regularly including the remains of bog bean (*Menyanthes*), horsetail (*Equisetum*), rannoch-rush (*Scheutzeria*), common reed (*Phragmites)*, and of wood and dwarf shrubs. Peat dominated by the remains of *Sphagnum* and brown mosses is also common in aapa mires, and likewise a combination of all the peat types. Brown moss peats are particularly found in the bottom parts of peat layers, and especially in the mires of central Lapland.

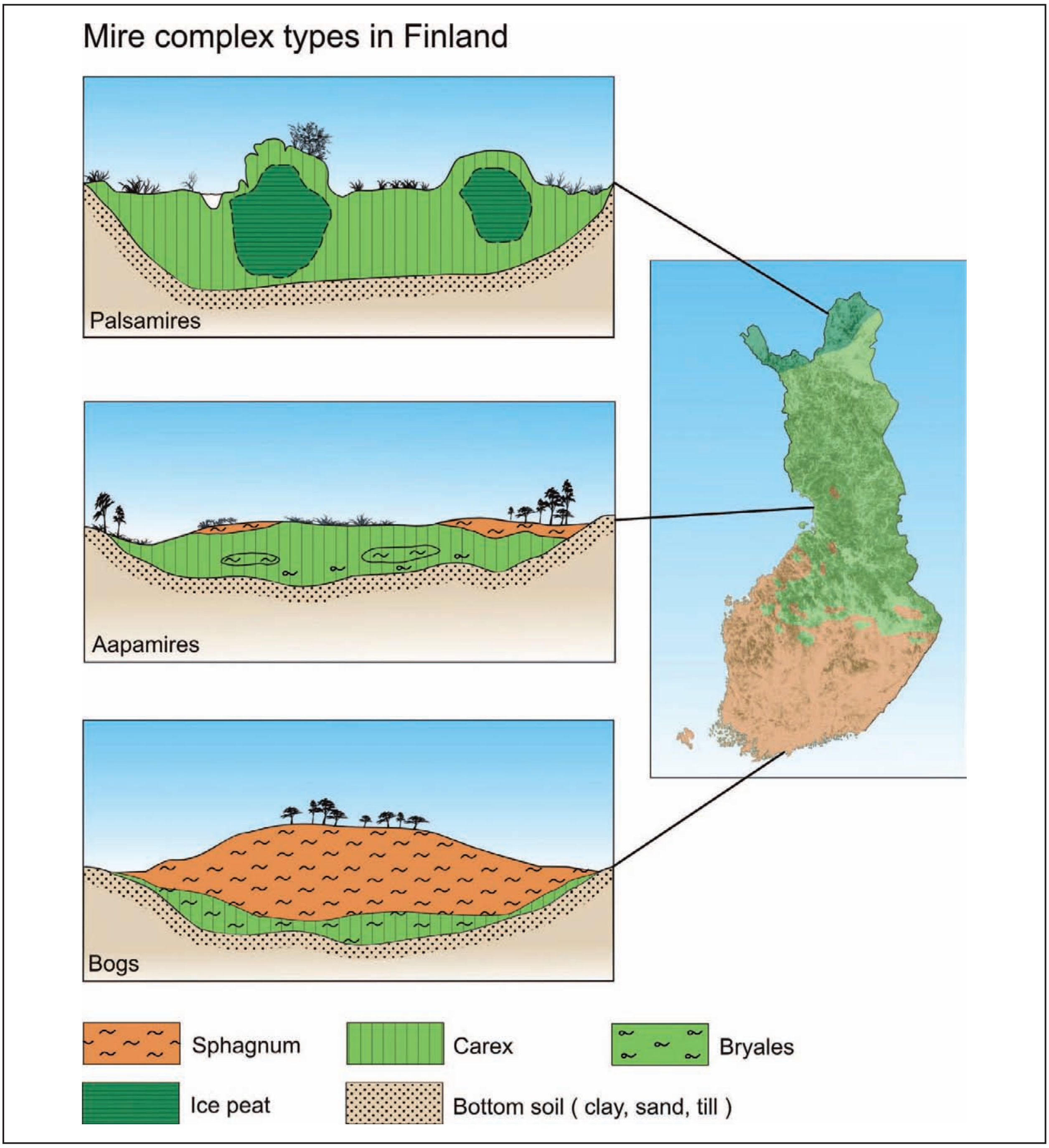

Figure 4. The main mire complex types in Finland; raised bogs, aapa mires and palsas.

Sphagnum peat accounts for 54% and *Carex* peat for 45% of feasible peat reserves in Finland (Figure 5). The remaining 1% is composed of *Bryales* peat, the bulk of which is encountered in the North Finland area. The highest values for the degree of humification are located in Lake Finland (central Finland), where wood remains often also occur in peat. Chance often influences the physical properties of peat: for example, a brook bed may become blocked and the ash content can thus increase. The average ash content is 3.4% of dry mass, the sulphur content 0.20% (ca. 0.09–10%) of dry mass and the dry bulk density 87 kg/m^3 (ca. 40–220 kg/m^3) in the peat layer *in situ*.

The mean depth of geological mires is 1.41 m (Figure 6). Peat layers are deepest in southern Finland (Uusimaa and Kanta-Häme regions), and partly in the southern Finnish lake area, the Region of North Karelia and in the area of central Lapland. The average depth of mires is often more than 3

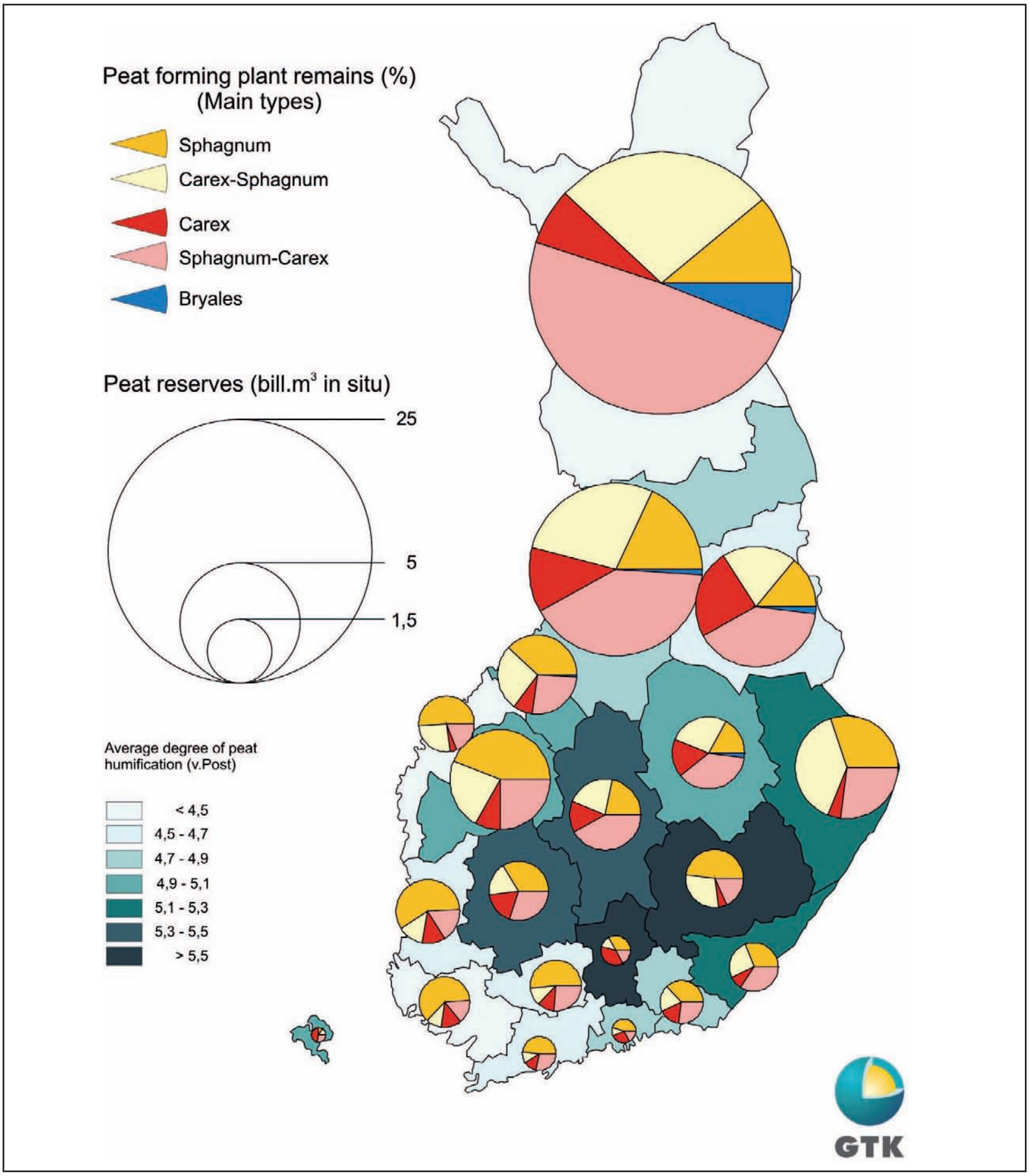

Figure 5. The main peat types and average humification value in Finland.

metres. The thickest drilled peats (12.3 m peat) are located in Torronsuo in Tammela and Raimansuo in Janakkala. The shallowest peatlands lie in the west coast area of Finland and in North Ostrobothnia, in the area bordered by the towns of Oulu, Kajaani, Kiuruvesi and Raahe. The average depth of mires in this area is often less than 1 metre. In the area exceeding 1.5 m in depth, the peat layer is 2.50 m thick on average. Altogether, 37% of Finnish mires, i.e. 1.9 million ha, have a peat layer thicker than 1.5 m.

According to the peat investigations, the national peat reserve totals 69.3 billion m^3 *in situ*, including peatlands larger than 20 hectares. One-third of peat reserves are located in Lapland, one-third in the Regions of Northern Ostrobothnia and Kainuu and one-third in southern Finland. The dry solids of peat are estimated at 6.3 billion tonnes, while the carbon storage of Finnish mires totals 3.2 billion tonnes. The average carbon content of peat is 51.5%.

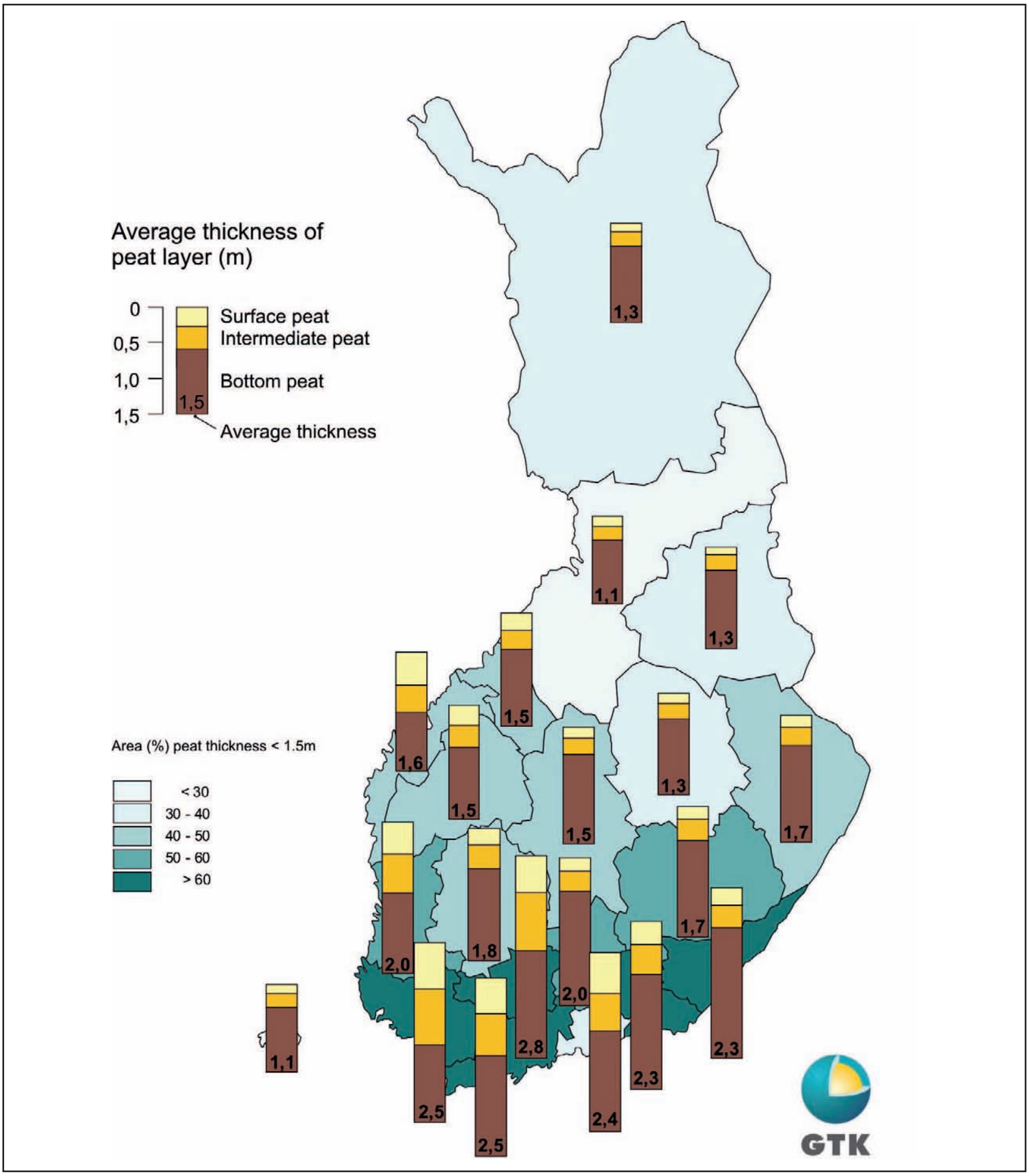

Figure 6. The thickness of peat layers in Provinces of Finland.

Peatlands that are technically suitable for the peat industry cover a total area of 1.2 million ha and contain 29.6 billion m^3 of peat *in situ* (Figure 7*)*. Peat production takes place on 0.06 million hectares of the peatland area. Slightly humified peat suitable for horticultural and environmental use totals 5.9 billion m^3 *in situ*. The reserves of horticultural peat lie in the southwestern part of Finland. The energy peat reserve is 23.7 billion m^3 *in situ* and its energy content is 12 800 TWh. This is comparable with the remaining oil reserves of Norway, 1 008 million tonnes of crude oil with an energy content of about 11 700 TWh (World Energy Council 2009)

The energy density of the mire areas appropriate for energy peat production is 0.54 MWh m^3 *in situ*. The peat reserve technically suitable for industrial purposes includes all peatlands in Finland. The economic and environmental limitations have not been taken into account in the previous assessment.

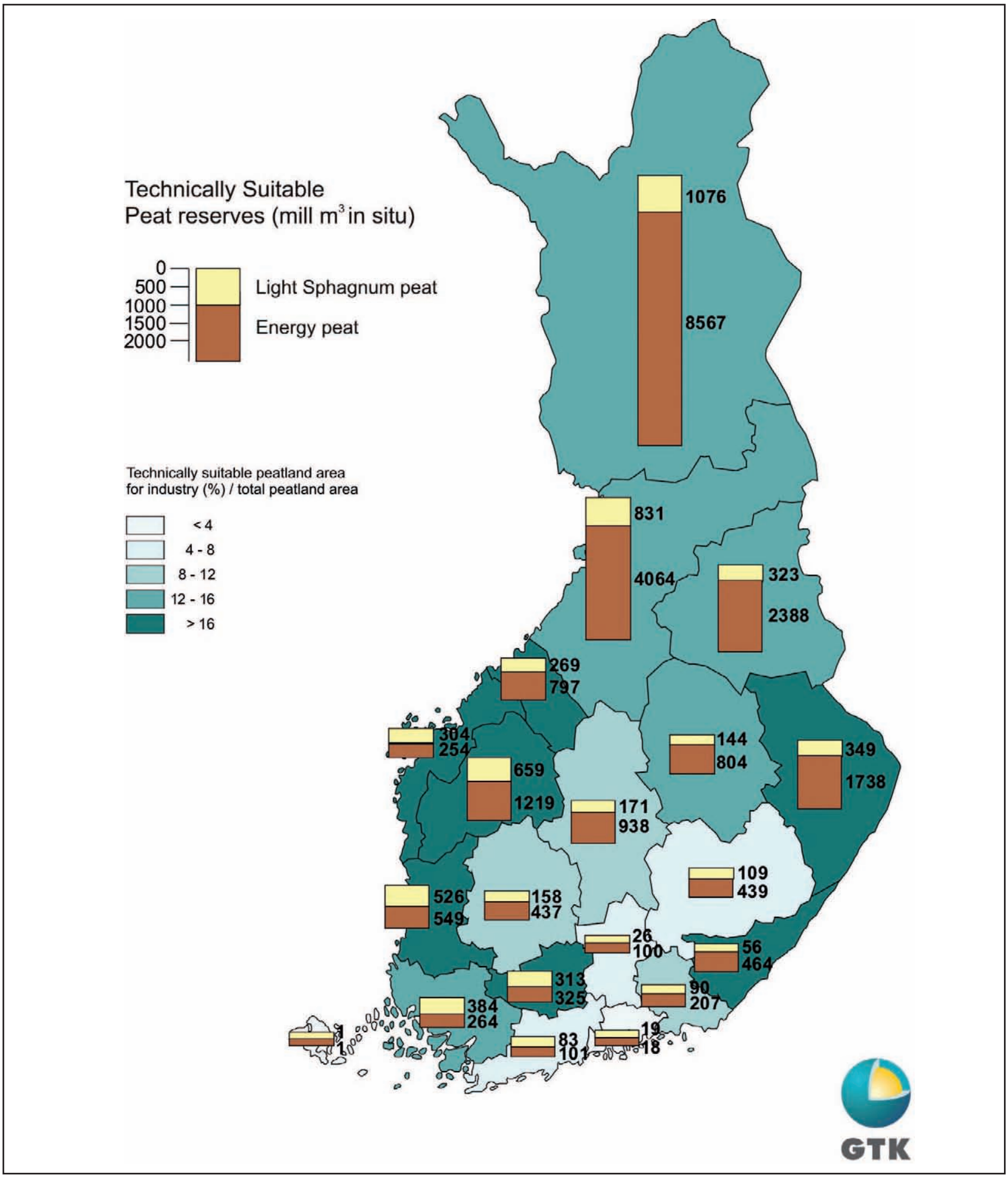

Figure 7. Estimated technically suitable peat reserves and suitable peatland area for industry in relation to the total peatland area.

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THE SUFFICIENCY OF PEAT FOR ENERGY USE ON THE BASIS OF CARBON ACCUMULATION

by
Markku Mäkilä

Mäkilä, M. 2011. The sufficiency of peat for energy use on the basis of carbon accumulation. *Geological Survey of Finland, Special Paper 49*, 163–170, 6 figures and 1 table.

The purpose of this study was to compare the average annual carbon accumulation of surface peat layers younger than 100 years with the estimated use of energy peat by separate provinces of Finland in the year 2020. The annual carbon accumulation of surface peat layers is 3.44 million tonnes for the mire area of 6.737 million hectares that is accumulating peat. This is of the same size as the estimated use of peat carbon in the year 2020, i.e. 28.2 TWh, which approximates to 3.28 million tonnes of carbon. Carbon accumulation is higher than the estimated use in the regions of Lapland and Pohjanmaa-Kainuu, whereas in the remaining regions carbon accumulation is lower than the estimated annual use of energy peat carbon.

Keywords (GeoRef Thesaurus, AGI): mires, peat, carbon, deposition, fuel peat, utilization, sustainable development, Finland

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INTRODUCTION

There has been considerable discussion of the balance between peat carbon accumulation and the use of energy peat. The purpose of the study presented in this paper was to compare the average annual carbon accumulation of surface peat layers younger than 100 years with the estimated use of energy peat in the year 2020. New peat accumulates all the time on most of the mires in Finland. This accumulating layer is still in the rapid gas exchange zone, where CO_2 released in the decay process is captured by the living surface vegetation to be used in the growth of new plant biomass, which after a few years will again start to decay. Rapid carbon accumulation and turnover of peat carbon occur in young surface layers in the same way as in a growing forest. The climate impact of surface peat layers is indistinguishable from the impact of the forest, so the use of surface carbon in accumulation calculations can be considered reasonable.

Peat formation

Sphagnum (moss) and *Carex* (sedge) peat form in different ways. *Sphagnum* moss grows from the apical bud and respectively lower layers die and form peat (Figure 1). In *Carex* peat (and also in the formation of other high plants), the most important constituents are roots (Figure 2). A certain proportion of roots dies and regenerates, so besides living roots there are roots of different ages in the same peat volume. Finally all roots die and form peat.

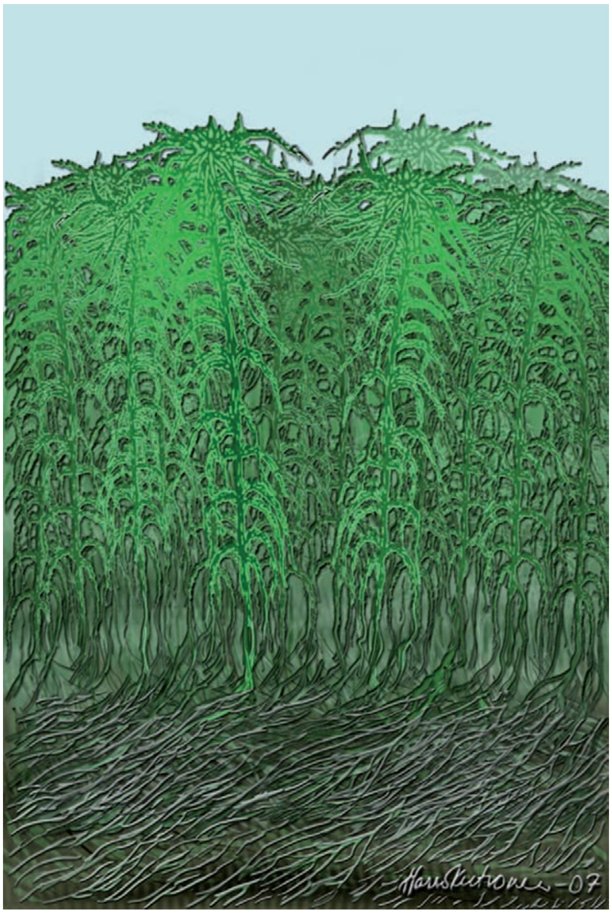

Figure 1. Formation of *Sphagnum* peat. Picture drawn by Harri Kutvonen.

Figure 2. Formation of *Carex* peat. Picture drawn by Harri Kutvonen.

Peat layers are in a dynamic state. Relatively thick (up to 40 cm) surficial layers consist of living and dead biomass, which slowly changes (decomposes) to peat. It is also well known that the living roots of sedges can penetrate down to a depth of two metres in the peat layers, making even deeper layers a mixture of peat and living biomass. Although the biomass of these deep-growing roots is relatively small, they may contribute significantly to the accumulation of carbon, because decomposition in the anoxic layers (catotelm) is slow (Saarinen 1996). As the decomposition continues slowly under anoxic conditions, a small proportion of the carbon deposited in the catotelm is subsequently converted to methane (CH_4). Methane is a 25-fold stronger greenhouse gas than carbon dioxide. This anoxic layer is still in the slow gas exchange zone. The peat layers below ground thus consist of different components, which have different climate impacts.

Moisture, especially its temporal distribution, is the main factor controlling *Sphagnum* production. Thus, both the amount of precipitation and the distance to the groundwater level are important for *Sphagnum* production. However, other climatic factors (e.g. the mean annual growing season temperature and growing degree-days) have also been shown to correlate with moss growth. The fact that carbon accumulation rates are higher in coastal *Sphagnum* bogs than in older raised bogs is not only due to climate, but also to the fact that coastal bogs are in the early phase of their development (Figure 3). This type of young bog produces more moss on the surface and the amount of peat decayed and compacted in the entire bog is lower than in an old bog.

Figure 3. A coastal bog from Storslättmossen, Mustasaari, where the *Sphagnum* peat layer is growing rapidly. Two metres of peat has accumulated during 800 years. Photo: Markku Mäkilä.

The rate of carbon accumulation is higher in raised bogs than in minerotrophic aapa mires. Aerobic decay is more efficient in aapa mires that receive nutrients and oxygenated water from adjacent mineral soils (Figure 4), whereas ombrotrophic raised bogs are only fed by rainwater. In minerotrophic aapa mires, oxygen is transported into the peat via the roots of sedges, where it contributes to the decay of peat layers. As far as northern aapa mires are concerned, the short growing season, severe winters with a strong frost action and often the highly permeable subsoil have resulted in a lower rate of carbon accumulation and highly compressed peat deposits (Figure 4).

Figure 4. A northern aapa mire from Luovuoma, Enontekiö, where the *Carex* peat layer is growing slowly. Almost two metres of peat has accumulated during 9800 years. Photo: Markku Mäkilä.

MATERIAL AND METHODS

The starting point for this study was the estimated use of energy carbon by separate provinces of Finland in the year 2020 (Flyktman 2009). The average annual carbon accumulation in the last 100 years was used to calculate the rate of peat carbon accumulation (Mäkilä & Goslar 2008). In addition, some samples were taken from Lapland during 2009 and added to the study material. The average annual carbon accumulation during the last 100 years was examined with 433 radiocarbon dates using bulk density and carbon pool measurements from 86 peat columns (Figure 5). The peat columns represented mires varying in depth, age, natural state and nutrient conditions, from both aapa mire and raised bog regions in southern and central Finland, as well as four peat columns from Russian Karelia. The calibration program and age-depth modelling developed at Poznan Radiocarbon Laboratory was used.

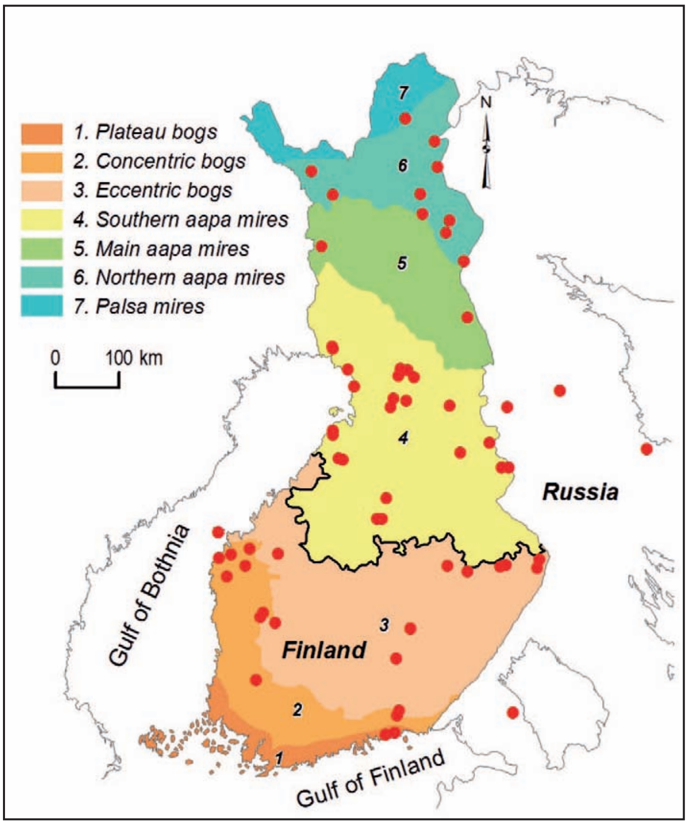

Figure 5. Numbered regions of mire complex types in Finland and location of the studied mires. Study points are marked with red points. The region to the south of the black line contains a raised *Sphagnum* bog area; to the north of the line is a *Carex* aapa mire area.

RESULTS

Mire area

According to the latest statistics, the total area of peatlands in Finland is 9.29 million ha (http://www.gtk.fi/luonnonvarat2/turve/turvemaat.html) (Finnish Statistical Yearbook of Forestry 2009, Kaakinen & Salminen 2008, verbal knowledge (TTL, 02/2010 and MTT, 11/2009). When organic croplands (0.33 million hectares) and the peat production area (0.06 million hectares) are deducted from this peatland area, we obtain a mire area of 8.90 million hectares pertaining to forest science (VMI 10). When the area of transformed mires (2.163 million hectares) is deducted from the mire area pertaining to the Finnish Forest Research Institute, we obtain a peat accumulating mire area of 6.737 million hectares. On transformed mires, the ground vegetation consists of upland vegetation. There is practically no accumulation of new peat on the mire surface in many places. However, there is still some accumulation of organic material in the peat layer because of forest litter from the root system. Transformed mires can actually release more carbon that they accumulate, as the dried peat layers rapidly decompose in oxygen rich conditions and thus release more CO_2 than in natural wet conditions.

Estimated use of energy peat in the year 2020

The CO_2 emission from peat combustion is 0.381 t CO_2/MWh (105.9 g CO_2/MJ) (Vesterinen 2003). The total emission from energy peat combustion is 10.74 million tonnes CO_2, which means 2.97 million tonnes of carbon per year if the estimated use of energy peat carbon is 28.2 TWh in the year 2020. Besides this, over 1 million tonnes of CO_2 or 0.3 tonnes of carbon (IPCC seminar 2008) are lost in production fields and stocks. The use of 28.2 TWh of energy peat consumes 3.28 million tonnes of carbon (Table 1 and Figure 2). The carbon emission during the production phase is included in the calculations of carbon use.

Table 1. The estimated use of energy peat carbon in the year 2020 and the average annual carbon accumulation of the surface peat layers younger than 100 years on the basis of regions demarcated by Forest centres.

Region	Province	Estimated use of carbon year 2020			Carbon accumulat.
		provincially		regionally	regionally
		TWh	mill. t. C	mill. t. C	mill. t. C/yr
	Uusimaa, Ahvenanmaa	0.51	0.06		
	Varsinais-Suomi	0.50	0.06		
	Itä-Uusimaa	0.08	0.01		
	Satakunta	1.73	0.20	0.67	0.19
1. Southern	Kanta-Häme	0.47	0.05		
	Päijät-Häme	0.39	0.05		
	Kymenlaakso	0.78	0.09		
	Etelä-Karjala	1.26	0.15		
	Pirkanmaa	1.34	0.16		
	Etelä-Pohjanmaa	2.40	0.28		
2. Western	Pohjanmaa	2.05	0.24	1.14	0.53
	Keski-Pohjanmaa	0.52	0.06		
	Keski-Suomi	3.48	0.40		
	Etelä-Savo	0.75	0.09		
3. Eastern	Pohjois-Savo	1.88	0.22	0.37	0.30
	Pohjois-Karjala	0.59	0.07		
4. Kainuu – Pohjanmaa	Kainuu	0.60	0.07	0.84	1.18
	Pohjois-Pohjanmaa	6.64	0.77		
5a. Lapland, S	Lappi	2.24	0.26	0.26	1.10
5b. Lapland, N	Lappi (Enontekiö, Utsjoki, Inari)				0.14
5. Lapland	Lappi, total				1.24
Total		28.2	3.28	3.28	3.44

Carbon accumulation

The average annual carbon accumulation of surface peat layers younger than 100 years and the estimated use of energy peat carbon in the year 2020 have been divided into five regions on the basis of Forestry centres (Table 1 and Figure 6.) Furthermore, the Lapland area has been divided into Southern and Northern Lapland. Peat columns were collected from study sites of varying depth, age, nutrient conditions and degree of natural state typical for the peat layers of each region. The highest annual carbon accumulation is in *Sphagnum*-dominated Western and Southern Finland (1 and 2), being 0.70 t/ha and 0.67 t/ha, respectively. The lowest carbon accumulation is 0.24 t/ha in the regions of Northern Lapland (5a) and 0.42 t/ha in Southern Lapland (5a). The carbon accumulation is 0.53 t/ha in the region of Eastern Finland and 0.60 t/ha in the region of Kainuu-Pohjanmaa. The carbon accumulation of all regions is obtained by multiplying the amount of carbon by the rate of peat accumulation in each mire area (Finnish Statistical Yearbook of Forestry 2009) (Table 1 and Figure 6).

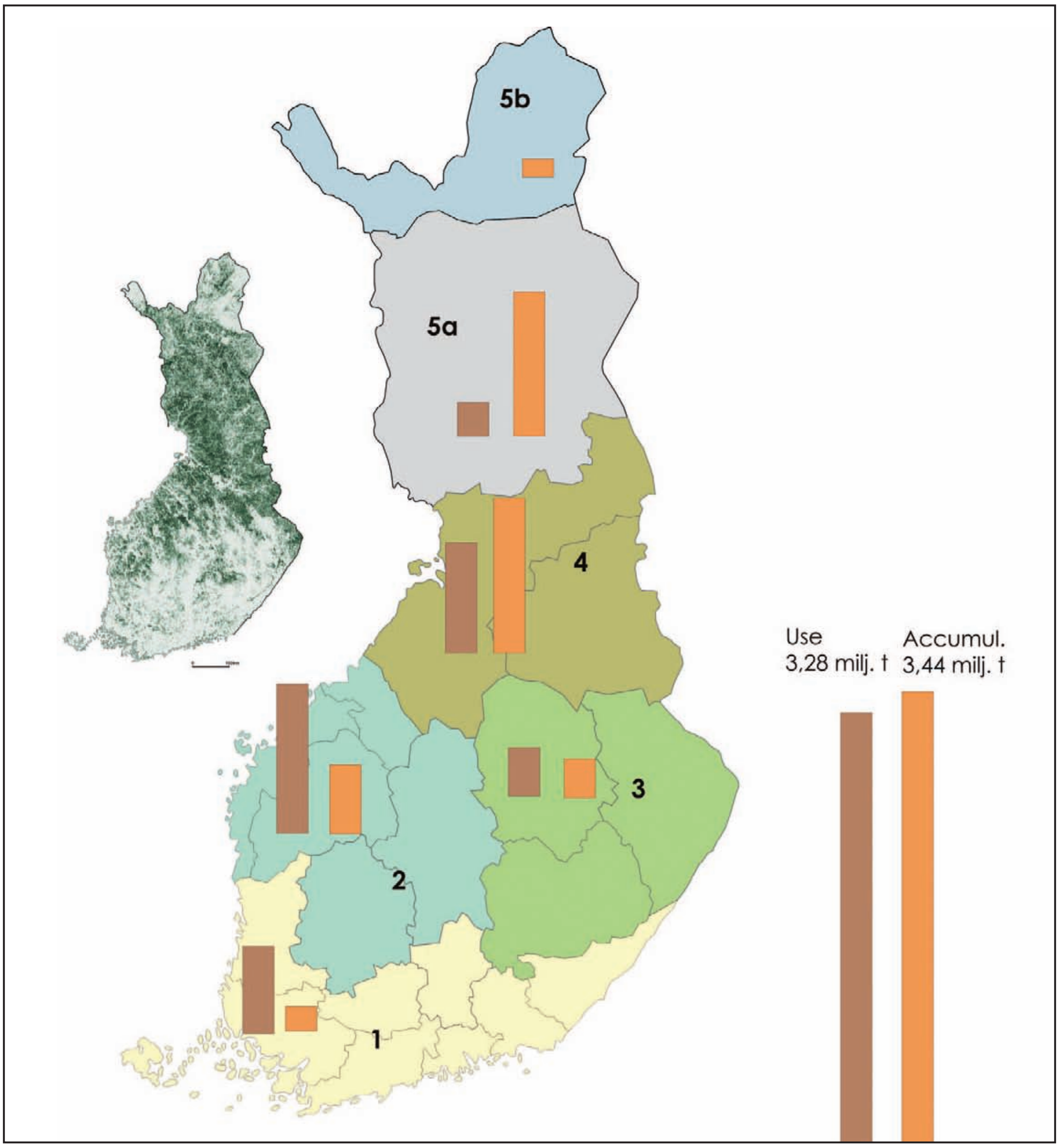

Figure 6. The estimated use of energy peat carbon in the year 2020 and the average annual carbon accumulation of surface peat layers younger than 100 years in different regions and in the whole country. The distribution of mires is shown by the darker areas in the inset map.

CONCLUSIONS

According to the large and accurate radiocarbon dating material of GTK, the annual carbon accumulation of the vitally living surface peat layers younger than 100 years is 3.44 million tonnes for the Finnish mire area (6.737 million hectares) that is still effectively accumulating peat. The carbon accumulation rate is the same as the estimated use of peat carbon in 2020, i.e. 28.2 TWh, which approximates to 3.28 million tonnes carbon. The rate of carbon accumulation is higher than the rate of use in the regions of Lapland and Pohjanmaa-Kainuu, whereas in the remaining regions, carbon accumulation is lower than the annual estimated use of energy peat carbon (Table 1 and Figure 3).

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CARBON ACCUMULATION IN PRISTINE AND DRAINED MIRES

by
Markku Mäkilä

Mäkilä, M. 2011. Carbon accumulation in pristine and drained mires. *Geological Survey of Finland, Special Paper 49*, 171–177, 3 figures and 2 tables.

The carbon accumulation of 73 peat columns from 48 pristine and drained mires was investigated using a total of 367 dates and age-depth models derived from bulk density measurements. Peat columns were collected from mires of varying depth, age, degree of natural state and nutrient conditions in aapa mire and raised bog regions and coastal mires from southern and central Finland and Russian Karelia. Particular attention was paid to the accumulation of carbon over the last 300 years, as this period encompasses the best estimates of the oxic layer (acrotelm) age across the range of sites investigated.

In general, drained mires are initially more nutrient-rich than pristine mires. Organic matter decomposes more rapidly at drained sites than at pristine sites, resulting in thinner peat layers and carbon accumulation but a higher dry bulk density and carbon content. The average carbon accumulation was calculated as 24.0 g m^{-2} yr^{-1} at pristine sites and 19.4 g m^{-2} yr^{-1} at drained sites, while for peat layers younger than 300 years the respective figures were 45.3 and 34.5 g m^{-2} yr^{-1} at pristine and drained sites. For the <300-year-old peat layers studied here, the average thickness was 19 cm less and the carbon accumulation rate 10.8 g m^{-2} yr^{-1} lower in drained areas than in pristine areas.

The amount carbon accumulation of surface peat layers depends upon the mire site type, vegetation and natural state; variations reflect differences in plant communities as well as factors that affect biomass production and decay rates. The highest accumulation rates and thus carbon binding for layers younger than 300 years were measured in the ombrotrophic mire site types (*Sphagnum fuscum* bog and *Sphagnum fuscum* pine bog), and the second highest rates in wet, treeless oligotrophic and minerotrophic mire site types. The lowest values of carbon accumulation over the last 300 years were obtained for the most transformed, sparsely forested and forested mire site types, where the water table was lowest. Depending on the nutrient conditions of mires, carbon binding can decrease or increase after drainage. At the most nutrient poor sites, carbon binding can increase after drainage.

Keywords (GeoRef Thesaurus, AGI): mires, peatlands, drainage, peat, carbon, deposition, nitrogen, Holocene, Finland, Russian Federation, Republic of Karelia

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INTRODUCTION

Whilst the carbon accumulation of peat layers has been quite intensively studied in mires (e.g. Tolonen et al. 1992, Turunen et al. 2002, Laine et al. 2004, Mäkilä 1997, Mäkilä et al. 2001, Mäkilä & Moisanen 2007, Mäkilä & Saarnisto 2008), information on carbon accumulation in drained mires is scarce (e.g. Minkkinen et al. 1998, Laine et al. 2004). This paper describes a comparative study of rates of carbon accumulation of three types of boreal mires, with and without artificial drainage. The approach involves the derivation of mean carbon accumulation rates, as well as the rates over their full Holocene lifetimes. The aim of this study was to examine the influence of drainage, mire site type and vegetation on the accumulation of carbon over the last 300 years and to define the role of mires as a carbon sink and source.

MATERIALS AND METHODS

Net rates of carbon accumulation over different time periods were determined by ^{14}C dating of material from different depths of peat columns. These were collected in connection with a Geological Survey of Finland peat inventory from 69 peat columns from 48 mires in southern and central Finland and four columns in Russian Karelia. The quantities of carbon sequestered during recent centuries and over the entire lifetimes of the mires were determined using a total of 367 dates (186 ^{14}C AMS and 181 conventional dates) and age-depth models derived from bulk density measurements (Mäkilä & Goslar 2008). Several datings were performed for different depth zones of some mires (3–19 dates per column).

Study sites

The locations of the study sites relative to the principal Finnish mire regions (aapa minerotrophic mire and raised oligotrophic bog) are indicated in Figure 1. The sites were also classified as pristine or drained. A pristine mire is defined here as one that appears to largely be in a natural condition and undrained, although marginal ditches may be present (Mäkilä & Goslar 2008).

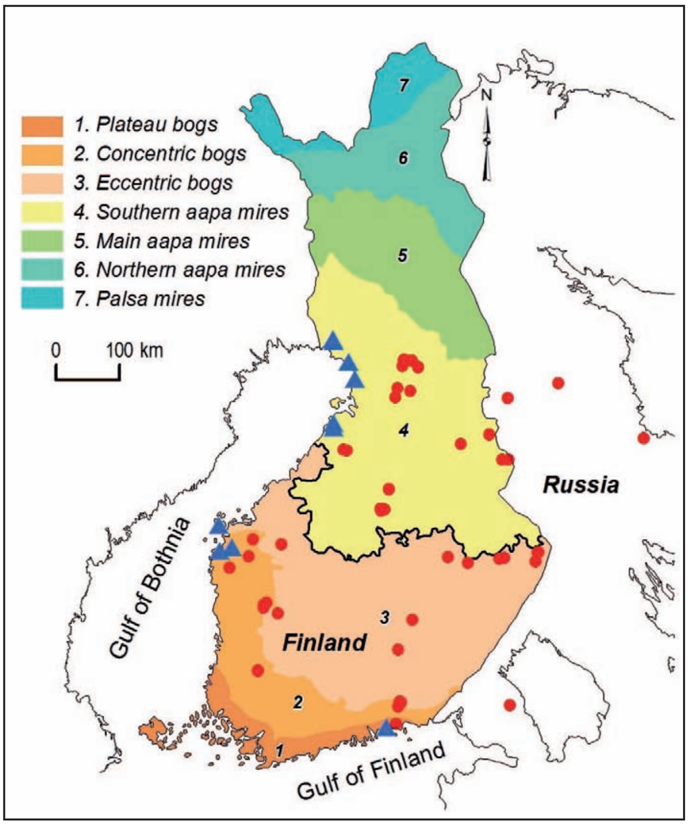

Figure 1. Locations of the study sites superimposed on the mire complex type regions (numbered 1–7) of Finland according to Ruuhijärvi & Hosiaisluoma (1989). Coastal mires are marked with blue triangles. The raised bog region occurs to the south of the black line (Regions 1–3) and the aapa mire area to the north (Regions 4–7).

Sample collection

Shallow volumetric samples of 10x10 cm square and 20 cm deep were obtained using a metal frame (Mäkilä & Goslar 2008) (Figure 2). Deeper samples were obtained using a volumetric piston sampler (8 cm diameter, 20 cm long) or a 5-cm-diameter Russian peat sampler.

Figure 2. A mire surface profile, revealed during the collection of a shallow volumetric peat sample from Kuuhkamonneva, Vihanti. Photo: Markku Mäkilä.

Dry bulk density measurements, carbon and nitrogen analysis

Dry bulk density and water content were determined from volumetric samples dried to constant weight at 105 °C. A Leco CHN 600 analyser was used to determine carbon and nitrogen contents as proportions of total dry matter.

AMS ^{14}C dating

In order to obtain high-resolution records, samples for ^{14}C dating were taken from (3–5 mm thick) slices. The material selected was mostly pure *Sphagnum*, because this species forms the bulk of most peat deposits. As the amount of pure *Sphagnum* available in each sample was small, the only suitable method for ^{14}C dating was accelerator mass spectrometry (AMS), which was carried out at the Poznan Radiocarbon Laboratory (Poz) in Poland (Goslar et al. 2004, Goslar et al. 2005). Accurate dating is important for all approaches, and is highly important when using age-depth models to calculate rates of peat increment and carbon accumulation. AMS dating can provide more accurate dating results than conventional ^{14}C dating because it requires much less material for the analysis and is often more precise (smaller error estimate). This is why AMS ^{14}C dating has been used with surface peat layers. The samples taken before 2003 were dated in the ^{14}C laboratory of the Geological Survey of Finland (Su).

RESULTS

Calculation of accumulation rate and carbon pool

The long-term apparent rate of carbon accumulation for the entire peat deposit (LARCA), and the actual rate of carbon accumulation (ARCA 300 = layers <300 years old) were calculated using peat columns of known dry bulk density, carbon content and age according to Clymo et al. (1998) The following equation was used to the calculate carbon accumulation rates:

$A^c = r \times \rho \times C \times 1000$

Where A^c = carbon accumulation rate (g m^{-2} yr^{-1}), r = rate of vertical peat increment (mm yr^{-1}), ρ = dry bulk density (g cm^{-3}) and C = carbon content as a proportion of dry bulk density (%). Separate mean values were calculated for different mire site types, regions and on the basis of the natural status of mires, i.e. pristine v. drained.

Dry bulk density, carbon and nitrogen contents

The average dry bulk density in peat layers younger than 300 years was 56.9 kg m^{-3} at pristine sites and 68.6 kg m^{-3} at drained sites. The proportion of carbon and the nitrogen was slightly lower at pristine sites than at drained sites (Table 1). As the carbon content remains rather similar in different types of environments, the change in the C:N ratio is mainly due the proportional change in nitrogen (N). The C:N ratio increased as the proportion of nitrogen decreased. Importantly, higher carbon accumulation rates correlated with a low nitrogen content and high C:N ratio. A higher peat increment (thickness) correlated with a low dry bulk density, low nitrogen content and high C:N ratio (Table 1). In the present study, the lowest nitrogen and carbon contents were found in coastal *Sphagnum* bogs and the highest in the *Carex* aapa mire region, whilst the C:N ratio was slightly higher in coastal mires than in the raised bog region (Table 1).

Table 1. Mean values of the carbon accumulation rate, thickness, dry bulk density, C and N content and C:N ratio for surface layers younger than 300 years of the study sites, calculated according to mire region and natural state.

Region	Natural state	Carbon accumulation rate g m^{-2} yr^{-1}	Thickness m	Dry bulk density kg m^{-3}	C %	N %	C:N Ratio %
Aapa mire	Pristine	36.0	0.40	60.0	46.0	1.46	34.7
	Drained	30.0	0.31	68.3	45.8	1.50	37.9
Raised bog	Pristine	46.0	0.55	56.2	46.1	0.90	53.4
	Drained	33.7	0.32	69.3	47.5	1.34	40.6
Coastal mire	Pristine	60.4	0.74	52.4	44.5	0.99	46.5
	Drained	65.9	0.69	63.0	45.8	0.87	53.5
All studied columns	Pristine	45.3	0.53	56.9	45.8	1.16	43.7
	Drained	34.5	0.34	68.6	46.8	1.36	40.6

Carbon accumulation rate

The average carbon accumulation values in entire peat layer was 24.0 g m^{-2} yr^{-1} at pristine sites and 19.4 g m^{-2} yr^{-1} at drained sites. The average carbon accumulation calculated for each of the three mire regions was 14.6 g m^{-2} yr^{-1} for the aapa mire region, 19.8 g m^{-2} yr^{-1} for the raised bog region and 43.0 g m^{-2} yr^{-1} for coastal mires (Table 2). The mean value for peat layers younger than 300 years was 33.8 g m^{-2} yr^{-1} for the aapa mire region, 38.4 g m^{-2} yr^{-1} for the raised bog region and 61.3 g m^{-2} yr^{-1} for coastal mires (Table 1). The carbon accumulation rates were lower at drained sites than at pristine sites, except for coastal mires, whereas dry bulk density and carbon content were higher at drained sites than at pristine sites, except for the aapa mire region (Table 1).

Table 2. Mean values of the apparent carbon accumulation rate, thickness and age for entire peat profiles, calculated for each of the three mire regions and a natural state.

Region	Natural state	Carbon accumulation rate g m^{-2} yr^{-1}	Thickness m	AMS-^{14}C Age yrs cal. BP
Aapa mire	Pristine	14.3	2.71	8312
	Drained	15.2	1.84	5586
Raised bog	Pristine	23.6	3.78	5585
	Drained	17.5	2.58	6953
Coastal mire	Pristine	40.9	1,80	1653
	Drained	53.2	1.74	1005
All studied columns	Pristine	24.0	2.78	5857
	Drained	19.4	2.31	6138

Plant components and the degree of decomposition estimated from the preservation state of moss remains indicate that the carbon accumulation rate for layers younger than 300 years is highest at ombrotrophic mire site types (*Sphagnum fuscum* bog and *Sphagnum fuscum* pine bog), and the second highest rates were recorded at wet, treeless oligotrophic and minerotrophic mire site types. The lowest values for layers younger than 300 years were obtained for the most transformed, sparsely forested and forested mire site types (Figure 3).

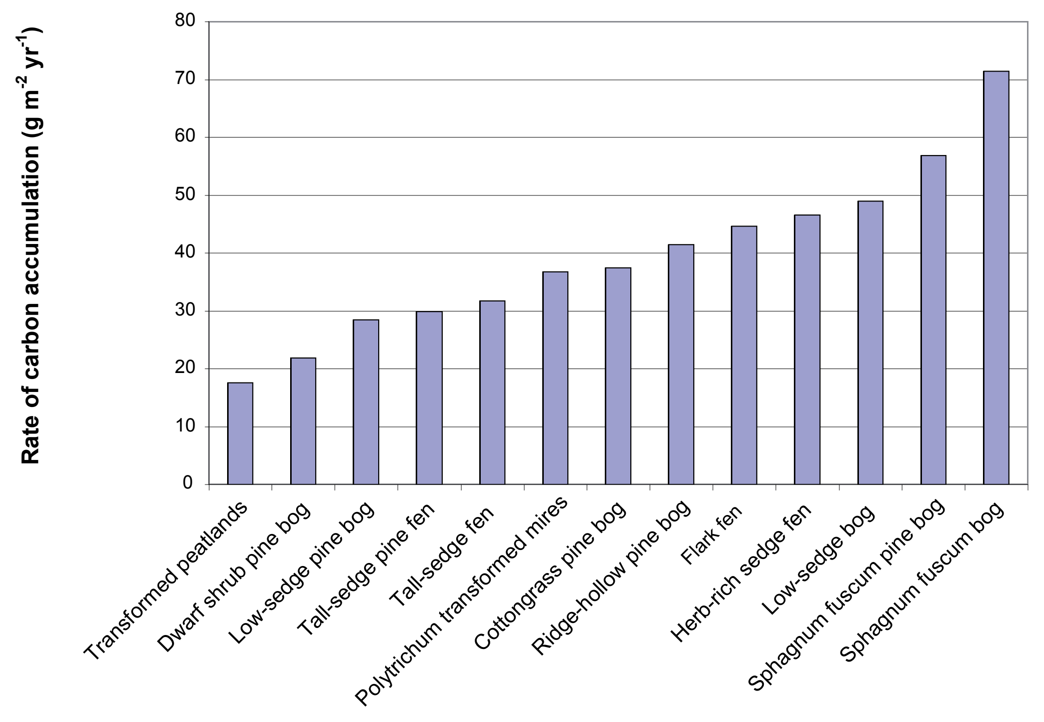

Figure 3. Average carbon accumulation rates for layers younger than 300 years, calculated for the different mire site types and drained peatlands represented amongst the study sites. English names of mire site types according to Laine & Vasander (1990).

DISCUSSION

Variation in carbon accumulation rate in relation to mire site type and peat type

Due to natural mire succession and variations in local conditions, spatial variation in the carbon accumulation rate can largely be explained in terms of the composition of the vegetation and decomposition rates. Connections have commonly been observed between mire vegetation, its nutrient content and moisture status (Laine & Vanha-Majamaa 1992, Laine et al. 1995, Laiho 2006). The highest carbon accumulation rates and thus carbon binding were found in coastal mires, where species of *Sphagnum* sect. *Acutifolia* with a low carbon and nitrogen content are prevalent. This younger bog type produces more moss than an old bog, and the amount of decayed and compacted peat is lower.

For *Carex* species, production is mainly determined by the availability of nutrients such as nitrogen and phosphorus, whereas decay rates vary according to the nutrient contents of their different parts (Thormann et al. 2001). In the present study, the lowest nitrogen and carbon contents were found in coastal *Sphagnum* bogs and the highest in the *Carex* aapa mire region, whilst the C:N ratio was slightly higher in coastal mires than in the raised bog region. The lower carbon accumulation values of <300-year-old surface layers were recorded where *Carex* species dominate and *Sphagnum* moss is mainly decomposed, and the lowest values were found in sparsely forested and forested mire site types where the water table was lowest.

Effect of drainage on carbon accumulation

In the present study, carbon accumulation rates were generally lower at drained sites than at pristine sites, whereas dry bulk density and carbon content were higher at drained sites than at pristine sites. Drained sites are often initially more nutrient-rich than pristine areas. Organic matter decomposes more rapidly, resulting in thinner peat layers and lower carbon accumulation as well as a higher dry bulk density and carbon content than at pristine sites (Table 1). At nutrient-rich sites the decomposition of peat can increase so much that carbon is lost from peat to the atmosphere, whereas in the most nutrient poor sites, carbon binding can increase after drainage. Methane emissions in drained areas are always lower than in pristine areas (Laine et al. 2004).

For the less than 300-year-old peat layers studied here, the average thickness was 19 cm less and the carbon accumulation rate 10.8 g m^{-2} yr^{-1} lower in drained areas than in pristine areas (Table 1). The low bulk density and high total porosity of peat means that drainage causes subsidence of the mire surface, which may be in the order of 15–40 cm during the first decades after drainage (Minkkinen & Laine 1998). The slower rate of vertical growth is mainly explained by secondary compaction, reflected by the greater dry bulk density values for drained areas, which in turn are confirmed by the data of Mäkilä (1994) for almost 50 000 volumetric samples collected from pristine and drained mires in various parts of Finland. Initially, most of the subsidence occurs through physical collapse of the peat matrix as water is removed, but later the phenomenon is increasingly attributable to oxidation and decomposition of the peat (Päivänen & Paavilainen 1996).

As a direct result of drainage, buoyancy is lost and the moss carpet collapses, causing the surface of the mire to sink. Later, subsidence continues as the rate of oxic decomposition in the surface layers increases. However, upward growth of mosses and the accumulation of organic matter at the surface of the peatland may continue simultaneously with decomposition and compaction of sub-surface peat (Laine et al. 2004). Carbon accumulation generally decreases after drainage, but in some cases the height growth of peatlands does not end. This is because decomposition conditions do not become radically better after drainage and increased tree growth enhances the flow of organic carbon to the soil (Minkkinen et al. 1999). In drained peatlands, a *ca*. 10 cm layer of raw humus formed by mosses and tree litter is often found on the original surface (Minkkinen et al. 1999). Mires of this kind are also included in the present study, showing that carbon binding can increase after drainage.

CONCLUSIONS

It is difficult to compare peat properties and carbon accumulation rates between pristine and drained mires. Drained sites are often initially more nutrient-rich than pristine areas. Organic matter has decomposed more rapidly, resulting in thinner peat layers and lower carbon accumulation as well as a higher dry bulk density and carbon content than at pristine sites. Besides the natural state, the accumulation of carbon by surface peat layers also depends on the mire site type and vegetation. Variations reflect differences in plant communities as well as factors that affect biomass production and decay rates. The highest accumulation rates and thus highest carbon binding for layers younger than 300 years were measured in ombrotrophic mire site types, and the second highest rates in wet, treeless oligotrophic and minerotrophic mire site types. The lower values over the last 300 years were obtained for sparsely forested and forested mire site types and the lowest values were from the most transformed peatlands where the water table was lowest. Depending on the nutrient conditions of mires, carbon binding can decrease or increase after drainage. At the most nutrient poor sites, carbon binding can increase after drainage. The results indicate how important it is to understand the carbon accumulation rates of surface layers and the long-term dynamics of mire carbon accumulation in order to set the current flux estimates in perspective.

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GEOENERGY RESEARCH AND ITS UTILIZATION IN FINLAND

by
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Kallio, J., Leppäharju, N., Martinkauppi, I. & Nousiainen, M. 2011. Geoenergy research and its utilization in Finland. *Geological Survey of Finland, Special Paper 49*, 179–185, 5 figures.

Geoenergy is energy that is stored in the ground or water and used to heat and cool buildings. Most shallow geoenergy originates from solar radiation, and in Finland it is utilized via heat pumps. Geoenergy from the bedrock is utilized by means of borehole heat exchangers (BHE). The thermal properties of a BHE and the bedrock can be determined using a thermal response test (TRT). The Geological Survey of Finland (GTK) has its own TRT rig built in 2008. TRT results are used for case-specific modelling of BHE systems, which includes optimizing the number, depth and location of the BHEs. Careful modelling ensures that a BHE system is sustainable and the possible temperature changes in the geoenergy source are moderate. BHE systems can be observed in situ using the distributed temperature sensing (DTS) method. A DTS device measures temperatures via a fibre optic cable and is used, for instance, to determine the temperature profile of the bedrock.

Keywords (GeoRef Thesaurus, AGI): energy sources, geothermal energy, bedrock, boreholes, temperature logging, thermal response test, distributed temperature sensing, Finland

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GEOENERGY IN FINLAND

Geoenergy is energy that is stored in soil, bedrock, groundwater, sediment layers or lake, river or sea water. Geoenergy in Finnish conditions is mostly shallow geoenergy stored in the first hundred metres of the Earth's surface. Most of this shallow geoenergy originates from solar radiation and a smaller proportion consists of geothermal energy from the inner parts of the Earth's crust. Geoenergy is used to heat and cool buildings and utilized by means of heat pumps in areas of low enthalpy (cool crust), such as in Finland. The seasonal performance factor (SPF) of a heat pump is usually about 3, which means that 2/3 of the energy comes from the Earth, free of charge. The rest comes from electricity required to run the pump. Geoenergy is a renewable, sustainable and environmentally friendly energy form.

The Geological Survey of Finland (GTK) aims at increasing the utilization and general awareness of geoenergy and its application in Finland. GTK has strongly invested in R&D and technology transfer activities, the development of its own methodology and practices and the promotion of geoenergy together with commercial actors and end-users. The focus is on large-scale commercial projects such as shopping centres, office buildings and logistics centres in cooperation with companies and other leading domestic and international research institutes. Most of the projects are commercial, and the obtained data are therefore confidential.

The total number of ground-source heat pumps (GSHP) and also the number of GSHPs installed per year have rapidly increased in the 2000s, as Figure 1 illustrates. Finland is one of the countries with fastest growing number of heat pumps. The total number of GSHPs installed in Finland by 2008 was approximately 46 000, and about 7 500 new heat pumps were installed in 2008. The annual increase in this sector is approximately 30%. (Suomen Lämpöpumppuyhdistys Sulpu ry., Finnish Heat Pump Association 2009)

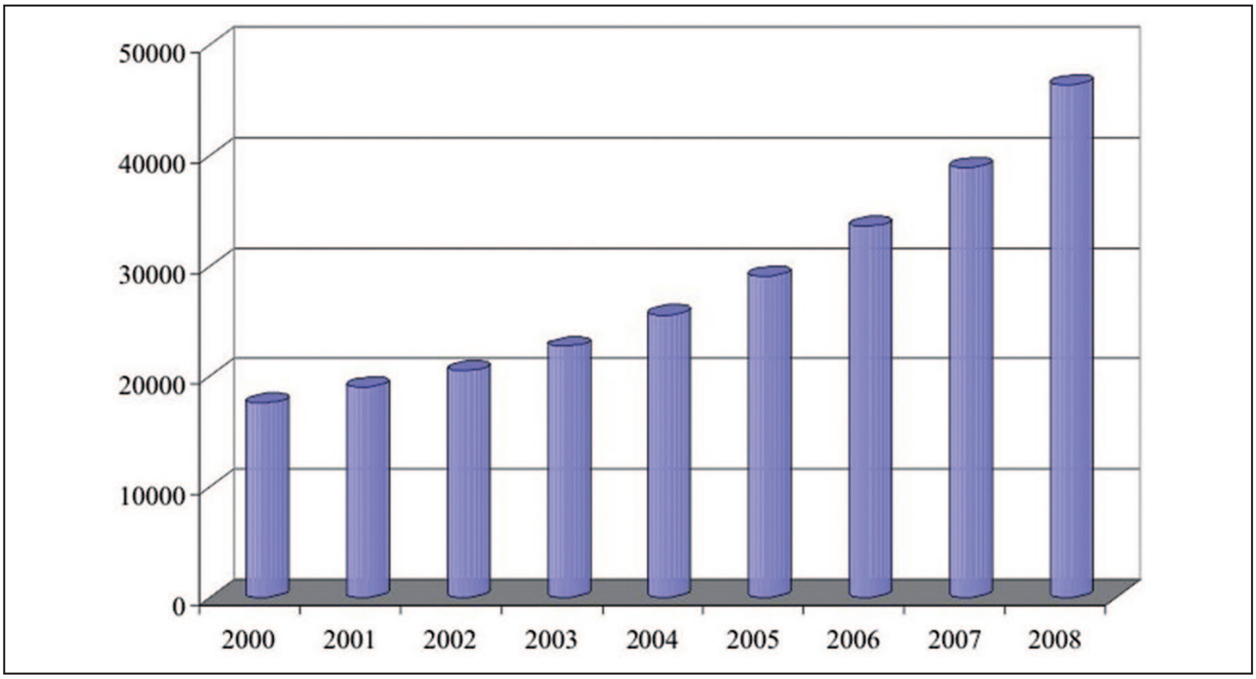

Figure 1. Total number of ground source heat pumps in Finland in 2000–2008. (Suomen Lämpöpumppuyhdistys Sulpu ry., Finnish Heat Pump Association 2009)

GEOLOGICAL SETTINGS IN FINLAND REGARDING GEOENERGY

The average heat flow in Finland is 0.037 W/m^2, which is below the continental average of 0.065 W/m^2. The geothermal gradient is usually 8–15 K/km. The low gradient is due to the Precambrian geology, with a very thick lithosphere (150–200 km). The climatically controlled annual average ground temperatures range from over 6 °C in southern Finland to less than 2 °C in Northern Lapland (Figure 2). (Kukkonen 2000)

The average thermal conductivity of Finnish rocks is 3.24 W/(m*K) (Peltoniemi 1996). In most rock types, the mean thermal conductivity is 2–4 W/ (m*K). Thermal conductivity is controlled by the mineral composition, texture and porosity of the rock and pore filling fluids (Clauser & Huenges 1995).

GTK will compile a national map of the geoenergy potential in Finland, which is affected by factors such as the lithology, depth of soil, groundwater conditions and the thermal conductivity of the bedrock. A national borehole register is also in progress.

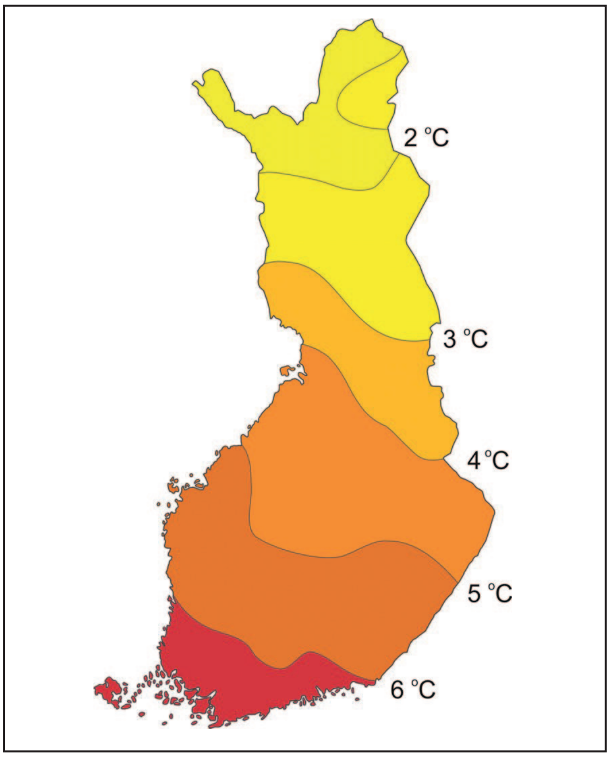

Figure 2. Annual average ground surface temperatures in Finland. (Leppäharju 2008)

THERMAL RESPONSE TEST (TRT)

TRT measurement

The idea of a thermal response test (TRT) is to measure the thermal properties of a borehole *in situ*. A TRT simulates the behaviour of a borehole heat exchanger (BHE). The TRT equipment heats up the heat carrier fluid at constant power and circulates it through the BHE. When the fluid temperatures in the ingoing and outgoing pipes are measured, the effective thermal conductivity and thermal resistance of the borehole can be determined. These parameters are needed in modelling a BHE system. (Eklöf & Gehlin 1996)

TRT measurements have become increasingly popular since the late 1990s. Nowadays, it is a routine procedure in many countries for designing a large BHE system (Sanner et al. 2005). TRT measurement has become a necessity for modelling a large BHE system with several BHEs, enabling scaling of the BHE system based on reliable underground data.

In Finland, the first thermal response test (TRT) equipment was constructed in spring 2008. In 2009, GTK conducted a total of 17 thermal response tests at 8 sites. Most of the research areas were sites where a commercial building or a residential area will be constructed. The TRT results were used in modelling the BHE system. GTK's TRT rig is especially designed for the cold climate and uses advanced technology in measurement control and data collection.

Figure 3. A thermal response test in progress in 2009. Photo: Ilkka Martinkauppi, GTK.

Method development

The International Energy Agency (IEA) has several Implementing Agreements (IA) concerning renewable energy, among other topics. One of these IAs is Energy Conservation though Energy Storage (ECES). GTK is the representative of Finland in ECES and one of the subtask leaders in ECES Annex 21.

ECES Annex 21 is focused on the development and unification of the thermal response test, especially for underground energy storages. In Annex 21, experts from 15 countries are working together to compile TRT experiences worldwide, to develop the method further and disseminate the knowledge gained and the technology. Annex 21 will also initiate a worldwide TRT standard.

In connection to the cooperation in ECES, but also separate from it, GTK has started agreement-based cooperation with the Japanese Kyushu University and Professor Fujii's team. This work is concentrating on top-quality development of borehole heat exchanger theory and modelling. GTK is also coordinating a national GEOENER project, which is aiming at the concept development of large-scale geoenergy systems. Several Finnish companies from different branches together with educational institutes are participating in GEOENER.

DISTRIBUTED TEMPERATURE SENSING

Distributed temperature sensing (DTS) involves the measurement of temperature with a fibre optic cable. The DTS device sends a laser pulse to the fibre, which works as a temperature sensor. The laser pulse of a particular wavelength scatters and some of it returns to the DTS device to be analyzed. The backscattered light contains information about the temperature at the scattering point, which is determined by the travel time of the incident light. The backscattering is caused by the Raman effect.

The Raman effect produces temperature-dependent Stokes and anti-Stokes signals, and their amplitude ratio is used to determine the temperature. The DTS device simultaneously measures the temperatures along the whole cable length. To obtain accurate temperature readings, every measurement must be calibrated. After good calibration the temperature accuracy is better than 0.1 C. (Tyler et al. 2009)

GTK uses DTS in geoenergy research to measure borehole temperatures and monitor BHE systems that are in use. The monitoring of active boreholes provides valuable information on how the system functions *in situ* and how the adjacent boreholes in a large BHE system affect each other. GTK recommends DTS monitoring for large BHE systems. GTK has also carried out some tests with simultaneous DTS and TRT measurements. One interesting aspect in the future would be to monitor the heat outflow from new buildings to the ground under them.

Figure 4. A DTS measurement in 2009. The DTS device is the light grey box under the laptop. Photo: Ilkka Martinkauppi, GTK.

MODELLING OF THE BOREHOLE HEAT EXCHANGER SYSTEM

Modelling of the BHE system means optimizing the number, depth and location of the boreholes. The area reserved for the boreholes, thermal properties of the bedrock, monthly heating and cooling needs of the buildings and technical properties of the borehole and heat carrier fluid all affect the modelling results. It is necessary to conduct TRT measurement before modelling the BHE system so that the exact thermal conductivity of the bedrock and the thermal resistance of the boreholes are known. GTK optimizes every system case-specifically in close co-operation with HVAC (heating, ventilation, air-conditioning) engineers. GTK has mostly designed large BHE systems consisting of tens of boreholes.

In heating mode (winter), the heat pump extracts heat from the boreholes, which causes the system to cool down. In cooling mode (summer), some energy is returned to the boreholes. In Finland, buildings usually need more heating than cooling, so the geoenergy source tends to cool down. Careful modelling of the BHE systems makes sure that the annual temperature decrease in the system is low enough. In this way, the coefficient of performance (COP) of the heat pump remains continuously high and the whole BHE system is efficient and sustainable. It is also important to note that the boreholes affect each other.

CASE STUDY: GEOENERGY STUDY FOR A LOGISTICS CENTRE IN SIPOO, SOUTHERN FINLAND

In autumn 2008, GTK carried out an extensive geoenergy study for the retail cooperative SOK in Sipoo, Southern Finland, at a site where a new SOK logistics centre will be built. The study included geological bedrock mapping, a fracture study, bore powder analysis and TRT measurements.

The geological bedrock mapping revealed a diagonal contact between two different rock types, diorite and granite gneiss, in the middle of the area. In addition, the granite gneiss was much more fractured than the diorite. Therefore, test boreholes were drilled on both sides of the contact and an additional borehole was placed near the contact. The TRT measurements showed that there is a significant difference in the effective thermal conductivity between the diorite and the gneiss sides of the contact.

The results were used in modelling a BHE system for the hall. The final BHE system will consist of 150 BHEs, each 300 metres deep. Optical cables for DTS measurements will be installed in some of the boreholes, and in the coming years GTK will monitor the temperature development of the BHE system.

Figure 5. A thermal response test in Sipoo. Photo: Ilkka Martinkauppi, GTK.

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CO_2 CAPTURE AND GEOLOGICAL STORAGE APPLICATIONS IN FINLAND

by
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Aatos, S., Kujanpää, L. & Teir, S. 2011. CO_2 capture and geological storage applications in Finland. *Geological Survey of Finland, Special Paper 49*, 187–193, 2 figures.

This article introduces the pioneering CO_2 capture and geological storage (CCS) technology development projects in Finland and their geological applications at the Geological Survey of Finland (GTK) in collaboration with Finnish CCS technology research and development partners and administrative authorities. The CCS projects have been funded by the Finnish CO_2 producing and CCS technologies developing industry, the Finnish Funding Agency for Technology and Innovation (Tekes) and GTK. In this paper, special emphasis is placed on presenting research and development results and proposals for CCS in Finnish conditions that have been produced during recent collaboration between VTT Technical Research Centre of Finland and GTK.

Keywords (GeoRef Thesaurus, AGI): carbon dioxide, carbon sequestration, underground storage, bedrock, serpentinite, Finland

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INTRODUCTION

In recent years, carbon capture and storage (CCS) has emerged as one of the potentially best technologies for mitigating the ongoing climate change. The idea is to separate carbon dioxide (CO_2) from an industrial source, such as a power plant or a CO_2-emitting industrial plant, and transport it to a geological storage site, where the CO_2 is to remain isolated from the atmosphere for thousands of years. CCS is currently seen as a temporary solution for industrial mitigation of CO_2 while awaiting the development of CO_2-neutral or zero CO_2 emission technologies and processes.

Geological storage of CO_2 (CGS) by injection into underground reservoirs at a depth of 800 metres or more appears to be the only storage alternative that has been demonstrated on a sufficiently large scale by the oil and gas industry. These reservoirs include depleted oil and gas reservoirs, saline aquifers and deep unmineable coal seams. The reservoirs need to have stratigraphic or other low permeability layering to trap the CO_2 in subsurface conditions. CO_2 can also be injected to enhance the production yield of nearly depleted oil and gas reservoirs. Safe utilisation of underground geological storage requires continuous monitoring of the migration of CO_2 in the reservoir. In addition, a closed storage site needs to be monitored in order to ensure that the CO_2 remains stored. Natural physical and chemical subsurface analogues of CO_2 storage found in various geological environments help in estimating the long-term behaviour CO_2 in geological storage. (IPCC 2005)

CCS technology is not yet commercially available, but it is under extensive research and development globally. Mineral carbonation or fixation of CO_2 into mineral carbonates is also a theoretically possible option for CCS, but feasible energy-efficient technologies have not yet been developed (Zevenhoven & Fagerlund 2009).

The possibilities for applying CCS in Finland have been identified by a national research project entitled "Application of carbon capture and storage in Finland (CCS Finland, 2008–2010)", coordinated by VTT Technical Research Centre of Finland and financed by Tekes. In the project, as part of the CCS chain from the industrial emission source to the geological storage site, the Geological Survey of Finland (GTK) has been offering geological expertise on Finnish geology. A key result from these studies is that Finnish crystalline bedrock is generally not favourable for large-scale CO_2 storage, since the free pore space in the hard granitic and gneissic rocks is minimal.

During the CCS Finland project, GTK has also provided geological expertise in a national background group established by the Finnish Ministry of the Environment during the preparation of the EU CCS directive. The new CCS directive (EU 2009) presents a legal framework for enabling environmentally-safe capture and geological storage of CO_2 in the European Community. The directive regulates the planning, opening, operating, closing and monitoring of storage sites and includes legal procedures for the transportation of captured CO_2 between member states.

Some aspects of long-term carbon dioxide storage by mineral carbonation have previously been investigated in the project "ECOSERP" by GTK as part of the national collaborative research project "CO_2 Nordic Plus" (Zevenhoven et al. 2006).

CCS IN FINLAND

Most Finnish CO_2 emissions originate from energy-intensive industry as well as heat and electricity production based partly on fossil fuels. In 2008, the national carbon dioxide emissions that formed part of the EU trading scheme amounted to 36 Mt/a. There were 63 large (>0.1 Mt/a) stationary CO_2 emission sources in Finland in 2008, of which 5 sources exceeded 1 Mt/a of CO_2 emissions (EU ETS 2009). The largest fossil CO_2 emission sources are located along the Finnish coast, but they are spread quite evenly apart, except for an accumulation around the Helsinki region (Figure 1).

In Finland, several companies and research institutes are actively developing CCS. Fortum and TVO are planning to develop a CCS solution for their Meri-Pori power plant, which will begin operation in 2015. The captured CO_2 is planned to be shipped by tankers to the North Sea for storage. CCS could also be applied for condensing power plants based on coal and peat if the price of CO_2 emission allowances becomes feasible in the coming decades.

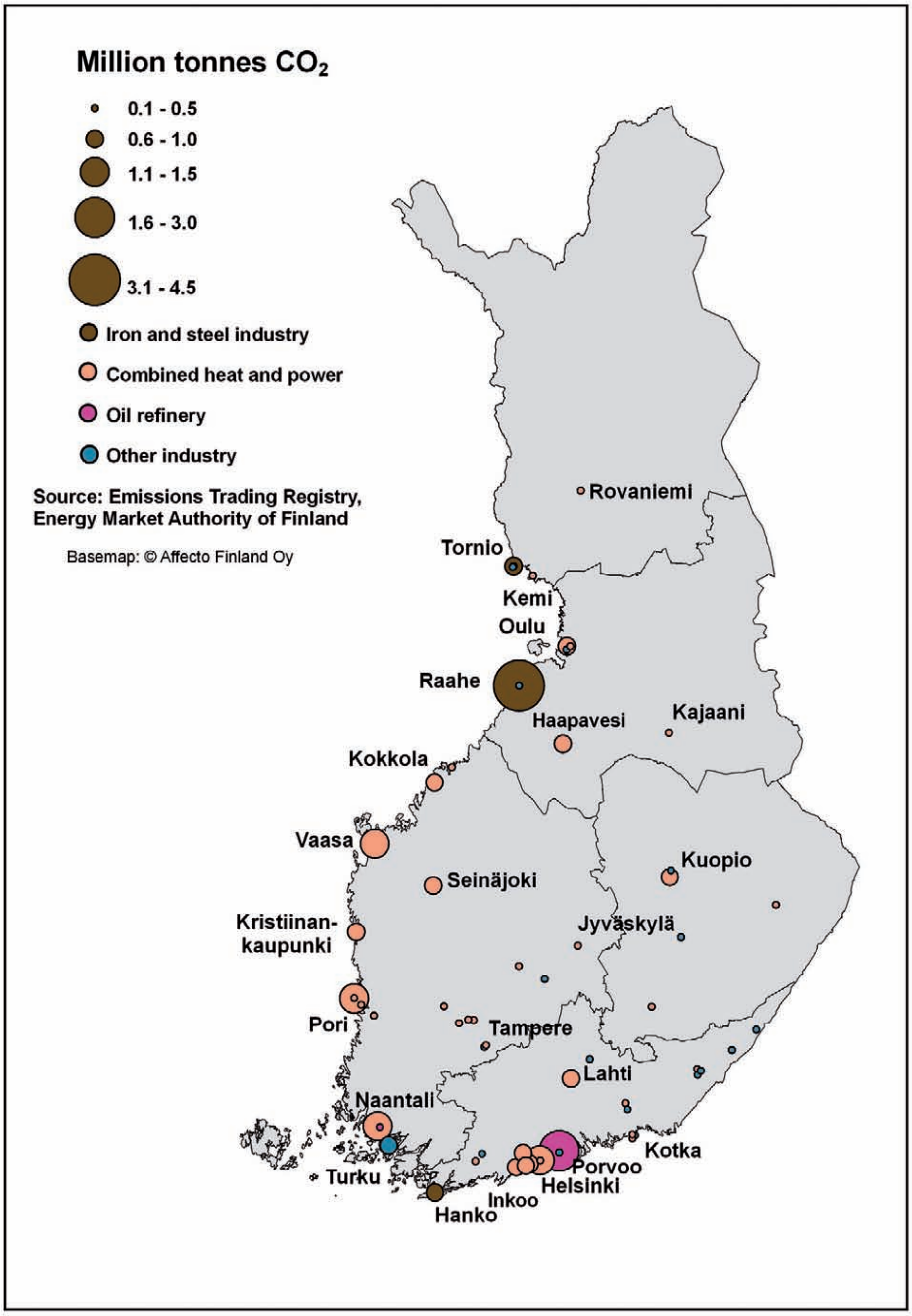

Figure 1. The largest CO_2 emission sources in Finland in 2008 (Figure source: CCS Finland project. GIS map production: Matti Partanen, GTK).

GEOLOGICAL STORAGE POTENTIAL OF CO_2 IN FINLAND

The CGS capacities of the sedimentary bedrock formations of Finland and the Finnish economic zone in the Baltic Sea area have been screened on the country level by Solismaa (2009) according to the site selection procedure for CO_2 storage projects. The prospects for storage of CO_2 are insignificant in Finland. The Finnish bedrock is mainly of Precambrian age (Figure 2) and does not have any hydrocarbon reservoirs. Most of the sedimentary rocks are compact, which makes the occurrence of saline aquifers unlikely. Insufficient geological data are available on the physical storage properties of Finnish sedimentary rocks. Despite the existence of younger sedimentary rock formations in the Finnish sea area, their characteristics and depth are relatively unknown (Solismaa 2009). The closest verified storage formations to Finland are located in Sleipner in the North Sea and Snøhvit in the Norwegian Barents Sea. The distance from the costal industrial plants to the current CO_2 injection sites ranges from 900 to 2 400 km.

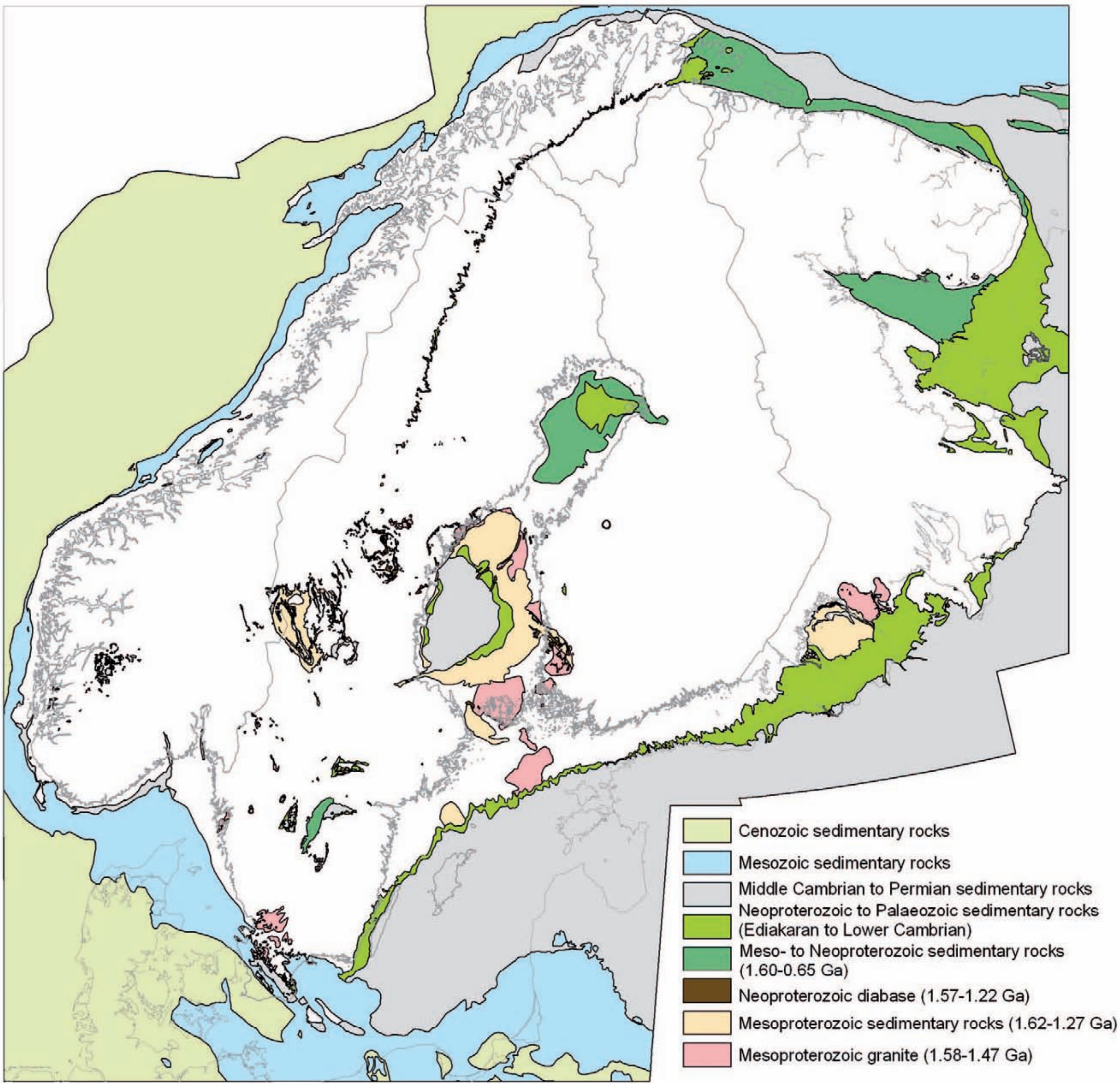

Figure 2. Sedimentary rocks on the Fennoscandian shield and surrounding areas (Solismaa 2009, modified from: Koistinen et al. 2001, legend: Jukka Kousa, GIS map production: Matti Partanen).

The Finnish peat formations and weathered bedrock occurrences are also too thin for CGS purposes (Mäkilä & Pajunen 2008, Kejonen 2010). Although the Quaternary deposits may have sufficient porosity for storing CO_2 (Cherepovitsyn & Ilinsky 2006), the thickness of the Finnish Quaternary deposits is expected to be insignificant for CGS.

CONDITIONS FOR INTERMEDIATE STORAGE OF CO_2 IN FINNISH BEDROCK

The transportation by ship of captured and liquefied CO_2 will generate a need for intermediate storage facilities for CO_2 at shipping terminals. At current transportation volumes of CO_2, cylindrical steel tanks have been shown to be the best solution due to their commercial availability and modular construction, which also makes the proven technology easily scalable. However, when the storage volume substantially exceeds that currently needed at CO_2 terminals, storage in a cavern excavated in solid bedrock could become the most economical alternative. Kaarstad & Hustad (2003) proposed that cavern excavation should be considered when the storage volume reaches 50 000 m^3 of CO_2.

The CO_2 storage cavern design is analogous to existing rock cavern storages for liquefied gas (e.g.

for petroleum or propane, LPG). Unlined rock caverns have widely been used to store liquid propane, with standardized operational recommendations for both the cavern itself and for the surface installations (SFS-EN 1918-4:en, SFS-EN 1918-5). Rock cavern storages are applicable to geological conditions such as hard igneous or metamorphic rocks (granite, gneiss and andesite), sedimentary rocks (limestone, cemented sandstone, quartzite, chalk and shale) and marl (SFS-EN 1918-4:en).

Following the working principles of unlined LPG rock storage caverns, the containment of liquid CO_2 in a cavern is hydraulically ensured by the prevailing groundwater pressure. Adequate hydraulic pressure is ensured by locating the cave at sufficient depth below the groundwater table. Artificial water curtains can be drilled to surround the cave if necessary. Besides the natural hydrostatic head and the overall hydrological setting around the cavern, the maximum operating pressure is defined on the basis of geothermal temperature (SFS-EN 1918-4:en).

In order to keep the stored CO_2 at its highest density in a liquid state, the cavern pressure and temperature must be as close as possible to the triple point (5.2 bar, -56.6 °C). Therefore, a similar pressure and temperature as envisaged for semi-pressurized large-scale CO_2 carrier ships should be used. Aspelund et al. (2006) recommend a pressure of 6.5 bar and a temperature of -52.0 °C for both intermediate storage at the terminal and the ship transportation stage.

Ikäheimonen et al. (1989) have described refrigerated rock cavern storage as one of the most economical uses of underground space, e.g. in Finnish applications for warehouse purposes. The scope of the previously mentioned underground gas storage standards does not cover refrigerated gas storage (SFS-EN 1918-4:en, SFS-EN 1918-5). The concepts of refrigerated hard rock cavern gas storage have been outlined for the US Department of Energy. Refrigerated cavern rock types are expected to be strong, uniform, consistent and free of fractures. Large sized refrigerated, self-supporting and tight caverns are preferred to be constructed in impervious igneous and metamorphic rocks (PB-KBB INC. 1998).

The rock cavern wall undergoes physical changes due to refrigeration. According to Glamheden & Lindblom (2002), the compressive rock stresses relax, existing fractures open and new fractures emerge as a consequence of low temperatures. If needed, the cavern can be tightened and reinforced by applying a lining, such as steel supports and shot concrete (Glamheden & Curtis 2006). The low temperature of stored CO_2 would in any case cause an ice ring of groundwater around the cavern, and thus undesired mixing of stored CO_2 and groundwater should not occur.

Underground rock cavern storage for gas may cause detectable and perceptible local seismic events near or along geological faults by tectonic stress. Other observable causes may result in existing cavities breaking up via stress release, e.g. by a rising groundwater level. This fact has to be considered in planning and monitoring rock cavern gas operations (Brož et al. 2001), as well as groundwater effects.

MINERAL CARBONATION

Research on carbon capture and storage by mineral carbonation was started in Finland by Helsinki University of Technology (HUT). GTK joined the research in collaboration with HUT, Outokumpu and later with Åbo Akademi in 2004, with the combined economic and environmental interest of finding a sustainable use for serpentine mineral waste as a source of metals and a mineral trap for the fixation of CO_2 emissions. The most sustainable Finnish options for magnesium sources needed in mineral carbonation were ultramafic mineral process wastes or by-products of metal and mineral production, such as serpentinite and serpentine from the extractive and metal industry. Other potential magnesium-bearing mineral options include olivine, pyroxenes, amphiboles and talc. In the research project it was estimated that if technically, economically and environmentally feasible mineral processing and mineral carbonation processes were available for serpentine, in Eastern Finland there may exist a potential of ca. 85 km^3 of serpentinites (serpentine content 50–70%) *in situ* for CCS purposes. The socio-environmental and other restrictions were considered in this GIS-based serpentinite inventory. The amount of serpentine *in situ* could be sufficient for storing 2–3 Gt of CO_2 in carbonates (Teir et al. 2006).

Further development of mineral carbonation applications in Finland has been continued by Åbo Akademi, HUT (at present Aalto University School of Science and Technology), VTT and Turku University, examining the fixation of CO_2 by producing carbonates from steelmaking slags and calcium and magnesium silicates.

DISCUSSION AND CONCLUSIONS

In this paper we have briefly summarized the results of recent studies in geological CCS development at GTK, and have presented some areas of further geological interest among CCS studies in Finland.

Because of the scarcity of suitable rocks of sedimentary association for CGS in Finland, Finnish industries will have to co-operate with the EU and other neighbouring countries to gain access to suitable long-term geological storage formations in logistically optimal areas. However, feasible options for underground liquefied gas storage may occur, as in other areas with igneous or sedimentary rock basins elsewhere in the world. The intermediate geological gas storage possibilities at and near CO_2-releasing industrial plants should be investigated more in detail.

In Finland, geologically the most interesting areas for long-term storage research are in the application of mineral carbonation, e.g. in subsurface and environmental geology, mineralogy and the geochemistry of carbonates and carbon conscious mineral technologies in the extractive industry, as well as in solving environmental problems.

ACKNOWLEDGEMENTS

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3 Research serving urban needs and land use planning

An aerial view of the high-tech business and university campus in Espoo where GTK's headquarters are also located. (Photo: Helifoto Oy)

3 RESEARCH SERVING URBAN NEEDS AND LAND USE PLANNING

Introduction

Research at the Geological Survey of Finland (GTK) related to land-use and infrastructure covers a wide spectrum of applied themes united by the common question of how geoscience can contribute to the planning and maintenance of modern societies. Urbanisation and accelerating climate change are the main drivers affecting the research. In Finland, the population has also tended to move to larger cities, which presents further challenges for planners and builders. Construction and maintenance costs, raw material supply and sustainable use of the environment have long been, and will remain, the key questions to be addressed. The overall costs of a construction process are firmly fixed in the initial stages of the process, where geology-based land-use planning may lead to a substantial reduction in construction costs, thus contributing the maximum impact of geodata for citizens, constructers and society.

In Finland, the pressures of land-use are largely concentrated in areas with fine-grained and compressive soils formed as a result of the history of the Baltic Sea. Two thirds of Finland's land area has been submerged under the sea or an ice lake that formed after the melting of the Scandinavian Ice Sheet: this is more than in any other European country. Research on the relationship between geological factors and geotechnical properties in fine-grained soils is one of our focus areas, aiming at better understanding of the founding conditions of soils that are poor in quality and costly to construct on.

The Baltic Sea and seafloor is becoming more heavily affected by human activities. Recent activities, such as the construction of offshore windfarms, harbours, the North European Gas Pipeline from Russia to Germany and plans for submarine mining, call for an effective transnational approach to management and marine spatial planning. Marine landscape maps recently developed for the Baltic Sea provide an approach to broad-scale, physical characterization and a basis for physical planning of the marine environment. Geochemical studies on the offshore soft sediments indicate a positive but slow recovery of the condition of the seafloor of the Gulf of Finland.

The natural concentrations of harmful elements and substances in Finnish soils and bedrock vary considerably according to the type of geological deposit and the region, in some regions exceeding the threshold and guideline values defined for the assessment of soil contamination. Medical geology research has shown that that while many substances from our geological environment are essential for both human beings and ecosystems, they may occasionally be associated with certain health disorders. The geochemical baselines, and their linkage to various land-use and health-related issues, constitute one of our research topics.

One of the latest emerging societal demands for geoscience is related to the potential future impacts of climate change on land-use. In particular, research on adapting to the impacts of climate change has rapidly evolved. GTK is actively involved in many EU-funded projects dealing with sea level rise and the impact on aquifers due to increasing precipitation. Cost-benefit analyses of adaptive measures are an integral part of the research.

Hannu Idman

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OPPORTUNITIES FOR URBAN GEOLOGY IN FINLAND: MAPPING, DATABASES AND DATA PROCESSING FOR LAND USE PLANNING AND CONSTRUCTION

by
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Ikävalko, O., Jarva, J., Ojalainen, J., Ojala, A. & Tarvainen, T. 2011. Opportunities for urban geology in Finland: mapping, databases and data processing for land use planning and construction. *Geological Survey of Finland, Special Paper 49*, 197–204, 4 figures.

The Geological Survey of Finland (GTK) has systematically mapped the hard bedrock and the loose surficial deposits of the country during its 125-year history. Nowadays, data collection is focusing more on densely populated and urban areas. The need for geological data is evident in different areas of land use planning and construction, and in their raw material needs. Due to the considerable variation in surficial conditions, more exact data are required for local scale land use planning and construction than traditional geological mapping can provide.

Urban geology in Finland has focused on collecting and reproducing geodata for different stakeholders, such as planners, engineers, authorities, consulting firms, land owners and the general public. The importance of geological information required for land use planning and the development of urban areas is growing. Several urban geological projects of GTK related to urban area development and construction have dealt with the challenging foundation conditions and with bedrock quality surveys for underground construction. The development of construction suitability maps of ground and bedrock, investigations of water supply and baseline studies have also been significant. The development of Internet-based GIS services is in progress to better provide geological information for stakeholders.

The need for geological data on the urban environment has been analyzed based on interviews with a wide range of users. The most significant potentials of urban geology are in the development of geological information use in land use planning - not only the mapping procedures and data collection, but also the interpretation of data and application of the information in the planning process.

Keywords (GeoRef Thesaurus, AGI): urban geology, land use, urban planning, construction, mapping, data bases, data processing, Finland

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INTRODUCTION

Urban geology does not have very long traditions in Finland. Considerable work has been done during the 125-year history of the Geological Survey of Finland (GTK) in the systematic geological mapping of bedrock and surficial deposits. The use of geological maps has been significant in exploration geology, but the utilization of geological data in urban geology has not been so evident. Only a few systematic studies have provided geological information for sustainable urban development. At the end of the 1980s and during the 1990s, public awareness and interest in urban geology increased. Nowadays, awareness of the significance of geological information in our living environment, and especially in densely populated areas, has risen.

The aim of urban geology at GTK is to collect and interpret geodata on the urban environment, and to provide geological information for different stakeholders, such as planners, engineers, authorities and the general public.

Urban geology is based on understanding of the long geological history and the evolutionary processes in nature. This is also the key to estimating the technical properties of the ground and bedrock. Geological information is essential for regional planning, zoning, construction and infrastructure development. Geoscience is also required in environmental applications such as waste management, the assessment of soil contamination and remediation needs, water supply, the mapping of geological hazards and risk management.

GEOLOGY FOR URBAN AREAS IN FINLAND

Geology has had a major role in the development of the urban environment. Originally, urban areas were settled by taking advantage of geological or geomorphological features for housing, defence, commerce and the use of water resources and construction materials. Nowadays, urban growth has extended into 3D space. The spread is lateral, upwards by building high houses and downwards by utilizing underground space. The development has been the same all around the world. As a consequence of urban development and growth, more demanding and challenging conditions are being faced more often.

Finland is characterized by relatively young urban areas and small city centres. Urbanization has been strong and rapid during the past 20–40 years. The lack of easily useable land has led to the construction of buildings in soft soil (loams) areas with demanding foundation conditions, especially in southern and western Finland. In the old city centres, the use of underground space is nowadays important for the development of infrastructure and urban transport (the Helsinki Metro). This is strongly dependent on the geological properties of the bedrock. In Finland, the old hard Precambrian crystalline bedrock has usually provided an excellent basis for the excavation of underground space.

Data collection in urban areas

In Finland, urban geological data collection has focused very strongly on studies of the varying surficial conditions (Figure 1). Traditional geological maps of bedrock and Quaternary sediments have been prepared at the scales of 1:100 000 and 1:20 000. These data often provide a good basis for regional land use planning, but more detailed data up to 1:2 000 scale are needed for detailed local planning purposes. A special area of interest is the identification of demanding foundation conditions, where considerable benefit can be gained through the economic analysis of foundation costs in planning. The scale and the purpose of urban geological investigations are usually site-specific and they are planned in co-operation with the end-users.

Urbanized areas can be difficult to investigate due to the existing infrastructure and constructions, as well as artificial soil covering the area. The natural ground is rarely visible. To better understand the geological environment in urbanized areas, all the existing data from recent soil surveys are of great value. Drilling data and airborne geophysical measurements provide essential information on the thickness and properties of the overburden. Other geophysical applications such as ground penetrating radar and gravity measurements are needed to study soil layers and structures in more detail. Finally, observation pits and field investigations are required to verify the soil structures and ground conditions.

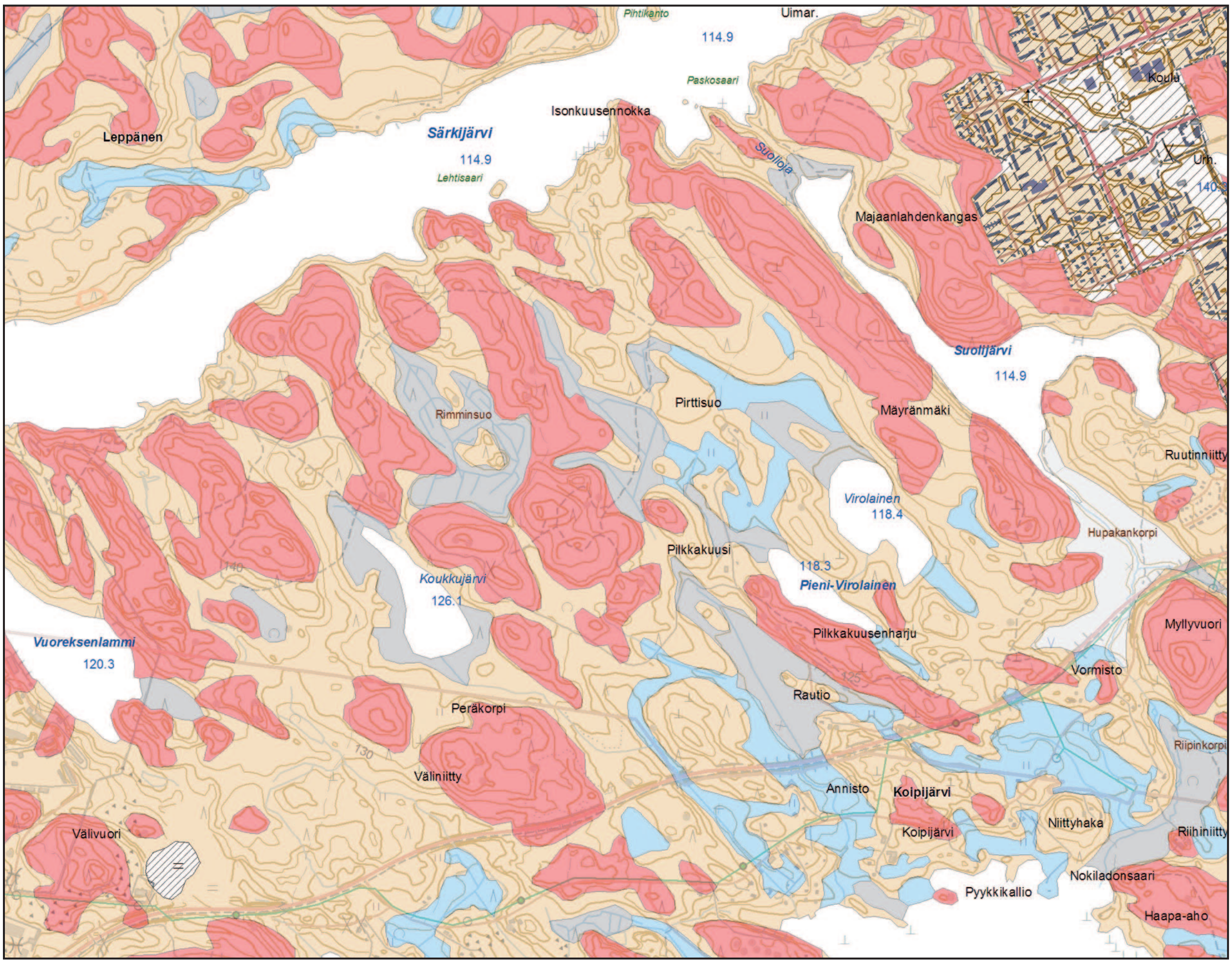

Figure 1. A map of the Quaternary deposits in the Tampere region. Geological conditions are highly variable. Bedrock areas are coloured with red, clay areas with blue, moraine areas with light brown, peat areas with brown and lakes with white. The map area is approximately 4 km x 3 km. Quaternary geological map 1:20 000 © GTK. Basemap © National Land Survey of Finland, licence no. MML/VIR/TIPA/217/10.

The thickness of the overburden and its stratigraphy, as well as properties of the topsoil are usually the most interesting data for an engineer or planner when defining the foundation conditions of the area. Airborne 3D laser scanning data offer new possibilities to examine the ground topography for urban planning purposes.

Underground construction requires data on the surface altitude and quality of the bedrock. Fragmentation of the bedrock, fracturing, the zones of weakness (faulting, jointing, shear zones) and other quality issues influence rock construction. GTK is focusing its bedrock data collection on urban areas, where the need for information is the greatest. New mapping methods include the use of digital mapping with data collection devices, and the application of terrestrial 3D laser scanning surface models in the interpretation of bedrock weakness zones.

Challenging construction conditions

It is inevitable in southern Finland, and particularly in the capital region, that land use planning and the building of new infrastructure is concentrating in areas with fine-grained sediment deposits often up to tens of metres in thickness. These areas have very challenging foundation and construction conditions, and the stabilization of the overburden is perhaps the most important issue (Fang & Daniels 2006). It is known that due to geological history (i.e. the BSB, see Ojala this volume), the engineering-geological properties of fine-grained sediments in Finland vary considerably, both vertically and horizontally, even within a very limited area (Figure 2). Therefore, the efforts of Gardemeister (e.g. 1973, 1975) and more recently of Ojala et al. (2007) and Ojala (e.g. 2007, 2009) have been targeted at investigating the extent to which the geotechnical properties of the fine-grained sediments depend on geological factors in different parts of the Finnish coastal region. These studies have aimed at providing geological and geotechnical information for land use planning and ground engineering, as discussed with examples by Ojala (this volume).

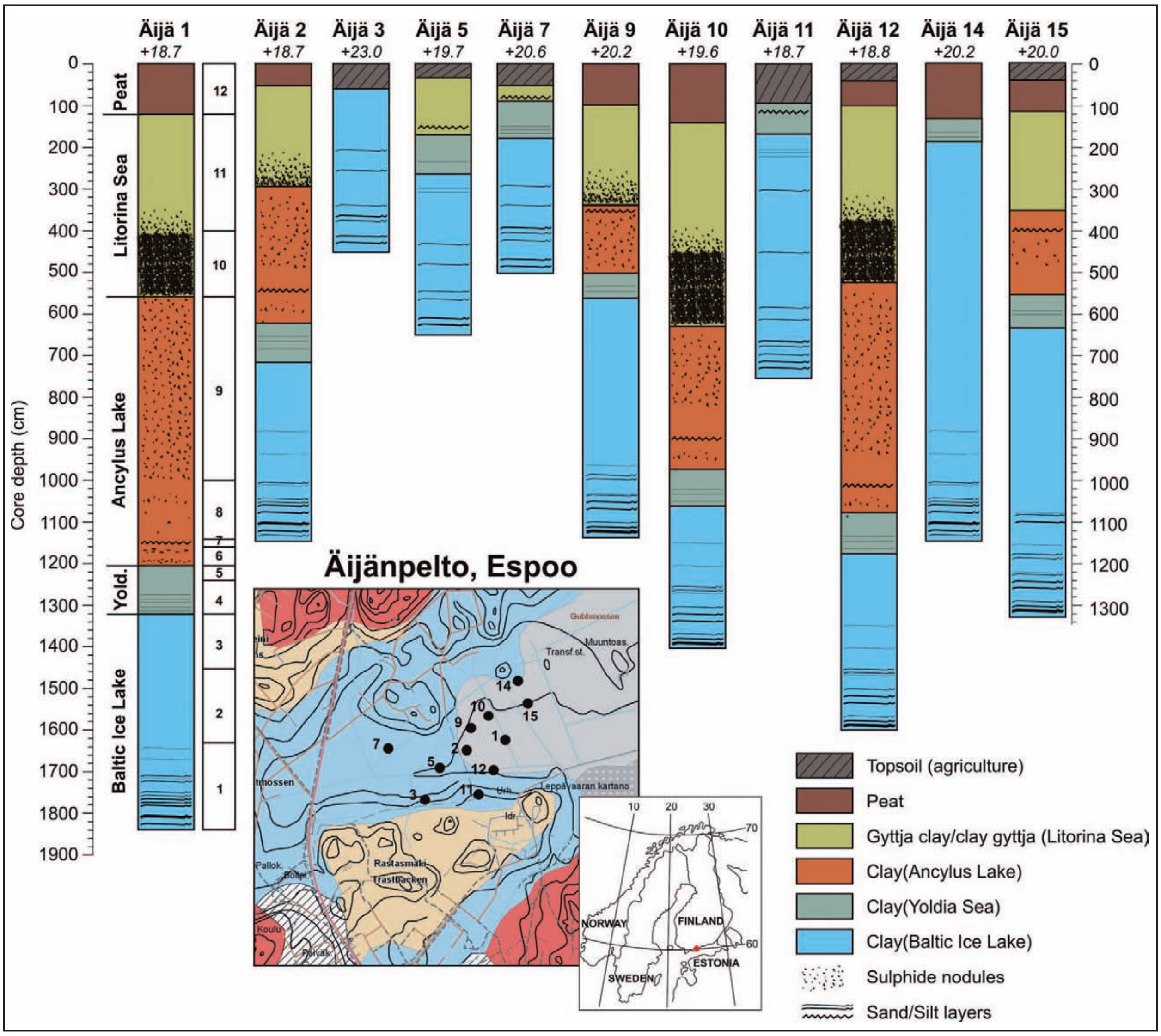

Figure 2. An example of a sedimentological study from the Äijänpelto region in Espoo (Ojala 2007). The selected sediment description columns indicate that the composition and structure of the fine-grained deposits vary substantially with depth and also between coring locations. Numbers (1 to 12) alongside the leftmost description column represent different lithological units identified in sediment stratigraphy by Ojala (2007).

Urban geological databases

Urban geology sets new requirements for the type and quality of geological data. GTK has already automated its map production through the use of geographic information systems (GIS), and most datasets are available in digital format. Traditional geological mapping of bedrock and Quaternary sediments has been carried out at the scales of 1:20 000 or 1:100 000. Geological mapping data are publicly available via the Internet from online map servers.

The most important objectives of the urban geological work at GTK are to ensure the availability of geological information at the national level and to promote the versatile utilization of geological information in society. GTK aims at ensuring the storage of geological information from different information sources in urban and densely populated areas. Information is produced in different phases of development activities in society, when areas are planned, constructed and rebuilt.

GTK has developed several geological information systems to be used in planning, construction and for educational purposes. The GeoTIETO system was created in cooperation with the municipalities of the Helsinki metropolitan region (Kuivamäki et al. 2006). A similar data system was created for the Tampere region in the TAATA project (Kuivamäki 2009). These databases provide users with updated geological data online.

A new Government Decree on the assessment of soil contamination and remediation needs (214/2007) has generated a need for reliable and readily accessible data on the baseline concentrations of elements in Finnish soils. This information is provided via a national geochemical baseline database, TAPIR, which was published in August 2009 (Jarva et al. 2010). Finland has been divided into geochemical provinces to better provide information on regional geochemical baselines. The database combines information gathered by GTK, other research institutes, universities and consultant companies. Data on individual sampling sites are not publicly available, but all existing data are used in calculating regional statistics. Statistics are separately calculated for each geochemical province and each soil type. In addition to the most common statistical parameters such as the median or mean, the upper limit of the baseline variation within a geochemical province is an important parameter for decision makers that is provided by the database.

GTK is also implementing a project aimed at creating an online-based ground investigation register (Figure 3). Once completed, the ground investigation register will offer data from different data sources nationwide in map-based systems. The aim is to collect the existing metadata into one register, which will provide information on existing ground investigations and help to gather the necessary survey data.

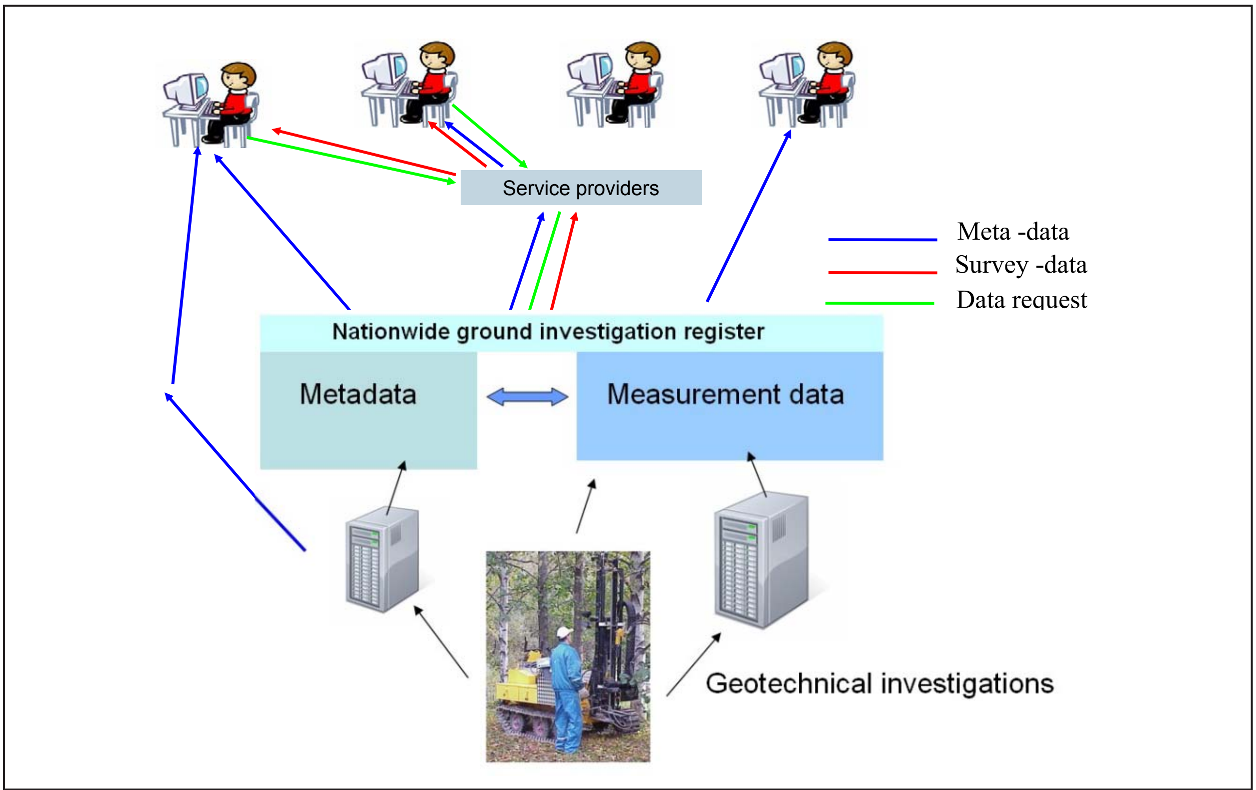

Figure 3. Data flow model in a ground investigation data system. Field survey data are saved in different databases and metadata on surveys are collected into a metadatabase. Data can be located through metadata information, and distributed to end users from databases through the Internet.

Urban geological applications for land use planning

Survey data can be used to create end-user oriented, interpreted geological maps. Thematic geological maps, such as construction suitability maps, can be created for extensive areas based on existing data. When the data are sufficient, 3D geological models can be offered for use. Typically, an accurate elevation model based on airborne laser scanning data is integrated with mapping data, and the interpretations are summarized on these thematic maps.

GTK has utilized geological databases and data processing in several large infrastructure projects in Finland. Preliminary data processing and interpreted geological knowledge have been used in an underground railway tunnelling project in the capital area of Helsinki (Pajunen et al. 2007), in constructing a new harbour at Vuosaari, in the Savio railway tunnelling project (Elminen et al. 2007), in nuclear waste management and in several constructability analyses.

Land use planning in Finland is regulated by the Land Use and Building Act (132/1999). The Act states, among other things, that the suitability of a building site must be appropriate for the purpose. The construction suitability of land depends on its geological history and geotechnical properties, such as the bearing capacity, frost susceptibility, the depth of the load bearing layer, slope steepness and the depth of the groundwater table.

Construction suitability maps have been produced to serve regional and local master plans, especially in the planning of future construction areas (e.g. Jarva et al. 2006, Laakso et al. 2010). Information on the qualitative (good – poor) construction conditions of the land helps in making rough estimations of the overall foundation costs of the area (Figure 4). Construction suitability maps can be used to focus more detailed geological investigations on the most critical areas and to make indicative evaluations of the construction costs.

Information on Quaternary geological deposits, their characteristics, the thickness of soil layers (especially fine-grained sediments) and slope steepness are used to estimate the construction conditions. The maps can be utilized in land use planning to locate areas suitable or non-suitable for building. However, more investigations are needed to ensure the depth of the load bearing layer and other geotechnical properties. The maps could also provide information on the depth of the groundwater table, possible soil contamination, floods, landslides or other natural hazard prone areas, potential areas for geoenergy as well as protection and other specific areas.

The construction suitability of bedrock has been analyzed based on the tectonic structure of the Svecofennian crust of southern Finland (Pajunen et al. 2008). Geological data on zones of weakness and on crustal terranes/blocks have been presented in the form of a construction suitability of bedrock map. Data from the map have been used in the development of the Helsinki Underground Master Plan and in several underground construction projects.

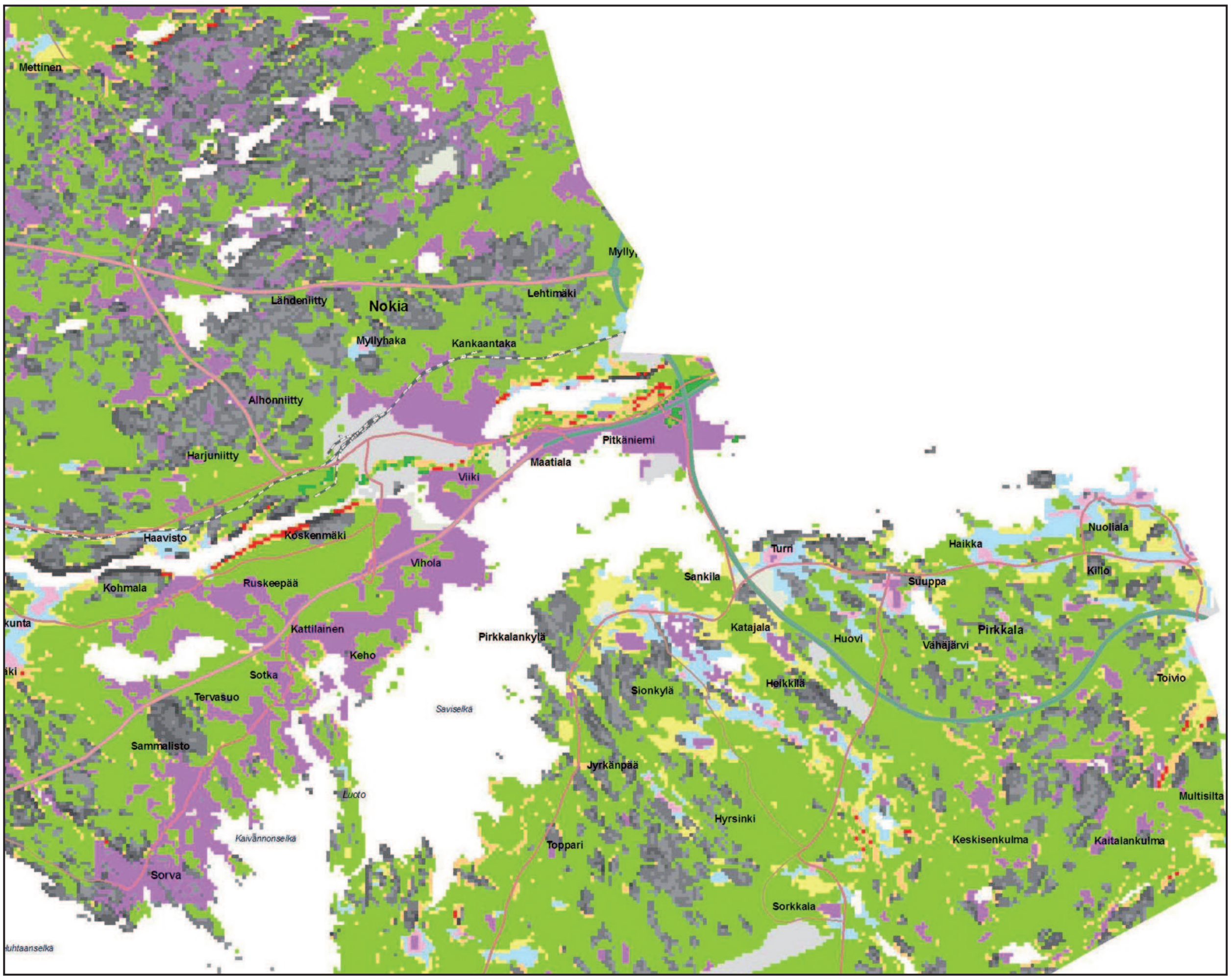

Figure 4. A map of the suitability for construction of the Nokia area in the Tampere region, Finland. The map area is approximately 2 km x 2 km. Foundation conditions are good in areas coloured with green and poor in areas coloured with purple. Bedrock areas are indicated with a grey colour. Quaternary geological map 1:20 000 © GTK. Basemap © National Land Survey of Finland, licence no. MML/VIR/TIPA/217/10.

OPPORTUNITIES AND CONSTRAINTS OF URBAN GEOLOGY

Need for urban geological information

In order to assess the need for geological information and evaluate its impact from the user's perspective, GTK has carried out evaluation studies based on interviews with a wide range of users in the urban areas of Helsinki and Tampere. The need for geological data has also been assessed based on the frequency with which various Internet pages on urban geology at GTK have been accessed.

The main conclusions of these investigations have been that:

- Existing geodatabases available via the Internet are not well known and so far have seldom been used.
- Geodatabases should be made more user friendly and their content should be more informative to better reach and serve the target audience.
- The national online-based ground investigation register was found relevant and useful.
- The utilization of geological information in land use planning should be further developed.
- Local studies on construction conditions and site-specific geological studies were found useful, especially for new development areas.
- Methods of cost analysis (foundation conditions, geological risks) should be developed to better serve land use planning.
- Urban geology can cover many topics that should be taken into account in land use planning, such as geological risks, climate change, the utilization of fill or man-made ground, baseline concentrations, the modelling of catchment areas and studies on water supplies.

Opportunities in urban and sub-urban development

Results from the evaluation study of urban geological information needs were further analysed and following conclusions were made:

- The methods to be used in land use planning should be further developed to take better into account of geological properties. This means better understanding of the foundation conditions and their effect on construction costs. Construction suitability maps should better serve planning at the local level by pointing out optimal solutions for different land use options. The whole process from data collection to end-use of the data should be developed.
- New products derived from geological maps and data should be developed. These products could include three-dimensional models of the regional and local geology, the results of soil surveys, new laser-scanned terrain models and mapping results based on new, more accurate observations.
- Expertise and know-how on the characteristics of areas with soft soil (loams) as well as their geological and geotechnical properties should be further developed. Pilot studies have shown the relevance of geological and geophysical studies in the characterization of the properties of loam, for example in the Suurpelto area of Espoo in Finland in 2006–2008
- New databases and information systems will be developed to promote geological information for urban areas via the Internet. GTK's role as a national geological information service centre is to collect and save different kinds of geological data from several data sources in the urban environment. GTK's task is to integrate the data processing, make high level interpretations from the data and be active in the standardization of formats.
- Knowledge of brittle bedrock structures is necessary in order to provide reliable information for a variety of applications. These properties are connected to the structures and rock type groups. Places in which the bedrock is weak are located by means of fissure classification, kinematics of brittle structures, and surveys of other geological factors defining the processes by which fragmentation occurs in the bedrock. Examples of such applications include the impact of strain and its fluctuations on the fragmentation properties of bedrock, fragmentation estimates, and assessment of the thickness of overburden

CONCLUSIONS

To respond to the needs for urban geological information, GTK has launched an urban geology research programme. The aims of the programme are to develop the use of geological data in land use planning, produce and generate relevant geological data for urban land use planners and investigate potential environmental impacts. One objective is to create a geological data system that will allow users to examine and visualize geological information. The urban geology research programme will benefit city planners, regional associations, authorities, infrastructure builders, the National Roads Administration, the Finnish Rail Administration, real estate developers, consulting firms, land owners, construction material producers and companies specialized in earthworks and dredging. The urban geology research programme is co-operating closely with other research programmes of GTK to serve stakeholders in the best available way. Sustainable urban development and cost savings in land use planning will be achieved by producing and providing relevant geological data for end-users and by better communication with decision makers.

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CONSTRUCTION SUITABILITY AND 3D ARCHITECTURE OF FINE-GRAINED SEDIMENTARY DEPOSITS IN SOUTHERN FINLAND – EXAMPLES FROM ESPOO

by
Antti E. K. Ojala

Ojala, A. E. K. 2011. Construction suitability and 3D architecture of fine-grained sedimentary deposits in southern Finland – examples from Espoo. *Geological Survey of Finland, Special Paper 49*, 205–212, 4 figures.

The geological background to the appearance of fine-grained sediment deposits in southern Finland is that they were formed during the retreat of the continental Fennoscandian ice-sheet at around 13 000 years ago and during the subsequent phases of the Baltic Sea basin (BSB). As a consequence, the sediment deposition environment has varied significantly due to several reasons. The primary variables have been the discharge intensity of meltwater from the retreating Fennoscandian ice sheet, the relative water depth (sea level rise vs. glacioeustacy), the water salinity (i.e. fresh water/brackish water), and the intensity of primary productivity due to climate change and nutrient availability. Fluctuations in these boundary conditions through time and space have caused drastic changes in the composition and structure of fine-grained deposits in the area. The purpose of this paper is to introduce engineering-geological studies on fine-grained sediments, with recent examples from two localities in the Espoo area. The objectives of this work have been to provide sufficient relevant information on the structure, composition and overall distribution of fine-grained sediments in the Finnish capital region for better understanding of the founding conditions and the enhancement of land-use planning.

Keywords (GeoRef Thesaurus, AGI): sediments, clay, silt, gyttja, lithostratigraphy, engineering properties, Holocene, Suurpelto, Perkkaa, Espoo, Finland

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INTRODUCTION

During recent decades the expansion of urban areas (urbanization) has evidently brought about an increased need for comprehensive geoscientific maps and fine-scale geological information for land-use planning and construction, the supply and sustainable use of natural resources, and for environmental protection. The aim of urban geosciences is to investigate, process and present geological data, for instance, in such a way that it can provide useful information for planners and decision makers. Urban geoscience combines the disciplines of engineering geology, environmental geology, sedimentology and regional planning, which are applied to improve the management and planning of urban areas (de Mulder 1993). The main instruments in urban geosciences are thematic geoscientific maps, databases and geological models. It is of fundamental importance in urban geosciences to site-specifically identify and carefully evaluate the relevant geoscientific factors and the potential threats that control the urban environment. Usually, a map of integrated geological, geotechnical, and environmental variables is prepared for different purposes in separate places according to the planning needs and requirements.

Today, a considerable amount of attention must be paid to the construction and maintenance costs of new sites as well as the sustainable use of the environment. This is concretized in aspects such as foundation depths, potential environmental risks and high construction costs due to unfavourable surface and/or subsurface geological characteristics. A good way to prepare for these difficulties and reduce the potential risks is to consider the geological characteristics and geotechnical constraints in the context of public planning for land use, building infrastructure, and the use of underground space. One of the longer-term purposes of urban geoscience is to develop new geoscientific methods (or method combinations) and data treatments that could be efficiently and economically applied to enhance sustainable development and the rational use of urban areas.

In Finland, the decades-long migration to a few larger cities in the south will probably continue in the future (Tilastokeskus 2008). As a consequence, the focus of land use and construction will concentrate on those areas where thus far unconstructed natural soils are very poor in quality and construction projects are difficult and challenging (Stapelfeldt et al. 2009). In the coastal cities, this means that land-use planning will also be targeted areas with fine-grained sediment deposits and often with compressive soils (Fang & Daniels 2006) that have formed since the last deglaciation and during the history of the Baltic Sea basin (hereafter BSB). In recent Holocene geological history, about 70% of the present land area of Finland was submerged by sediment-loaded BSB waters for thousands of years. The reason for the development of this vast sedimentation basin in the Scandinavian region was the isostatic land surface depression caused by the weight of the Northern-European ice sheet. Since deglaciation the surface has been rebounding, causing land uplift of up to 250 metres in the Kvarken area of western Finland (Breilin et al. 2005). The sediments deposited during the BSB stages contain high-compression clay strata and mud with a poor bearing capacity, which presents a major challenge to Finnish infrastructural planners and builders compared with those in other European countries. In the capital region in southern Finland, for example, extensive areas of bedrock and glacial overburden are covered by post-glacial fine-grained clay and silt deposits that are up to tens of metres in thickness (Alalammi 1992) (Figure 1). Is known that even within a limited area, significant differences in the spatial distribution, textural and structural characteristics, and geotechnical properties (i.e. shear strength, consolidation properties) exist among the fine-grained deposits (Gardemeister 1975, Ojala et al. 2007) in southern Finland.

Gardemeister (e.g. 1973, 1975) has been a pioneer in studying the engineering-geological properties of fine-grained sediments in Finland. One of his key ideas was to investigate the extent to which the geotechnical properties of the fine-grained sediments depend on geological factors in different parts of the country. The purpose of this paper is to introduce more recent examples of fine-grained sediment studies from two localities in the Espoo area. The objectives of this work have been to obtain new information on the structure, composition and overall distribution of fine-grained sediments in the Finnish capital region for better understanding of the founding conditions and the enhancement of land-use planning. This has been done by combining thorough studies of sedimentological characteristics, geochemical investigations and geotechnical information, such as Swedish weight sounding tests, to model and predict the surface and subsurface conditions of fine-grained deposits.

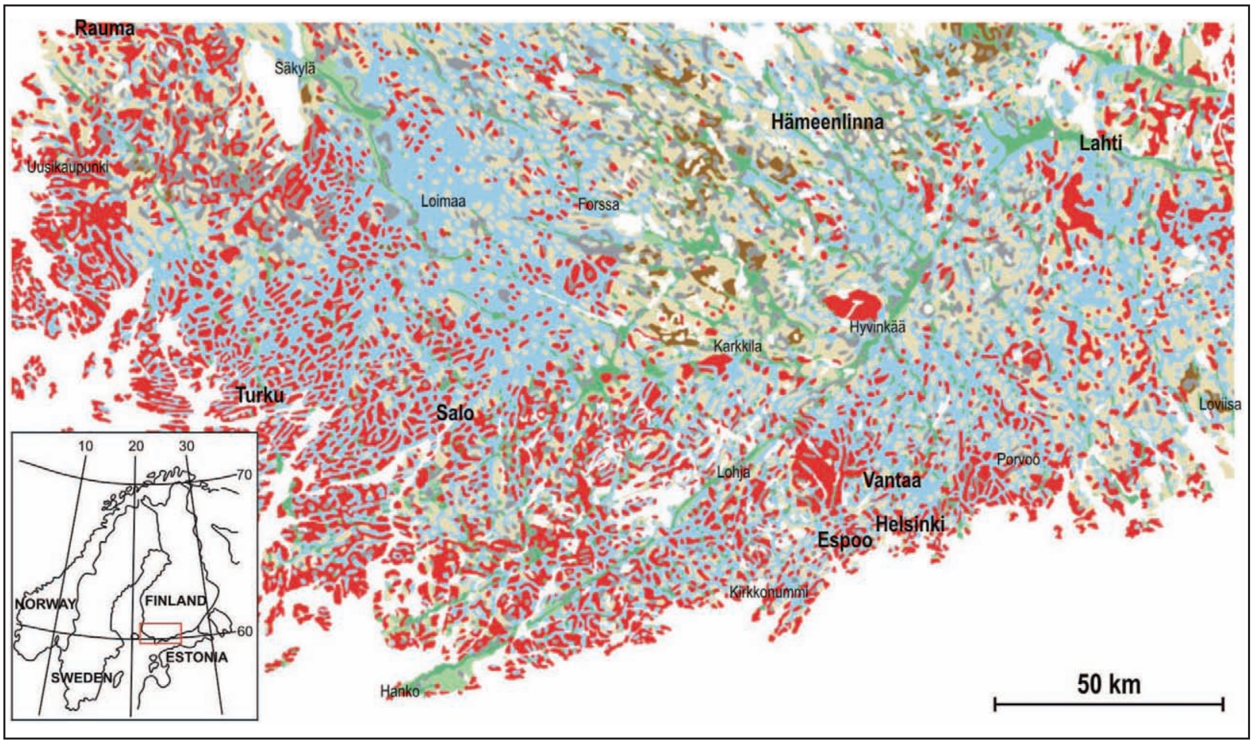

Figure 1. Distribution of Quaternary formations in southern Finland. Fine-grained sediments are present in low-lying areas in southern and SW Finland that were once under the ancient Baltic Sea Basin. The average thickness of these deposits is about 10 metres (Gardemeister 1975). Basemap © National Land Survey of Finland, licence no. MML/VIR/TIPA/217/10.

FINE-GRAINED SEDIMENTS IN SOUTHERN FINLAND

Different types of fine-grained sediments (clay and silt) have formed over a long period of time due to physical and chemical weathering of the bedrock (primary source) and cohesive soil (secondary source). Clay and silt deposits in Finland mainly occur in southern and SW parts of the country and in coastal areas (Figure 1). They have typically formed in a process of secondary sedimentary erosion and deposition associated with glacial-interglacial cycles and deposited (or re-deposited) in an aquatic environment during the BSB history. The main mineralogical group of clays in Finland is illite, but vermiculite and chlorite also occur in smaller amounts in these sediments (Gardemeister 1975). They appear with either a laminated (varved) or a massive (homogeneous) structure.

The semi-enclosed Baltic Sea is presently one of the largest brackish water basins in the world. Since the latest Weichselian deglaciation, the BSB has gone through two freshwater and two brackish-water stages. These are known as the Baltic Ice Lake (*ca.* 13 000–11 600 BP, *freshwater*), the Yoldia Sea (*ca.* 11 600–10 700 BP, *partly brackish*), Ancylus Lake (*ca.* 10 700–9 000 BP, *freshwater*), and the Litorina Sea (*ca.* 8000–, *brackish*) (e.g. Björck 1995, Andren et al. 2000). These stages resulted in different kinds of sedimentary environments in the BSB region, depending on prevailing factors such as: (i) the water depth (ii) the amount of freshwater and the suspension load of material arriving from the retreating glacier, (iii) water stratification, salinity and chemistry, (iv) re-deposition, and (v) organic primary production. As a consequence, different stages of the BSB are represented by different sedimentary strata and sediment composition, and all these have characteristic index properties such as the humus and water content, clay content, plasticity and fineness number, and mineralogy. These index properties are important from the standpoint of engineering geology.

Recently, Laakso (2008) classified the appearance of fine-grained sediments in southern Finland during different evolutionary stages of the BSB based on a digital elevation model, aerogeophysical characteristics, and available information on land uplift and shore displacement during the last 12 000 years. More thorough geological field reconnaissance, sample coring, and the description of type-sections from representative localities have enabled a detailed 3D characterization of their sedimentological features in different areas (e.g. Ojala & Palmu 2007, Ojala et al. 2007). Such studies provide valuable scientific and technical information for land-use planning and ground engineering, particularly for tasks such as the determination of construction suitability and stabilization.

EXAMPLES FROM THE ESPOO AREA

Recently, several studies have been designed and carried out to characterize the physical and chemical properties of fine-grained sedimentary deposits in the Finnish capital region (Ojala 2007a, Ojala 2007b, Ojala & Palmu 2007, Ojala et al. 2007, Ojala 2009). As an example, the Suurpelto project was launched in 2005 in cooperation with the city of Espoo, the Geological Survey of Finland, the University of Helsinki and Helsinki University of Technology, aiming to provide interdisciplinary and comprehensive information from the Suurpelto area, which is composed of a fine-grained deposit of silt and clay up to 25 metres thick (Ojala et al. 2007, Stapelfeldt et al. 2009). Based on geotechnical information, it is known that the composition and geotechnical properties (e.g. strength, consolidation characteristics and acidity) of the Suurpelto deposits vary both vertically and horizontally, making it a challenging site for founding and construction.

Figure 2 indicates the thickness and distribution of the Litorina Sea phase and post-Litorina Sea phase gyttja clay/clay gyttja/gyttja deposits that lie on top of late- and post-glacial clays (Ojala & Palmu 2007, Ojala et al. 2007) in the Suurpelto area. They are composed of very soft organic-rich (humus content 5–15%) fine-grained sediments that have a high water content of up to 200% (Ojala et al. 2007). An increased organic and water content has a significant effect on geotechnical properties, presenting a challenge for tasks such as embankment construction and the stabilization of the soil (e.g. Gardemeister 1975, Stapelfeldt et al. 2009). According to Gardemeister (1975), the plasticity index (I_p) and liquid limit (w_L) are often appreciably greater in Litorina sediments than in other types of sediments deposited during the evolution of the BSB. The organic-rich and soft deposits with a high soil compression in the Suurpelto study site are up to 12 metres in thickness and mainly distributed in the southernmost parts of the area, which is, in this case, in the lowest elevation. At certain levels (see Ojala et al. 2007), these fine-grained deposits contain naturally elevated concentrations of sulphide that mostly lie in anoxic conditions below the present groundwater level. Artificial or natural lowering of the groundwater level will probably cause considerable depression of the ground and potentially lead to acidification, i.e. the formation of sulphuric acid, which is a potential risk to the environment as well as the durability of underground constructions and foundations (Ojala et al. 2007, Törnqvist 2008). It has also been shown that it is more difficult to obtain a sufficient stabilization effect for sulphide-containing organic-rich sediments using traditional binders (cement/lime) (e.g. Andersson & Norrman 2004). Soils "in situ" and processes used to rework the properties of soils (e.g. stabilization), as well as the potential environmental hazards are often included in engineering-geological studies (de Mulder 1993). Over a period of decades, the acidity of sulphide clay may cause major difficulties and unexpected surprises for concrete and steel pillars and foundations under buildings, and this therefore needs to be taken in account when planning and calculating the foundation requirements and parameters.

The three-dimensional geological model of the Suurpelto area and a cross-section made from the 3D model of the Suurpelto deposits show rather well the overall thickness of the fine-grained deposits, but also in more detail how different geological units appear in the area (Figure 3) (Ojala et al. 2007). The deposits are thicker in the central parts of the basin and thin towards the peripheral areas. Importantly, the lower part of the Litorina Sea deposits, which is richest in sulphide, lies *ca*. 8–10 metres below the sediment surface in the central part of the basin, but is much closer to the surface in peripheral areas. Figure 3 also indicates how dependent the geotechnical properties are on different geological sediment types. From the geoengineering perspective, the total thickness of the fine-grained overburden is often the most important information. However, it is also important to know how the engineering-geological index properties vary site-specifically, both horizontally and vertically, and this is something a 3D geological model is capable of showing.

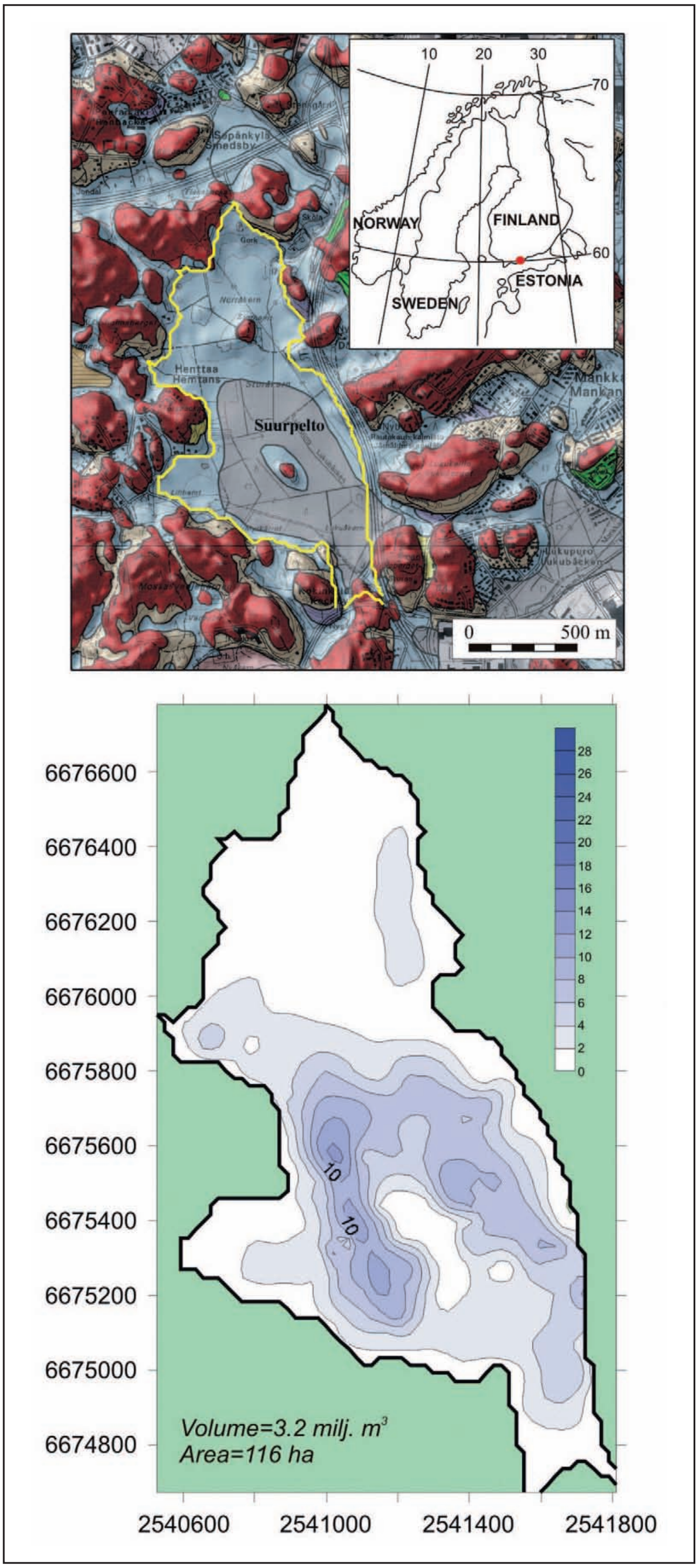

Figure 2. Thickness and distribution of organic-rich soft sediments in the Suurpelto area. Basemap © National Land Survey of Finland, licence no. MML/VIR/TIPA/217/10.

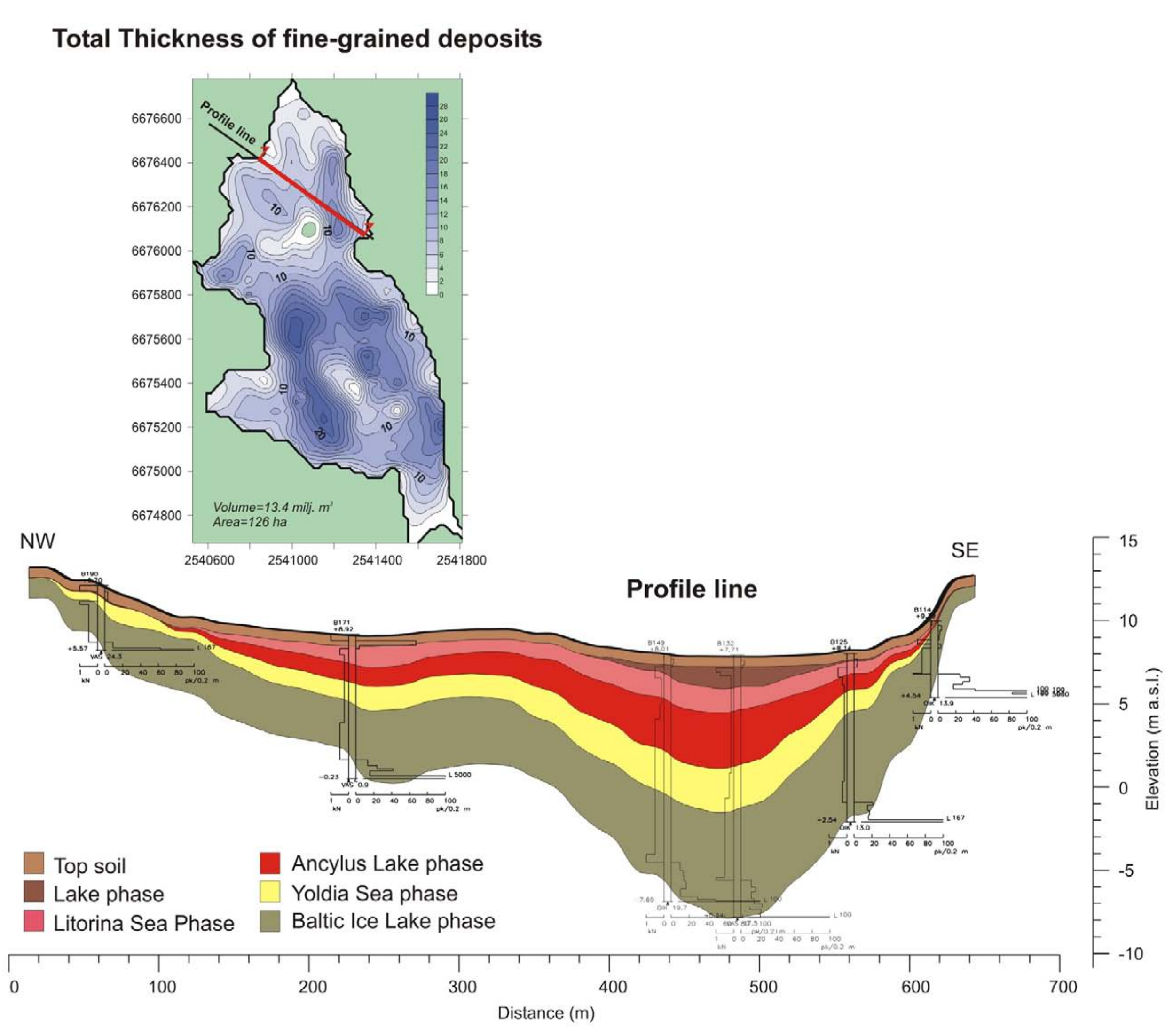

Figure 3. Cross-sections of the Suurpelto sediment deposit, which are based on a grid of coring locations (Ojala et al. 2007), show the continuity of the major units deposited in the area during the BSB history. The geo-engineering properties of soils depend on the geological properties of fine-grained material.

One of the purposes of the multidisciplinary studies has been to obtain new information on the engineering-geological properties of fine-grained sediment deposits in southern Finland and particularly in the capital region. General information for comparing sedimentological and engineering-geological properties has been derived from detailed investigations of one or several type sections per study site (e.g. Ojala & Palmu 2007, Ojala et al. 2007). These coring locations have been determined based on the characteristics of each locality, the bedrock topography and terrain as well as case-specific study interests. Figure 4 shows an example of such coring and a sediment description from the Perkkaa area in Espoo. Fine-grained deposits in the Perkkaa area contain extensive sand/gravel/silt layers and lenses throughout the sediment stratigraphy. These layers are well represented in the sediment stratigaphy, explaining some of the characteristic features seen in the geotechnical information. Even though the Suurpelto and Perkkaa sites are located only ca. 5 km apart and their sediment deposits have been formed during the same BSB stages, their sedimentological properties are very different, resulting in different founding circumstances. A better understanding of the general characteristics and geoengineering properties of fine-grained deposits based on differences in the geological sedimentary environment will not only enhance sustainable and cost-effective planning of urban land use, but will also improve the implementation of relevant environmental and geological data in urban geosciences in Finnish coastal cities.

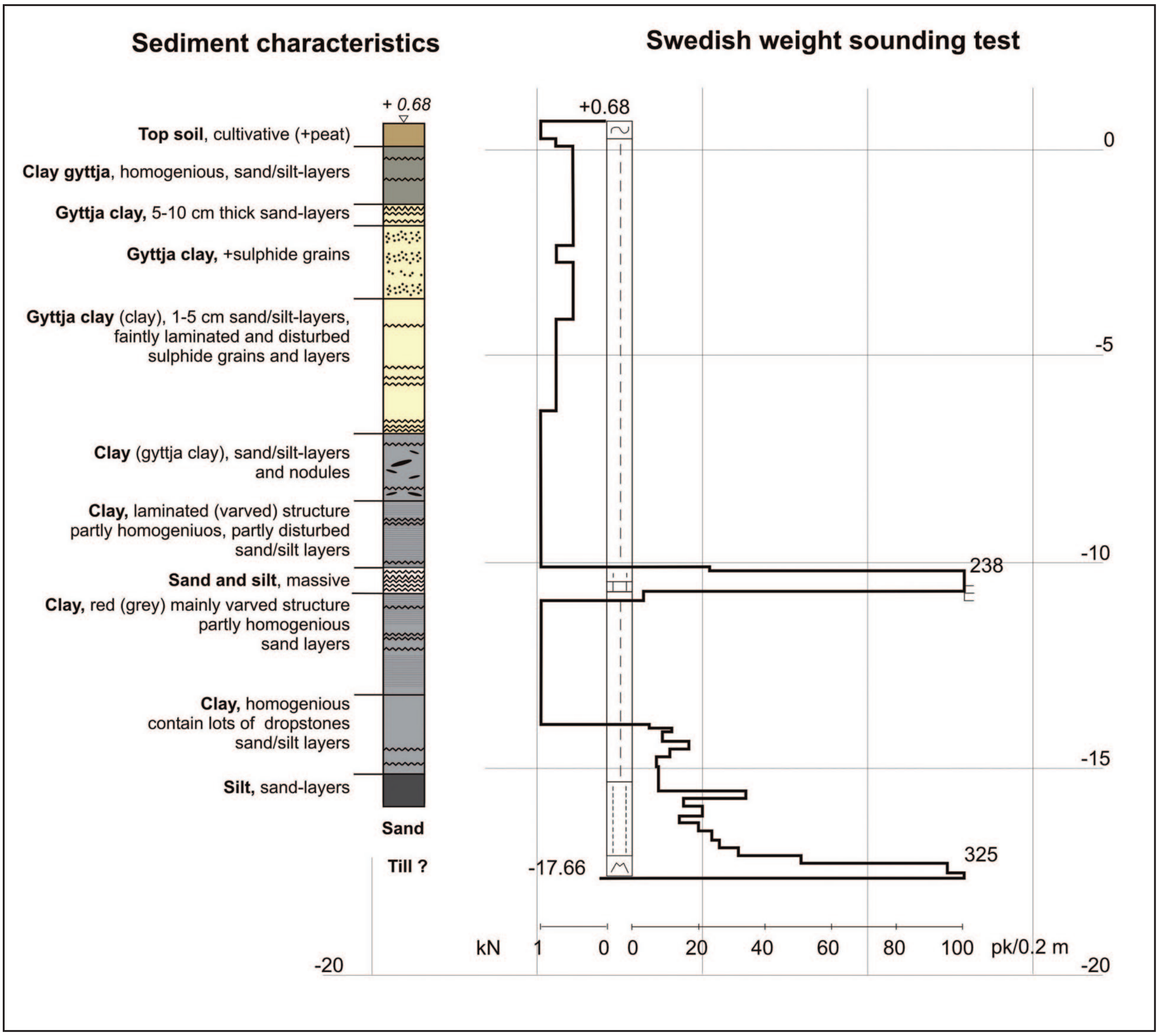

Figure 4. An example of an engineering-geological type section from the Perkkaa area in Espoo. Coring location Perkkaa 1 in Ojala (2009).

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ARSENIC IN THE PIRKANMAA REGION, SOUTHERN FINLAND: FROM IDENTIFICATION THROUGH TO RISK ASSESSMENT TO RISK MANAGEMENT

by
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Ruskeeniemi, T., Backman, B., Loukola-Ruskeeniemi, K., Sorvari, J., Lehtinen, H., Schultz, E., Mäkelä-Kurtto, R., Rossi, E., Vaajasaari, K. & Bilaletdin, Ä. 2011. Arsenic in the Pirkanmaa region, southern Finland: From identification through to risk assessment to risk management. *Geological Survey of Finland, Special Paper 49*, 213–227, 5 figures.

The RAMAS Project investigated the occurrence of arsenic in the Tampere region (Pirkanmaa), assessed the potentially arising health and ecological risks at the regional scale, and presented recommendations for preventive and remediation actions. The three-year project (2004–2007) received financial support from the EU LIFE Environment programme. The implementing partners were the Geological Survey of Finland, Helsinki University of Technology, the Pirkanmaa Regional Environment Centre, the Finnish Environment Institute, Agrifood Research Finland, Esko Rossi Oy and Kemira Kemwater.

The project mapped the areas where natural arsenic concentrations are elevated in bedrock, the soil cover or in groundwater and surface waters. Arsenic contents in arable land, crops, and in some wild berries and mushrooms were analysed. Correspondingly, the most important potential anthropogenic sources were located and evaluated.

Concerning the human health risk, potable water from drilled wells was determined to be the main exposure route. The exposure for arsenic was demonstrated in a biomonitoring study. Arsenic concentrations in urine were clearly elevated among those households using arsenic-bearing well water. An epidemiological survey revealed that certain cancer types linked to arsenic are statistically more frequent in those areas where the health limit value for arsenic (10µg/l) in well waters is commonly exceeded. Many of the local municipalities have made major efforts to extend the public water supply network to those areas suffering from elevated arsenic concentrations. Arsenic is not a problem in arable lands, and its uptake by plants also seems to be very low. However, it is less appreciated that both the till cover and bedrock in the region may locally contain naturally high arsenic concentrations.

The most important anthropogenic arsenic sources in the region include a few wood treatment plants that have utilized copper-chromium-arsenic solutions in their production, and closed sulphide mine sites. The environmental and ecological risks related to the various arsenic sources were evaluated and the most urgent needs for remediation measures were identified. Preventive decisions already made during the planning phases of land use activities are the most effective risk management measure both in terms of health and ecological risks.

The RAMAS project has published several reports and risk area maps, which can be downloaded from the project's website: www.gsf.fi /projects/ramas.

Keywords (GeoRef Thesaurus, AGI): environmental geology, arsenic, background level, bedrock, soils, ground water, surface water, human activity, risk assessment, risk management, Pirkanmaa, Finland

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ARSENIC IN THE NATURAL ENVIRONMENT

Arsenic (As) is a natural component of bedrock. It ranks twentieth in abundance among the elements in the Earth's crust. The abundance of arsenic in the continental crust is generally given as 1.5–2 ppm (NRC 1977, Reimann & Caritat 1998). Thus, it is relatively scarce. Nevertheless, it occurs as a major constituent in more than 200 minerals (NRC 1977, Smedley & Kinniburgh 2002). Of these minerals, arsenopyrite (FeAsS) is by far the most common.

Geological processes have dispersed arsenic to locations where it is more susceptible to dissolution and transport to the biosphere, such as water-conducting fractures in bedrock and the soil cover. Human activities have also released arsenic into the environment, generating contaminated areas with occasionally very high arsenic concentrations.

Arsenic is a redox sensitive element, which means that it may be present in a variety of redox states.

The common oxidation states are –3, 0, +3 and +5 (CRC 1986). Under oxidising conditions, the predominant form of arsenic in water and soil is the oxidised form, arsenate (As^{5+}), while under more reducing conditions, arsenite (As^{3+}) may be the dominant arsenic species (e.g. Cullen & Reimer 1989). At a near neutral pH, which is common for groundwaters, arsenate is present as negatively charged oxyions, $H_2AsO_4^-$ or $HAsO_4^{2-}$, whereas arsenite remains in the form of uncharged H_3AsO_3 until the pH is raised to 9. The geochemical properties of these dissolved arsenic forms differ, and this combined with the prevailing conditions in the water-rock/soil system has significant implications for the behaviour of arsenic in the environment.

Naturally occurring arsenic in drinking water has been identified as a global problem since the 1980s (Dhar et al. 1997, Battacharya et al. 2007). In South and South East Asia, at least 50 million people exposed to arsenic suffer from cancer and other arsenic-related diseases. Wide areas in South America and the US have been reported to contain an excess of arsenic in groundwater. In most areas of Central and Western Europe, arsenic concentrations in subsoil are elevated (Salminen et al. 2005). This is also reflected in the quality of groundwaters.

In the early 1990s, some alarming findings were published, mainly from Taiwan and Bangladesh, concerning the health effects of arsenic. As a consequence of these findings, the WHO recommended that the human health-based limit value for arsenic in drinking water should be reduced from 50 µg/l to 10 µg/l (WHO 1993). National authorities in many countries followed this recommendation, including the Finnish Ministry of Social Affairs and Health (STM 1994a, 1994b). In 2007, threshold and guideline values for arsenic in soil were defined (Government Decree 214/2007). The threshold value for assessing the arsenic contamination of the soil and the need for remediation is 5 mg/kg. If the natural background value demonstrated for an area is higher than this, it is applied instead. Soil is regarded as contaminated if the guideline values of 50 mg/kg (residential areas etc.) or 100 mg/kg (industrial areas, parks etc.) are exceeded. The guideline values are based on either ecological or health risks.

Since the 1980s, geochemical mapping conducted in Finland has revealed several areas with elevated arsenic concentrations in bedrock and soil (Koljonen et al. 1992, Loukola-Ruskeeniemi & Lahermo 2004). One widespread arsenic anomaly is located in a densely populated area in the southern part of the country, in the Tampere region (Figure 1). When the analytical methods for water analysis improved in the early 1990s, excess arsenic was also detected from bedrock groundwater. Combined with the reported adverse health effects arising from rather low arsenic concentrations, municipalities and health authorities were motivated to launch a number of studies in this region (e.g. Backman et al. 1994, Kurttio et al. 1998, 1999, Carlson et al. 2002, Vaajasaari et al. 2002).

There has been considerable interest in arsenic from other perspectives, as well. Numerous potential anthropogenic sources of arsenic have been identified in the Pirkanmaa region, such as wood impregnation plants, power plants, mines, landfill sites and other waste treatment plants (Blinikka 2004, Melanen et al. 1999, Register of Contaminated Land Areas). In this context, the local authorities have monitored arsenic, for instance, in fresh waters and sewage around suspected contaminated areas.

Earlier studies have been site- or target-specific without any wider consideration of the impact on the whole community or the environment. Furthermore, the existing information is spread between numerous files and registers and is not readily accessible to users. This was the starting point and acted as the promoter for the integrated arsenic project proposal "Risk assessment and risk management procedure for arsenic in the Tampere Region" (RAMAS), submitted to the EU LIFE Environment programme. The proposal was successful and the project was implemented in 2004–2007.

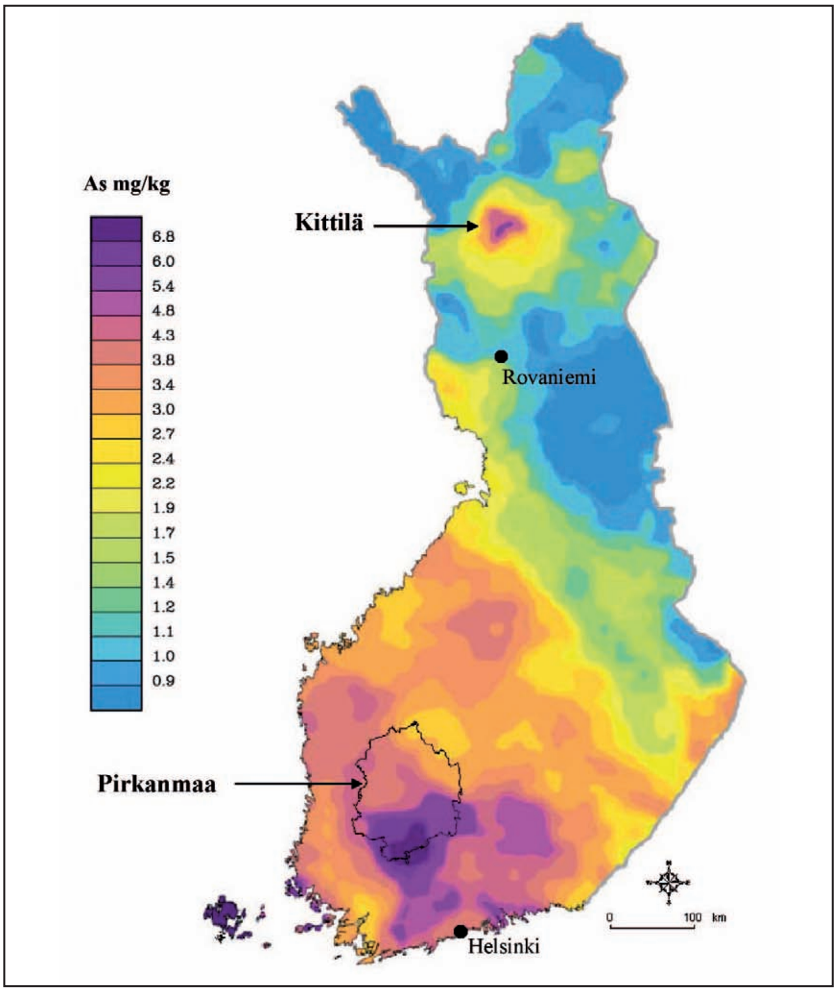

Figure 1. Distribution of arsenic in glacial till in Finland (modified from Koljonen et al. 1992).

RAMAS PROJECT: INVESTIGATIONS AIMING AT ARSENIC RISK MANAGEMENT IN THE PIRKANMAA REGION

In brief, the general aims of the RAMAS project were to compile all the available data on natural and anthropogenic arsenic from the study area, to fill the possible data gaps with supplementary studies, to carry out environmental and health risk assessments based on this knowledge, and finally, to identify possible needs for risk management actions arising from the outcomes of the risk assessment.

The project organization brought together institutions and researchers with wide-ranging expertise on the various aspects of environmental risk assessment and management. The participating organisations had access to a major part of the historical data, whether in the files of research institutes or in the registers of authorities, and they were able to provide almost all the analytical services the project needed. The project partners included the Geological Survey of Finland (beneficiary), Helsinki University of Technology, the Pirkanmaa Regional Environment Centre, the Finnish Environment Institute, Agrifood Research Finland, Esko Rossi Oy and Kemira Kemwater. More detailed information on the project and the resulting information can be found at the project’s website: www.gtk.fi/projects/ramas.

APPROACH AND RESULTS OF THE PROJECT

The RAMAS project was the first in Finland to create an overall, large-scale risk management strategy for a region that has both natural and anthropogenic contaminant sources. The regional risk assessment was based on selected test cases. These included households or farms that had utilized arsenic-bearing water and soil for a long time, wood impregnation plants and abandoned mine areas. All relevant information was gathered and the assessment of arsenic uptake by crops, ecotoxicological testing and biomonitoring (human exposure) were carried out to obtain a better understanding of the exposure-response relationships in the area.

The following sections present a summary of the main project tasks dealing with: natural arsenic sources (Backman et al. 2006, Mäkelä-Kurtto et al. 2006, Backman et al. 2007b), anthropogenic arsenic sources (Parviainen et al. 2006, Bilaletdin et al. 2007, Parviainen et al. 2009, Placencia-Go´mez et al. 2010), risk assessment (Schults & Joutti 2007, Sorvari et al. 2007), risk management (Lehtinen & Sorvari 2006, Backman et al. 2007a, Lehtinen et al. 2007a) and dissemination of results. The two first tasks collected and reported geochemical and other information related to the various arsenic sources, providing the input for the risk assessment task. The risk management task, in turn, addressed the needs for preventive and remediation measures identified on the basis of the ecological and health risk assessments. The Final Report by Loukola-Ruskeeniemi et al. (2007), directed at the local authorities and population, tied together the outcomes and provided recommendations for arsenic-related risk assessment specifically tailored for the Pirkanmaa Region.

The RAMAS project has published 11 technical reports covering all the disciplines of the project (see www.gtk.fi/projects/ramas). These reports not only describe the work carried out and the methods applied, but they also provide the primary, unpublished data collected from different sources and the new data produced by the project. All reports, except for two, are in English. The Final Report, however, was written in Finnish, because it was considered beneficial in order to reach the attention of the authorities in municipalities, regional environmental centres and licensing agencies. The international audience was addressed in 13 conference presentations. In addition, more than 40 presentations were given in national forums. This dissemination is still continuing following the closure of the RAMAS project, and a number of scientific publications are under preparation.

Natural arsenic sources

Natural arsenic in the area is derived from arsenic bearing minerals, which are locally enriched in the metamorphosed, crystalline bedrock (Lahtinen 1996, Lahtinen et al. 2005, Rasilainen et al. 2007). Due to the action of geological and geochemical processes, arsenic has transferred to groundwater and soils. Glaciogenic events were particularly important in dispersing arsenic into the surrounding areas. The study area can be geologically divided into three units. In the northern half of the area, granitic bedrock dominates and the arsenic concentrations recorded in all geological media were at the average level encountered in the country. The arsenic problem is clearly focused in the southern part of the Pirkanmaa Region, where metamorphosed volcanic rocks are common constituents of the bedrock (Backman et al. 2006). These same units also have potential for Au occurrences, for which arsenic is commonly used as a pathfinder element. There have even been some attempts to apply elevated arsenic concentrations in groundwater in the identification of interesting areas for gold exploration (Ruskeeniemi et al. 2007).

Arsenic concentrations in shallow groundwater and surface waters are generally low, below 1 µg/l. Hence, arsenic is not an issue for the public water supply, which is based on these shallow water reservoirs. The major concern is focused on drilled wells, which are used by private households and other small units. Altogether, 1 237 arsenic analyses from drilled wells were available. In 22.5% of the wells, the limit value of 10 µg/l was exceeded. All these arsenic wells are located in the southern part of the study area. Most of the samples that underwent arsenic speciation analysis were arsenate (As^{5+}) dominated.

Elevated arsenic concentrations in soils are related to till, which is the main soil type in the region. The regional arsenic anomaly extending from the Tampere Region towards the south was already recognized in the nationwide geochemical mapping of till (Koljonen et al. 1992). The median value for arsenic in the study area is twice that of the rest of the country (5.3 mg/kg vs. 2.6 mg/kg). There are areas where the arsenic concentrations have been found to exceed the limit value for contaminated soil

(50 mg/kg for residential areas and 100 mg/kg for industrial areas). The highest measured concentration was 9 280 mg/kg. Arsenic concentrations tend to increase downwards in the soil profile and the highest concentrations are generally in the basal part of the sequence (Figure 2). This observation has important implications for the handling of arsenic-bearing till. Arsenic concentrations in other soil types are also higher in the so-called arsenic province in South Pirkanmaa than in the rest of the country. In sand and gravel, the arsenic content was 8.7 mg/kg in topsoil and 10.3 mg/kg in subsoil (N = 50), and in clay the respective figures were 7.2 mg/kg and 8.0 mg/kg (N = 59) (Hatakka et al. 2010).

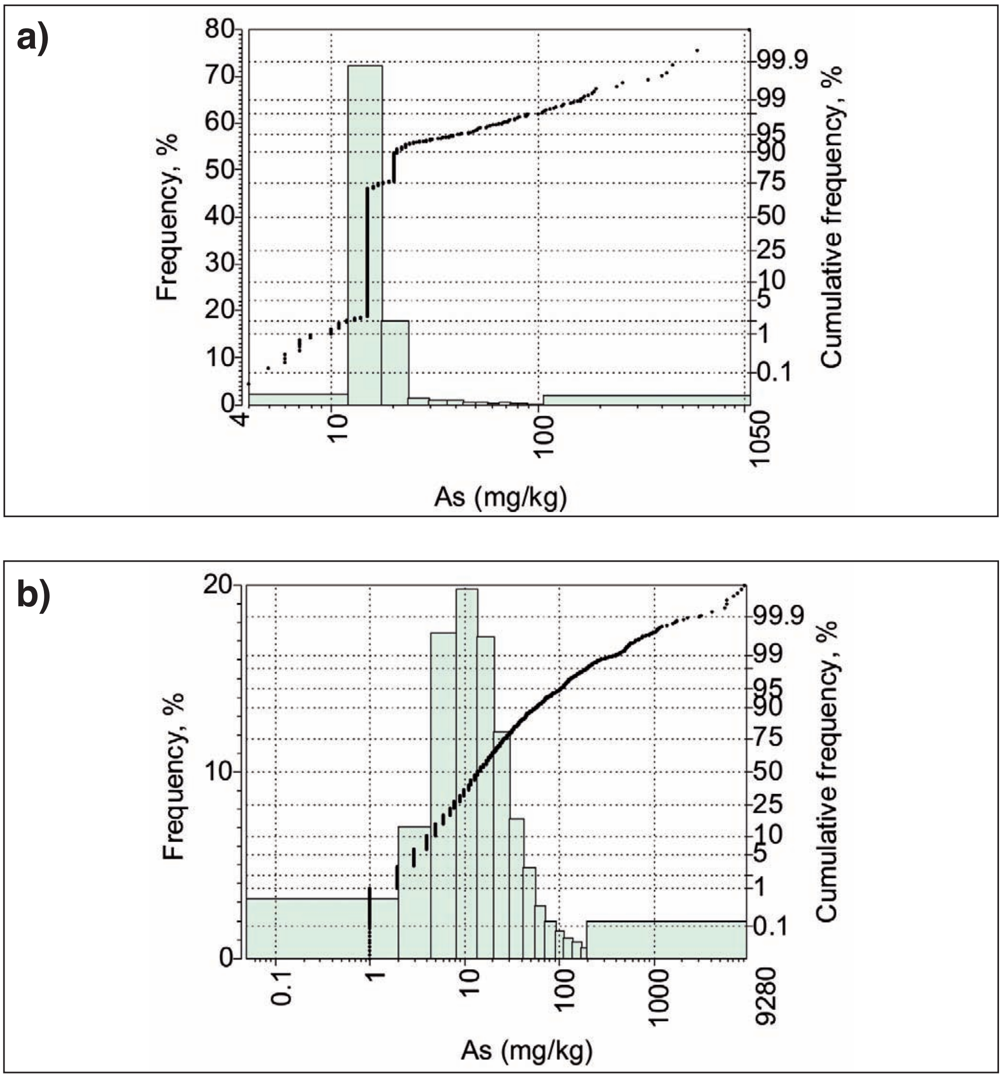

Figure 2. a) Arsenic in top soil (n = 1431) and b) basal till (n = 9392) (Backman et al. 2007b).

Locally high arsenic concentrations in bedrock groundwater may pose a risk to public health in the southern part of the region. In shallow groundwater and surface water the arsenic concentrations were low. In some cases the high arsenic content in bedrock and soil may give rise to environmental problems and require careful consideration in land-use planning. The RAMAS project produced a series of geochemical maps presenting the arsenic distribution in various geological media. In addition, an integrated geochemical risk area map was compiled, where the observed arsenic concentrations relative to the guideline values for drinking water (10 µg/l), soil (50 mg/kg) or bedrock (50 mg/kg) were applied to evaluate the source of the risk (Figure 3).

The contents of arsenic and other elements in arable and forest soils and crops were investigated at selected farms. The 13 farms studied were located in areas where the arsenic concentrations in till were known to be elevated. The aims were to compare arsenic concentrations between arable and forest soils, between soil layers, between crop species and between high- and low-arsenic areas. Wheat grains (*Triticum aestivum L.*), potato tubers (*Solanum tuberosum L.*) and timothy grass (*Phleum pratense L.*) were the selected crop species, because they are important in the human food chain (Mäkelä-Kurtto et al. 2006).

Arsenic contents in arable soils ranged from 2.90 to 6.80 mg/kg dry matter (dm) in the plough layer and from 2.84 to 4.82 mg/kg dm in the subsoil. These values are at the national level, despite the elevated arsenic concentrations in the surroundings. Only about 1% of the total arsenic was in a soluble form in the soil plough layer. The arsenic content in corresponding forest soils was somewhat higher, but distinctly lower than in till. This is due to the differences in the source and the transport distance of the geogenic material forming these soil types. The source for clays and other fine-grained soils, typically cultivated in this region, is further away in low-arsenic bedrock areas, while tills represent the local, arsenic-rich bedrock. A major source of arsenic in arable and forest land seemed to be of geogenic origin. Obviously, the surface layers have received a minor amount of additional arsenic from anthropogenic sources, such as atmospheric deposition and fertilizer preparations (Mäkelä-Kurtto et al. 2006).

Arsenic contents in the crops were at a low level, and on average increased in the following order: wheat grains (0.005 mg/kg dm), potato tubers (0.011 mg/kg dm) and timothy grass (0.014 mg/kg dm). Peeled potatoes contained less arsenic than unpeeled ones. Soil-to-plant uptake factors of arsenic were also low, being on average 0.001 for wheat grains and potato tubers and 0.004 for timothy grass. Arsenic had one of the lowest soil-to-plant uptake factors among the elements studied. The limited data on forest berries and mushrooms collected in the project did not indicate any arsenic uptake, either (Backman et al. 2007b).

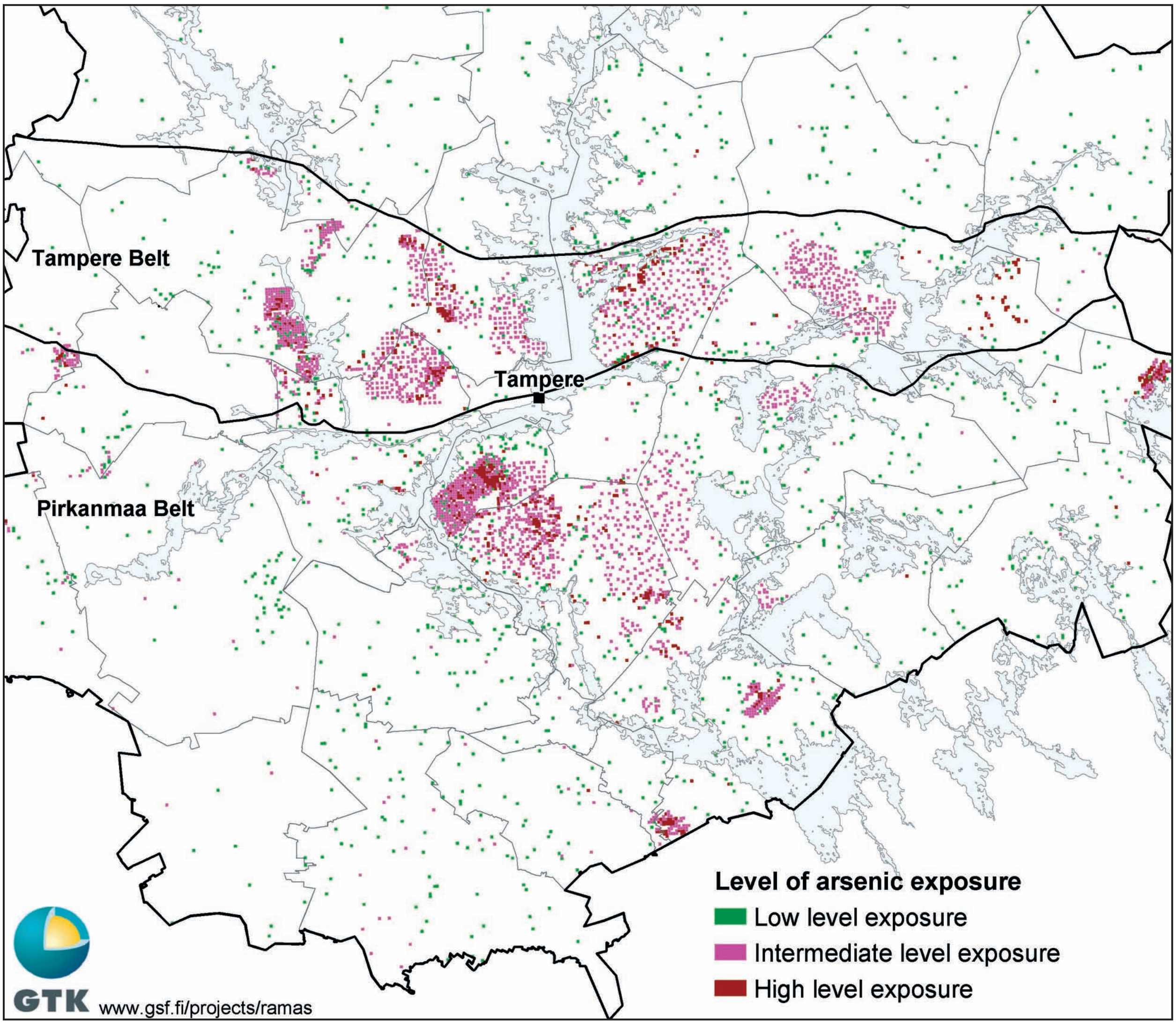

Figure 3. Integrated geochemical risk area map based on the comparison of observed concentrations and the guide-line values for arsenic in groundwater, soil or bedrock. The northern part of the study area is not shown due to the consistently low risk (Pasanen et al. 2007).

Anthropogenic arsenic sources

Data on anthropogenic arsenic sources were acquired in relation to chemicals (wood impregnates, pesticides), products (ammunition, fertilizers, fodder), and industrial activities such as mining and waste treatment sites. The RAMAS project also investigated the possible role of landfill leachates in mobilizing naturally occurring arsenic from the surrounding till. The most relevant arsenic sources in the Tampere region were determined to be wood preservative plants and old mine sites (Parviainen et al. 2006).

Altogether, 14 wood treatment plants were identified in the study area, two of which were in operation until late 2006, when the use of wood treatment based on chromated copper arsenate (CCA) was banned. The negligent use of CCA products, inappropriate storage of CCA-treated wood and the use of the impregnated wood in the past have caused soil, surface water and groundwater contamination. Concentrations of arsenic in the contaminated soils at CCA plants in the study area range from 3 up to 12 000 mg/kg. The majority of harmful elements from the CCA-contaminated soils have already leached and migrated over time and at present the leaching is slow but continuous. The ecotoxicological tests carried out within the RAMAS project demonstrated that the soils heavily contaminated by CCA appeared to be toxic to some organisms. There were also indications that copper rather than arsenic might be the cause of environmental hazards (Schultz & Joutti 2007).

Mining of sulphide ores leaves behind waste rock and tailings, giving rise to acid mine drainage and the consequent release of harmful elements. There are five mine sites in the study area, two of which, the Haveri Cu-Au mine and the Ylöjärvi Cu-W-As mine, were assessed in the RAMAS project. The ore in Ylöjärvi contained 1 200–4 600 mg/kg of arsenic, while at Haveri the arsenic concentrations were well below 100 mg/kg.

The Ylöjärvi mining area was already identified as a potential source for arsenic contamination several decades ago, and the nearby surface waters have been monitored since the 1970s. The tailings area has an impact on the quality of surface waters, and the active period of the mine can be traced from the lake sediment layers of nearby lakes and streams (Carlson et al. 2002, Parviainen et al. 2006). The tailings area contains high concentrations of arsenic ranging from 1 000 to 2 200 mg/kg, resulting in runoff containing up to 250 µg/l of arsenic. The arsenic concentrations in surface waters gradually decline downstream so that after 7 km, the load to Lake Näsijärvi is 3–14 µg/l (Bilaletdin et al. 2007). It is evident from the lake sediment profiles that much more arsenic was available along the route during the mining period. During mining, the sediment layers of Lake Näsijärvi contained 235 mg/kg of arsenic, whereas the natural background level was 17 mg/kg. The recent sediments still contain twice the natural background amount of arsenic, indicating that the tailings area is continuously stressing the environment.

Risk assessment

To assess the risks of environmental arsenic to human beings and biota, case-specific, quantitative human health risk assessments (HRA) and ecological risk assessments (ERA) were carried out. These risk assessments focused on the specific site types previously identified in the RAMAS project. In the study area, such site types included former wood treatment plants that had used CCA, mine sites, and areas with a naturally high level of arsenic in soil or groundwater (Sorvari et al. 2007).

The ecological risk assessment followed a tiered approach recommended at national and international levels (Figure 4). In tier 0, the environmental concentrations of arsenic were compared with various ecological benchmark values, *i.e.* risk-based concentration limits. Exceeding of the benchmarks normally indicates the need for a more detailed *i.e.*, baseline assessment (tier 1). Some uptake and intake models were used to derive risk estimates for the identified key species. In tiers 0 and 1, all available concentration data on arsenic in different media (soil, water, air, sediment) were used. In tier 2, the data were amended according to the results of ecotoxicity tests (Schultz & Joutti 2007), which measure harmful effects on test organisms under controlled standard conditions. As test species we used aquatic and terrestrial organisms: microbes, plants and soil animals. Besides the toxicity of the contaminants, their environmental fate is of concern when assessing the factual risks. Hence, a combination of leaching tests, measuring the potentially available fraction of a compound, and ecotoxicity tests with soil samples allowed the derivation of some estimates of possible environmental risks in the future.

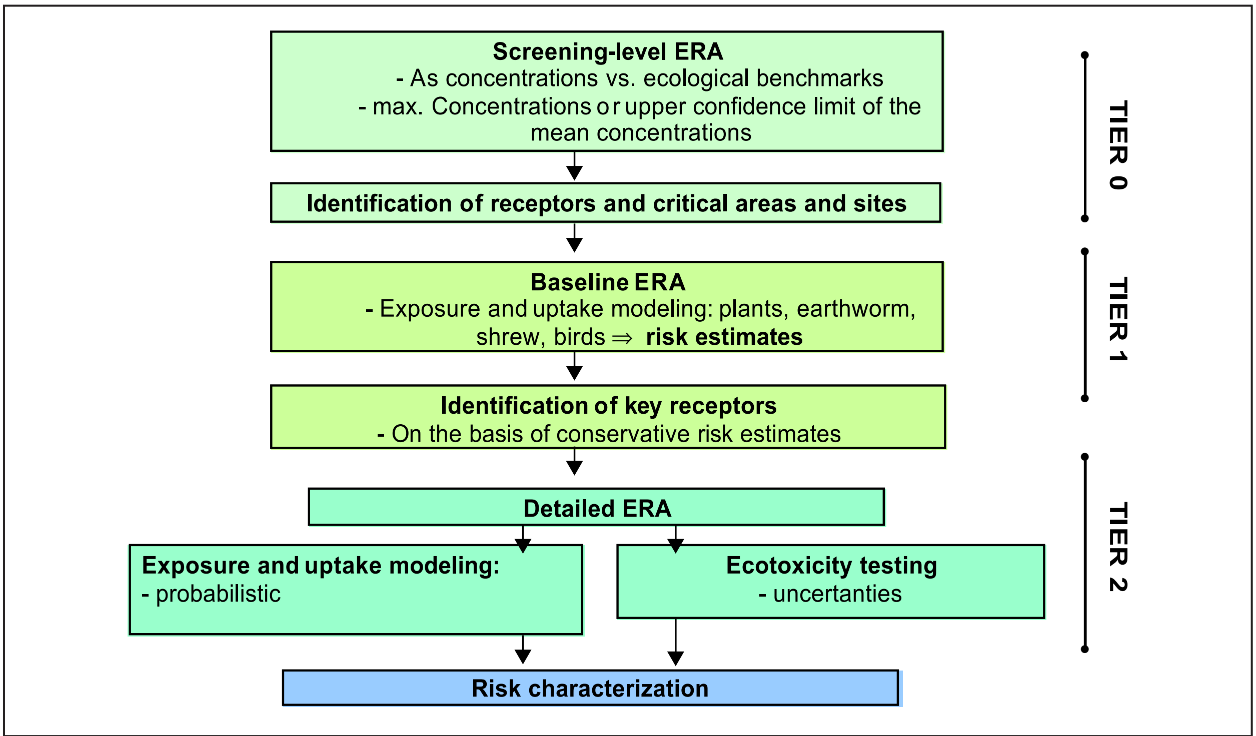

Figure 4. Tiered approach followed in the ecological risk assessment (Sorvari et al. 2007).

The assessment of human health risks (HRA) was based on exposure modelling (Sorvari et al. 2007), human biomonitoring (Lehtinen et al. 2007b) and epidemiological studies (Pasanen et al. 2007). In exposure modelling, all the potential intake routes (food consumption, direct contact with soil and consumption of drinking water) were taken into account. Statistical estimates of intake from drinking water were calculated using Monte Carlo simulation based on the results from analyses of arsenic in well water samples. Exposure from other than site-specific sources was estimated from national level data. The potential exposure arising from the key anthropogenic hot spot areas, *i.e.*, mine sites and CCA wood impregnation plants, was also considered. In the case of anthropogenic sources, the primary calculations were based on the highest arsenic levels in order to cover the "worst case" exposure scenarios. The results from the biomonitoring study (urine analyses) and the epidemiological study (the incidence of several cancer types) were used to verify the potential human exposure and risks on the population scale.

The ***ecological risk assessment (ERA)*** based on chemical data and exposure uptake modelling using conservative assumptions resulted in very high risk estimates, *i.e.* hazard quotients (HQs), in the case of the former wood impregnation plant and the mine site. Based on these results, all study sites pose ecological risks varying from moderate to high. Ecotoxicological studies confirmed the high risk for the CCA plant. The physical properties of the tailings limited the use of all the test species, but similar risks were also observed for the mine site. Only a low risk was observed for areas with high natural arsenic in till (Schultz & Joutti 2007). When the results from all the different study methods were combined, the mine site appeared to pose the highest ecological risks compared with the other study sites.

The ERA showed that even naturally occurring arsenic may cause adverse effects on the most sensitive species. Hence, we can expect that some selection of species has occurred in areas with high concentrations of naturally occurring arsenic in soil. The highest natural concentrations in soil are found in the deeper layers, which limits the exposure of biota, whereas the risks to groundwater quality may be high. In the case of excavations, such material can be brought up to surface layers, where it can pose significant risks to biota. Due to the toxicity and steep dose-response effects of arsenic, safety margins need careful consideration in areas with elevated background levels. The risks to the aquatic ecosystem adjacent to the mine site are not expected to decrease with time, considering the vast amount of arsenic stored in the tailings area (Sorvari et al. 2007).

The ***health risk assessment*** indicated that the arsenic content in the dug well waters, typically below 1 µg/l, apparently does not pose any significant health risk to consumers. The average total arsenic intake by drilled well water users was estimated to be 0.56 μg/kg/d. The probability of exceeding the safe exposure level was estimated to be 5.9 to 46%, depending on the applied regulatory value (Sorvari et al. 2007, Rossi et al. 2007). However, the arsenic intake estimates differ considerably between the different parts of the study area. The biomonitoring study verified exposure from drinking water, *i.e.*, the concentrations of arsenic excreted in urine were highest among the users of water containing elevated concentrations of arsenic (Lehtinen et al. 2007b). However, in a few cases, high urinary concentrations were detected even though people were not exposed through drinking water. These elevated concentrations might be associated with occupational exposure or exposure, for example, in hobbies. Some evidence for an elevated cancer incidence within the Tampere region was obtained, although the results need to be interpreted with caution due to several sources of uncertainty that may bias the results (Pasanen et al. 2007). Nevertheless, this is a clear signal that underlines the need for further studies on the health impacts of arsenic and preventive actions to reduce the exposure.

The health risks related to arsenic are further discussed in Kousa et al. in this volume.

Risk management

In the first phase of the risk management task of the RAMAS project, the methods applied in the management of arsenic-related risks were surveyed using the literature and expert interviews as information sources (Lehtinen et al. 2006). These methods can be classed as policy instruments, informational mechanisms or technical methods. In the second phase, the study specifically focused on the risk management procedures adopted in the study region and on the identification of possible development needs (Lehtinen et al. 2007a).

There are no definite or established criteria for a ‘good’ risk management (RM) process. However, some factors, such as an adequate connection with risk assessment and sufficient participatory practices, can be identified as being the main contributors to a ‘good’ RM process. The stakeholder involvement during RAMAS was extensive and based on the identification of the key local and regional level actors (Figure 5).

According to the risk assessment carried out within RAMAS, the main human health risks in the study region are from arsenic in drinking water, particularly that originating from drilled wells. These risks have been restricted, for instance, by expanding the water supply network. Such activities have also been subsidized by the State. It is important that these expansions are continued in the future. Here, regional land use and water supply planning play an important role. Household-specific methods are also available for the removal of arsenic from drinking water. However, the equipment is not yet widely used.

In the Tampere region, the population centres are focused in the arsenic-rich areas and even in the vicinity of the old mine sites, posing a risk to human health. The expansion of residential areas to old mine sites or former wood impregnation sites, for example, may result in significant additional risks to human health. It is also necessary to ensure that in the future, the contamination at former mine sites will not extend to potential new residential areas.

Data on those contaminated sites that might contain arsenic, e.g. mine sites and wood impregnation plants, have been collected and are maintained in a national register. So far, remediation measures have been carried out at 8 of the 14 wood treatment plants in the study area. At present, only a few remediation methods are available for soils contaminated with arsenic and other inorganic compounds in Finland. Hence, soil excavation and treatment off site is still the most common remediation method. As an alternative option to remediation measures, the most contaminated hot spots at CCA plant sites could be marked in the field in order to avoid human exposure. Some of the former CCA plants are located on important groundwater areas (class I). In such areas, it is important to consider potential risks to groundwater quality. From the viewpoint of environmental risks, old mine sites are particularly relevant owing to their large spatial scale. So far, no notable remediation activities have been realized at mine sites in the Tampere region.

It is recommended to particularly restrict human activities in the tailings areas of mine sites in order to eliminate the distribution of arsenic to the environment via air and surface run off. Here, active remediation measures would be one option. The wetlands between mine sites and larger water systems effectively bind arsenic and hence hinder its migration further in the water system. The functioning of such natural ‘purification units’ should be maintained.

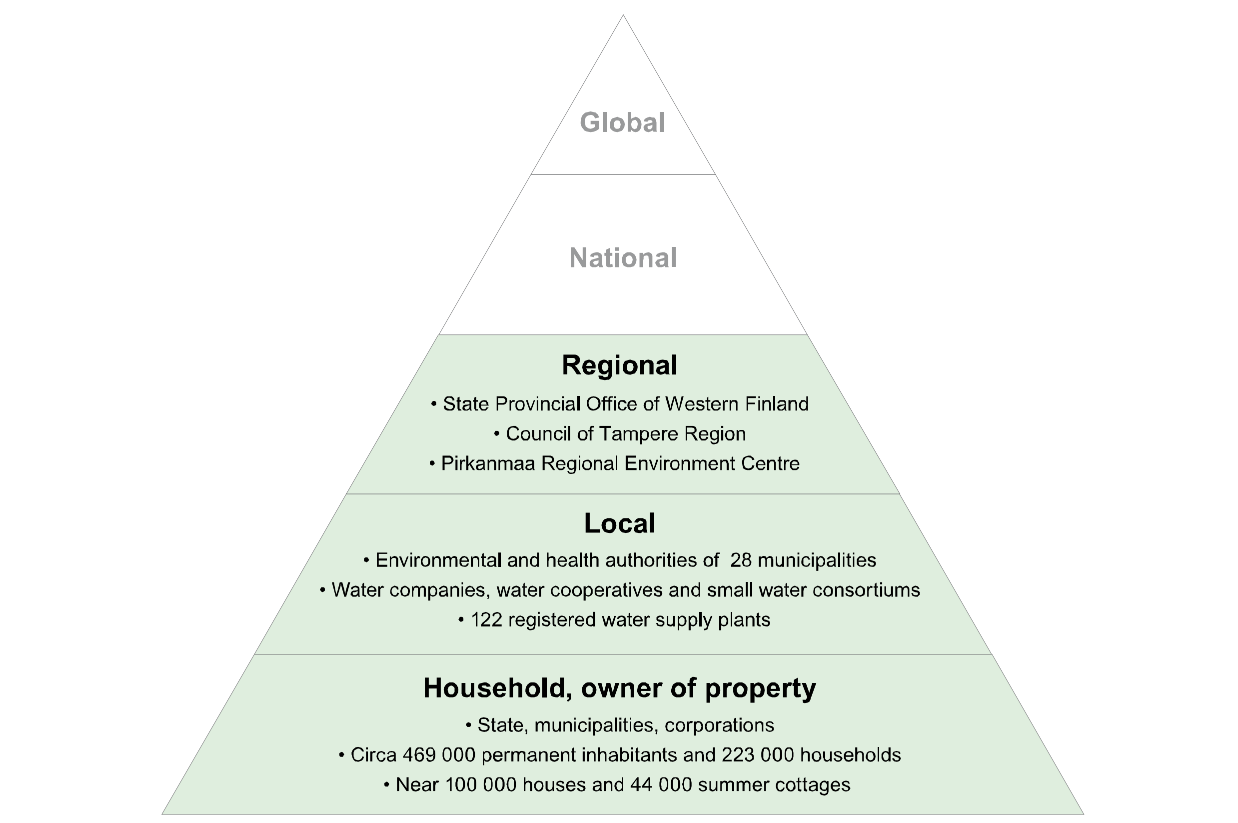

Figure 5. Stakeholders in the study area involved in the management of risks associated with environmental arsenic (Lehtinen et al. 2007).

RAMAS AND THE THEMATIC STRATEGY FOR SOIL PROTECTION

The RAMAS project was planned and realized in the spirit of the EU Thematic Strategy for Soil Protection (COM(2006)231 final). The multidimensionality of risk management decisions that consider soil contamination was acknowledged in RAMAS. Assessment of the environmental and human risks is a vital element, but other elements also influence risk management decisions such as the available policy instruments, resources and technology, pressures on the use of land and other natural resources, existing operational structures (e.g. administrative practices, ownerships) and socio-cultural aspects.

Little attention has in general been paid to the protection of other recipients of arsenic compounds than groundwater, which could be used for drinking and other household purposes. During the RAMAS project, the human health effects and their regional extent, especially the risk of cancer, attracted the greatest attention among the stakeholders. It is clear that food safety and health is tightly interlinked with soil protection, as stated in the thematic strategy. However, the other recipients need consideration. As stated in the soil strategy: “soil is interlinked with air and water in such a way that it regulates their quality.” In the case of larger contaminated areas, such as historical mining areas, risk assessment and management should be based on larger drainage areas, even at river basin scale. Therefore, we support the idea of assessing possible synergies between soil protection and measures incorporated in river basin management plans under the Water Framework Directive.

The development needs of the ecotoxicological methodologies were once again confirmed in RAMAS. The task of defining differences in the bioavailability of arsenic originating from different sources, such as natural or anthropogenic sources, proved to be very demanding. In Pirkanmaa, even the determination of the origin of soil contamination can be very complicated. On the other hand, the discrimination between natural and anthropogenic origin is only needed for decisions concerning liability issues, and is not necessary in the planning of risk management.

The mine sites investigated in the RAMAS project were far too large for a remediation approach in which the contaminated material is transported to another location. Correspondingly, it is difficult to envisage that any constructed arsenic removal facility would be cost-effective in the case of the studied tailings-lake-stream-lake system. Instead, it is recommended that the functioning of the natural wetlands should be maintained, and perhaps even strengthened. Further investigations are needed in order to better understand the mechanisms by which arsenic binds in freshwater ecosystems.

TRANSFERABILITY OF THE RESULTS

Arsenic is already an identified problem in many areas and is likely to cause problems in many others, although not yet recognized. This is due to the abundance of arsenic in geologic materials and its relatively common use in industry and agriculture. Presently, the industrial use of arsenic is restricted in many countries, but the historical consumption has left behind sites that require remediation. Therefore, arsenic is a target for a large number of projects worldwide. Due to the multidisciplinary nature of the arsenic issue, it is necessary for environmental projects and programmes to learn from each other. This underlines the necessity for transferability, which in turn demands good documentation and the application of standardized methods when relevant. Certain features, such as climatic conditions, geology and national legislation or practices, limit the application of information produced elsewhere. However, many outcomes are transferable, either as direct solid data or as model approaches applied elsewhere.

The RAMAS project has aspired to promote data transfer in all its actions. Besides the several presentations given in international conferences and national forums, the project has published 11 reports, in which the methodology has been described in detail and the primary analytical data have been presented. The reports also provide the geological context, sampling and other features, which may be needed when the representativeness of the information is evaluated. The reporting was planned in such a way that both national and international end users were taken into account.

The primary, geochemical data are mainly relevant to geology, but somewhat also to the climate. Countries that have crystalline, metamorphic bedrock and a similar glacial history to Finland can benefit most from the datasets themselves, but also from the experience gained in how to plan and conduct geochemical sampling campaigns, the effects of sample treatment and which fraction to analyse. The limited transfer of arsenic from soil to crops and wild berries, the presence of arsenic in water ecosystems in both dissolved and solid forms and the overall arsenic concentrations in different geologic materials are examples of findings that could be useful in all environments.

One way to improve the transferability is to use standardized methods. A number of ISO and EN standards provide guidance on the various laboratory methods for environmental samples. This, of course, aims to enhance the applicability of the produced data, regardless of its origin. However, the standardisation is not fully comprehensive. In cases where internationally agreed methods are not available, the Decree on the Assessment of Pollution Level and Remediation Need for Soil (2007) given by Finnish Government, for instance, proposes the use of otherwise well-established practises. Presumably, this is also the case in many other countries. Therefore, the transferability of a project is dependent on detailed documentation of the methodology, as has been carried out in RAMAS.

In this context, it may also be useful to question the principles of standard methods themselves. Are they really optimal for the particular material under investigation? There is no doubt that there must be generally accepted concepts, but are the results for the low-pH glaciogenic soils typical of northern areas comparable with those, e.g. from Mediterranean soils of different chemistry and origin. What is good for contaminated soils does not necessarily work for natural soils. It might be useful to try somewhat tailored methods to meet the local requirements and, if possible, combine the results from different approaches. Clearly, more development and international co-operative research is needed in this field.

In Finland, more sophisticated risk assessment procedures have lately become more common instruments in decision making concerning soil remediation. Nevertheless, ecotoxicological methods are only occasionally used as part of risk assessment, probably because ecotoxicological testing is usually time-consuming and expertise is not easily available. However, the wider use of biological tests should be encouraged, since they provide direct information on the effects on biological systems, which are often very difficult to assess by other means. They also circumvent the basic question concerning the bioavailable fraction of contaminants, which is always associated with the use of concentration data. The very limited database on the ecotoxicity of harmful elements in natural Finnish soils, and especially for the organisms typically used in laboratory tests (earthworms, potworms, ryegrass etc.), complicated the interpretation of the ecotoxicological data in the RAMAS project. This calls for combined efforts to create such databases for international use.

An important outcome from any project, which is however often ignored, is the identification of gaps in data or in our understanding of the processes and the recognition of defects and shortcomings in methods. If adequately appraised and clearly expressed, these aspects are valuable for future projects and also for authorities and other end users when they are evaluating the state of knowledge in their fields of responsibility. Therefore, the RAMAS project has carefully analysed all the steps taken, from the collection of historical arsenic data to the risk assessment and risk management procedures, and has discussed at length the development needs in the Final Report directed to the Finnish audience, authorities in municipalities and environmental agencies and other target groups. The topic-specific discussions in English are available in the thematic reports available at the project's website and in a number of conference papers.

CONCLUSIONS FROM THE RAMAS PROJECT

The environment in Pirkanmaa, as well as environmental research, management and decision making, are expected to benefit from the outcomes of the RAMAS project in several ways. The project produced a considerable amount of information, which was refined to provide recommendations addressing aspects from initial data collection to risk management procedures. At least the following benefits can be mentioned:

- The spatial distribution of arsenic in the natural environment is now better understood. The areas with elevated or high arsenic concentrations in bedrock, soil and groundwater were identified with reasonable accuracy. The potential mechanisms of arsenic release from its primary source and the hazard it may pose to the ecosystem and human health were reviewed.

- Anthropogenic arsenic contamination was evaluated and the most problematic sites were identified. The data collected from and around a closed sulphide mine revealed that arsenic is continuously transported away from the source area, and distant ecosystems that are not adapted to elevated arsenic concentrations may thus be affected. A robust transport model was constructed to quantify the movement of arsenic in a watercourse impacted by a mine site

- It is important to realize that harmful components may occur in several chemical forms and compounds. In till, arsenic was found to be incorporated in primary sulphides derived from the bedrock. Sulphide fragments have preserved under the low-oxic conditions in the basal part of the till bed, while in the upper part of the sequence, weathering has disintegrated the primary minerals and released heavy metals and arsenic. Released arsenic has then bound to secondary iron and manganese compounds enveloping other soil particles. Arsenic is remobilized from these phases under different conditions and at different rates, which has implications in the assessment of risks. Rapid standard field or laboratory tests do not necessarily reveal the actual risk related to slowly weathering phases. Another implication is that these aspects must be considered when selecting the appropriate remediation methods

- A significant amount of new ecotoxicological data was produced for different types of contaminated and natural soils, evidencing the toxicity of arsenic-bearing soils to both invertebrates and plants used as test organisms. Undisputable arguments of this kind are valuable when debating the necessity for remediation measures

- Ecotoxicological laboratory methods were used and modified to be better applied to different soil materials. It is important that the results of ecotoxicity tests are carefully and critically interpreted. Especially when multiple contaminants are present, sufficient data and sophisticated statistical methods are of great value to demonstrate and identify the causative compounds

- Toxicity tests indicated that the concentration-effect curve is very steep for arsenic, *i.e.* the response was very dramatic once a certain threshold concentration had been exceeded. This observation points to the need for large safety margins regarding permitted arsenic concentrations in soil.

- It is possible that some local species may be rather tolerant of arsenic, even at high levels. The balance between species and the geochemical environment is achieved over time and results in natural biodiversity. The situation is different if the ambient geochemical balance is abruptly disturbed, e.g. by human activity, and the natural environment does not have enough time to adapt to this change

- Legislation, on the national or EU level, does not fully take into account elevated natural concentrations. The focus is on anthropogenic contamination, although the adverse effects on organisms may be the same despite the adaptation to background concentrations. Furthermore, both natural and anthropogenic sources may occur in the same areas, such as in the case of mine sites or at a construction site where naturally high-arsenic soils become anthropogenic sources when excavated

- It is strongly recommended that national geochemical mapping or monitoring programmes, or other activities producing geochemical information, would consider a wider spectra of elements and not only those that are topical for the particular project itself. During the work of this project, it was frequently found that otherwise extensive data sets did not include arsenic analyses. The reason was generally that arsenic was not considered relevant for the conducted study

- The goal of the RAMAS project to carry out regional risk assessment and risk management for natural and anthropogenic arsenic and to consider the risks for both ecosystems and human health was quite ambitious. This was the first such attempt in Finland, and there were not many examples from other countries, either. Environmental risk assessment is normally carried out for spatially limited sites and for well-known chemical hazards. The selected approach, despite being laborious, also has clear synergy benefits. It motivates the formation of a truly comprehensive view of the problematic issue, arsenic in this case. This concept, including the identification of potential arsenic sources and the compilation of exposure-response scenarios, can be directly used for planning similar activities elsewhere. There are also better possibilities for compact and more elaborated interpretation of the results due to the wide scientific expertise engaged in multi-disciplinary projects. This type of "screening project", related to arsenic or other harmful elements, can be recommended for all countries.

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GEOLOGICAL AND GEOCHEMICAL METHODS IN ENVIRONMENTAL RISK ASSESSMENT IN URBAN AREAS: EXAMPLES FROM FINLAND AND RUSSIA

by
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Tarvainen, T., Jarva, J., Klein, J, Luoma, S. & Backman, B. 2011. Geological and geochemical methods in environmental risk assessment in urban areas: examples from Finland and Russia. *Geological Survey of Finland, Special Paper 49*, 229–236, 4 figures.

The Geological Survey of Finland has applied geological and geochemical data in various risk assessment procedures in urban areas and developed environmental risk assessment methods for land use planning purposes. Information on geochemical baseline concentrations in soil is needed to provide reference values in the assessment of soil contamination. GTK maintains a national geochemical baseline database that provides information on baseline concentrations in various soil types and in various regions with high natural trace element concentrations. Climate change could pose a risk to groundwater resources. Studies in Hanko, South Finland, indicate that the shallow sandy and gravelly aquifers in low-lying coast areas are most sensitive to changes in sea level and to storm surges. The integration of geological information in city management to prevent environmental risks was investigated in St. Petersburg, Russia. Seven geological risk factors were identified and an integrated geological risk map showing the distribution of risk levels over the city area was developed.

Keywords (GeoRef Thesaurus, AGI): environmental geology, urban environment, risk assessment, geochemical methods, soil pollution, baseline studies, climate change, ground water, Finland, Russian Federation

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INTRODUCTION

Geological, geochemical and geophysical data can be applied in various risk assessment procedures in urban areas. Risks in urban areas can be related to the ground stability, to geological and other natural hazards, to hazards caused by climate change or to the migration of potentially harmful elements and species in urban environments. Compared with general geological mapping, more detailed data up to the scale 1:2 000 are needed in urban areas.

The Geological Survey of Finland (GTK) has carried out urban geological research projects in Helsinki and Tampere Regions. Environmental risk assessment methods for land use planning purposes have also been developed in co-operation with other research organizations and land use planners, and they have been applied, for example, in St. Petersburg, Russia. Risk assessment methods have also been applied to pilot sites with soils affected by a heavy anthropogenic input and to groundwater areas that are important as sources of drinking water for urban settlements.

GEOCHEMICAL MAPPING AND APPLICATIONS IN RISK ASSESSMENT

Information on geochemical baseline concentrations in soil is needed to provide reference values in the assessment of soil contamination, especially in areas where the natural concentrations of trace metals are often high. In the Finnish definition of geochemical baselines, the baseline concentration in soil refers to both the natural geological background concentration and the superimposed diffuse anthropogenic input of elements. GTK maintains a national geochemical baseline database that provides information on baseline concentrations in various soil types and in various regions with high natural trace element concentrations (Jarva et al. 2010). Geochemical baselines can also be applied in environment impact assessment, in environmental permits related to land extraction as well as in decision making in other environmental studies.

In Finland, the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) provides threshold values and two guideline values for more than 50 potentially harmful elements and substances in soil. A threshold value is the maximum concentration of a potentially harmful substance (or the group of substances) causing negligible risk to the environment and human health. It is a fixed value prescribed in the Decree. Soil contamination and remediation needs must be assessed if the concentration of one or more substances in soil exceeds the threshold value. The geochemical baseline concentration, however, is regarded as the trigger value in areas with a baseline concentration higher than the threshold value (Anon. 2007). This applies particularly in the case of toxic metallic elements, since baseline concentrations may naturally be rather high.

In the Southern Pirkanmaa region, the natural concentrations of arsenic in soil are usually higher than the threshold value, 5 mg kg^{-1}, prescribed in the Decree. According to the national geochemical baseline database, the upper limit of the background variation in sandy soils in Southern Pirkanmaa is 26 mg kg^{-1}. Thus, a measured arsenic concentration of 20 mg kg^{-1} in an old industrial site would lead to basic risk assessment of soil contamination in most parts of Finland, but in Southern Pirkanmaa a similar concentration in sandy soil can be regarded as a normal baseline concentration. If the concentrations of other elements do not exceed the trigger values, there is no need for further assessment of soil contamination (Tarvainen & Jarva unpublished).

In addition to threshold values, the Decree includes upper and lower guideline values that must be used as a tool in basic risk assessment. Guideline values describe maximum acceptable risks to the environment and human health. The upper guideline values can be applied to industrial areas, and the lower ones to other land use types (Reinikainen 2007). Many of the guideline values are defined on the basis of ecological risk, and the national baseline levels are considered in the derivation process. If regional baseline values are available, the guideline values based on ecological risks can be modified accordingly. However, if the guideline values are based on human health risks, the guidelines should not be modified using the baseline data (Jarva et al. 2010).

GTK, in co-operation with the Finnish Environment Institute, has defined regional guideline values for some areas. Regional guideline values are calculated as the sum of ecologically determined limit values and baseline concentrations. For example, the highest ecologically acceptable concentration for zinc in non-industrial areas would be 210 mg kg^{-1} based on ecological data determined under laboratory conditions. In Finland, the median value of zinc concentrations is 31 mg kg^{-1} in the most common soil type, glacial till. The lower guideline value for zinc is prescribed in the Decree as 250 mg kg^{-1} (calculated and rounded from 210 mg kg^{-1} + 31 mg kg^{-1}). In the fine grained sediments of the South Finland metal province, the baseline concentration of zinc is 180 mg kg^{-1}. Thus, the regional lower guideline value for the fine grained sediments of the South Finland metal province can be calculated as 210 mg kg^{-1} + 180 mg kg^{-1} = 390 mg kg^{-1}.

In addition to the ecological and health risks, soil contamination can pose a risk to the quality of groundwater. Risks to groundwater have not always been considered in the definition of guideline values. Thus, additional information on the potential risk to groundwater quality is needed, especially if a contaminated site is located in an important groundwater area. Besides the total amount of contaminants and the total concentrations, the mobility of contaminants is a key factor in the assessment of risks to groundwater.

Local soil – soil solution coefficients or K_d values provide an estimate of the mobility of potentially harmful elements. GTK has determined local K_d values for areas with naturally elevated metal or arsenic concentrations and for areas with a heavy anthropogenic input of metals or arsenic (Tarvainen & Jarva 2009). Local K_d values can be used to estimate the maximum acceptable concentrations in soil to protect shallow aquifers. In areas with elevated natural heavy metal or arsenic concentrations, metals and arsenic are usually strongly bound to the mineral soil. Site-specific guidance values based on the local K_d values are often higher than the lower guideline values prescribed in the Decree. Thus, a naturally high metal or arsenic concentration does not usually pose an added risk to the quality of shallow groundwater.

Figure 1 provides an example from a soil with an anthropogenic input of lead (Pb). The guideline value of Pb for drinking water is 0.01 mg L^{-1}. At the study site, the concentrations measured from soil water dilute by 1:10 in groundwater. Thus, the highest acceptable concentration of Pb in soil water would be 0.1 mg L^{-1}. The local K_d value for Pb measured from a topsoil sample was 392 L kg^{-1}. Consequently, the highest acceptable Pb concentration in topsoil would be 392 L kg^{-1} x 0.1 mg L^{-1} = 39 mg kg^{-1}. This figure is much lower than the lower guideline value of 200 mg kg^{-1} prescribed in the Decree.

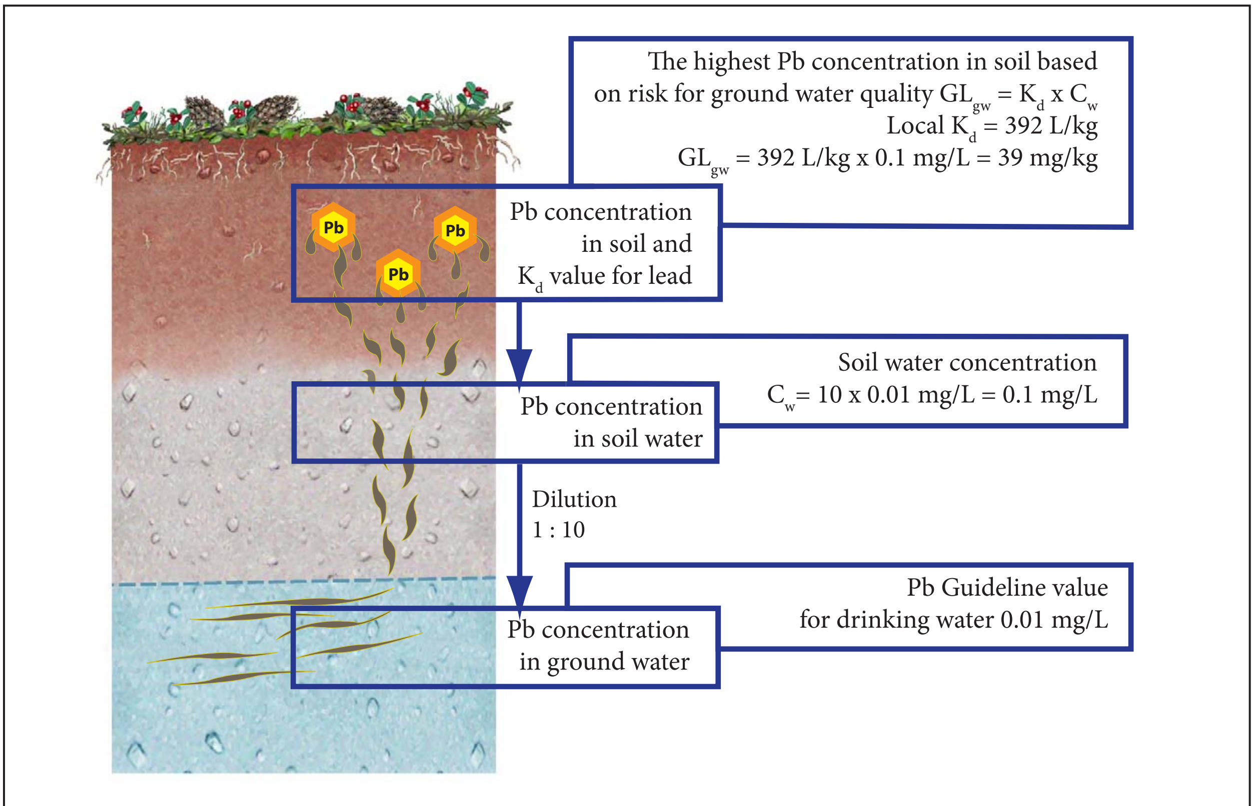

Figure 1. A scheme illustrating the use of local K_d values in the assessment of risk for groundwater quality in an area with high anthropogenic lead loading. Drawing by Harri Kutvonen, GTK.

CLIMATE CHANGE AND POTENTIAL GROUNDWATER RISKS

In addition to soil contamination, climate change can pose risks to groundwater resources that are important as sources of drinking water for urban settlements. By the year 2100, the climate is predicted to be different from the present day: the sea level may rise and storm surges that push water masses towards the south coast of Finland are expected to become more common in the late 21st century (Marttila et al. 2005). This might cause changes in groundwater resources along seashore aquifers and in the water supply, which may occur in parallel with an increased demand for water as the population and water consumption increase in the area.

The town of Hanko lies above an aquifer that is surrounded by the sea. The potential risks for groundwater quality and quantity, therefore, are not only due to urban development, but also due to the impacts of sea level change. Recent studies on the impact of sea water level changes on groundwater quality and quantity in Hanko aquifer indicate that the shallow sandy and gravelly aquifers in low-lying coast areas are most sensitive to changes in sea level (Backman et al. 2007). The level of the groundwater table in aquifers bordered by the sea reflects changes in the sea level. The fluctuation of the groundwater table in the Hanko aquifer follows the sea level changes after a short delay (Figure 2).

The impacts of urban development on groundwater quality are due to different sources, including land use, transportation and infrastructure. Groundwater contaminants are closely linked to urban land use practices, such as leaking underground storage tanks, malfunctioning private septic systems, spills or leaches from industrial sites or accidents, road salts from de-icing, treated/untreated storm water runoff, sewage overflows, and sand and gravel excavation. The increase in asphalt and concrete cover, preventing infiltration, has reduced the recharge of groundwater. Overpumping of groundwater has also occurred. Climate change scenarios in the Hanko area could be significant if the total annual precipitation and the intensity of specific storm surges increase as predicted. The impacts of urban areas, storm surges, infrastructure, and run off from extreme weather events can readily mobilize contaminants that have accumulated in the area into groundwater.

Good understanding of the characteristics of groundwater aquifers, including recharge and possible sea water intrusion, as well as the best management practices (policies, processes) could be effective in adapting to and managing the impact of climate change. A significant sea level rise in the Hanko coastal area in the near future could cause problems with water supply management and urban develop planning in the Hanko area, as well as in many other coast aquifer areas. Research carried out in the Hanko area has led to the proposal of a conceptual model for the protection of the shallow groundwater aquifer at Hanko, as well as other coastal aquifers (Figure 3), which could provide a broader context and guidelines for decisions by local authorities on water supply management in the urban development area.

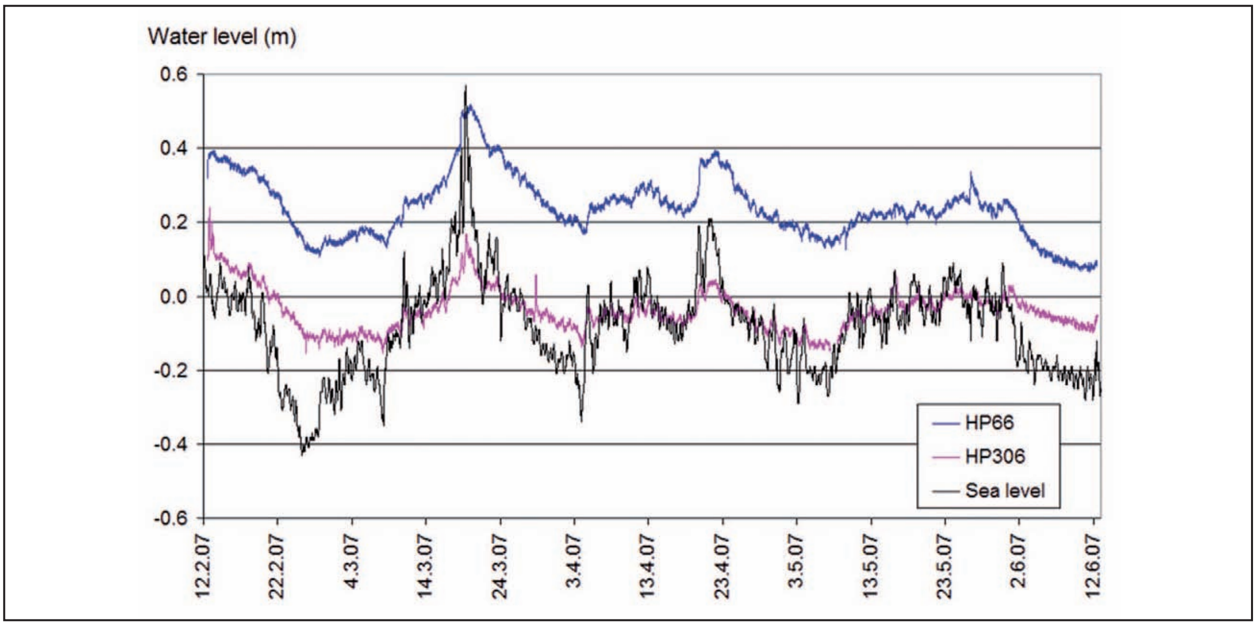

Figure 2. Groundwater level of observation wells HP66 (blue) and HP306 (pink) located in the Hanko area, and sea level (black) data during 12.2.–12.6.2007 (Backman et al. 2007).

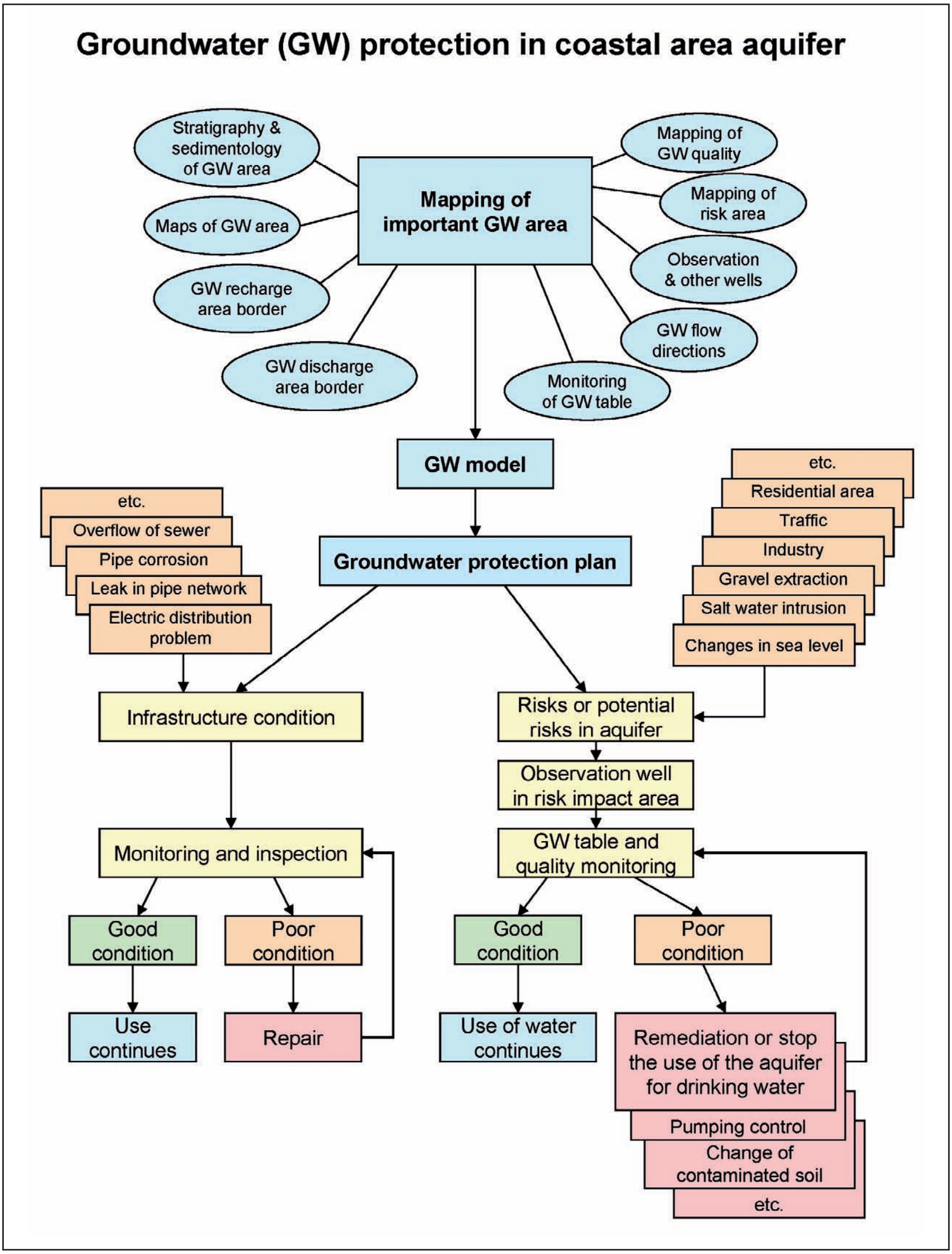

Figure 3. Groundwater (GW) protection strategy for the coastal area aquifer (Backman et al. 2007).

DIGITAL GEOLOGICAL MAPS IN URBAN RISK ASSESSMENT

The case study in the Hanko area demonstrated that geological and (geo)chemical risks for groundwater should be taken into account in the decision making. The same is also true for other kinds of geological risks. Sustainable and cost-effective land use planning requires information on geological conditions. Geological characteristics, including overburden thickness, soil type and the depth of the groundwater layer, greatly affect foundation costs. Geological risk factors such as seismic activity, radon, elevated baseline concentrations of potentially harmful elements and the potential for landslides should also be taken into consideration in the land use planning process. The data collected by various types of geological and geochemical mappings, risk assessments, drillings and geophysical measurements provide information for risk studies in the urban environment.

The integration of geological information in city management to prevent environmental risks was investigated in St. Petersburg, Russia, in an international project partly funded by the EU Life Third Countries Programme (LIFE06 TCY/ROS/000267). The project, entitled "GeoInforM", included studies on the geological information needs of different stakeholder groups, the collection and processing of geological data for a regional geological database, groundwater flow modelling, geological risk mapping, the development of tools to provide access to the geological maps as well as training of end-users. The project was coordinated by the Committee for Nature Use, Environmental Protection and Ecological Safety of the Government of St. Petersburg. Partners in the project included the State Ministry of Urban Development and Environment of the City of Hamburg, the Province of Milan, St. Petersburg State Geological Company and GTK. GTK was responsible for the development of a geological risk mapping methodology (Jarva & Klein 2009). The core of the developed methodology that was applied in St. Petersburg is a matrix that assigns a certain level of potential geological risk depending on the combination of land use and geological characteristics.

In St. Petersburg, the potential geological risk was assessed according to the type of land use (32 classes), indicating the vulnerability of the area, and the geological risk factor (7 risk factors). The degree of risk was estimated for seven geological risk factors covering the same area. The potential geological risk was determined in nominal values comprising four risk levels: risk level 1: potentially low geological risk for the current/indicated type of land use, risk management not needed; risk level 2: potentially medium geological risk for the current/indicated type of land use, risk management recommended; risk level 3: potentially high geological risk for the current/indicated type of land use, risk management needed; and risk level 4: potentially very high geological risk for the current/indicated type of land use, risk management obligatory. The estimations of risk levels were based on expert opinions. In St. Petersburg, the estimations were performed by four experts specialized in geology, risk assessment and land use planning.

Based on the matrix that assigns a potential risk level, a map presenting the potential geological risk was created for each geological risk factor. The nominal values indicating the geological risk potential were transformed from the matrix separately for each land use type and each geological risk factor. This enabled the related geological risk value in the matrix to be unambiguously identified for each grid cell.

An integrated risk map including all seven geological risk factors was created by selecting the highest risk potential assigned to one of the seven factors. This approach is very cautious, since it might highlight one geological factor that causes the highest risk, but ignore all other geological factors that could indicate a favourable place for the selected land use. However, areas with potentially low geological risk predominate in the area of St. Petersburg (Figure 4).

The geological risk maps were published in the Geological Atlas of St. Petersburg, which was one of the main outcomes of the GeoInforM project (Philippov et al. 2009).

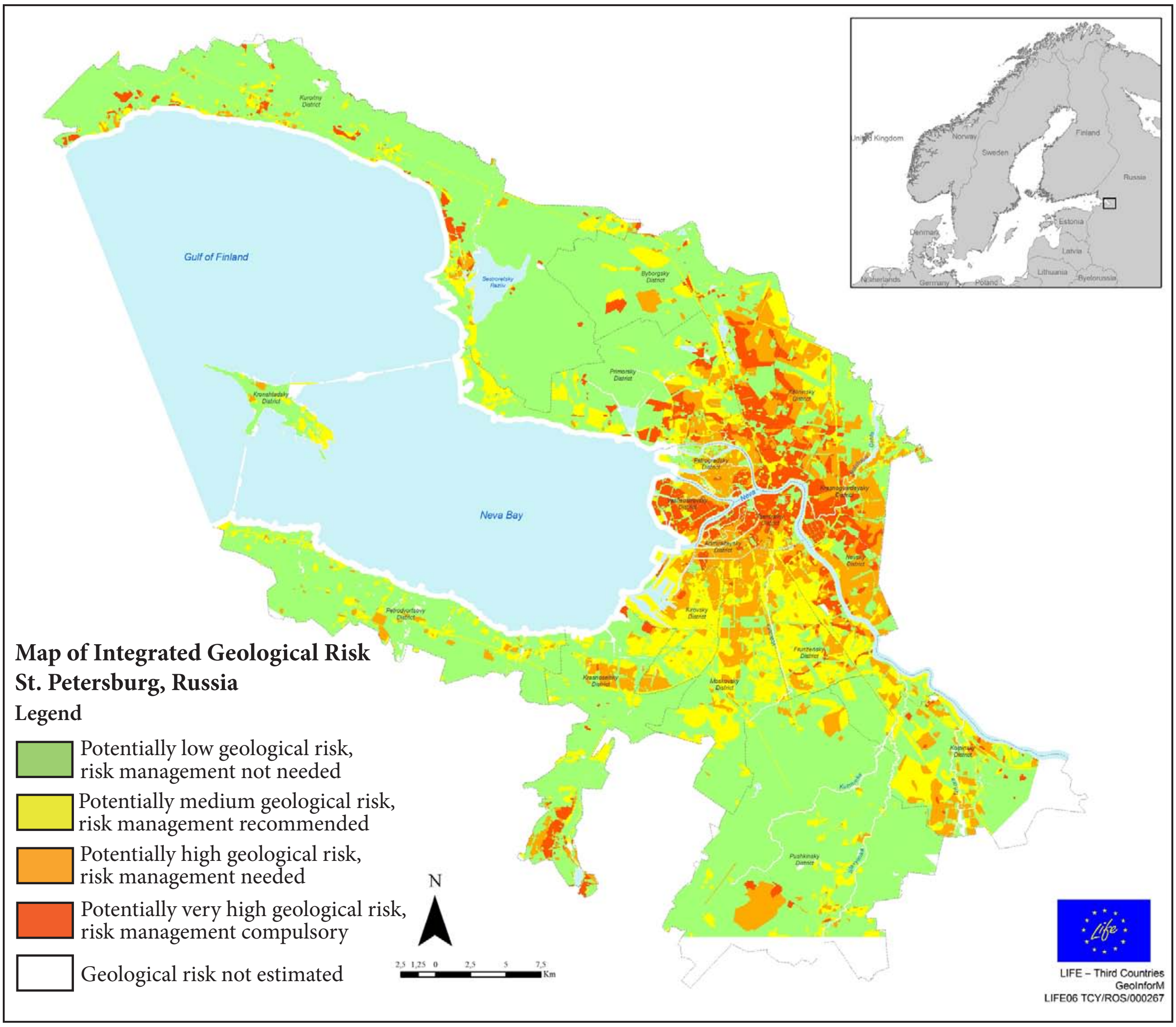

Figure 4. Integrated geological risk map of St. Petersburg (from Philippov et al. 2009).

CONCLUSIONS

Geological information is needed in risk assessment within urban areas as well as in the protection of groundwater resources that are essential for urban settlements. The geochemical baselines of soil can be used in the assessment of regional risk levels for potentially harmful elements. Detailed digital geological maps are needed for sustainable land use planning. A three-dimensional picture of geological formations would help in understanding the consequences of sea level rise and some other impacts of global climate change. Close co-operation between GTK and city authorities makes it possible to integrate geological information, including the geological risks, in land use planning and other decision-making procedures.

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EVALUATION OF NATURAL GEOCHEMICAL BACKGROUND LEVELS

by
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The Geological Survey of Finland has carried out several nationwide geochemical mapping programmes providing geochemical datasets for exploration and environmental studies. One application of the geochemical datasets is to evaluate geochemical background levels. The assessment of contamination due to industrial activities depends upon the evaluation of background levels.

Geochemical background levels can be defined and quantified in several ways with different outcomes. Numerous authors have attacked the background assessment problem by generating various statistical procedures for estimating the level or threshold for concentrations assumed to represent the background. None of the methods have been generally accepted as a de facto standard. Some methods assume a normal distribution, leading to trimming or normalization procedures and some are based on more generally applicable nonparametric methods.

We suggest a simple statistical description of a distribution assumed to represent a background, and provide the non-parametric median, confidence interval of the median and a modified beanplot. We demonstrate the method on data from the vicinity of the Talvivaara Ni-Cu-Zn mine in eastern Finland, and present the differences in levels between the mineralized and non-mineralized subareas in various sampling media. Our results show that the natural geochemical background in stream sediments and stream water can vary significantly across lithologies, and that medians with confidence intervals together with diagrams such as beanplots are useful tools for assessing the background levels.

Keywords (GeoRef Thesaurus, AGI): geochemistry, background level, stream sediments, stream water, metals, nickel, statistical analysis, Talvivaara, Finland

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INTRODUCTION

Mining activity may cause acid mine drainage, but natural background levels of potentially harmful elements or compounds may already have been elevated in the area before mining commenced. The background level varies depending on the climate, vegetation and geological environment. In glaciated terrains such as those of northern Europe, Canada and northern Russia, the bedrock is covered by glacial formations. Here, a comprehensive evaluation of the geochemical background level should be based on a variety of sampling materials, including bedrock, glacial till, stream and lake sediments, surface water and groundwater.

At the Geological Survey of Finland (GTK), several nationwide geochemical sampling campaigns were carried out during the last three decades of the 20th century. In the following section, the geochemical mapping programmes are summarized. Uncertainty assessment of regional geochemical datasets was then introduced, since in geochemistry the usefulness of the data depends on its certainty. Different approaches to evaluate geochemical background levels are summarized. We also demonstrate a new procedure to evaluate the natural background with a case study around the Talvivaara Ni-Cu-Zn deposit in eastern Finland.

GEOCHEMICAL MAPPING CAMPAIGNS

Finland was one of the pioneers in nationwide geochemical mapping and the development of methodology in chemical analyses and map presentations. Tens of programmes have been carried out at reconnaissance, regional and more detailed scales (Salminen & Tarvainen 1995). Selected mapping campaigns are listed below.

Finland is a glaciated terrain where glaciogenic drift, mainly till, covers the bedrock almost everywhere. Thus, till was chosen as the sampling medium for the first regional-scale geochemical surveys in Finland. Till samples were collected along traverses 1–1.5 km apart, and the sampling site spacing was 100 m (Kauranne 1975, Björklund et al. 1977). Samples were analysed with a tape-fed multichannel emission spectrometer for 17 elements. Over 16 000 samples were collected during 1975 (Kauranne 1975). Later on, the sampling strategy was changed, and in a comprehensive geochemical mapping program carried out in 1982–1994, about 82 000 till samples were collected with a density of one sample per 4 km^2. The samples were analysed by ICP-AES in the chemical laboratory of GTK (Koljonen 1992).

A regional scale sampling (1 sample/5 km^2) of lake sediments was carried out between 1973 and 1984 from the Finnish Lake District. The sampled area was 80 000 km^2 and the total number of samples 16 058. The samples were analysed by atomic absorption spectrophotometry and neutron activation (Tenhola 1988).

During 1978–1982, the Geological Survey of Finland systematically collected about 5 900 water samples from all over Finland, from natural and captured springs, dug wells and drilled bedrock wells (Lahermo et al. 1990). In a project entitled "One Thousand Wells", GTK in 1999 collected about 1 000 groundwater samples throughout the country (Tarvainen et al. 2001, Lahermo et al. 2002). In the early 1990s, stream water and stream sediments were collected from 1 100 sampling sites (Lahermo et al. 1996). This sampling was repeated (every fourth sampling site) in 1995 and 2000 (Tenhola 2004), and later on in 2006.

In more detailed studies, e.g. for gold prospecting, till samples have been collected along traverses 50–100 m apart with a sampling interval of 10–20 m. In the early 1990s, samples were analysed by AAS, but later on by ICP-AES and ICP-MS in the chemical laboratory of GTK.

GTK has been actively involved in several international geochemical mapping campaigns covering parts of the country:

The Nordkalott Project (1980–1986) was a multi-element and multimedia project carried out jointly by Norway, Sweden and Finland (Bølviken et al. 1986). The sampling density was 1 sample per 30 km^2 in an area of 250 000 km^2. Sampling materials were fine and heavy mineral fractions of till and stream and lake sediments.

The Kola Ecogeochemistry Project was initiated in 1991 in co-operation with the Central Kola Expedition and the Geological Surveys of Finland and Norway (Reimann et al. 1998). In this project, chemical substances of both natural and anthropogenic origin were studied in the northern parts of Norway, Finland and in northwestern Russia. The sampling materials were moss, humus and soil horizons B and C.

From 1999 to 2003, a multipurpose regional geochemical mapping project (Barents Ecogeochemistry) was carried out jointly by scientists from Finland, Russia and Norway (Salminen et al. 2004). The project covered Finland and the northwestern part of Russia, in total 1.55 million km^2. Up to 48 elements were analysed from stream water and sediment, soil profiles, humus and moss.

The FOREGS Geochemical Baseline Mapping Program covered most of Europe (Salminen et al. 2005). The sampling density was one sampling site per 5 000 km^2. C-horizon samples, topsoil, humus, water, minerogenic stream sediment and overbank sediments were collected.

In addition to the Nordic countries, regional-scale geochemical mapping campaigns have been carried out in Europe, America and Asia since the 1980s.

UNCERTAINTY ASSESSMENT OF GEOCHEMICAL DATA

Uncertainty is a much broader concept than random error in sampling or analysis. It is accumulated from uncertainty components inherent in geochemical knowledge, complexity, sampling, measurements, modelling, presentation, and even consumers' skills or knowledge, as well as purpose of use. In fact, the uncertainty of a data set may be acceptable for one purpose it is intended for, but rejectable for another. Uncertainty components, when identified, have to be modelled and their impact measured. When data are used or modelled to present a particular feature, conceptual uncertainty comes into play. A vague, confusing or unclear concept may then cause additional uncertainty that is difficult to detect and assess.

Uncertainty assessment of geochemical data has become increasingly important in obtaining reliable assessments of background levels. Regional geochemical data, in particular, have become crucial for the assessment of various environmental effects, and estimates of their certainty are highly valuable. In geochemistry the usefulness of the data depends directly on its certainty.

At GTK, several nationwide geochemical mapping projects have been carried out, as summarized above. The uncertainty of the data and reliability of maps were considered in the early 1970s. A repeated sampling scheme was implemented to estimate the variability in sampling, the effects of sample preparation and the analytical error. The scheme provided data for analysis of variance and simple scattergrams showing the relationship between variation within sampling sites, analytical error, and the geochemical relief to be mapped. Values below detection limits were recognized, stored in databases and considered in statistical procedures and on maps. Effort was put into presenting uncertainty on maps, such as the shaded coloured surface of the Bootstrap-estimated weighted median, which shows both regional and local variation (Gustavsson et al. 2001). Thus a practice for handling uncertainty was established.

GEOCHEMICAL BACKGROUND LEVELS

Salminen & Gregorauskiene (2000) stated that the geochemical 'baseline' comprises the background level together with a small amount of contamination, while the 'background' level is uncontaminated and natural. They considered the baseline as a fluctuating reference surface over a wide area.

Here, we focus on the everlasting problem of determining the geochemical background level in the vicinity of a mineralized area. Reimann & Garrett (2005) emphasized that the natural background level depends on the location and scale. The background level should be assessed locally in a geologically homogeneous area, a subarea of a larger geologically complex region, because an overall level would not be informative in any particular subarea. Any division into subareas would, however, be uncertain due to geological complexity and insufficient information on when to stop dividing. The uncertainty of data also accumulates from the sampled material, sampling design (randomness, representativeness), size of sampling units, sample preparation, analysis, and so forth. If the follow-up is based on stream sediments, the background in stream sediments is needed as a reference. Thus, even the purpose of using the background level plays a crucial role in selecting the assessment method.

Geochemical background levels can be defined and quantified in several ways with different outcomes. We consider the concept of geochemical background to be a vaguely defined entity, and an exhaustive and unambiguous specification of its level is therefore difficult to express. As a consequence, a single measure of this entity is vague and would not necessarily correspond to the definition. Therefore, an interval expressing the uncertainty around the level would be more reasonable.

Numerous authors have attacked the background assessment problem by generating various statistical procedures for estimating the level or threshold for concentrations assumed to belong to the background. None of these methods have been generally accepted as a de facto standard, although some of them provide useful results. Some methods assume normality, leading to trimming or normalization procedures, while others are based on more generally applicable nonparametric methods.

A recent review of approaches and assumptions regarding backgrounds and baselines was presented by Galuszka (2007). Reimann et al. (2005) compared three statistical approaches and concluded that only the cumulative probability plot, or the Q-Q-plot, provides a clearer answer to the background question, since it shows thresholds for subpopulations that can be extracted spatially on maps and their statistical parameters can be estimated.

We suggest a simple statistical approach for describing the background. Assuming that the data represent some sort of a background, we provide the non-parametric median as the background level, the confidence interval of the median as its uncertainty, and a modified beanplot (Kampstra 2008) as a presentation of the data values. We demonstrate the method on data from the Talvivaara region and present the differences in levels between the mineralized and non-mineralized subareas in various sampling media. This statistical presentation method was first published for the evaluation of geochemical background levels by the present authors (Loukola-Ruskeeniemi et al. 2009).

CASE STUDY: TALVIVAARA Ni-Cu-Zn DEPOSIT

Geochemical studies at Talvivaara, eastern Finland, were carried out by the Geological Survey of Finland on a variety of materials during the 1980s and 1990s. At the end of the 1970s, planning for geochemical mapping programmes started with the principal aim of producing data for mineral exploration (Kauranne 1975). Pilot studies were needed before the regional sampling, and Talvivaara was chosen as a test area in view of the high nickel concentrations in the bedrock. In addition to other sampling materials like glacial till samples, 670 organic and minerogenic stream sediment and 197 stream water samples were chemically analysed (Figure 1).

A junior company, Talvivaara Mining Company Ltd, is currently mining the Talvivaara deposit and has carried out environmental monitoring and environmental impact assessment in the area since 2004. However, the key for the evaluation of background levels is the old data collected in the 1980s and 1990s, before the large-scale mining activities began.

The statistical method

The median with the confidence interval presented on modified beanplots provides information on the background level, its uncertainty, and the frequency distribution within categories (mineralized, non-mineralized, lithological units, etc.). The beanplot, which we have slightly modified, is an alternative to Tukey's boxplot. We preferred the beanplot because it is particularly useful for considering vaguely defined geochemical backgrounds. The strengths of this method are the following: 1) it depicts data in categories; 2) it is robust to outliers or values below detection limits (if their proportion is less than 50%); 3) it portrays medians and their 95% confidence intervals graphically in categories together with the data; 4) it displays the estimated densities and individual values within categories and may uncover data clusters; 5) it considers measurement errors as Gaussian kernels for the estimation of frequency distributions; and 6) it is non-parametric, i.e. independent of distribution laws.

The estimation of the median and its confidence interval is based on the binomial distribution, which is also applied in the non-parametric quantile test (Conover 1999). We used the beanplot package (Kampstra 2008) available in the R environment (R Development Core Team 2009).

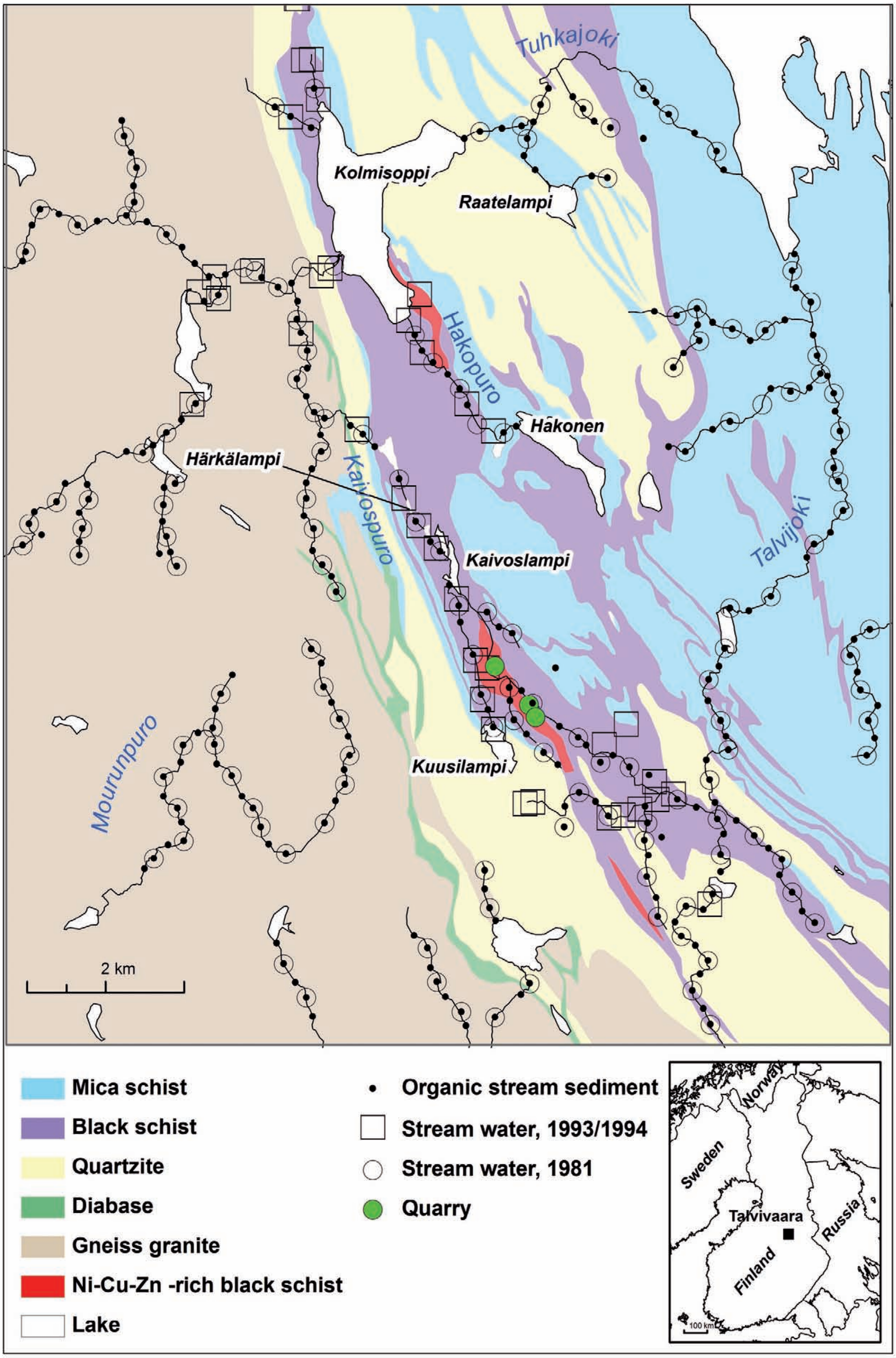

Figure 1. Geological map of the Talvivaara area in eastern Finland with sampling sites for stream sediments and stream water in the 1980s and 1990s. 'Black schist' refers to graphite and sulphide rich metasedimentary rock (Loukola-Ruskeeniemi 1995, Loukola-Ruskeeniemi & Heino 1996). Map compiled by Alpo Eronen (Geological Survey of Finland).

Stream sediments

Two types of organic stream sediments, 540 in all, were collected at Talvivaara in 1981: (i) allochthonous well-decomposed organic sediments ('gyttja') deposited on the bottom of streams and (ii) autochthonous, poorly decomposed 'peat' samples (containing abundant remnants of plants, e.g. *Carex* sp.) collected from the stream bank, if possible beneath the prevailing water table. To allow a comparison of these two types of sediment, they were collected simultaneously from each sampling site. Duplicate samples were collected, simultaneously with the actual samples, from every tenth sampling point.

The analysis was based on ignited samples and atomic absorption spectroscopy. Simultaneously with the organic samples, minerogenic stream sediment samples were collected (101 samples). The samples were wet sieved at the sampling site, and the < 0.175 mm fraction was taken for analysis.

All stream sediments comprised five sub-samples that were collected 20–50 metres downstream of each other.

Concentrations of Ni, Co, Cu, Zn, Pb, Cd, and Fe in organic and minerogenic stream sediments were found to be much higher in the black schist area than in the areas with gneiss granite, quartzite and mica schist (Figures 2 and 3). Nickel concentrations in well-decomposed organic stream sediments (gyttja) closely reflected the underlying bedrock. For example, the median concentration of Ni for well-decomposed organic stream sediment samples was 93 mg/kg in the black schist area and 16 mg/kg in the areas consisting of gneiss granite, quartzite and mica schist in the Talvivaara area.

Stream water

From every second stream sediment sampling point, a stream water sample was simultaneously collected in 1981. In 1981, pH values were low with a median value of 4.3 in stream waters in the Ni-Cu-Zn-rich black schist area. The low pH of stream water in 1981 was due to the pilot excavations between 1978 and 1980, when three quarries were excavated.

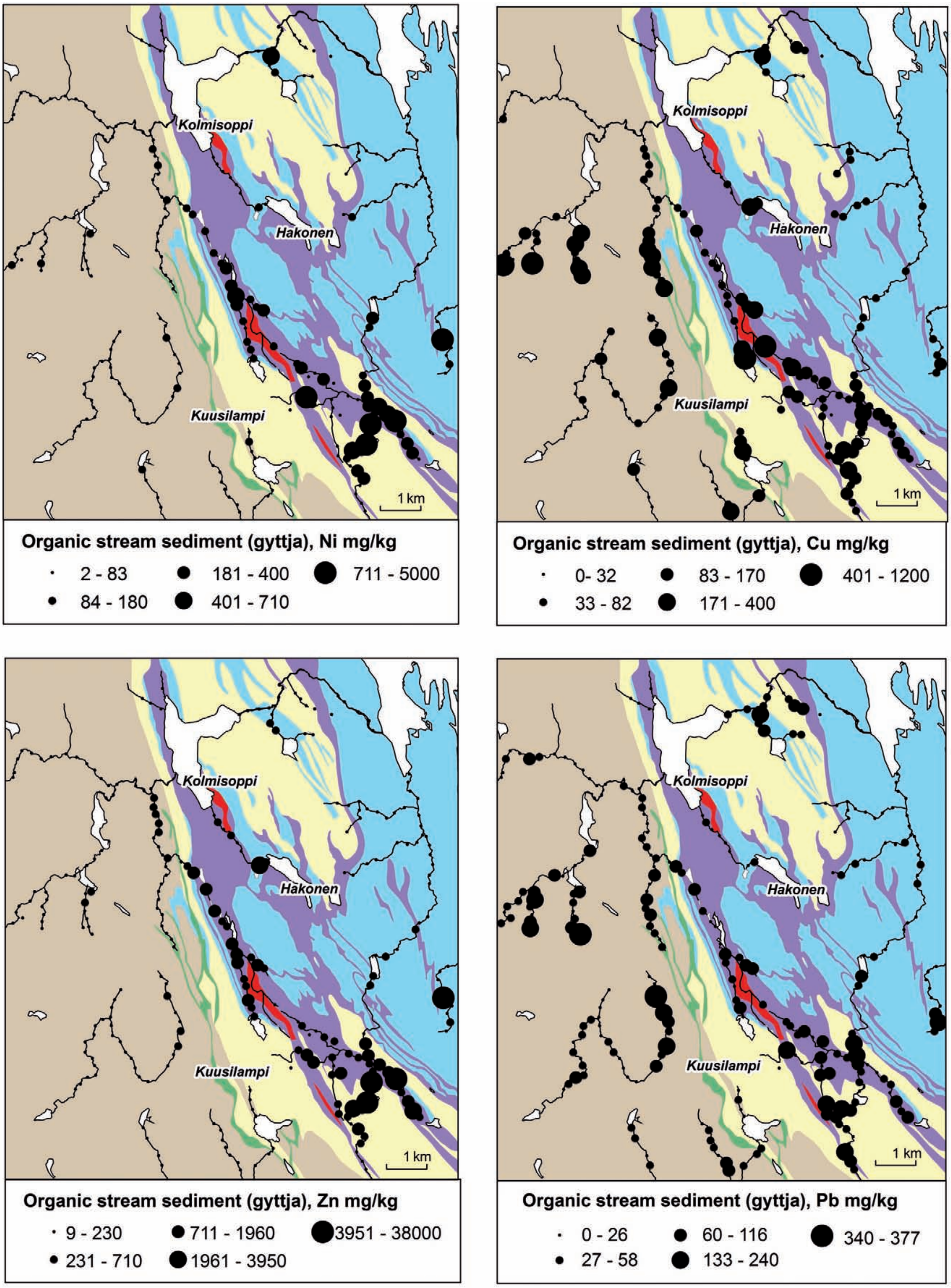

Figure 2. Nickel, copper, zinc and lead concentrations in well-decomposed organic stream sediments at Talvivaara in the 1980s. Please see Figure 1 for the rock types of the geological map. Maps compiled by Alpo Eronen (Geological Survey of Finland).

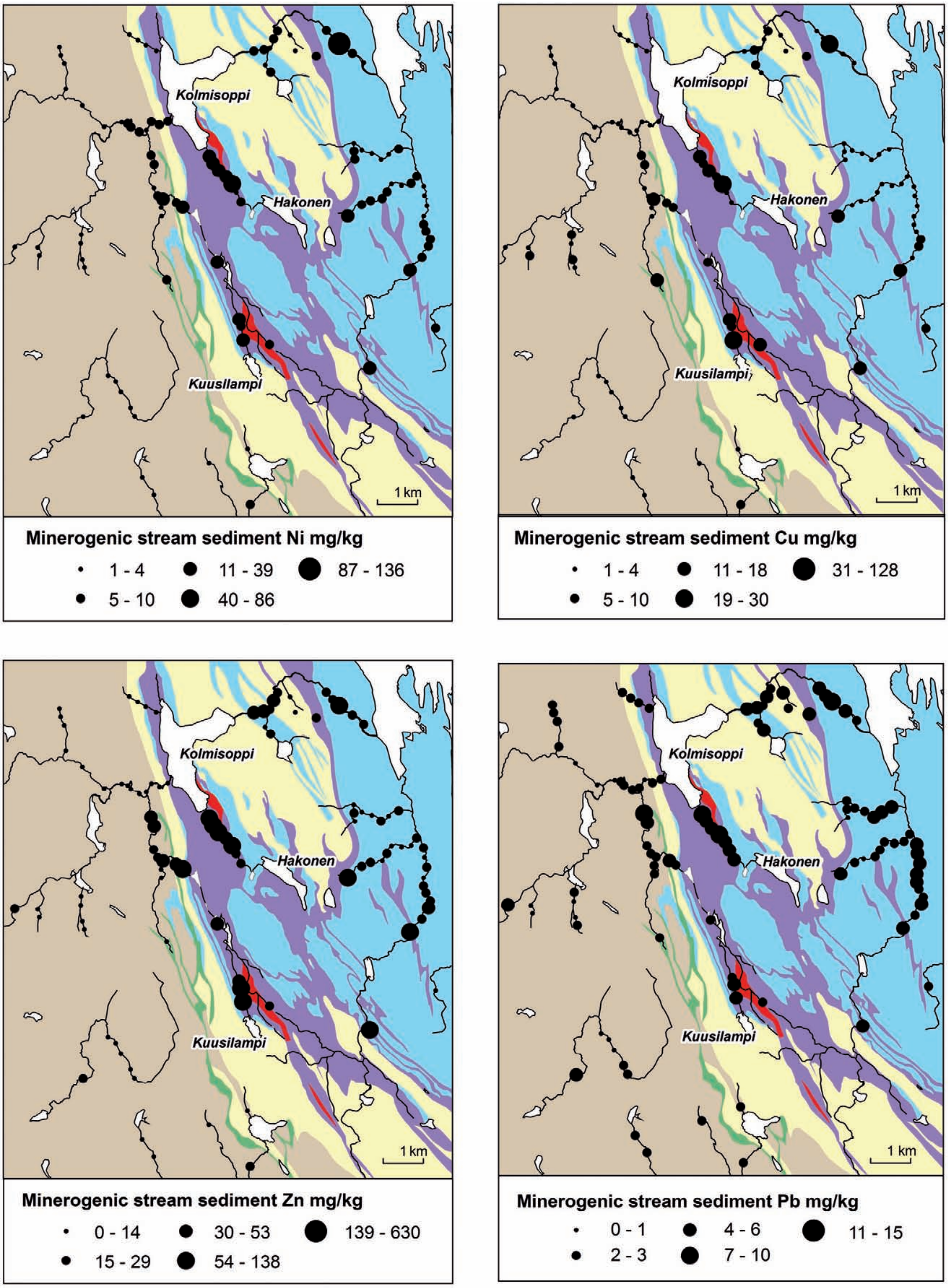

Figure 3. Nickel, copper, zinc and lead concentrations in minerogenic stream sediments at Talvivaara in the 1980s. Please see Figure 1 for the rock types of the geological map. Maps compiled by Alpo Eronen (Geological Survey of Finland).

Geochemical background levels at Talvivaara

The black-schist-hosted Ni-Cu-Zn deposit at Talvivaara was also reflected as elevated Ni, Cu, and Zn concentrations in glacial till, organic and minerogenic stream sediments, stream water, lake sediments and groundwater under natural conditions (Loukola-Ruskeeniemi et al. 1998, Tenhola & Loukola-Ruskeeniemi, unpublished data).

The geochemical background level for nickel for well-decomposed organic stream sediments in the Talvivaara black schist area was determined as 93 mg/kg and the 95% confidence interval for the median was (69, 116). These are high values compared with those of the granite gneiss – quartzite – mica schist area at Talvivaara: 16 mg/kg (14, 20) (Figure 4). The median values at Talvivaara are higher than the median average for Finnish organic stream sediments, 13.9 mg/kg, reported by Lahermo et al. (1996).

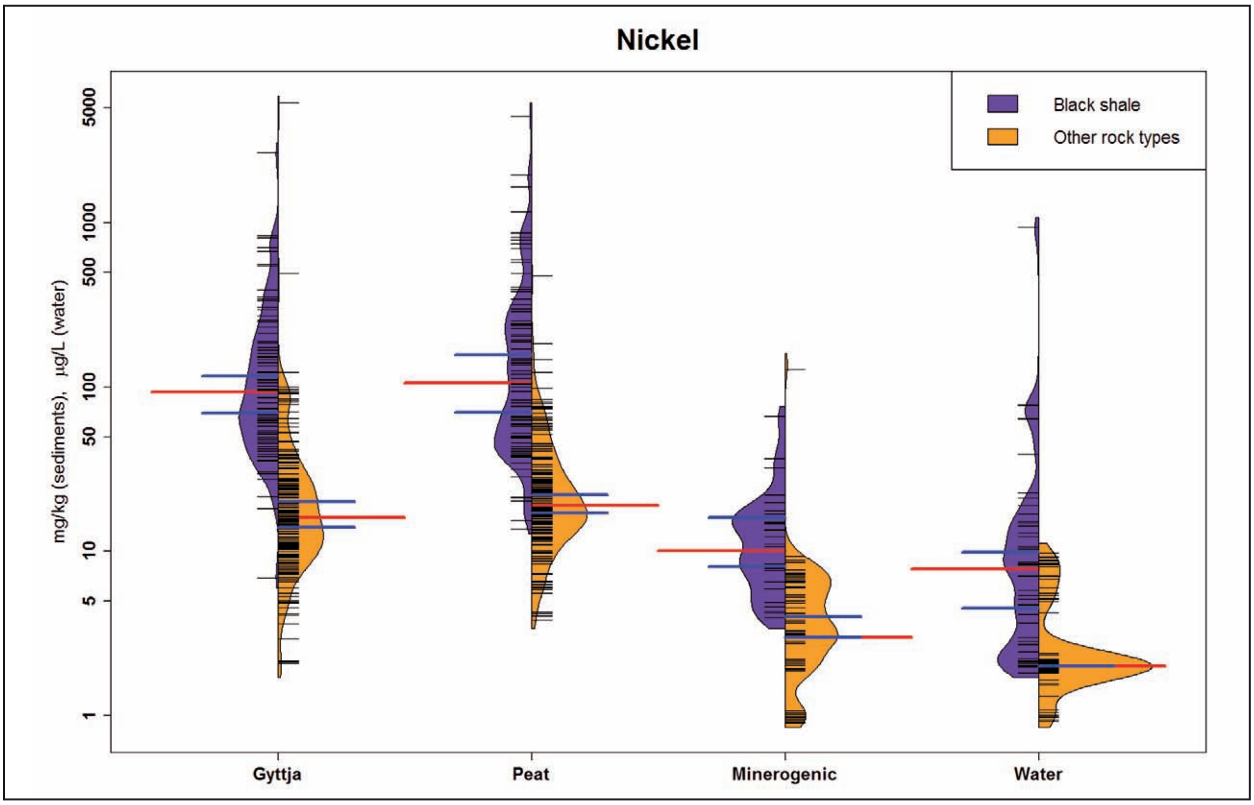

Figure 4. A modified beanplot showing the variation of Ni contents in stream sediment (mg/kg) and stream water (µg/L) samples at Talvivaara classified by the main rock type in the catchment area of the stream: black shale (C- and S-rich metasedimentary rock, also called 'black schist') and other rock types (mica schist, quartzite, and gneiss granite in Figure 1). 'Gyttja' refers to well-decomposed and 'Peat' to poorly decomposed organic stream sediment. 'Minerogenic' refers to minerogenic stream sediment and 'Water' to stream water. Red line segments show group medians, shorter blue line segments show the 95 % confidence limits of medians, and short black line segments show data values. A Gaussian kernel distribution is generated around each value and the shapes of the pods illustrate the composite distributions. The y-axis is logarithmic.

CONCLUSIONS

Regional geochemical mapping data are applicable for the assessment of geochemical background levels when the sampling and analytical procedures are kept systematically unchanged through the entire mapping programme. Regional subsets are then directly comparable and local background levels can be evaluated in relation to the whole data set. Limitations in the assessment arise from sampling density, which defines the spatial resolution of the data. Small subsets may contain an insufficient number of samples for a reliable evaluation of the background level. In addition, relatively high detection limits may lead to uncertainty in the assessment of background levels in small datasets.

Median values and confidence intervals for medians provide feasible estimates of the natural geochemical background and its variation. In a case study on the Talvivaara Ni-Cu-Zn deposit, the geochemical background level for nickel for well-decomposed organic stream sediments in the black schist area was 93 mg/kg and the 95% confidence interval for the median was (69, 116), which are high values compared with those of the adjacent granite gneiss – quartzite – mica schist area at Talvivaara: 16 mg/kg (14, 20). The median values at Talvivaara are higher than the median average of nationwide geochemical mapping for Finnish organic stream sediments, 13.9 mg/kg. Our results show that the natural geochemical background can vary significantly across lithologies, and that medians with confidence intervals together with beanplots are useful tools for assessing background levels.

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EVALUATION OF THE RELATIONSHIP BETWEEN THE NATURAL GEOLOGICAL ENVIRONMENT AND CERTAIN CHRONIC DISEASES IN FINLAND

by
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Medical geology, a sub-field of geology, is closely linked to environmental epidemiology. The focus of the geomedical studies is on the natural geological environment in relation to the distribution of health problems among humans and animals. Several medical geology studies have been performed at GTK during recent decades and three of them are summarized in the present article. It is important to understand the geographical variation of certain chronic disease occurrences when generating hypotheses regarding potential natural environmental risk factors for the disease in question.

The results of the SPAT project (Development and application of new methods for determining the geographical variation of health phenomena in Finland, 1998–2000, and Geographical variation of non-communicable diseases, 2002–2004) showed that high water hardness, especially high Mg concentrations in local ground water, was geographically associated with a lower incidence of acute myocardial infarction.

The health risk assessment of the RAMAS project (Risk assessment and risk management procedure for arsenic in the Tampere region, 2004–2007) showed health risks if arsenic-rich water from drilled bedrock wells was used as drinking water. The study implied an increased incidence of some typically As-induced cancers in the study population with a potential long-term exposure to drinking water containing As.

The results from a sulphide-rich bedrock area in eastern Finland indicated that the use of dug well water, as well as the consumption of local potatoes and mushrooms, slightly increased the Hg concentration in the hair of local residents in areas with elevated Hg concentrations in bedrock. However, the most important route of Hg to humans was via the consumption of fish, and the methyl-mercury content of the fish was not originally derived from bedrock but was rather related to lakes located in topographic depressions with large catchment areas. Hg concentrations in the muscle of noble crayfish (*Astacus astacus* L.) were also higher on average in lakes located in topographic depressions.

In Finland, geographical variation in the occurrence of certain chronic diseases has remained relatively stable for decades, which warrants further studies from the viewpoint of medical geology. Close co-operation between geoscientists, health scientists and statisticians will also be necessary in future multidisciplinary medical geology studies.

Keywords (GeoRef Thesaurus, AGI): medical geology, ground water, drinking water, arsenic, mercury, health risks, acute myocardial infarction, cancer, Finland

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INTRODUCTION

Medical Geology

Medical geology is defined as a multidisciplinary science concerning the relationship between natural geological factors and human and animal health, and understanding of the influence of environmental factors on the geographical distribution of such health problems (Selinus 2004). Medical geology can be linked with environmental epidemiology, which comprises the study of environmental factors that lie outside the immediate control of the individual (Rothman 1993). The natural geological environment is expected to be safe for human health. Actually, many substances from our geological surroundings are essential for both human beings and ecosystems. Examples of beneficial elements include calcium and magnesium, which we obtain from drinking water, dairy products, wholegrain products and vegetables. However, the natural environment may occasionally be associated with certain health disorders. This phenomenon is the concern of medical geology, a growing sub-field of geology (Finkelman et al. 2001). The Geological Survey of Finland (GTK) has initiated or participated in several geomedical studies during more than ten years (Table 1). A pilot study using the geochemical databases of GTK to compare the geochemical environment in areas of low and high coronary heart disease mortality was published in 1997 (Kousa & Nikkarinen 1997). Loukola-Ruskeeniemi et al. (1999) studied the migration of mercury (Hg) and other potentially harmful elements from sulphur-rich bedrock, such as black shale areas, to aquatic ecosystems and local residents. The authors reported that the main pathway of methylmercury to humans was fish consumption (Loukola-Ruskeeniemi et al. 2003). The occurrence of black shale bedrock in the habitat was reflected in the trace element concentration profile of the blood and hair of local residents (Kantola et al. 2008). Nikkarinen et al. (2001) investigated naturally occurring asbestos and fibrous minerals and their impact on the environment in eastern Finland. They found that in certain areas the soil contains asbestos and can cause the dusting of fibres from soil to air. These materials are generally located in sparsely inhabited areas, which limits correlation studies on natural asbestos and asbestos-related diseases. The salient point in medical geology studies is the availability of geochemical background information on the environment. A map of environmental geochemistry was published by GTK in 2005 (Tarvainen et al. 2005). Collaborative studies on the association between the incidence of certain chronic diseases and constituents of well water have been performed by the National Institute for Health and Welfare, THL (formerly the National Public Health Institute, KTL), and the Geological Survey of Finland, GTK (Kousa et al. 2004, 2006, 2008, Moltchanova et al. 2004). The occurrence of environmental arsenic and the consequent health risks were studied on a regional scale in the Pirkanmaa area within an EU supported RAMAS project (Loukola-Ruskeeniemi et al. 2007). Additional information on the RAMAS project can be found in the article by Ruskeeniemi et al. in this volume.

Geographical variation of certain chronic diseases

The occurrence of several chronic non-communicable diseases is known to vary geographically in Finland. The distribution of cardiovascular diseases (Karvonen et al. 2002, Havulinna et al. 2008a), diabetes (Rytkönen et al. 2001, Lammi et al. 2009) has been studied in the SPAT project. All these studies have implied that specific genetic and/or environmental risk factors for the diseases are likely to exist in the high-risk areas in eastern and central parts of the country. Geographical variation in several cancers in Finland has also been reported (Pukkala & Patama 2008).

Understanding of the geographical variation in the occurrences of certain chronic diseases is important for the generation of hypotheses regarding the potential natural environmental risk factors for the diseases in question. The projects SPAT (acute myocardial infarction, AMI, diabetes) and RAMAS (cancer) studied the link between health risks and the natural geological environment. In addition, trace element concentrations in hair and blood samples of local residents were investigated in the Talvivaara area in eastern Finland with naturally sulphur-rich bedrock. The working hypothesis was that the sulphur-rich natural environment might have a minor impact on coronary heart disease mortality.

Table 1. Studies of medical geology that GTK has initiated or participated in during 1981–2008.

Study/Project	Area	Period	Exposure	Health risk	Main results	Comments
Szalay et al. 1981	North Karelia		Mn, Cu, Zn	CVD	Mn (regional association)	No statistical analysis
Kousa & Nikkarinen 1997	#Area 1: Halikko, Lieto, Paimio, Uusikaarlepyy Area II: Marikarvia, Ruukki, Siikainen Area III: Outokumpu, Vaala	1961–1985	20 elements; 1 255 soil samples 149 ground water samples	CHD mortality	Area I (low risk): Mg (median) 6.86 mg/L. Area III (high risk): Mg 2.35 mg/L, p = 0.0003	
Kurttio et al. 1998	Orivesi (Pirkanmaa)	1993–1994	As in well water	Metabolism of As	As-tot in urine (geometric mean): Current users 58 µg/l , controls 5 µg/l , p < 0.001	
Kurttio et al. 1999a	Whole of Finland	1981–1995	As in well water	Bladder and kidney cancer	Bladder cancer: As 0.1–0.5 µg/l ; RR 1.53 (95% CI 0.75-3.09) As ≥ 0.5 µg/l ; RR 2.44 (95% CI 1.11–5.37) Kidney cancer: no association	Exposure 2–9 years prior to diagnosis
Kurttio et al. 1999b	Whole of Finland	1981–1994	F in well water	Hip fracture	F >1.5 mg/l: RR 2.09 (95% CI 1.16–3.76)	
Kaipainen-Seppänen, Aho ja Nikkarinen 2001	Whole of Finland	1987		Rheumatoid arthritis	Incidence of RA (men and women) Vaasa: 16.3 (95% CI 9.8 to 24.3) Joensuu: 44.8 (95% CI 34.6 to 57.3)	Regional differences in the RA incidence detected / the reasons probably environmental
Nikkarinen et al. 2001	Tuusniemi, Outokumpu, Kaavi and Heinävesi		Respirable asbestos fibres in the soil	Mesotelioma and lung cancer		Asbestos in soil can lead to transfer of fibrous dust from soil to air. Health risk not investigated
Loukola-Ruskeeniemi et al. 2003	Sotkamo and Kaavi	1997–2002	Hg in human hair, crayfish, surface waters, organic stream and lake sediments, and bedrock in different bedrock areas	CHD	120 women and 105 men Hg in human hair: Sotkamo: 2.85 µg/g Kaavi: 1 µg/g	Consumption of fish was the strongest determinant for Hg in hair. However, concentrations in Sotkamo were higher than in Kaavi due to differences in natural geological environment.
Kousa et al. 2004 (SPAT)	Whole of rural Finland, excluding Lapland, Åland and Turku Archipelago	1983,1988, 1993	°dH*, Mg, Ca, Al, Cu, F^-, Fe, Zn, Cr and NO_3 in ground water	AMI incidence	°dH posterior mean -0.97 (95% HDR -2.14; -0.03)**	One unit increment in °dH associated ~ 1% lower incidence
Moltchanova et al. 2004 (SPAT)	Whole of Finland, excluding Lapland	1987–1996	Zn, NO_3 in ground water	Type 1 diabetes incidence	Zn posterior mean 0.02 (95% HDR -0.21; 0.24) NO3 posterior mean 0.26 (95% HDR -0.93; 1.38)	No marked geographical association

Table 1. Continues...

Study/Project	Area	Period	Exposure	Health risk	Main results	Comments
Nikkarinen & Mertanen 2004	Central Finland and Lake Ladoga-Bothnian Bay zone	2001–2002	Heavy metals in edible mushrooms	Ag, Cd, Cu, Se intake via mushrooms		Areal variation in exposure is considerable; health risk not investigated
Kousa et al. 2006 (SPAT)	Whole of rural Finland, excluding Lapland, Åland and Turku Archipelago	1983,1988, 1993	Ca, Mg, Ca/Mg, Cr in ground water	AMI incidence	Mg mg/L posterior mean (%) -4.9 (95% HDR -8.8;-0.9)** Ca/Mg posterior mean (%) 3.1 (95% HDR 0.5;5.7)***	1 mg/L increment in Mg associated ~5% lower incidence. One unit increment in Ca/Mg ratio associated ~ 3% higher incidence.
Lehtinen et al. 2007b (RAMAS)	Tampere region (Pirkanmaa)	2007	As	Urinary As	U-As(tot) median: 20.3 ug/l (users of water with elevated As content); 14.4 ug/l (whole study population)	
Loukola-Ruskeeniemi et al. 2007 (RAMAS)	Tampere region (Pirkanmaa)	2004–2007	As in the natural and anthropogenic environment	Several cancers	Risk assessment and risk management	Final report
Pasanen et al. 2007 (RAMAS)	Tampere region (Pirkanmaa)	1981–2000	As in drinking water	Several cancers	Liver cancer RR 1.52 (CI 1.19–1.92)	
Kantola et al. 2008	Sotkamo, Kaavi	1997–2002	Hg, Ca, Mg, Zn, Cu, Se and Cd in human blood, hair, drinking water and fish	CHD		Impact of sulphide-rich bedrock was reflected in Hg, Se, Cd and Ca concentrations in human samples.
Kousa et al. 2008 (SPAT)	Whole of rural Finland, excluding Lapland, Åland and Turku Archipelago	1993–2001	Mg, Ca, Al, Cu, F^-, Fe, Zn, Cr and NO_3 in ground water	AMI incidence	Mg mg/L posterior mean -2.2% (95% HDR -3.91; -0.28)**	1 mg/L increment in Mg associated ~2% lower incidence.
Pasanen et al. 2008 (FINNMERAC)	Harjavalta, Ni mg/kg Zone 1, Ni > 440 Zone 2, Ni 200–400 Zone 3, Ni 80.200 Zone 4, < 80	1981–2000 1981–2005	Human exposure for environmental metals	Several cancers, CVD	Zone 1; cancer of respiratory organs (women): RR 2.44 (95% CI 1.12–4.64) (n = 9) Zone 2; IHD 1991–2005 (men): RR 1.32 (95% CI 1.06–1.63) (n = 88)	

Area I: mortality index 42–80, Area II: mortality index 91–101, Area III: mortality index 114–152
* °dH total water hardness
** full spatial model
*** separate spatial model

SPAT PROJECT

The SPAT project (*Development and application of new methods for determining the geographical variation of health-related phenomena in Finland*) started in 1998, coordinated by THL (Helsinki). One of its objectives was to investigate the association of the geographical distributions of certain chronic diseases with potential environmental risk factors such as geochemical variables in local ground water. Co-operation between GTK and THL continues to this day.

Probably the best known example of unevenly distributed disease occurrence in Finland is cardiovascular disease (CVD). Despite the decreasing trend in mortality and morbidity due to coronary heart disease (CHD) (Karvonen et al. 2002, Salomaa et al. 2003) during recent decades, higher mortality from CHD in eastern Finland than in western and southern parts of the country has been recognized for over 60 years (Kannisto 1947, Karvonen et al. 2002, Havulinna et al. 2008a). Several epidemiological studies from different countries have suggested an association between water hardness, Ca and/or Mg and CHD. However, some conflicting results have also been presented (reviewed by Monarca et al. 2006).

The Eastern Finland Office of GTK and THL carried out studies on the geographical variation in the incidence of acute myocardial infarction (AMI) (Kousa et al. 2004, 2006, 2008), childhood type 1 diabetes (T1DM) (Moltchanova et al. 2004) and type 2 diabetes in young adults (unpublished data) in relation to the geochemistry of local groundwater in rural Finland. No clear geographical association was found between the geochemistry of well water and the incidence of T1DM in children and type 2 diabetes (T2DM) in young adults. The results of our previous studies from three cross-sectional years, 1983, 1988, and 1993, suggest an inverse association between water hardness, especially Mg, and the incidence of AMI (Kousa et al. 2004, 2006). Later results were mainly based on the recent analyses of the AMI risk during 1991 to 2003 in relation to the natural geological environment (Kousa et al. 2008).

Materials and methods

Study subjects, population, data on covariates and statistical analysis in the SPAT study

The geographical variation in the incidence of AMI and its association with the geochemistry of well water was studied across a 13-year time period in 1991–2003 among men and women aged 35–74 years from rural Finland, excluding Lapland, Åland and the Turku Archipelago. A total of 93 215 AMI cases, 67 761 men and 25 454 women, were included in the analysis. Data on first AMI events, both fatal and nonfatal, were obtained from the Finnish Cardiovascular Disease Register (CVDR) (Laatikainen et al. 2004). Every Finnish resident has a unique personal identification number, which enables the location of each resident according to the map coordinates of the place of residence at the time of diagnosis. Map coordinates for each case were obtained from the Population Register Centre. The geo-referenced data on the population at risk were obtained from Statistics Finland. Geochemical (well water) data on total water hardness, Mg, Ca, Al, Cu, F^-, Fe, Zn, Cr and NO_3^- contents were obtained from the hydrogeochemical database of GTK. The database includes analysis results for over 10 000 samples, mostly well waters, and element concentrations determined for the most part by ICP-MS and ICP-AES. Geochemical data, age and sex were included as covariates in the spatial models. All data were aggregated into regular 10 km x 10 km grid cells, independent of administratively defined boundaries, for the Bayesian spatial modelling, and also to ensure the protection of privacy of individuals. The validity of the spatial statistical analysis used in this study has been demonstrated elsewhere (see e.g. Rytkönen et al. 2001, Moltchanova 2005). Only rural areas were included in the analyses, because people in the rural areas mostly use well water, whereas urban dwellers use public tap water.

Results and discussion

The age-adjusted incidence of AMI was 589/ 100 000/year (95% HDR 584, 593) in men and 177/100 000/year (95% HDR 175, 179) in women in rural Finland. No distinct association was found between any geochemical constituents in well water and the AMI risk in the full model with all covariates. Based on existing knowledge of the association between water hardness and the AMI risk, the effects of the two main components of water hardness were estimated in a separate model with Ca and Mg as covariates. A 1 mg/l increment in the Mg concentration in well water was associated with an average decrease of 2.2% in the incidence of AMI. The concentration of Ca did not have any marked effect on the incidence of AMI (Table 2). The results of our previous study from three cross-sectional years, 1983, 1988 and 1993, showed that a one unit increment in the Ca/Mg ratio was associated with a 3% increase in the incidence of AMI (Kousa et al. 2006). The other geochemical constituents included in the present study did not have any additional effect on the geographical variation in the incidence of AMI.

Table 2. The estimated regression coefficients of Ca and Mg on the incidence of the first acute myocardial infarction in men and women (pooled) in 1991–2003 in rural Finland (Kousa 2008).

Element	Posterior mean (%)*	95% HDR[a]
Ca mg/l	-0.1	-0.6 ; 0.4
Mg mg/l**	-2.2	-3.9 ; -0.3

The regression coefficients were estimated in the spatial model with Ca and Mg as covariates.
* Adjusted for age and sex.
** 95% HDR does not include zero
[a] Highest density regions

The incidence of AMI followed a quite similar geographical pattern for both sexes, implying that geographically specific risk factors are the same for men and women. The results of the SPAT project showed that high water hardness, particularly high Mg concentrations in local ground water, was associated with a lower AMI incidence. A regionally high Ca concentration in well water in relation to the Mg concentration was associated with a higher incidence. The results of the SPAT project indicated that despite the country-wide favourable trend in CHD mortality and morbidity, high CHD risk areas still remain in the eastern part of Finland, where they have been observed for over 60 years (Figure 1). Although Mg deficiency is not common in Finland, these findings suggest that populations living in areas with a low total water hardness but high Ca/Mg ratio in local groundwater may have an increased risk of CHD.

In the SPAT project the geographical variation in the incidence of AMI in relation to geochemical constituents in ground water was examined using a flexible geographical scale without administrative areas. The health data aggregated by administrative areas are often inadequate for geographical research. Diseases do not recognize boundaries defined for administrative or political purposes, and a finer geographical scale is often more appropriate for geographical epidemiological studies (Rytkönen 2004).

The findings were controlled for age and sex but not for potential confounding factors such as hypertension, cholesterol and smoking. However, it is not presumable that major CHD risk factors are basically associated with soft drinking water (Monarca et al. 2006), and thus they did not conform to the requirements of confounding factors in this study.

Group-level associations and aggregations are not necessarily consistent with measurements at the individual level. Thus, possible ecological bias may introduce a major source of uncertainty in ecological inference. Studies using aggregated data describe the association between disease incidence and the average level of exposure to an environmental risk factor, but not the causative role of the factor. Thus, group level inferences are not transferable to the individual level. However, ecological studies are significantly cheaper and less time consuming than cohort follow-up studies. Ecological studies are useful for generating hypotheses and as a starting point for individual studies. Geomedical studies with an ecological design give epidemiologically interesting crude indications for the association of certain geological factors and diseases in question.

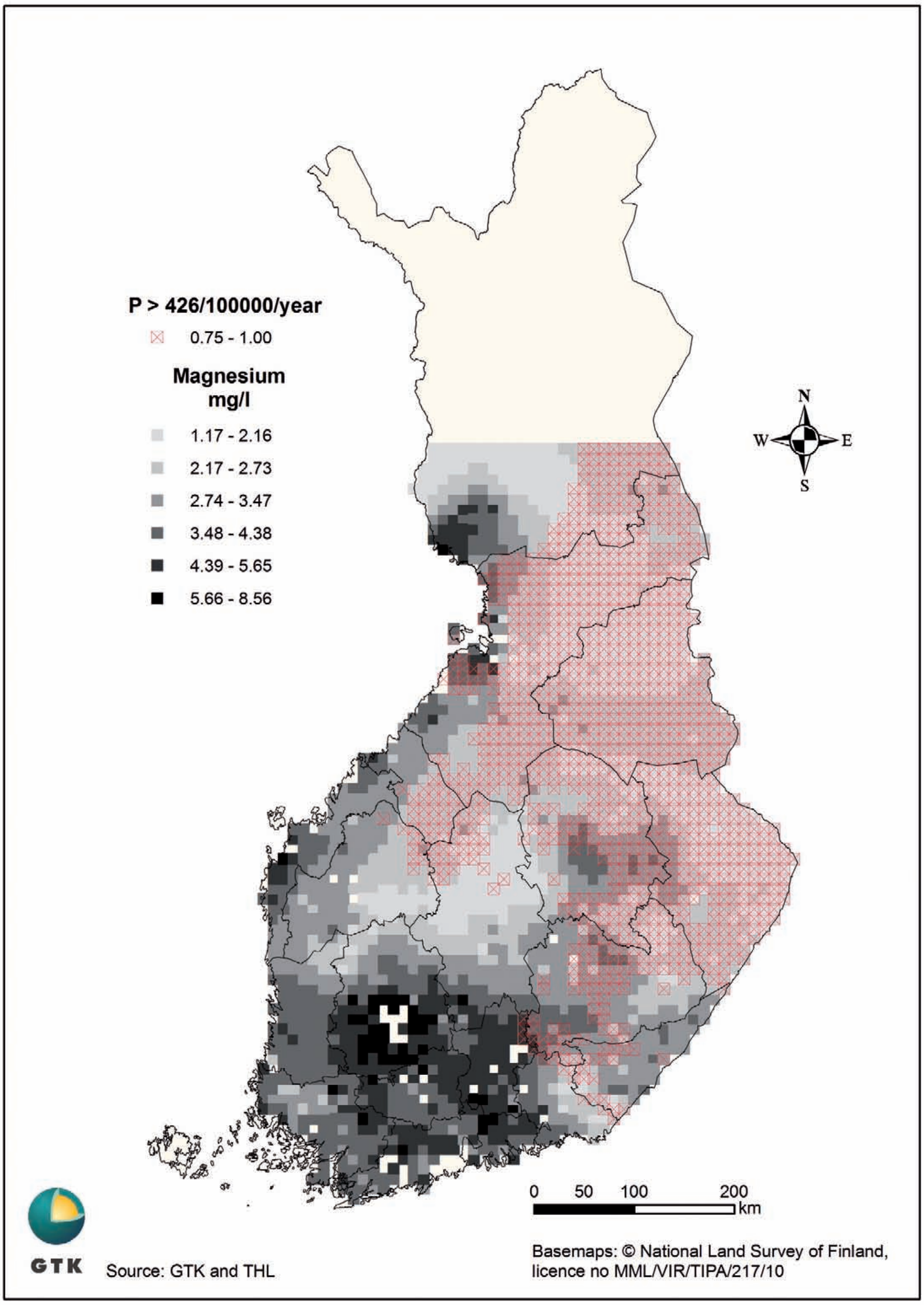

Figure 1. Posterior probability (P) of the AMI risk exceeding the overall country risk of 426/100 000/year among 35- to 74-year-old men and women (pooled) in 1991–2003 (red symbols). Regional distribution of Mg (mg/l) concentration in local ground water in rural Finland (greyscale).

RAMAS PROJECT

The EU-LIFE supported RAMAS project (*Risk Assessment and Risk Management Procedure for Arsenic in the Tampere Region*) started in 2004, co-ordinated by GTK. It focused on the Tampere/Pirkanmaa region, which covers an area of around 15 000 km^2 and comprises almost 500 000 inhabitants and 91 groundwater areas classified as being important for water supply. Pirkanmaa includes one of the several natural As anomalies in Finland. Groundwater contamination by arsenic (As) is in fact a problem that is recognized worldwide. Inorganic arsenic is a well-known human carcinogen. In 1993, the WHO recommended new, lower guidelines for arsenic in drinking water (10 µg/l). At the same time, GTK launched the first investigations on arsenic in drilled wells in the Pirkanmaa region (Backman et al. 1994). Kurttio et al. (1998, 1999a) conducted the first evaluation of arsenic-related health risks in the area. In addition to the natural anomalies in bedrock, till and ground water, Pirkanmaa includes several point sources of arsenic resulting from human activities such as wood preservation, mining and the disposal of wastes (e.g. ashes) (Parviainen et al. 2006). These sites may pose a threat to human health owing to soil rather than groundwater contamination.

Materials and methods

In the RAMAS project, the regional risk management (RM) needs associated with arsenic in the Pirkanmaa region were identified on the basis of targeted environmental studies and risk assessments (Lehtinen et al. 2007b). The environmental studies included chemical analyses of groundwater, soils, crops and surface water in the identified anomaly areas and selected contaminated sites (Backman et al. 2006, 2007, Mäkelä-Kurtto et al. 2006). The assessment of the risks to human health was based on exposure modelling, human biomonitoring and epidemiological studies, which relied on the national cancer register (Sorvari et al. 2007, 2010, Pasanen et al. 2007, Lehtinen et al. 2007a, Rossi et al. 2007). Based on the results, regional risk maps were produced using ArcGIS 9.2 software. Here, information on the coverage of the water supply network, population distribution, anomaly areas and relevant anthropogenic sources were combined, considering the future land use plans.

The assessment of risks to human health was based on different methods (Sorvari et al. 2007, Rossi et al. 2007). Firstly, the average life-time daily arsenic intake in different exposure scenarios was assessed (Figure 2) using generic models depicting human exposure. The estimates of the average daily dose (ADD) were further compared with reference values, i.e. acceptable daily intakes (ADIs), to produce quantitative risk estimates.

The risk assessment based on exposure models was carried out in two phases. In Phase 1, the daily dose of As from drinking water was calculated using the preliminary, pre-RAMAS results from analyses of arsenic in well water samples. Background exposure, i.e. exposure from other than site-specific sources such as non-local foodstuffs, was estimated from national data. Food crops cultivated in areas of elevated arsenic in soil contained only very low levels of arsenic (if any), and would not therefore pose a hazard to human health.

In Phase 2, the risk assessment was refined by including new concentration data produced in the RAMAS project. The potential exposure arising from the identified key anthropogenic hot spot areas, i.e. mine sites and CCA wood treatment plants, was also considered. The primary calculations were based on the highest arsenic levels in order to cover the "worst case" exposure scenarios. The estimated ADDs were divided by different ADI values issued by the WHO, RIVM and USEPA to produce deterministic risk estimates, i.e. hazard quotients (HQ). Excess life-time cancer risks were determined by applying cancer slope factors and unit risk values (exposure through inhalation). A probabilistic assessment based on Monte Carlo simulation using CrystalBall© software was also carried out to determine the risks at the regional level.

To complement the data on the health risks assessed by modelling and to verify potential exposure and risks at the population scale, a separate biomonitoring study and an epidemiological study were carried out. The biomonitoring study was run by the Finnish Institute of Occupational Health and the Finnish Environment Institute (Lehtinen et al. 2007a). The Environmental Epidemiology Unit of the National Public Health Institute was responsible for the realization of the epidemiological study (Pasanen et al. 2007).

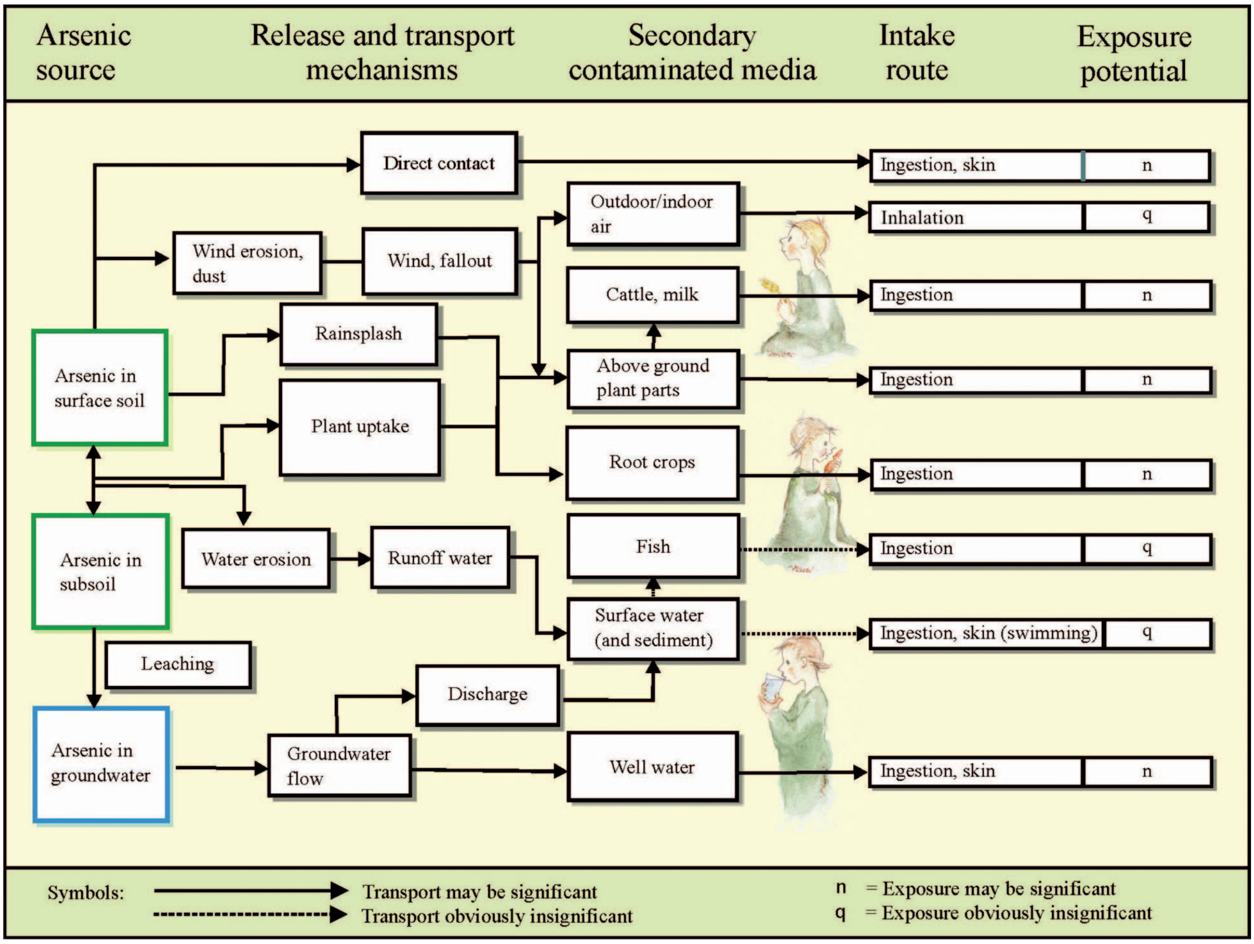

Figure 2. A conceptual model describing the potential exposure of a farm resident to local, naturally occurring environmental arsenic (Sorvari et al. 2007). Pictures drawn by Pirkko Kurki.

The biomonitoring study was carried out by monitoring the arsenic concentration in the urine of selected residents in Pirkanmaa (Lehtinen et al. 2007a). The study population comprised both households that used their own wells as a source of drinking water, containing varying concentrations of arsenic, as well as households that were connected to a public water supply system or had another alternative source of drinking water (e.g. bottled water). The study population comprised 40 persons representing 15 households. Inorganic arsenic species (As^{3+}, As^{5+} and total arsenic) were determined by a hyphenated high performance liquid chromatography - hydride generation - atomic fluorescence spectrometry (HPLC-HG-AFS) technique (Hakala & Pyy 1992). Because of the higher sensitivity and linearity, atomic fluorescence detection was used instead of atomic absorption described in the original procedure (Hakala & Pyy 1995).

The epidemiological study was based on spatial analysis of the As-related cancer risk incidence within the whole Pirkanmaa region (Pasanen et al. 2007). The hypothesis was that in the long term, elevated arsenic concentrations in household water are reflected in a higher incidence of certain cancer types compared with the population not exposed to arsenic through household water. Therefore, the cohort, i.e. the study population fixed to a certain study year, had to be selected so that the development of cancer could appear in the statistics. Moreover, the probability of using private wells had to be considered, since we did not have exact data on the number of wells used as a source of household water or information on the households/persons who had used private well water during the studied time period. For the analyses, data on arsenic concentrations in ground water collected within RAMAS were mapped using grids suitable for spatial epidemiological analysis.

Results and discussion

The results from the health risk assessment demonstrated health risks if water from drilled wells is used as drinking water (Sorvari et al. 2007). The risk was found to be highest in the southern part of the study area, where arsenic concentrations in bedrock and soil were higher than in the northern part. The inclusion of background exposure and exposure to arsenic in soil resulted in an average total daily dose of 0.16–55 µg/kg/d, with a mean value of 0.68 µg/kg/d (median 0.27). The ADI values varied between 0.3 and 1.0 µg/kg/d, and the highest estimate thus exceeded the lowest acceptable level by 180-fold. Food crops cultivated in areas with elevated arsenic concentrations in soil contained only very low levels of As (Mäkelä-Kurtto et al. 2006), and would not therefore pose a hazard to human health.

The maximum life time excess cancer risk was estimated to be $8.3*10^{-2}$. According to the statistical analysis, some 5.9 to 46% of the population would be experiencing unacceptably high exposure to As from well water (Pasanen et al. 2007, Sorvari et al. 2007, Rossi et al. 2007). Risks associated with dug well waters were estimated to mainly be insignificant. At CCA plant sites, the maximum excess cancer risk was estimated to be $2.3*10^{-3}$. Hence, exposure to arsenics at CCA plant sites may add to the total risk, particularly in the case of small children (age 1–6).

The biomonitoring study confirmed the exposure to arsenic in well water. Moreover, both the total arsenic concentration and the concentration of inorganic arsenic in urine correlated well with the arsenic concentration in well water (R^2= 0.95 and R^2= 0.83). The regional-scale epidemiological study revealed elevated incidences of liver cancer compared with the reference area. In addition, there appeared to be a higher incidence of bladder, skin and kidney cancers, although not all of the risk ratios were statistically significant. However, the results from the epidemiological study need to be interpreted with caution, since they involve several uncertainties.

As expected, elevated arsenic concentrations in groundwater proved to be the major issue associated with natural arsenic. Locally, soil contamination at some former wood preservation sites and mining areas also posed significant health risks, particularly if such areas had been developed as residential areas without prior remediation measures (Sorvari et al. 2007, Rossi et al. 2007, Lehtinen et al. 2007b, Loukola-Ruskeeniemi et al. 2007). In addition, the sediment of the water body adjacent to one of the old mine sites also posed a noteworthy risk, because this area was sometimes used for recreation (swimming).

Overall, it appeared that several risk management mechanisms had in fact already been adopted to restrict health risks caused by arsenic (Lehtinen et al. 2007b). Such mechanisms included policy and economic policy instruments (regulations, guidelines, subsidies for water supply), informational instruments (e.g. registers for contaminated sites, geological maps) and technical means (groundwater treatment, soil remediation). Nevertheless, additional risk management needs were identified. Since the ensuring of drinking water quality is the key issue in the management of health risks, the expansion of the water supply network and consideration of arsenic anomalies in the planning of residential areas should be promoted. At the local level, the marking of hot spots at arsenic-contaminated wood impregnation sites and restrictions on human activities at former mine sites are also recommended.

MIGRATION OF POTENTIALLY HARMFUL ELEMENTS FROM SULPHIDE-RICH BEDROCK TO AQUATIC ECOSYSTEMS AND LOCAL RESIDENTS IN EASTERN FINLAND

Sulphide-rich bedrock is reflected in elevated geochemical background levels of a number of potentially harmful elements in glacial till, soil, surface water and groundwater in eastern Finland (e.g. Loukola-Ruskeeniemi et al. 1998). However, the study of pollution in aquatic ecosystems requires more than the sampling of water and sediments. Benthic invertebrates such as noble crayfish (*Astacus astacus* L.) live and feed directly on sediments and may therefore be good indicators of sediment metal levels in the environment. Fish, moreover, act as an important link in the transfer of potentially harmful compounds from the environment to man. The study of the migration of harmful elements from sulphide-rich bedrock to aquatic ecosystems began in 1997 in the municipalities of Sotkamo and Kaavi in eastern Finland (Loukola-Ruskeeniemi et al. 1999). The research was focused on eastern Finland because coronary heart disease is more abundant there than in western and southern Finland. Although genetic factors and living habits are significant risk factors (e.g. Vuorio 1998), trace elements in drinking water and food are also implicated. Water hardness had already been reported to be inversely related to CHD mortality (Rylander et al. 1991, Kousa & Nikkarinen 1997). Intake of Hg associated with mortality of CHD (Salonen et al. 1995).

Materials and methods

The migration of potentially harmful elements from sulphide-rich bedrock to aquatic ecosystems and local residents was studied from samples of rock, surface water, organic stream sediment, organic lake sediment, noble crayfish and fish (Loukola-Ruskeeniemi et al. 2003). Organized in co-operation with the Health Centres of Sotkamo and Kaavi, 225 people participated voluntarily in the research by providing hair and blood samples (whole blood and serum). Of these, 83 participants had lived in an area with sulphide-rich bedrock for more than five years. Residential history, fish consumption, smoking, the consumption of local potatoes, vegetables and mushrooms, the source of drinking water, age, body weight and height were inquired in a questionnaire. Drinking water samples were taken from 88 households. Samples were analyzed at GTK and at the University of Kuopio.

Hg, Ca, Mg, Zn, Cu, Se and Cd in human blood, hair, drinking water and fish were analysed in the study. Drinking water and hair samples were analyzed for a comprehensive set of trace elements at GTK by ICP-MS and ICP-AES. Mercury concentrations in hair, crayfish, and fish samples were determined by cold vapour AAS, both at the University of Kuopio and at GTK. The results were in good agreement. The whole blood and serum samples were analyzed by AAS at the University of Kuopio.

General linear models were constructed to assess the variation in mean trace element concentrations in relation to the dichotomic variables. Covariance corrections were applied to the interacting variables in the partial correlation analysis.

Results and discussion

Sulphide-rich bedrock areas such as that around the present Talvivaara Ni-Cu-Zn mine in Sotkamo were compared with adjacent sulphide-poor bedrock areas. During sampling in the 1990s, the Talvivaara area was practically under natural conditions, since large-scale mining activities started in 2004. Sulphide-rich bedrock was reflected in elevated Ni, Cu, Zn, and Cd and low Ca concentration in glacial till, surface waters, organic stream sediments and lake sediments. In addition, mean Hg concentrations of the muscle of noble crayfish (*Astacus astacus* L.) were higher in lakes located in sulphide-rich areas (Loukola-Ruskeeniemi et al. 2003). The distribution of hair Hg content did not appear to correlate with the distribution of rocks with elevated Hg contents, but the main route of Hg to humans was via fish. People consumed fish not only from the lakes situated next to their residence, but also from lakes located in other bedrock areas. However, among the 'non-fish eaters', who consume fish less than once a week, in the Sotkamo sulphide-rich bedrock area with elevated Hg concentrations in bedrock, the use of dug well water, as well as the consumption of local potatoes and mushrooms, slightly increased the Hg content in the hair of local residents. In Sotkamo, Hg concentrations in the whole population both for fish eaters and non-fish eaters were higher than in Kaavi (Figure 3). This contribution may reflect the Hg load of the sulphide-rich bedrock under natural conditions (Loukola-Ruskeeniemi et al. 2003).

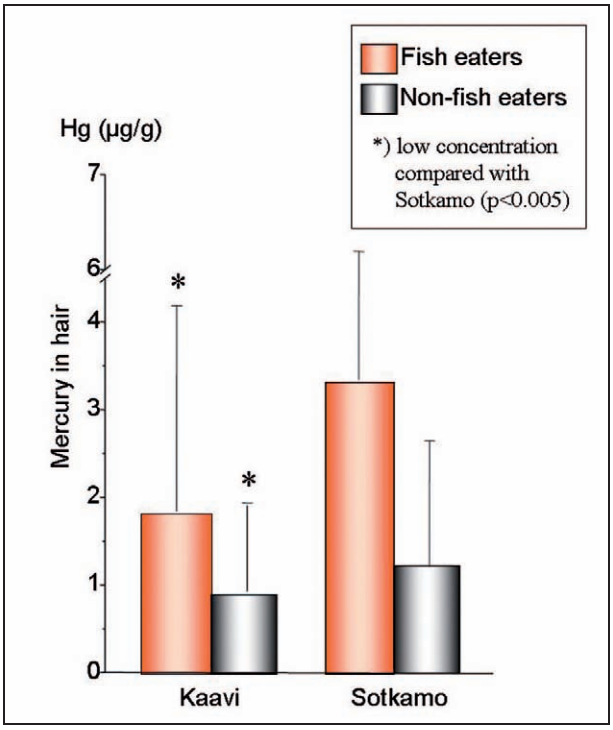

Figure 3. Mercury concentration in hair samples provided by local residents in the Kaavi and Sotkamo study areas, eastern Finland (Loukola-Ruskeeniemi et al. 2003). The concentration is higher among people who eat fish more than once per week (fish eaters). People who consume fish less than once per week are classified as non-fish eaters.

Selenium concentrations in serum and mercury concentrations in hair were higher in local residents in Sotkamo (mean Se 93.2 µg/l) than in Kaavi (87.9 µg/l) study areas. Calcium concentrations in serum were lower in people living in the sulphide-rich bedrock area in Sotkamo (91.3 ± 4.0 mg/l) than in the reference area in Sotkamo with a low sulphide content in the bedrock (94.7 ± 3.9 mg/l) (Kantola et al. 2008 and unpublished data). No such difference was recorded in Kaavi. The difference between Sotkamo and Kaavi might be due to differences in the Ca concentration in glacial till in these areas (Figure 4).

The cadmium concentration in whole blood samples of non-smokers living in the sulphide-rich bedrock area increased according to living time but decreased among the non-smokers living in the reference areas. Some high cadmium concentrations found in spring and dug well waters partly explain the potential long-term exposure in the sulphide-rich bedrock area.

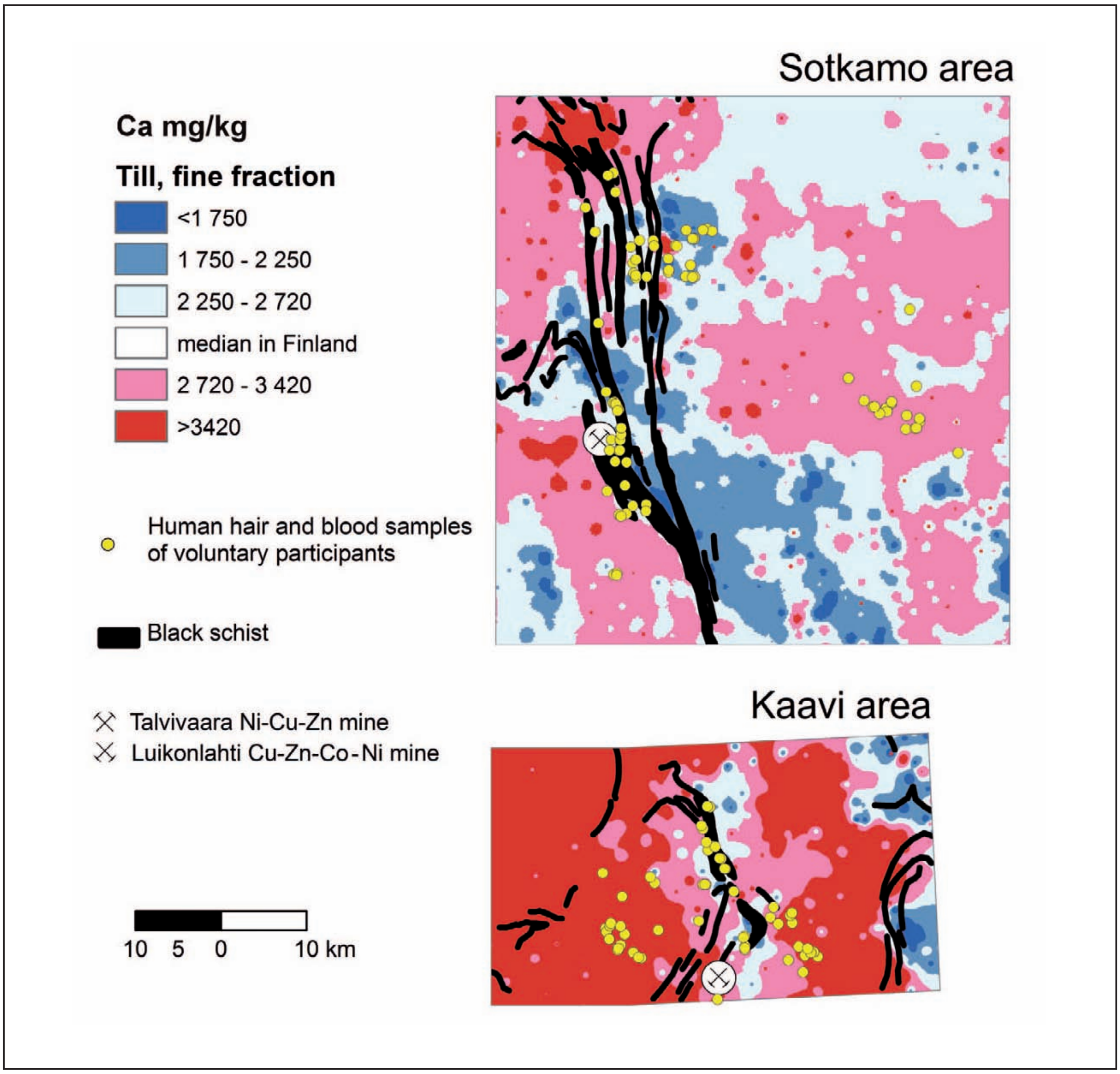

Figure 4. Calcium concentration of the fine fraction of glacial till in the Kaavi and Sotkamo study areas, eastern Finland. The median value represents that of the whole of Finland (Salminen & Lampio 1995). The impact of sulphide-rich bedrock can be seen as Ca depletion in till, especially in the Sotkamo study area, because the Talvivaara black schist horizon is extensive. Black schist formations are from Arkimaa et al. (2000) and the Ca concentration of till is from the Geochemical Database of GTK. Compilation of map by Heimo Savolainen. Black schist refers to graphite and sulphide rich metasedimentary rocks.

CONCLUSIONS AND FUTURE NEEDS

High As contents in well water can originate from geology. The problem has been discovered in Taiwan, Bangladesh and West Bengal, as well as in the Pirkanmaa region of Finland. In Finland, the quality of drinking water is strictly regulated with the exception of those households that rely on their private dug well or drilled bedrock well. The arsenic problem was identified and studied in Finland (Backman et al. 1994) immediately after the first discoveries in Taiwan, and many of the wells with high concentrations of As were closed. Even with less than 10 years of usage of As-rich drilled bedrock well waters, an elevated cancer risk might occur according to spatial epidemiological analysis (Pasanen et al. 2007).

Even low exposure of potentially harmful trace metals from food or drinking water can be reflected in the trace element concentration profile of human blood and hair over the long term. The results from eastern Finland, where bedrock areas with elevated Hg and those with practically no Hg were compared, indicate that the use of dug well water, as well as the consumption of local potatoes and mushrooms, slightly increased the Hg concentration in hair. Calcium concentrations in blood serum were lower in people living in calcium-poor bedrock areas and selenium concentrations, in turn, were lower. This implies that more attention should be paid to the combination of long-term exposure to potentially harmful elements and the long term insufficiency of essential elements, which might exist locally at the same time (Kantola et al. 2000, 2008).

In Finland, the geographical variation in occurrences of certain diseases warrants additional studies. In the case of AMI, further studies are needed to prove – or disprove – the association between the AMI incidence and water hardness.

The strength of the medical geology research in Finland is based on extensive networking between geologists, environmental scientists, experts in risk modelling and spatial analysis, and health scientists. The fact that the geographical variation in occurrence of certain chronic diseases in Finland has remained relatively stable for decades warrants further studies from the viewpoint of medical geology.

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ABBREVIATIONS

AAS	atomic absorption spectroscopy
ADDs	acceptable daily doses
ADI	acceptable daily intake
Ag	silver
Al	aluminium
AMI	acute myocardial infarction
As	arsenic
Ca	calcium
CCA	chromated copper arsenate
Cd	cadmium
CHD	coronary heart disease
Cr	chromium
Cu	copper
CVD	cardiovascular disease
CVDR	Cardiovascular Disease Register
°dH	German degrees
F	fluoride
Fe	iron
HDR	high density regions
Hg	mercury
HPLC-HG-AFS	hyphenated high performance liquid chromatography – hydride generation – atomic fluorescence spectrometry
ICP-AES	inductively coupled plasma atomic emission spectroscopy
ICP-MS	inductively coupled plasma mass spectrometry
Mg	magnesium
Mn	manganese
Ni	nickel
NO_3	nitrate
RA	rheumatoid arthritis
RIVM	The National Institute for Public Health and the Environment, The Netherlands
RR	risk ratio
Se	selenium
T1DM	type 1 diabetes
T2DM	type 2 diabetes
U-As	urinary arsenic
USEPA	US Environmental Protection Agency
Zn	zinc
WHO	World Health Organization

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USE OF GROUNDWATER FLOW, CONTAMINANT TRANSPORT AND GEOCHEMICAL MODELLING IN ENVIRONMENTAL RISK ASSESSMENT OF AN INDUSTRIAL SITE AT KOKKOLA, WESTERN FINLAND

by
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Backnäs, S. & van den Dool, G. 2011. Use of groundwater flow, contaminant transport and geochemical modelling in environmental risk assessment of an industrial site at Kokkola, Western Finland. *Geological Survey of Finland, Special Paper 49*, 263–278, 5 figures and 3 tables.

This article presents a modelling study of an industrial area occupied by the zinc plant of Boliden Kokkola Oy in the city of Kokkola, Western Finland, as an example of how modelling can be used in environmental risk assessment (ERA) to evaluate site-specific risks related to contaminant transport in the groundwater zone. The study demonstrated that groundwater flow, contaminant transport and geochemical modelling require extensive data on the geological and hydrogeological structure and geochemistry of the site. When sufficient data are available, groundwater flow and contaminant transport modelling can be used as valuable tool in environmental and especially groundwater risk assessment to predict contaminant transport pathways, travel times and concentrations, and geochemical modelling to estimate metal speciation in the aquatic phase. The fate, concentration and speciation of the metals can be further used in environmental risk assessment to evaluate the possible ecological and health risks related to contamination.

In this case study, the hydrological modelling software MIKE SHE was used to model groundwater flow and contaminant transport and the geochemical code PHREEQC-2 was used in modelling trace metal speciation in the groundwater. The MIKE SHE modelling results showed that no groundwater flow or metal transport occurs from the waste area of Boliden Kokkola Oy towards the groundwater area of Patamäki. Thus, the waste area does not pose a health risk to the groundwater abstracted from the Santahaka groundwater pumping station. However, the geochemical modelling demonstrated that zinc (Zn), cobalt (Co) and nickel (Ni) are mainly present in groundwater as free ions and may thus cause ecological risks to soil organisms.

Keywords (GeoRef Thesaurus, AGI): environmental geology, industrial areas, waste disposal sites, ground-water flow, trace metals, transport, geochemistry, models, pollution, risk assessment, Kokkola, Finland

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INTRODUCTION

Metal-contaminated industrial areas may pose a risk to the water supply and human health when located close to an aquifer used actively to abstract water. They may also pose an ecological risk if metals are accumulated in soil, sediment or the water phase. The incidence of a health risk depends whether the metals are leachable and may be transported to the raw water of a groundwater pumping station. On the other hand, ecological risks of the aquatic phase are related to the metal concentration and especially the speciation of soil water, groundwater and surface waters, because the bioavailability and toxicity of metals is associated with their speciation (e.g. Allen & Hansen 1996, Morel & Hering 1993, Florence et al. 1992). According to various authors, metals are readily bioavailable when they occur freely in the water, i.e. are only bound to water molecules, are less available when they form complexes with weak organic or inorganic ligands, and are not available at all when they are bound to strong organic ligands.

The environmental risk assessment (ERA) of an industrial area involves the examination of risks resulting from industrial activities that may pose threats to people, ecosystems and animals. ERA is a scientific tool that consists of risk assessment concerning human health and ecological risk assessment of environmental media and organisms. ERA involves a review of available data and the identification and quantification of the risks associated with the potential threat. The ERA process includes several phases: contaminant source and hazard characterization, determination of the transport pathway and fate, exposure assessment, dose-response assessment, and as a final phase, risk characterization (e.g. Ramaswami et al. 2005).

According to Leete (2001), groundwater flow modelling mimics the actual behaviour of groundwater in an aquifer system and is used to evaluate the possible contaminant transport pathways. It is a useful tool in ERA when groundwater abstraction is a potential exposure pathway and can combine sparse data into a coherent representation of the workings of a hydrogeological system (Leete 2001). Together, groundwater and contaminant transport modelling can provide information on changes in the concentration of pollutants from their source to discharge or withdrawal points. Geochemical modelling can be used to detect geochemical reactions in the soil-groundwater interface and the speciation of metals for the assessment of metal bioavailability and toxicity.

Groundwater flow, contaminant transport and geochemical models can be linked to an ERA tool and employed during the phases of hazard evaluation, determination of the fate and transport pathways of contaminants, and toxicity and exposure assessment. Human risk assessment and ecological risk assessment require the prediction of exposure to groundwater based on information on the direction and amount of groundwater movement, the chemical nature of the groundwater and the concentrations of undesirable constituents, as well as their interactions in the soil-water phase, interconnections with other water sources and potential for transformation during transport. This prediction can be achieved with modelling (Leete 2001).

Several hydrological and geochemical models are available for modelling groundwater flow, contaminant transport and geochemical reactions at local and areal scales. Hydrological and groundwater modelling programs are commonly based on MODFLOW code. The Groundwater Modelling System (GMS) (Owen et al. 1996) provides an interface for several 2D and 3D finite element and finite difference groundwater and transport models, such as MODFLOW 2000, MODPATH, MT3DMS/RT3D, SEAM3D and FEMWATER. FEFLOW (Kolditz et al. 1998) is groundwater modelling software also capable of modelling contaminant transport. It enables multi-species reactive transport via a reaction kinetics editor and linkage of the surface water component through an interface manager (IfM). The MIKE SHE modelling system, on the other hand, is a fully integrated modelling framework for simulating all land phases of the hydrological cycle and contaminant transport (Graham & Butts 2005). One of its advantages is a public interface (Open MI) for coupling with other software. The most common geochemical codes for equilibrium modelling are MINTEQA2 (Allison et al. 1990) and PHREEQC-2 (Parkhurst & Appelo 1999). They also form the basis for many reactive transport models, including MIN3P (Mayer et al. 1999), PHREEQC-2, HP1 (Jacques & Šimůnek 2005), HydroBioGeoChem (Yeh et al. 1998), PHAST (Parkhurst et al. 1995) and MODFLOW/MT3DMS-based models such as RT3D (Clement et al. 1998) and PHT3D (Prommer et al. 2003).

The aim of this study was to test how groundwater flow, contaminant transport and geochemical modelling can be used in environmental risk assessment of an industrial site in Finland. The hydrological modelling software MIKE SHE was selected for the modelling of groundwater flow and contaminant transport over GMS and FEFLOW, because of its applicability for local and large-scale hydrological modelling studies covering both groundwater and surface water modelling and also contaminant transport. PHREEQC-2 was selected as a geochemical model. The data requirements and suitability of MIKE SHE hydrological modelling software and the geochemical modelling program PHREEQC-2 in environmental risk assessment of groundwater pollution were evaluated in this study.

METHODS

Site description

The modelling site is located in the city of Kokkola, in the large-scale industrial area of Ykspihlaja, also known as Kokkola Industrial Park (KIP), and the nearby groundwater area of Patamäki on the Finnish west coast bordering the Gulf of Bothnia (Figure 1). The zinc smelter of Boliden Kokkola Oy and the cobalt refiner and producer OMG Kokkola Chemicals Oy are located at the area. The waste area of Boliden Kokkola Oy is located on the northwest coast of the industrial area. It was introduced in 1969 by Outokumpu Oy, and the jarosite suspension produced as a byproduct during the purification and refining of Zn was loaded in the waste area bounded by a soil embankment. In 1973–1974, dams of glacial till were built against the sea and the waste area was expanded towards the sea. In addition to jarosite, solid process wastes rich in iron (Fe) and sulphur (S) were also deposited in the waste area over a number of years (Luoma & Nuutilainen 2003). In 1996, the manufacturing process was changed and S concentrate was also introduced as a new waste fraction. Ni- and Co-rich process wastes from cobalt production by OMG Kokkola Chemicals Oy have also been loaded in the waste area since 1997 (Luoma & Nuutilainen 2003). According to historical information, some waste materials have been used on the western side of the industrial area as soil filling materials; some of these have since been excavated and transferred to the waste area (Luoma & Nuutilainen 2003).

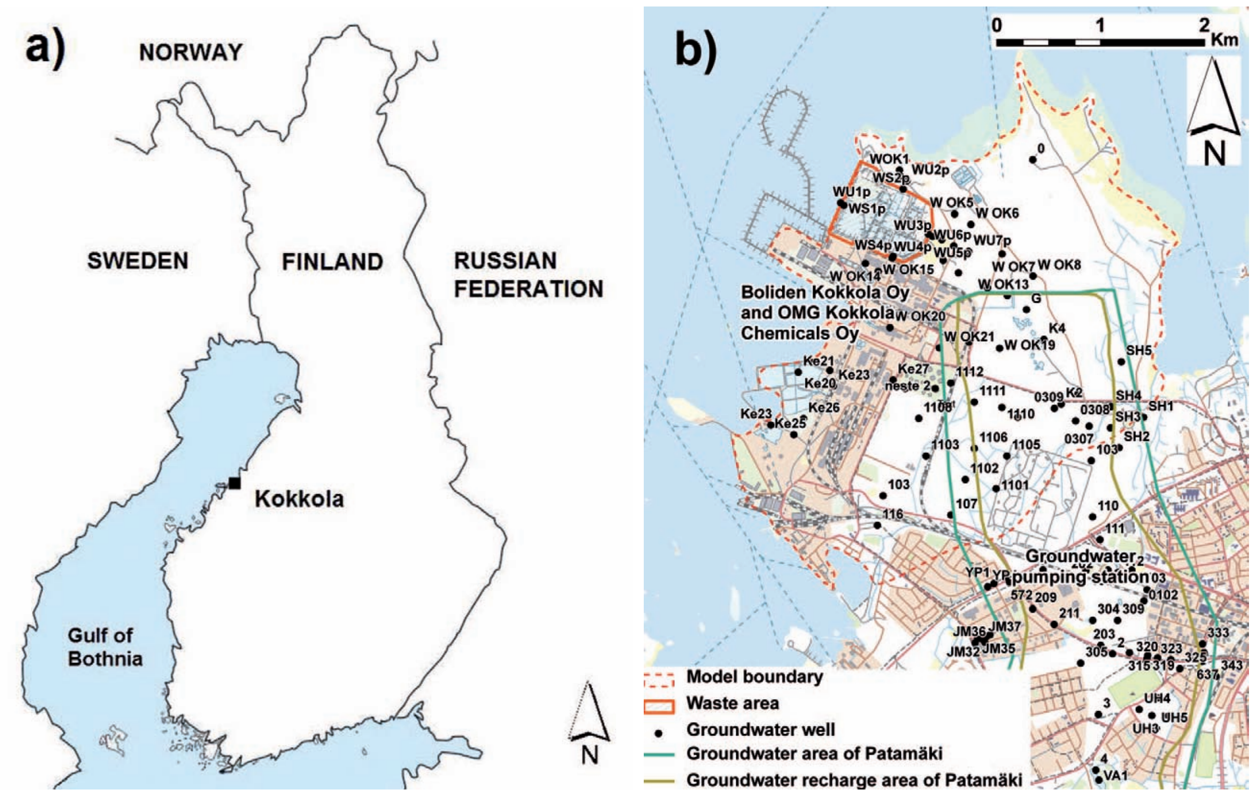

Figure 1. a) Location of the city of Kokkola on the Finnish west coast bordering the Gulf of Bothnia. b) Boundaries of the modelling area and locations of Boliden Kokkola Oy, OMG Kokkola Chemicals Oy, the waste area of Boliden Kokkola Oy, Patamäki groundwater area and the Santahaka groundwater pumping station of Kokkola Waterworks.

During 1999 and 2000, the waste area was surrounded by a leachate water collection and a groundwater monitoring system and a barrier wall consisting of 2.0 mm thick plastic film together with a combination of bentonite clay and cement (Luoma & Nuutilainen 2007). The barrier was extended to a depth of 11 m from the ground surface where the soil type throughout the profile was mainly sand, and to the layer of glacial till or bedrock when sand layers only occurred in the top soil. Impermeable basins were also built for the loading of S concentrate. The water level inside the waste area is kept 0.5 m lower than the surrounding groundwater and sea levels using a pumping station to maintain the flow directions towards the waste area and thereby prevent the contaminated water flowing towards the sea or groundwater. Currently, the combined size of the waste area and the embankments is 60 ha, with the waste fill area covering 45 ha (Pöyry Environment Oy 2007). The height of the waste area varies between +12 and +18 m (NN) in different sections, and the total amount of loaded waste materials is $5 \cdot 10^6$ m^3 (Nykänen 2006).

The groundwater area of Patamäki and the Santahaka groundwater pumping station of Kokkola Water are respectively located 800 m and 3 km south-east from the industrial area of Ykspihlaja. The catchment of the groundwater area is 8.5 km^2 and it emerges 6 000–6 500 m^3/d of groundwater. It is estimated that about 4 000 m^3/d of this groundwater emerges on the north side of the Patamäki groundwater area (Paalijärvi & Valjus 2008). The main geological deposit in the Patamäki groundwater area is a syncline glaciofluvial esker formed north-southwards in a bedrock fracture zone (Paalijärvi & Valjus 2008). It is composed of a 200 to 400 metres wide area of stratified gravel and sandy gravel deposited in deep water by a glacial meltwater stream and covered by finer sand and silt deposits during the melting of the glacier. The esker is surrounded by coarse and fine sand stratified in the vicinity of the esker as shore deposits. A delta formation known as Ykspihlajan niemi was deposited on the north side of the esker. Beyond the esker, under the sand deposits, silt deposited in deep water is present, which thus represents the old sea floor. Underneath the silt layers, gravely, sandy and silty till covers the bedrock as a ground moraine deposit. Clay formations are also likely to occur.

The industrial area of Boliden Kokkola Oy is located near by the esker, but is not within the catchment area of the groundwater pumping station of Patamäki. The soil in the industrial area mainly consists of sand with intervening fine-grained deposits (Paalijärvi & Valjus 2008, Luoma & Nuutilainen 2003). The largest amounts of fine-grained deposits are found in the western part of the industrial area. The thickness of the soil deposits is approximately 20–25 m. In a soil contamination study carried out in 2003, trace metal concentrations much higher than natural background concentrations were detected from the industrial area (Luoma & Nuutilainen 2003). The concentrations of trace metals varied from the natural concentration levels to concentrations exceeding the lower and upper guideline values set for harmful substances in soil in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (Vna 214/2007). The highest soil concentrations were detected in the vicinity of the waste area and the factory area of Boliden Kokkola Oy. According to Luoma & Nuutilainen (2003), the contamination is estimated to originate from the waste materials used as soil fill, leaks from industrial processes, basins, stockpiles, and from the waste area. The surface soil outside the industrial area also contains contaminants derived from air pollution. Groundwater quality in the industrial area has substantially improved since the barrier wall and leachate water collection system was constructed during 1999 and 2000 (Tammivuori 2007).

The bedrock topography varies in the industrial area and its surroundings from 35 m below the soil surface to bedrock outcrops on the west and northwest coast of Ykspihlajan niemi. According to bedrock studies (Luoma & Nuutilainen 2000), the rock type in the area is mica schist showing migmatitic features such as sparse quartz and pegmatite veins. Bedrock fractures have been detected in the region of the waste area by seismic soundings (Ihalainen 1999). Bedrock fracturing is partly due to weathering; thus, the surface of the bedrock is especially weathered in the fracture zones (Luoma & Nuutilainen 2000). During the installation of groundwater observation wells in 2008, strong fractionation of bedrock and groundwater discharge was detected on the east side of the waste area and the industrial area of Boliden Kokkola Oy (Paalijärvi & Valjus 2008). The mean annual temperature in the area is +2.8 ºC and rainfall averages 517 mm per year (Kalliolinna & Aaltonen 2003).

Data acquisition and processing

All available geological, geophysical and hydrogeological data on the target area were collected and processed (Table 1). The digital elevation model (DEM) was based on topography data provided by the National Land Survey of Finland incorporated with the surface elevations from drilling and groundwater well data of the KIP area. The DEM was hydrologically corrected to match the stream impressions to allow for the flow and accumulation of surface water. To ensure the correct run-off of the precipitation, all water elements (streams and ditches) were suppressed by 1 m and the general flow direction was checked. The boundaries of the model area were defined based on the location of i) sub-catchments and surface water flow directions estimated from the DEM, ii) the location of the KIP, the waste area of Boliden Kokkola Oy and the northern part of the nearby groundwater area of Patamäki and iii) the availability of geological and geochemical data from the target area. The selected model area is restricted to north and west by the sea and to the east and south by the northern part of the Patamäki groundwater area (Figure 1).

Table 1. Available geological and hydrological data, maps and time series used as an input to MIKE SHE with reference to the source, spatial discretization or number of measurements, and the year or period of investigation.

Data type	Source (Spatial discretization/ number of measurements)	Year/ Period
Topography/DEM	Data of the National Land Survey of Finland (25 m)	2007
Sub-catchment boundaries	Extracted from DEM using GIS algorithms	
Soil types and bedrock depth	Available data from drillings, seismic sounding, GPR	1999–2008
Soil distribution	Distributed by the Thiessen polygon method from drilling and geophysical data	
Groundwater levels	Available groundwater data (102 wells)	1987–2007
Hydraulic conductivities	Literature estimates and field measurements by Guelph permeameter (4 points/11 depths)	2007
Specific yield	Estimated (0.2)	
Specific storage coefficient	Estimated (0.0001)	
Porosity	Estimated (0.2–0.4)	
Zn in groundwater	Available groundwater data (36 wells)	2000–2007
Zn in soil	Available soil data (178 points/ 869 samples)	2003
K_d (Zn)	Calculated from the total Zn concentration in soil and soluble Zn concentration in groundwater	
Equilibrium sorption faction	Estimated (0.7)	

The geological 3D structure was based on data from drillings and geophysical investigations (seismic soundings, GPR, gravimetric method) of the KIP and Patamäki groundwater areas (Figure 2) (Luoma & Nuutilainen 2003, Luoma & Nuutilainen 2000, Ihalainen 1999, Paalijärvi & Valjus 2008, Paalijärvi 2007). In addition to discrete data sources, data on bedrock outcrops from the soil map 1:20 000 (Kukkonen et al. 1987) were used to produce a more complete dataset to describe the bedrock topology. This gave a good initial estimate of the spatial variation of bedrock in the area. However, this initial dataset was not enough to ensure the correct bedrock topography. Therefore, in areas where data were sparse, the soil depth data from groundwater well installations were used to estimate the bedrock depth. The total set of bedrock depth points (known and estimated) was combined and used in the "Topo to Raster" function of ArcGIS, which uses a constrained spline algorithm and interpolates the new raster based on the input order.

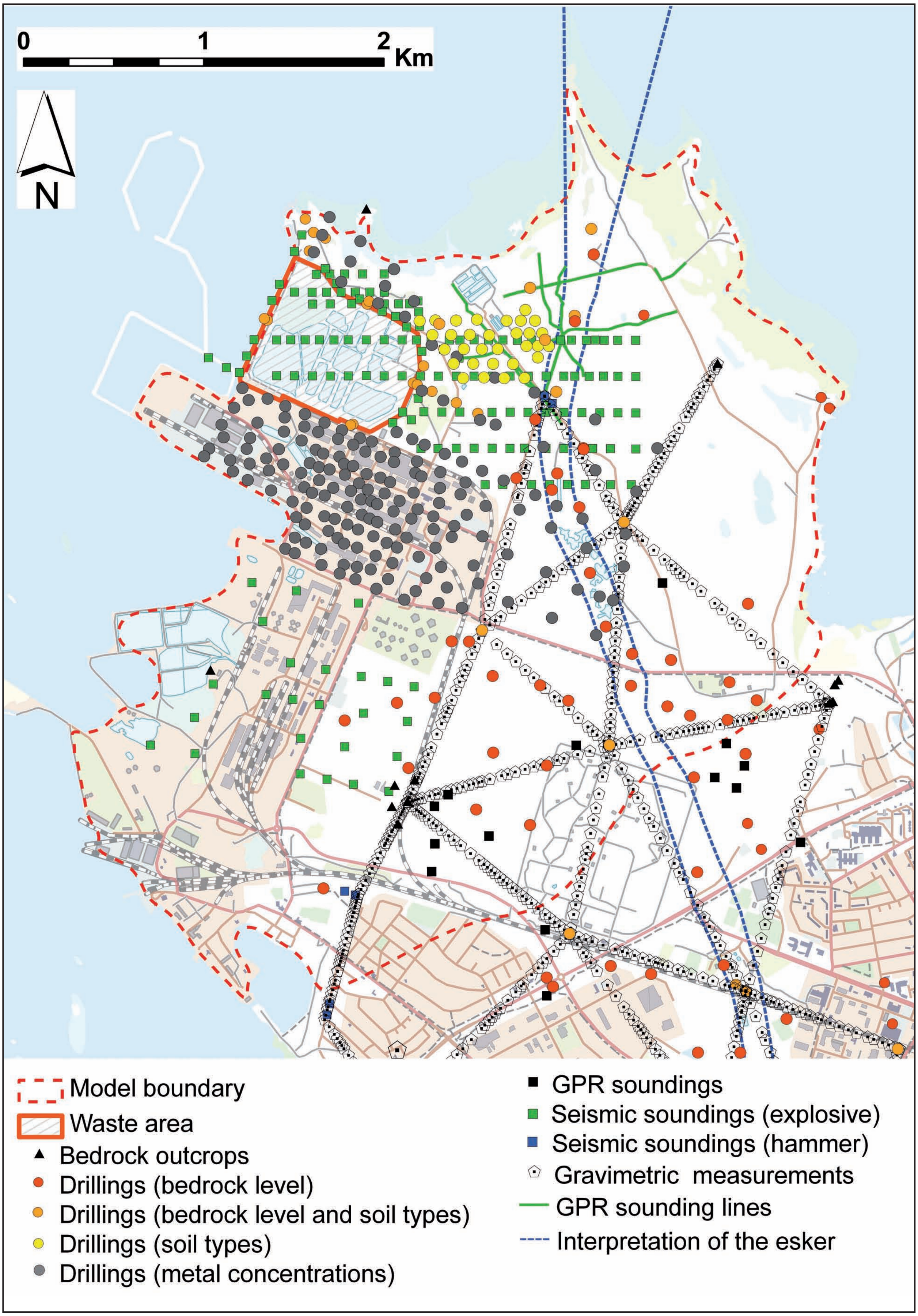

Figure 2. Available drilling and geophysical data used in determining the geological 3D structure of the model area.

To provide a suitable geological model with the initial soil distribution values for the selected hydrological modelling software, MIKE SHE, a tailor-made data management scheme, was developed using ArcGIS and Microsoft Excel. In MIKE SHE, the Quaternary deposits can be described as continuous layers throughout the modelling area or as lenses that, in contrast to layers, do not necessarily have to be created as continuous structures, but are formed within the layered model. The geological 3D model was developed with the assumption that the formations follow a vertical stratigraphical pattern, and although the layers are not consistent, they are continuous. It was created by coupling original data with estimations of the stratigraphy and formation of Quaternary deposits in the area to obtain secured boundary conditions and a suitable point distribution for interpolation. The available soil investigation data with additional interpreted points were transformed into a relative soil thickness (% of the total thickness) table (RST), which included the soil thickness and the soil type. Soil model points (SMP) were linked together based on the depth of each individual soil layer that was identified by using Thiessen (Voronoi) polygon boundaries to define the areas of influence around each set of points relative to all other points. Mathematically, Thiessen polygons are defined by the perpendicular bisectors of the lines between all points. This technique was used for all layers in the RST table, effectively constructing a dynamic set of polygons. The total set of SMP was used as input for the Thiessen Polygon Layer, and the percentage of each individual layer was then used as a marker in the Thiessen and TIN points (the nodes defining the Thiessen polygons). The output is a polygon layer in which all polygons have the attributes of the SMP. In the second stage, the soil types were grouped and split according their formation into layers that represent the interpreted occurrence of the soil layers. Additional information on the location and maximum area of the esker were added as line features dividing the previously formed Thiessen polygon layer to enable full definition of the esker. After insertion of the esker, inverse distance weighted (IDW) interpolation was used to create a smooth relative soil thickness towards the full extent of the polygon, where the points in the RST have a whole value (100 ~ 0) and the TIN points are the average of the bordering RST points. Finally, all the points (TIN points, Thiessen points and interpreted features) were used in combination with the Thiessen polygons and the RST table. The RST table was read bottom-up, processing the layers over the bedrock towards the soil surface, as the vertical lower boundary of the geological model was set to the bedrock surface interpolated previously and the vertical upper boundary was set equal to the elevation (DEM).

Groundwater level data from 1987 to 2007 and groundwater quality monitoring data from 2000 to 2007 were collected from Kokkola Water and Boliden Kokkola Oy. Additional groundwater monitoring was also performed in September 2007 by the Geological Survey of Finland and water samples were collected from 13 groundwater wells and a groundwater pond formed in an old gravel pit. All sampling points were analysed in the field for pH, Eh, specific conductivity (EC), temperature and dissolved oxygen using a multi-parameter water quality sond and recording device (YSI 600XLM, 650MDS). Filtered (0.45 µm) unacidified samples were used for the determination of major anions by ion chromatography. Dissolved organic carbon (DOC) was analyzed with an aqueous carbon analyzer from unfiltered unacidified samples. Major cations and trace metals were measured by inductively coupled plasma spectrometry (ICP-AES/ICP-MS) of filtered (0.45 µm), HNO_3-acidified samples. To ensure the quality of the samples, blank sample and replicate analyses were performed from one sampling point. The hydraulic conductivities of the top soil layers, consisting of coarse sand, sand, fine sand and silt, were also measured *in situ* with Guelph permeameter equipment by the Geological Survey of Finland in September 2007.

Modelling process, parameterization and calibration

The MIKE SHE modelling system (Graham & Butts 2005) was selected as a hydrological modelling program for modelling groundwater flow and contaminant transport paths. In MIKE SHE the hydrological processes are described and their simulation is performed in the water movement module (MIKE SHE WM). The water quality module (MIKE SHE WQ) can be used after water movement simulations to model contaminant transport.

At first, a conceptual model was constructed as a framework for the mathematical model. In MIKE SHE, catchment characteristics such as elevation and soil type are represented through the discretization of the catchment horizontally into an orthogonal network of grid squares. A grid with horizontal discretization of 25 x 25 m was used in the model to permit detailed presentation of the ground and bedrock topography and soil stratigraphy of the model area. The vertical variations in catchment characteristics are described in horizontal layers with variable depths. Computationally, the model was split into six layers describing depth levels of 0 to 2.5 m, 2.5 to 5 m, 5 to 10 m, 10 to 15 m and 15 to 25 m from the soil surface, and from the depth of 25 m to the bedrock level to enable consideration of groundwater flow and contaminant transport paths at different depths.

The geological model was constructed as a two-layered system of bedrock elevation and sand as the dominant soil type with other soil types as lenses to achieve the most reliable distribution of hydraulic conductivity in the study area. The geological model was described in a 25 x 25 m computational grid including soil elevation, soil structure and bedrock surface. As the model area is located in a peninsula, the horizontal boundaries of model area to the north, west and east were hydrologically closed by the sea, the level being -0.60 m (NN). On the southern side of the model area the average measured groundwater levels were set as boundary conditions. Altogether, data from 102 wells were used in the model. The barrier wall of the waste area was described as an impermeable layer with a hydraulic conductivity of $1 \cdot 10^{-15}$ m/s. The inner seepage water level in the waste area was set to the level -0.75 m (NN), i.e. approximately 0.5 m lower than in the surrounding area, as it was regulated with pumping. The amount of infiltration was estimated from the average precipitation and evapotranspiration in Kokkola using the data of the Finnish Meteorological Institute. The parameter classes were defined so that the parameter values could be identified to the highest extent possible in an objective way using the available field and literature data.

Groundwater flow and zinc transport modelling was carried out as steady-state modelling. The average flow directions and transport pathways were estimated in the saturated zone. Two scenarios were modelled: the situation before (1987–1999) and after (2000–2007) the waste area barrier wall and leachate collection system were introduced. Model calibration was performed using a standard automatic calibration procedure integrated into MIKE SHE, where one or a set of parameters can be calibrated. Prior to calibration, sensitivity analysis was carried out to establish which parameters had the greatest effect on the model and were thus primary in the calibration. The uncalibrated model, based on estimates of hydraulic conductivities from field data, literature and previous studies, was calibrated by adjusting the hydraulic conductivities of all soil types and layers in the model (Table 2). The calibration was carried out against the groundwater levels resulting in an on-site calibrated model. The modelling was performed as a steady-state model, because the available time series of groundwater levels were sparse, and the creation of a transient model was not therefore possible. For the same reason, the model was not validated.

Table 2. Hydraulic conductivities (m/s) of different soil types measured in the field by Guelph permeameter, estimated from the literature and calibrated in the model.

Geological layer	Soil type	$K_{measured}$	$K_{estimated}$	$K_{calibrated}$
Main aquifer	Coarse sand		$1 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Lenses	Gravel and cobbles		$1 \cdot 10^{-2}$	$5 \cdot 10^{-3}$
	Gravel		$5 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
	Fine gravel	$1 \cdot 10^{-3}$		$2 \cdot 10^{-4}$
	Coarse sand	$5 \cdot 10^{-4} \ldots 1 \cdot 10^{-4}$		$1 \cdot 10^{-4}$
	Sand	$5 \cdot 10^{-5}$		$5 \cdot 10^{-5} \ldots 1 \cdot 10^{-5}$
	Fine sand	$1 \cdot 10^{-5}$		$5 \cdot 10^{-6}$
	Gravely till		$1 \cdot 10^{-6}$	$5 \cdot 10^{-7}$
	Sandy till		$1 \cdot 10^{-7}$	$1 \cdot 10^{-7}$
	Silty till		$1 \cdot 10^{-8}$	$5 \cdot 10^{-8}$
	Silt	$1 \cdot 10^{-6}$		$1 \cdot 10^{-6}$
	Silty clay		$1 \cdot 10^{-9}$	$5 \cdot 10^{-8}$

A calibrated WM model was used to simulate the transport of dissolved and sorbed Zn from the waste area by adding a water quality calculation (WQ) to the model. The Zn adsorption-desorption process was simulated using equilibrium sorption with a linear isotherm. The retardation of Zn was described by a partition coefficient (K_d), which is the ratio of the quantity of the contaminant adsorbed per unit mass of solid to the amount of the contaminant remaining in solution at equilibrium (Zheng & Bennett 2002). K_d values were calculated from the measured total Zn concentration in soil and groundwater phases.

Geochemical modelling of the speciation of contaminants for site-specific risk assessment was performed by the thermodynamic geochemical reaction model PHREEQC-2 developed by the USGS (Parkhurst & Appelo 1999) using the Minteq (v4) database. Water sampling data from 13 groundwater wells and a pond formed in an old gravel pit were used in the modelling. Matlab code was developed to extract the molalities of species and saturation indexes of minerals that were focused on in the risk assessment. Zn, Ni and Co were selected as target metals due to their elevated concentrations in the soil and groundwater in vicinity of the waste area of Boliden Kokkola Oy.

RESULTS AND DISCUSSION

Groundwater flow paths and zinc transport

MIKE SHE modelling results show that before the waste area barrier wall and leachate collection system were built, the main flow direction from the waste area was towards the sea in all six computational layers representing the depth levels of 0 to 2.5 m, 2.5 to 5 m, 5 to 10 m, 10 to 15 m and 15 to 25 m from the soil surface, and from the depth of 25 m to bedrock level (Figure 3). In the industrial area of Boliden Kokkola Oy, the main flow direction has also been towards the sea, causing trace metals in the leachate to accumulate in the sediment phase (Figure 3). Thus, it is unlikely that groundwater flow has occurred from the waste area towards the groundwater area of Patamäki. Since the waste area barrier wall and leachate collection system were constructed, the main groundwater flow direction in the industrial area has been towards the sea and close to waste area towards it (Figure 4). Thus, no flow is occurring from waste area towards the groundwater area or towards the sea (Figure 4). Nowadays, the divide of the groundwater flow occurs 300 m north of its location before the waste area barrier wall and leachate collection system were built, probably due to increased groundwater abstraction at the Santahaka groundwater pumping station of Kokkola Water (Figure 4).

According to the MIKE SHE QW model of Zn transport, Zn in the mobile phase is not transported from the waste area of Boliden Kokkola Oy towards the Patamäki groundwater area (Figure 5). Although mobile Zn occurs in the groundwater zone surrounding the waste area, the main flow directions are towards the waste area and the Zn mobilized from the soil is transported to the leachate collection system of the waste area. Minor Zn transport may occur towards the sea near the coast line on the northern side of the waste area and on the southern coastal side of the industrial area of Boliden Kokkola Oy.

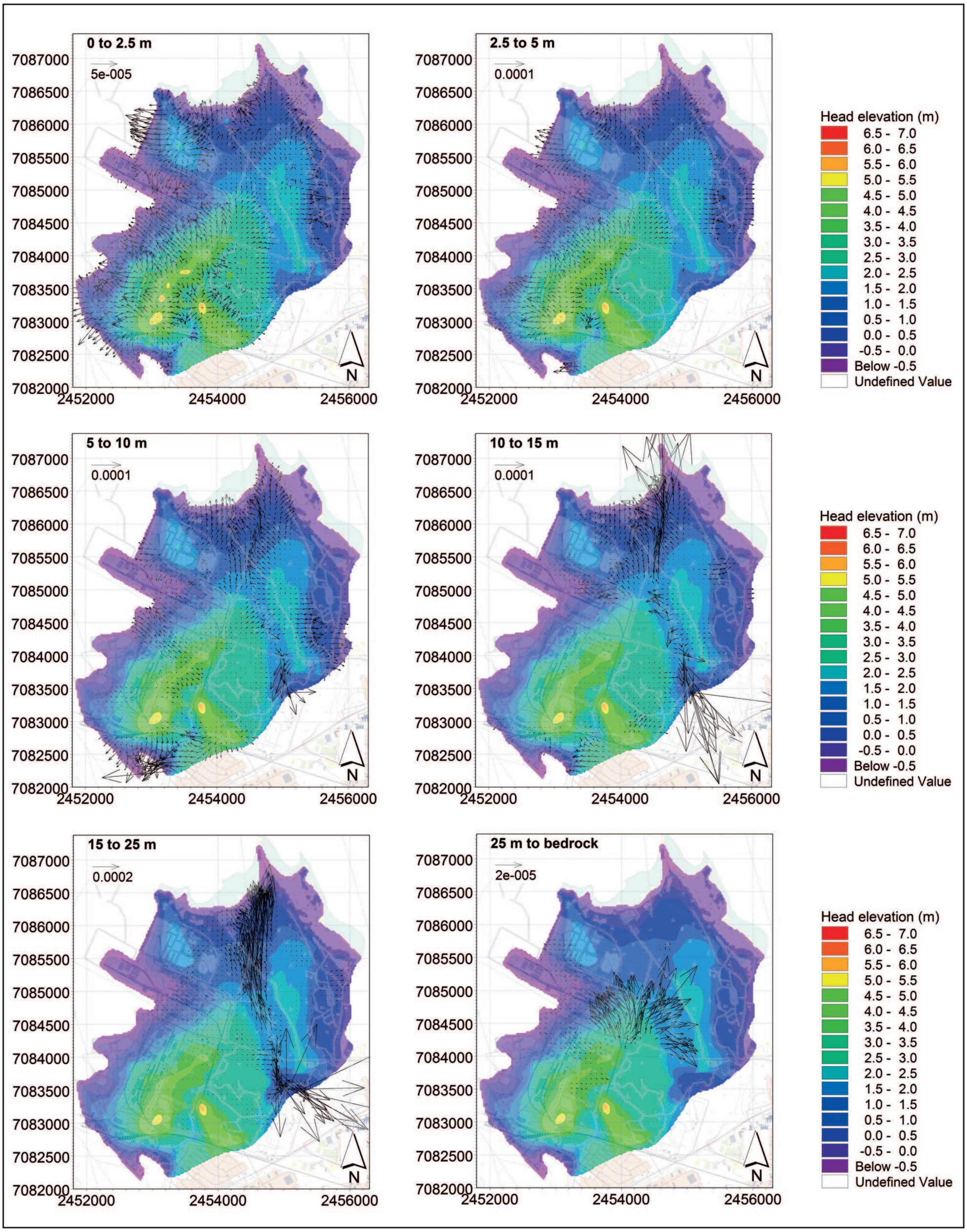

Figure 3. Modelled groundwater flow paths and hydraulic head elevations (NN) in the saturated zone in computational layers of 0 to 2.5 m, 2.5 to 5 m, 5 to 10 m, 10 to 15 m and 15 to 25 m from the soil surface and from the depth of 25 m to the bedrock level before the waste area barrier wall and leachate collection systems were built.

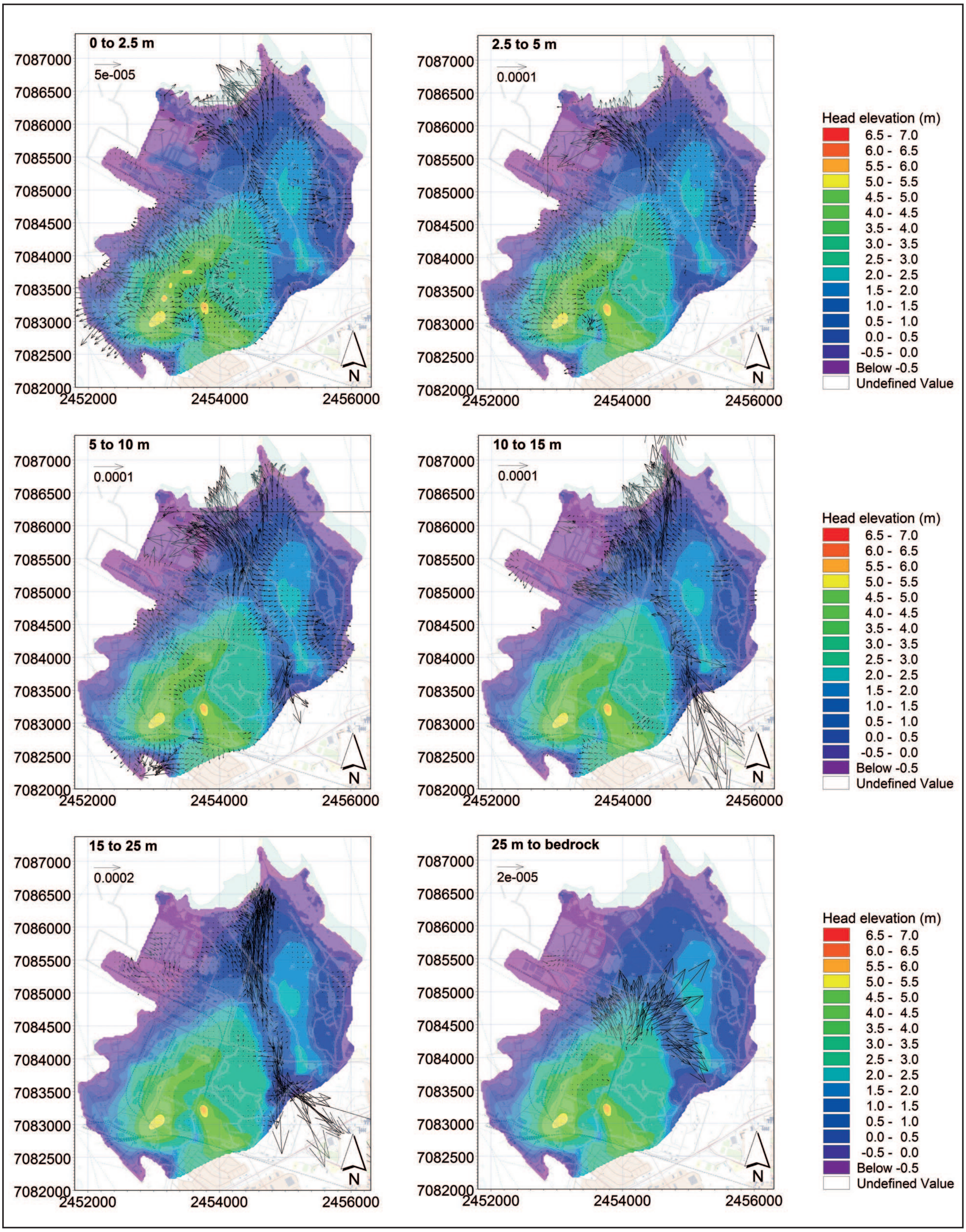

Figure 4. Modelled groundwater flow paths and hydraulic head elevations (NN) in the saturated zone in computational layers of 0 to 2.5 m, 2.5 to 5 m, 5 to 10 m, 10 to 15 m and 15 to 25 m from the soil surface and from the depth of 25 m to the bedrock level after the waste area barrier wall and leachate collection systems were built.

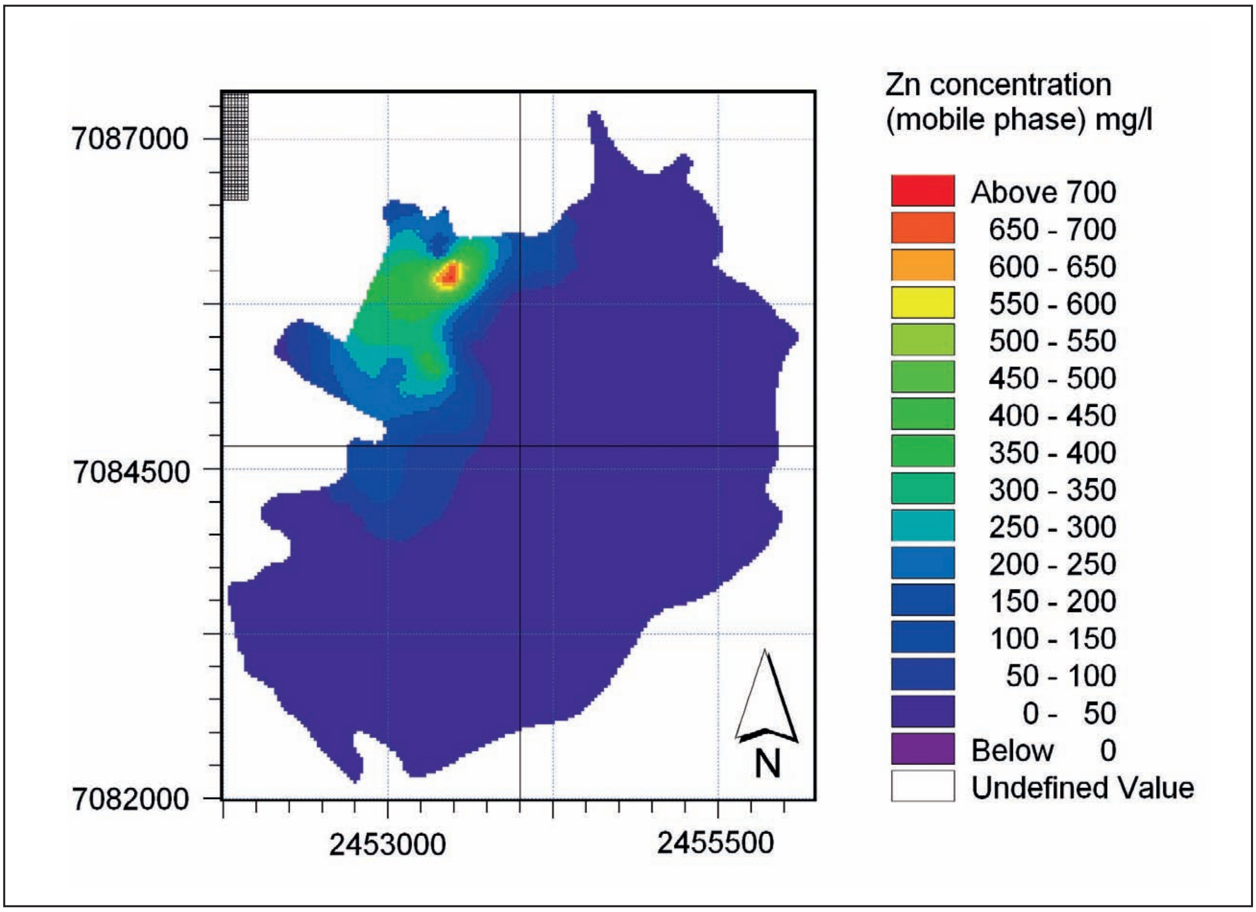

Figure 5. Modelled concentrations (mg/l) of mobile Zn in the saturated zone after the waste area barrier wall and leachate collection systems were built.

Metal speciation in groundwater

Results of the geochemical modelling (PHREEQC-2) showed that the complexing strength of the groundwater is low and Zn, Co and Ni mainly occur as free bivalent ions and complexes with sulphates (Table 3). From 9.4 to 96% of Zn occurred as Zn^{2+}, 0.01 to 74% as $Zn(SO_4)^{2-}$, 3.8 to 29% as $ZnSO_4^0$ and less than 0.3% as $ZnOH^+$, ZnF^+ and $ZnCl^-$. Except in the pond, $ZnOH^+$ and $Zn(OH)_2^0$ formed nearly 11% of the total Zn. From 71 to 97% of Co was found as CO^{2+}, 3 to 29% as $CoSO_4^0$ and altogether less than 0.5% was present as $CoCl^+$, CoF+, $CoHPO_4^0$ and $CoOH^+$. From 37 to 97% of Ni appeared as Ni^{2+}, 3.4 to 62% as $NiSO_4^0$ and less than 1.5% as $Ni(SO4)_2^{2-}$, $NiCl^+$, NiF^+ and $NiOH^+$. According to various authors, free ions are, in most cases, the most bioavailable fraction of a metal (e.g. Allen & Hansen 1996). Thus, the results indicate that the Zn, Co and Ni are highly bioavailable in the water phase.

Groundwater risk assessment

The results of groundwater monitoring (Table 3) revealed elevated silicon (Si), potassium (K), magnesium (Mg), Fe and aluminium (Al) soluble concentrations in the Patamäki groundwater area, which may indicate increased mineral weathering (mica) in the surface soil due to groundwater abstraction and the low sorption capacity of the young pedon. The results also revealed a low oxygen content and partly reduced conditions that maintain the solubility of trace elements in the groundwater of the esker formation. According to hydrogeological mapping of Finnish groundwater (Lahermo et al. 1990), the oxygen content is naturally low and the amount of dissolved humic material naturally high in the silt and clay covered eskers on the western coast of Finland, which causes reducing conditions and quite high concentrations of Fe and Mn in the groundwater. In the Patamäki groundwater area, pH levels and the sulphate concentration are also similar to the natural background values on the western coast of Finland (Lahermo et al. 1990).

Table 3. The EC, pH, Eh, concentrations of O_2, DOC and SO_4^{2-}, total soluble concentrations of Fe, Al, K, Mg, Mn, Si, Zn, Co and Ni and percentages of their most common species in the water samples taken from the groundwater wells and a pond formed in an old gravel pit.

Water sample	EC (mS/m)	pH	Eh (mV)	O_2 (mg/l)	DOC (mg/l)	SO_4^{2-} (mg/l)	Fe (mg/l)	Al (mg/l)	K (mg/l)	Mg (mg/l)	Mn (mg/l)	Si (mg/l)	Zn (mg/l)	Zn2+ (%)	$Zn(SO_4)^{2-}$ (%)	$ZnSO_4^0$ (%)	Co (µg/l)	CO^{2+} (%)	$CoSO_4^0$ (%)	Ni (µg/l)	Ni^{2+} (%)	$NiSO_4^0$ (%)
0310	152	6.19	126.2	1.34	3.2	79	6.65	0.305	7.74	7.14	2.80	21.0	0.07	92.1	0.1	7.8	28.5	92.9	7.0	37.9	92.7	7.2
110	142	6.28	-22.3	0.53	2.1	70	15.9	0.0484	6.29	5.98	1.35	17.3	0.31	92.8	0.1	7.1	13.6	93.5	6.4	14.3	93.4	6.6
K4	67	5.38	221.5	5.53	13	28	1.03	0.679	3.49	2.41	0.169	10.5	0.12	96.3	0.0	3.7	22.9	96.6	3.3	30.2	96.6	3.4
WOK10	722	4.99	215.9	3.06	4	606	97.2	23	2.60	26.3	2.84	31.1	13.9	76.3	1.1	22.6	935	80.4	19.6	702	78.6	21.4
WOK12	150	5.81	180.8	3.75	1	78	9.75	0.194	6.93	4.02	0.666	16.7	0.90	91.8	0.1	8.1	169	92.6	7.3	292	92.5	7.5
Pond (WOK13)	126	8.33	156.6	10.92	2.3	35	0.07	0.00129	5.29	5.98	0.03	2.99	0.01	84.9	0.0	3.9	0.25	92.1	3.8	0.77	94.7	4.0
WOK20	5690	4.3	215.8	4.68	9.1	9315	2715	242.5	16.3	164.5	6.22	34.75	60.6	24.6	46.8	28.5	1185	71.6	28.3	1390	48.1	51.4
WOK21	242	6.78	-3.7	3.95	1	102	21.0	0.0011	6.02	9.32	0.099	10.0	0.02	90.8	0.1	9.0	0.24	91.7	8.0	0.30	91.6	8.3
WOK7	63	6.17	177.9	4.33	1	28	2.48	0.0203	2.83	1.00	0.138	10.4	0.30	96.1	0.0	3.8	15.7	96.5	3.5	22.9	96.4	3.5
WS3p	6589	5.21	148.1	4.89	4.6	12400	1730	22.9	193	799	802	17.3	2080	24.4	52.5	22.8	18700	82.5	17.0	24600	53.0	45.6
WU1p	13104	6.26	-6.1	3.05	4.2	13900	1590	<0.05	128	806	347	19.2	138	11.1	71.0	17.8	8050	74.0	25.7	1210	39.9	58.7
WU2p	8926	6.57	-46.5	4.37	5.1	13900	1090	<0.05	90.0	523	626	18.7	8.18	9.4	73.7	16.8	8570	71.0	28.7	177	37.2	61.5
WU3p	901	6.54	-22	3.97	5.5	542	115	0.0295	8.87	37.1	7.60	19.8	50.3	76.7	1.1	22.0	398	80.7	19.0	185	79.0	20.8
WU7p	132	6.62	14.5	3.44	1	55	28.7	0.00642	7.89	4.62	1.04	17.3	0.02	94.1	0.0	5.8	0.28	94.5	5.2	0.27	94.6	5.3

The groundwater monitoring data (Table 3) additionally show that in the industrial area of Boliden Kokkola Oy the groundwater contains higher levels of trace metals and sulphate and is more oxygen rich than in the groundwater wells of the Patamäki groundwater area. Although the Zn, Co and Ni concentrations in all the analyzed groundwater samples except the samples taken from the wells WOK21 and WU7p and the pond water exceeded the values indicative of a good chemical status of the groundwater (60 µg/l Zn; 2 µg/l Co; 10 µg/l Ni) recommended by Finnish Environment Institute (Suomen ympäristökeskus 2010), as well as the average Finnish background concentrations (44.2 µg/l Zn; 0.766 µg/l Co; 3.29 µg/l Ni) (Lahermo et al. 2002), the concentrations in groundwater wells close to the Santahaka groundwater pumping station (0310, 110 and K4) are very low compared to the concentrations in the vicinity of the waste area of Boliden Kokkola Oy. The concentration of Ni in the groundwater close to the pumping station also does not exceed the quality standard (20 µg/l Ni) for drinking water (Vna 461/2000). For Zn and Co, similar quality standards for drinking water have not been enacted. The sulphate concentrations exceed the average Finnish background concentration (14.6 mg/l SO_4^{2-}) in all groundwater samples, but only exceed the quality standard (250 mg/l SO_4^{2-}) for drinking water and the limit value for a good chemical status (150 mg/l SO_4^{2-}) in the groundwater wells located in vicinity of the waste area and factory area of Boliden Kokkola Oy (WU3p, WU2p, WU1p, WS3p, WOK20, WOK10).

The slightly elevated soluble concentrations of Zn, Co and Ni in the Patamäki groundwater area may be a consequence of leaching of the trace metals accumulated in the surface soil due to historical air pollution from the smelter (Luoma & Nuutilainen 2003). The bedrock in the area may also affect the groundwater quality, because it consists of mica schist, which may contain iron and metal sulphides. Thus, the groundwater discharging from the bedrock fractures may naturally contain high concentrations of trace elements. According to the results of groundwater flow modelling, it is unlikely that leachate flow has occurred from the waste area of Boliden Kokkola Oy towards the Patamäki groundwater area, even before the barrier wall and leachate collection system were constructed (Figure 3, Figure 4).

The results of groundwater analysis (Table 3) indicate that the chemical nature of the groundwater in the Patamäki groundwater area differs from that in the industrial area of Boliden Kokkola Oy. This is supported by the results of the groundwater flow and contaminant transport modelling study, showing no flow or metal transport towards the Patamäki groundwater area and the groundwater abstraction wells in Santahaka. Thus, the waste area of Boliden Kokkola Oy does not currently pose any risk to the groundwater area of Patamäki.

However, the groundwater flow directions in the area are sensitive to changes in the groundwater level and the amount of abstracted groundwater, because of water level inside the waste area of Boliden Kokkola Oy is kept 0.5 m lower than the surrounding groundwater and sea water levels to maintain the flow directions in vicinity of the waste area towards it. Therefore, any land use changes close to the waste area may pose a risk if the groundwater levels change. If groundwater abstraction is increased, the groundwater flow directions may change so that flow directions close to waste area may turn towards the groundwater area of Patamäki. If this happens, old contaminants may be mobilized in the groundwater and transported towards the esker and groundwater abstracted from groundwater wells in Santahaka. It is also important to protect the ponds formed in old gravel pits, because they are directly connected to the water that is abstracted from the northern part of the esker.

According to the geochemical modelling, Zn, Co and Ni mainly occur as free cations, and are therefore highly bioavailable and toxic to organisms, even at low total concentrations. Thus, their occurrence at elevated concentrations in the area may have negative effects on soil organisms.

CONCLUSIONS

This study showed that the waste area of Boliden Kokkola Oy does not pose any risk to the groundwater area of Patamäki. However, the groundwater flow directions in the area are sensitive to groundwater level changes and the amount of abstracted groundwater. More detailed groundwater quality monitoring is therefore recommended to ensure the good quality of abstracted groundwater. When planning land use changes related to groundwater level changes or the excavation of soil, the possibility of metal leaching to the groundwater should be evaluated. An increase in groundwater abstraction should also be avoided, because it may affect the function of the waste area barrier system and also the geochemistry and mobility of metals in the soil.

The case study showed that hydrological, transport and geochemical modelling require extensive data on the geological and hydrogeological structure of the site and its geochemistry. When sufficient data are available, modelling can be used as valuable tool in environmental and especially groundwater risk assessment. Hydrological and contaminant transport modelling can be used to predict contaminant transport pathways, travel times and concentrations, and geochemical modelling to estimate metal speciation in the aquatic phase. The fate, concentration and speciation of the metals can be further used in environmental risk assessment to evaluate the possible ecological and health risks related to contamination.

Model testing highlighted that coupled reactive transport models would be a more optimal selection for modelling-assisted risk assessments studies than traditional flow and contaminant transport models. However, none of the present reactive transport models allows a heterogeneous surface topography and geological structure. Thus, model integration through coupling by Open MI or IfM is a promising alternative, allowing the use of complex hydrological 3D modelling software with geochemical reaction models or self-programmed geochemical modules. Hydrological software are more often developed to be Open MI compliant. Thus, modelling with MIKE SHE coupled with PHREEQC-2 through an Open MI interface would be a promising alternative for risk assessment studies involving ecological and health risk assessment of both groundwater and surface water systems, and is recommended to be tested in a follow-up study.

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ISOTOPE TRACING IN GROUNDWATER APPLICATIONS

by
Nina Kortelainen

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Isotope methods in hydrogeological studies of Finnish shallow glacigenic formations have been developed and applied at the Geological Survey of Finland (GTK) since the late 1990s. The Laboratory for Isotope Geology has analyzed oxygen and hydrogen isotopes in water samples on a routine basis since 1995, and the isotopic composition of inorganic carbon and strontium dissolved in water since 2000. The first detailed records on spatial and annual variability in the isotopic composition of precipitation and groundwaters in Finland were generated during 1995 to 2005. GTK has three active precipitation stations related to the Global Network of Isotopes in Precipitation (GNIP) programme operated by the IAEA. Isotope "fingerprinting", based on the isotopic difference between interacting water reservoirs, has been useful in several applied studies related to water management, especially artificial recharge (AR). At Tuusula Waterworks in southern Finland, the isotope ratios of oxygen and hydrogen have been utilized to calculate the mixing ratios between local groundwater and infiltrated lake water, and the carbon isotope method to quantify the processes of organic matter removal in artificial groundwater recharge. To understand the response of the natural groundwater system to artificial recharge and the mixing of infiltrated water with local groundwater, knowledge of the geochemical baseline and isotopic characteristics of the aquifer is essential. In the Virttaankangas groundwater formation, SW Finland, isotopic applications in AR have had a significant role in the planning of infiltration and monitoring of the active water plant, as well as assisting in the calibration of groundwater flow model. New isotope approaches for hydrogeology are being tested using the facilities of the Finnish Isotope Geology Laboratory (SIGL). Separation method for cations such as lithium, magnesium, calcium, strontium, lead and uranium are currently under development. The automated separation methods would significantly reduce the throughput time of samples. In contrast to oxygen and hydrogen, the isotopic differences in dissolved components in water are inherited from organic and inorganic atmospheric, industrial and anthropogenic sources, together with weathering processes during the interaction between minerals, soil and water.

Keywords (GeoRef Thesaurus, AGI): hydrogeology, isotopes, ground water, artificial recharge, surface water, infiltration, Finland

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BACKGROUND

The Geological Survey of Finland (GTK) has been the first research organisation in Finland to introduce isotope methods in hydrogeological studies, especially for shallow glacigenic formations. The driving force behind these activities has been the need to develop and apply isotope methods particularly to water management and artificial groundwater recharge. Stable isotope methods have been known among hydrogeological studies since the beginning of the 1960s. Natural elements and compounds are composed of different isotopes of certain elements. Isotope ratios of oxygen, hydrogen, carbon and strontium are widely used in hydrological studies to track, for example, different water sources, groundwater recharge processes, subsurface processes, geochemical reactions and reaction rates (e.g. Clark & Fritz 1997, Kendall & McDonnell 1998, Kendall & Doctor 2003).

Precipitation has a geographically specific isotopic fingerprint, which is inherited by the local groundwater. In isolated surface water reservoirs, the water mass is exposed to evaporation, which leads to isotopic enrichment compared to groundwater (Gonfiantini 1986). In practice, significant differences are often recorded between local groundwater and surface water reservoirs, as illustrated in Figure 1 of the Virttaankangas groundwater formation, SW Finland. The isotopic composition of the stable nuclides of oxygen and hydrogen, for instance, are measured as isotope ratios, which are reported using δ notation as the per mil (‰) difference relative to the international standard for oxygen ($\delta^{18}O$) and hydrogen (δD). In shallow aquifers, the isotopic compositions of oxygen and hydrogen are conservative parameters, which can generally only be changed by mixing with isotopically different water masses (Clark & Fritz 1997). Separating sources of mixed natural waters without isotope data is practically impossible, and isotope tracers are therefore a significant addition to the selection of more traditional hydrogeological methods.

The Laboratory for Isotope Geology has analyzed oxygen and hydrogen isotopes in water samples on a routine basis since 1995, and the isotopic composition of inorganic carbon and strontium dissolved in water since 2000. The initial focus of the study was to generate a background data set on the isotopic composition of surficial waters, here containing mostly precipitation and modern groundwater. During 1995 to 2005, the first detailed records on spatial and annual variability in the isotopic composition of precipitation and groundwaters in Finland were generated (Backman et al. 1999, Tarvainen et al. 2001, Kortelainen & Karhu 2004, Kortelainen & Karhu 2006, Kortelainen 2007, Kortelainen & Karhu 2009, Kortelainen 2009). The systematic acquisition of oxygen and hydrogen isotopes in precipitation provided a framework for better understanding aquifer recharge processes, the dimensions of hydrological systems and the responses of recharge to temporal and seasonal climatic variations and water-mineral interactions. The active regional network of isotopes in Finnish precipitation has gradually been established since 1999 at three monitoring stations in Espoo (southern Finland), Kuopio (central eastern Finland) and Rovaniemi (northern Finland). This continuous research activity is related to the Global Network of Isotopes in Precipitation (GNIP) programme conducted by the International Atomic Energy Agency (IAEA) in coordination with the World Meteorological Organization (WMO). The GNIP programme has gathered isotope data on stable oxygen and hydrogen as well as the radioisotope of hydrogen, i.e. tritium, from hundreds of precipitation stations around the world since 1961 (IAEA/WMO 2006). Finnish isotope records can also be downloaded from the GNIP database. Monitoring of this kind is critical in creating the basic isotope tools for hydrogeological studies (Clark & Fritz 1997).

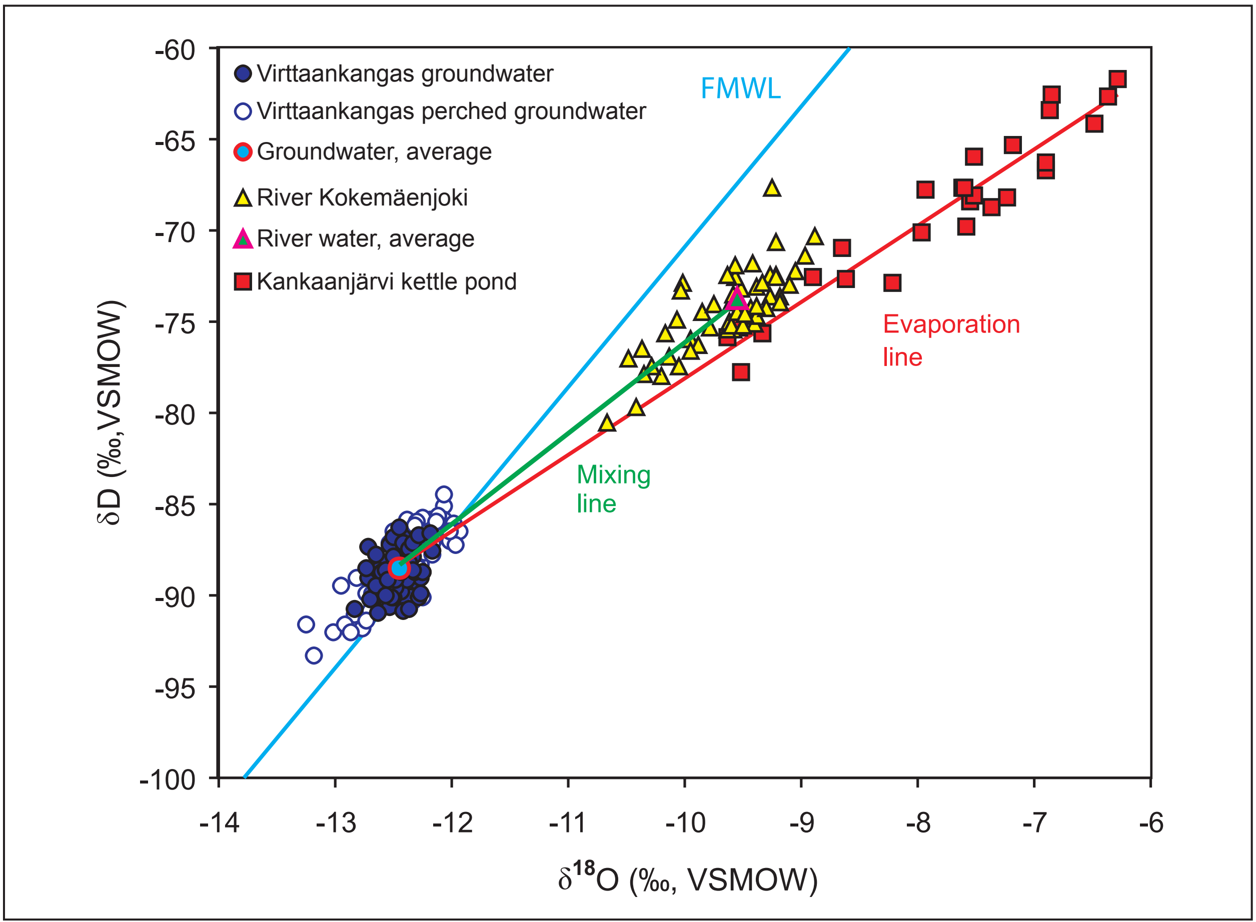

Figure 1. Isotopic composition of oxygen and hydrogen in Virttaankangas groundwater, Lake Kankaanjärvi and in Kokemäenjoki River. The groundwater is located on the Finnish meteoric water line (FMWL; blue line; Kortelainen 2007). The FMWL illustrates the linear correlation between the $\delta^{18}O$ and δD values recorded from the precipitation in Finland. The river water (yellow triangles) and the lake water (red squares) are dislocated from the FMWL. The lake water follows the local evaporation line (red line), which crosses the FMWL exactly at the mean isotopic composition of the Virttaankangas groundwater. This indicates that the Kankaanjärvi lake water originates completely from the Virttaankangas groundwater. The isotopic composition of Virttaankangas groundwater differs significantly from those of the illustrated surface waters, and mixing of them with groundwater would be easily detected from their isotope ratios. The green line is a mixing line between the long-term mean isotope values of groundwater and river water. Mixing of these two waters would settle the isotope values of the mixed water along the green line.

ISOTOPES APPLIED TO AR

Isotope "fingerprinting", based on the isotopic difference between interacting water reservoirs, has been useful in several applied studies related to water management, and especially to artificial recharge (AR). In a boreal environment such as Finland, AR is generally carried out by infiltrating water from lakes or rivers into glacigenic aquifers in order to produce naturally purified drinking water. In most studies, the traditional water isotopes, meaning oxygen and hydrogen, have been analyzed. At Tuusula Waterworks in southern Finland, for example, the isotope ratios of oxygen and hydrogen have been successfully applied to calculate mixing ratios between local groundwater and infiltrated lake water (Kortelainen & Karhu 2006). Besides the two main constituents of water (O, H), minor elements dissolved in the water such as carbon have an isotopically distinct composition in groundwater and infiltration water. Therefore, carbon can be used as an additional isotopic tracer. In boreal regions, reducing the total organic carbon (TOC) content of the infiltration water is one of the main challenges in the process of artificial recharge. In Finland, the recommended maximum level of TOC in potable water is 2 mg/L (Ministry of Social Affairs and Health 1994). Determination of the isotope ratios of dissolved inorganic carbon (DIC) and the content of inorganic and organic carbon in water has provided new information on the removal of organic matter from infiltrated water (Kortelainen & Karhu 2006, Kolehmainen et al. 2009, Kolehmainen et al. 2010). At Tuusula Waterworks, isotope methods were used for the first time to quantify the processes of organic matter removal in artificial recharge (Kortelainen

& Karhu 2006). In an optimal situation, the use of isotope methods would already be initiated in the planning stage as a basic part of an AR scheme. In order to understand the response of a natural groundwater system to artificial recharge and the mixing of infiltrated water with local groundwater, the geochemical baseline and isotopic characteristics of the aquifer should be monitored over a sufficiently long time period so that all normal variation in isotopes and the geochemistry of the groundwater are known. For example, in the Virttaankangas area, operated by Turku Region Water Ltd., the isotopic composition of groundwater has been monitored since 2000 (Kortelainen & Gustavsson 2004, Kortelainen & Karhu 2009). Isotopic applications in AR have had an essential role in the planning of infiltration and monitoring of the active water plant by predicting water pathways and mixing and the responses of aquifer geochemistry to recharge, as well as assisting in the calibration of groundwater flow model (Artimo et al. 2007, Artimo et al. 2008).

PRESENT AND FUTURE

New isotope approaches for hydrogeology are about to be tested at the facilities of the Finnish Isotope Geology Laboratory (SIGL). High performance ion chromatography (HPIC) techniques consisting of an automated sampler, an ion chromatograph and a fraction collector will enable the automatic separation of several selected chemical elements for isotopic analysis from liquid samples. Separation methods for cations such as lithium, magnesium, calcium and strontium are currently under development (Figure 2). Ion fractions will be analysed using the SIGL MC-ICP-MS instrument. Besides the aforementioned elements, the isotope ratios of lead and uranium, for example, can be measured from water samples with little or no sample preparation. Most importantly, the automated separation methods will significantly reduce the throughput time of samples. In contrast to oxygen and hydrogen isotopes, representing water itself, the isotopic differences of these dissolved components in water may be inherited from organic and inorganic atmospheric, industrial and anthropogenic sources, together with weathering processes during the interaction between minerals, soil and water (e.g. Clark & Fritz 1997, Kendall & McDonnell 1998, Kendall & Doctor 2003, Blum & Erel 2003). Isotopic differences may even exist within an aquifer, as illustrated in Figure 3 by the spread in the Sr isotopic composition, and these methods can therefore be used to reconstruct the hydrogeochemistry of a groundwater formation. Traditional isotope techniques such as those based on isotopes of oxygen, hydrogen and carbon will always play an essential role in water management studies, as they can be used to assess water pathways and provide a hydrogeochemical picture of a water reservoir. However, a revolution is also taking place in analysis using these traditional environmental isotopes. A completely new technique based on cavity ring-down spectroscopy (CRDS) will at least partially replace traditional mass spectrometric techniques (e.g. Brand et al. 2009, Newman et al. 2009), and most importantly, these new methods will significantly reduce the investment costs and thereby lower analytical costs.

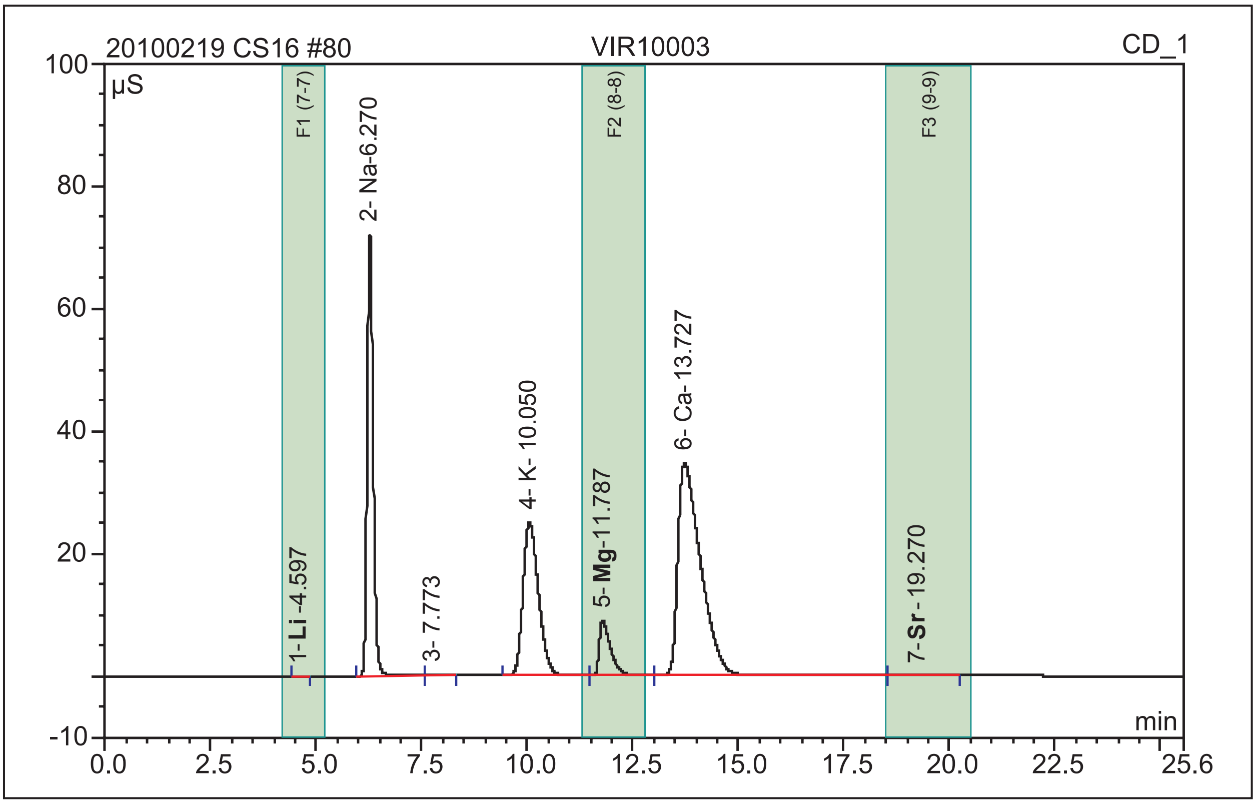

Figure 2. A cation chromatogram of Kokemäenjoki river water determined using GTK's ion chromatograph (Dionex, IC-3000). The collected ion fractions, including Li, Mg and Sr, are lined with green rectangles. The duration of the run was 25 minutes (horizontal axis) and the intensity of the detected ions was measured as electrical conductivity (µS; vertical axis). The total area of the peaks defines the concentration of the ions illustrated in the graph.

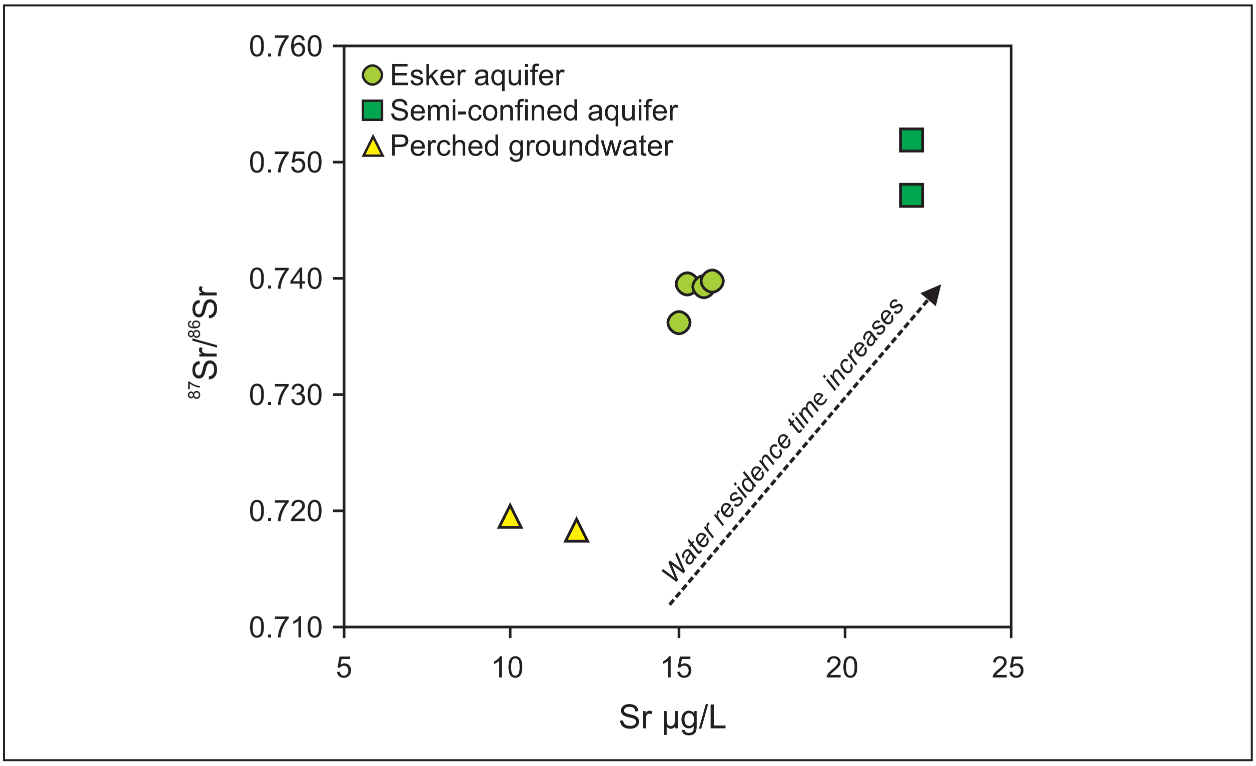

Figure 3. Variation in the strontium isotopic ratios and Sr concentrations in the Virttaankangas groundwater formation. The esker aquifer is the main productive aquifer, which is clearly differentiated from the perched groundwater and semi-confined aquifer by its Sr composition. Modified from Kortelainen & Karhu 2009.

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GEOSCIENCES SUPPORTING CLIMATE CHANGE ADAPTATION IN THE BALTIC SEA REGION

by
Johannes Klein and Philipp Schmidt-Thomé*

Klein, J. & Schmidt-Thomé, P. 2011. Geosciences supporting climate change adaptation in the Baltic Sea region. *Geological Survey of Finland, Special Paper 49,* 285–292, 3 figures.

Geosciences are rapidly developing sciences seeking to find solutions for important questions concerning societal needs and demands. Because of its deep understanding of climate changes during the Earth's history, geology can provide important contributions to the questions arising around the capacities and necessities of our society to adapt to both the current and potential future changes in the climate.

With two examples from Finland, this article illustrates that research on climate change impacts can contribute to a better capability to deal with the impacts of climate change at those levels where concrete adaptation measures have to be implemented and are visible and tangible for the population. The first example shows how the city of Kokkola utilized and integrated climate changes scenarios into local planning. The second example presents groundwater modelling and climate change scenarios for the adaptation of the water supply in Hanko.

Keywords (GeoRef Thesaurus, AGI): environmental management, climate change, environmental effects, sea-level changes, regional planning, ground water, water supply, Kokkola, Hanko, Finland

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INTRODUCTION

Geosciences are rapidly developing sciences seeking to find solutions for important questions concerning societal needs and demands. As geology is a descriptive science, it bases its argumentation on and draws its conclusions from empirical evidence, observations from nature, measurements and computer modelling. Geology is not entirely an exact science like physics, which can definitively and scientifically test all postulated theories. It is a science developed during the historical period of enlightenment that was demand driven from the start (mining) and continues to be so as an applied natural science.

One of the latest emerging societal demands for reliable scientific answers is the topic of climate change. Geology has been researching the causes and extent of climatic changes during the Earth's history for a long time, but the current focus is on the potential future impacts of climate change. Although the international focus on the causes, future development and potential mitigation of recent climate change is very much in the hands of meteorological sciences, the field of adapting to climate change has only recently been evolving strongly (e.g. Commission of the European Communities 2009a). Because of its deep understanding of climate changes in the Earth's history, geology can deliver important contributions to the questions arising around the capacities and necessities of our society to adapt to both the current and potential future changes in the climate.

BACKGROUND TO CLIMATE CHANGE IMPACT RESEARCH

The concentration of large parts of the population and many larger cities in the coastal areas of the Baltic Sea region makes these areas sensitive to climate change impacts, such as a rise in the sea level and subsequent changes in flood patterns (riverine and coastal), as well as impacts on water availability and quality (both surface and ground water) (Hilpert et al. 2007).

Under present climatic conditions and due to postglacial land uplift and subsidence, many coastlines in the southern Baltic Sea already face coastal retreat. This retreat in several southern Baltic Sea shores is not only based on land subsidence but is also locally favoured by the geology (Quaternary glacial deposits and sediments). The northern Baltic Sea shorelines mainly consist of crystalline bedrock (Kallio 2006). With the projected sea level rise, this retreat may intensify. Additionally, potential changes in overall precipitation and temperature patterns as well as extreme precipitation events will put further pressure on urban areas. The public water supply of many coastal towns is currently dependent on shallow groundwater aquifers that are vulnerable and sensitive to changes in precipitation patterns and the sea level. The intrusion of brackish water can affect the water quality of water supply facilities in coastal aquifers and requires measures such as the relocation of wells or adjustment of the water pumping rate (Tarvainen et al. 2011).

Changes in the hydrological cycle and higher temperatures (of water and air) caused by climate change could lead to shifts in the annual groundwater cycle and runoff patterns in rivers and catchment areas (Graham 2004, Meier et al. 2006). Most climate change scenarios project higher temperatures and higher precipitation as a yearly average, but especially in winter, which will lead to changing snow cover and flood patterns. In the Baltic Sea region, possibly higher evapotranspiration and a shift in the highest runoff period in catchment areas to an earlier time of the year (caused by less snow and more rain in winter) could contribute to droughts in the summer (Ruosteenoja et al. 2005). Important aquifers may also be affected by the mobilization of contaminants caused by a higher variability in the level of groundwater.

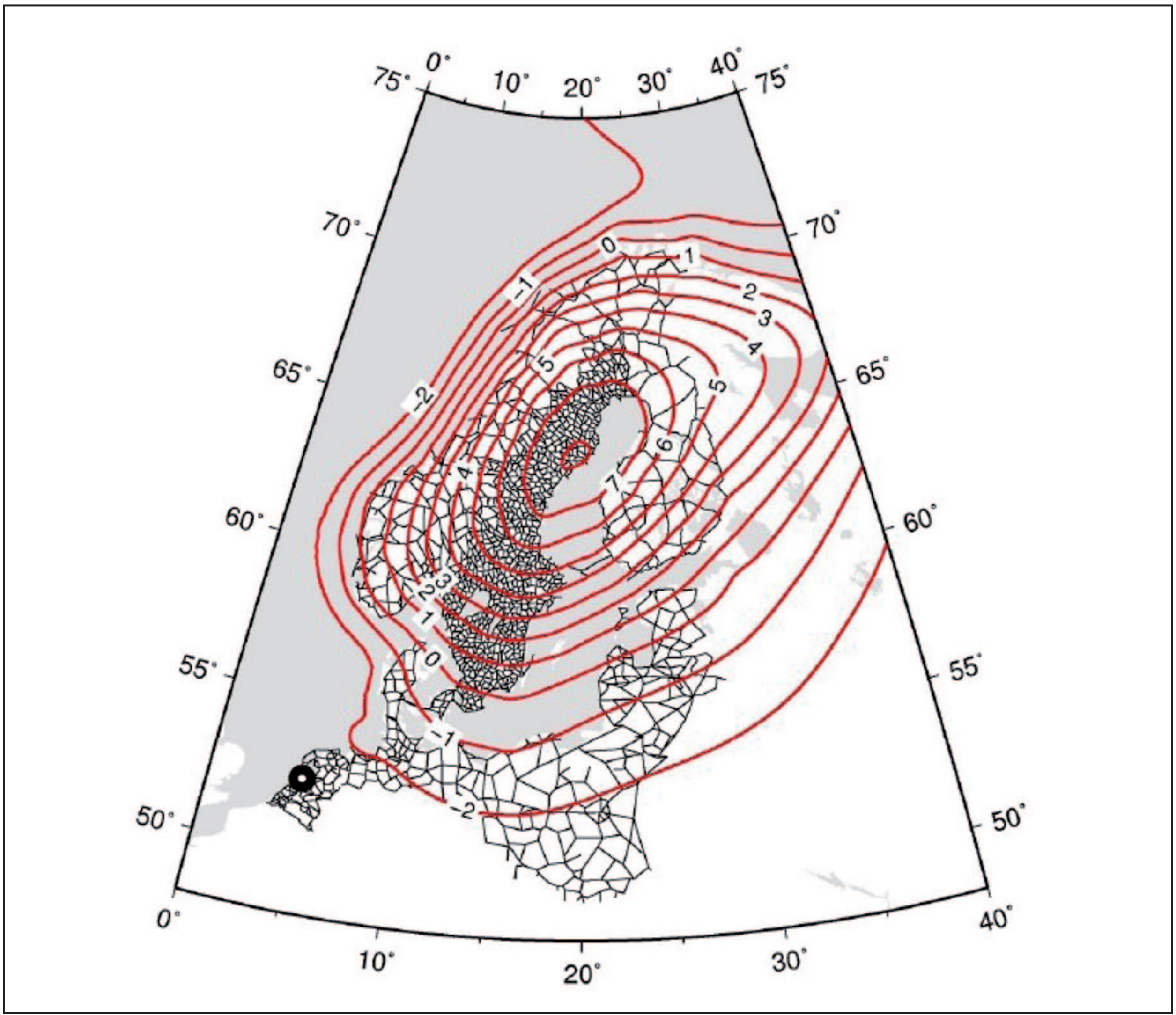

Figure 1. Postglacial land uplift and subsidence in the Baltic Sea region. Source: JUHTA 2008.

AIMS OF CLIMATE CHANGE IMPACT RESEARCH

The aim of applied research into the impacts of climate change is to achieve a better capability to deal with the impacts of climate change at those levels where concrete adaptation measures have to be implemented and are visible and tangible for the population. Assessment of climate change impacts on water bodies and the drinking water supply can contribute to the development of a sustainable water supply, safeguarding quality and quantity. Special emphasis has been placed on adaptation to sea level rise and the changing frequency and magnitude of floods facing the cities and regions located on the Baltic coast.

The Geological Survey of Finland is the lead partner of the project "Climate Change: Impacts, Costs and Adaptation in the Baltic Sea Region (BaltCICA)". The project is part-financed by the EU Baltic Sea Region Programme 2007–2013 and the partnership comprises 24 partners, including municipalities, regional authorities and research institutes. The project duration is from February 2009 to January 2012. The BaltCICA project is building on the experiences gained from the INTERREG IIIB projects "Sea level change affecting the spatial development in the Baltic Sea Region (SEAREG)" and "Developing Policies & Adaptation Strategies to Climate Change in the Baltic Sea Region (ASTRA)", in which GTK was also the lead partner. All three projects follow a logical chain of development. While SEAREG laid the basis for raising awareness of potential climate change impacts on regional development (Schmidt-Thomé 2006), ASTRA went a step further and assessed the potential impacts. The BaltCICA project is directly supporting local and regional decision makers in evaluating and implementing adaptation measures (Hilpert et al. 2007).

A study conducted within the frame of the ASTRA project revealed that the coastal municipalities and regional offices bordering the Baltic Sea are most concerned about storm events, sea level rise and water quality issues (Haanpää 2008). This has to be taken into account when performing research within the frame of regional development.

Documents on the national and EU level also reflect the need for climate impact research. In 2005, Finland published its National Strategy for Adaptation to Climate Change (Ministry of Agriculture and Forestry of Finland 2005). This states that: "Research should focus on acquiring the necessary knowledge basis on the impacts of climate change (both direct and indirect) affecting Finland." The EU White Paper on Climate Change Adaptation (Commission of the European Communities 2009a) calls for knowledge on the impacts of climate change, including socio-economic aspects and the costs and benefits of adaptation options. The availability of data to those who develop policy responses is essential.

The European Union Strategy for the Baltic Sea Region identifies adaptation to climate change as a growing challenge (Commission of the European Communities 2009b). The Baltic Sea Region Strategy's Action Plan highlights the importance of identifying impacts at local levels and ways to reduce the impacts (Commission of the European Communities 2009c).

EXAMPLES OF APPLIED RESEARCH

Kokkola

Kokkola, a medium sized town on the west coast of Finland, formed one case study of the ASTRA project. Kokkola was founded in 1620 adjacent to the Bothnian Bay (Baltic Sea). The postglacial rebound (land uplift) in this area has led to retreating shorelines, and the original city centre nowadays lies about 2.0 km from the coast. Over the longer term (~100 years), the rate of land uplift has amounted to 7 to 8 mm per year (JUHTA 2008, Vestøl 2006). However, looking more recently, land uplift has declined to approximately 5 mm per year due to sea level rise (Granberg 2000). Normal sea level variation in Kokkola is between –1.0 m to +1.5 m relative to the mean sea level. The city planning office of Kokkola was thus interested in sea level rise scenarios for the 21st century. The background is that Kokkola has experienced strong pressure to develop coastal housing. If the coastal land uplift were to continue at the present rate, the coastal areas could be easily developed, even with the lower glacial rebound effect of 5mm per year. However, what if the sea level rise and storm flood events become stronger and flood patterns change?

Kokkola participated in the ASTRA project to better understand the climate change scenarios and to evaluate how these can be integrated into local planning. The uncertainties of climate change scenarios played an especially important role in the assessments. Uncertainty in this context can be represented by two important components. The first component is epistemic uncertainty resulting from incomplete knowledge (e.g. climate sensitivity or the rate of heat uptake by the deep oceans). This uncertainty can probably be reduced over time by new knowledge or increasing computational power. The second component is stochastic uncertainty. This depends on the unknowable, such as future human behaviour. The assignment of probabilities to this kind of uncertainty can inevitably only be subjective, i.e. based on a degree of belief or expert assumptions. (Dessai et al. 2004)

Since probability calculations were not available to the city of Kokkola, and through a combination of expert opinion and the interest to be "on the safe side" from a planning perspective, the city chose to use the "high case" sea level change scenario originally developed under the SEAREG project. This scenario uses regional model results from the RCAO model driven by the ECHAM4/OPYC3 under the A2 emission scenario together with a global average sea level rise of 88 cm (Meier et al. 2006). According to these scenarios, it would be possible for the land uplift to be neutralized by sea level rise; in other words, the present coastline would not change over the 21st century. Consequently, the often-predicted increasing wind speed peaks during storm events and the increase in heavy rainfall would lead to changes in flood-prone areas. Two important locations for future housing development in Kokkola are the area of the 2011 Housing Fair and Morsiussaari Island.

The area for the housing fair to be held in 2011 was planned several years ago. Such a housing fair is an important event in Finland, as the houses built for the fair are later used for housing, which is an important asset for the investors. The housing fair in Kokkola is planned for a new housing area on the sea shore. In the course of the ASTRA project, the location of the 2011 Housing Fair was not changed, but the minimum elevation of the building ground above the mean sea level was increased by 1.0–1.2 m compared to previous plans on the seashore, and is now about 3.5 m (streets 3.0 m) above the mean sea level. In other words, the decision was taken that sea shore plots may be built on, but the lowest floor of the houses must be well above potential flood levels. The cost of each plot and house was calculated, including the artificial raising of the building ground, and the investors were willing to pay this extra cost because the demand for houses located on the sea shore is still rising.

Figure 2. Sea level rise and flood-prone areas in Kokkola under the "high case" scenario for the 2011 Housing Fair (Kallio 2006).

The second example, Morsiussaari Island, is a very popular place for summer cottages in the close vicinity of the city. The current trend in many European countries is to develop these temporary summer homes into houses that can be used all year round, and even to convert them into permanent homes. If the land continues to rise out of the sea as it has so far, such a conversion from a temporary to a permanent home would pose no problem. The interest of the land owners is certainly not only in converting the houses; the investments would also be justified by rising land and house prices. The city of Kokkola, on the other hand, carries the responsibility if land use plans are changed and natural hazards start to threaten the housing areas. Due to the scenarios used in the ASTRA project, changes to the land use plan for Morsiussari Island were put on hold until improved climate change scenarios and observed trends are analyzed. However, scenarios for sea level change are taken into account in the minimum elevation of buildings above mean sea level, e.g. when old cottages are renovated. The lowest building elevation for the newest building permits has risen to 2.5 m above the mean sea level. Thus, in renovating buildings, adaptation to sea level rise is put into practice in small steps or plot by plot.

Recommendations of the ASTRA project were also taken into account in building and city planning regulations. Several regulations are designed to offer protection from rising wind speeds, cold winds and storms on the shore. These include low houses with an optimal roof pitch against wind turbulence in yards, inner courtyards facing towards the south, plantations and fencing against cold wind directions, and also the directing of main streets crosswise to the coldest winds to avoid wind tunnel effects.

Hanko

GTK is currently the lead partner of the BaltCICA project, and carrying out two case studies in Finland. Groundwater movement is being modelled and assessed at aquifers in Tampere and Hanko.

The Hanko case study is focused on researching the impacts of climate change on a shallow groundwater formation located on the sea shore of the Baltic Sea in Southern Finland. The cape of Hanko, the southernmost tip of Finland, consists of relatively low sand and gravel deposits with an average altitude of only 13 m above sea level. It is part of the first Salppausselkä end moraine formation, the largest groundwater reservoir and gravel resource in Finland. The water supply for 10 000 inhabitants, industry and harbour areas in Hanko is entirely based on the fresh water of this formation.

The impacts of sea level changes on the groundwater can already be seen (see Tarvainen et al. 2011). Ongoing sea level fluctuation and precipitation changes have caused problems with both the quantity and quality of water in the wells of Hanko water works (Backman et al. 2007). The goal in the Hanko case study is to create a structural 3D model of the groundwater body and to model the groundwater flow. Climate change scenarios are being applied to assess the future options for the management of the water resources. The aim is to develop a backup plan safeguarding the water supply under changing climate conditions.

All relevant data for the modelling are being compiled. Data are being requested and collected from all the organizations operating in the study area: the Geological Survey of Finland, the City of Hanko, Uusimaa Regional Environment Centre, the Finnish Road Administration, the Port of Hanko, the Finnish Rail Transport Company (VR), the Finnish Defence Forces and local industries. Field studies including geophysical methods have been conducted and groundwater observation wells installed in areas where no data are available.

From April 2009 until March 2010, fluctuations in the groundwater table and groundwater quality were monitored at ten groundwater observation wells at a high temporal resolution. The three-dimensional geological and groundwater flow modelling of Hanko cape aquifer has been carried out from the geological and geophysical data, utilizing the integration of ArcGIS/ArcInfo and Groundwater Modelling Software (GMS). Figure 3 presents cross sections of the Hanko aquifer, separating the loose Quaternary layers lying on the hard crystalline bedrock.

Adaptation to climate change is still a new issue in Hanko, and few measures have been taken so far. In the BaltCICA project, Hanko together with the Geological Survey of Finland is developing a set of adaptation options. The options will be jointly assessed and compiled to form a backup plan for the water supply. The results could be utilized in similar geological formations in other regions of the Baltic Sea. The adaptation options will be discussed in a workshop and an excursion for water supply experts from the Baltic Sea region.

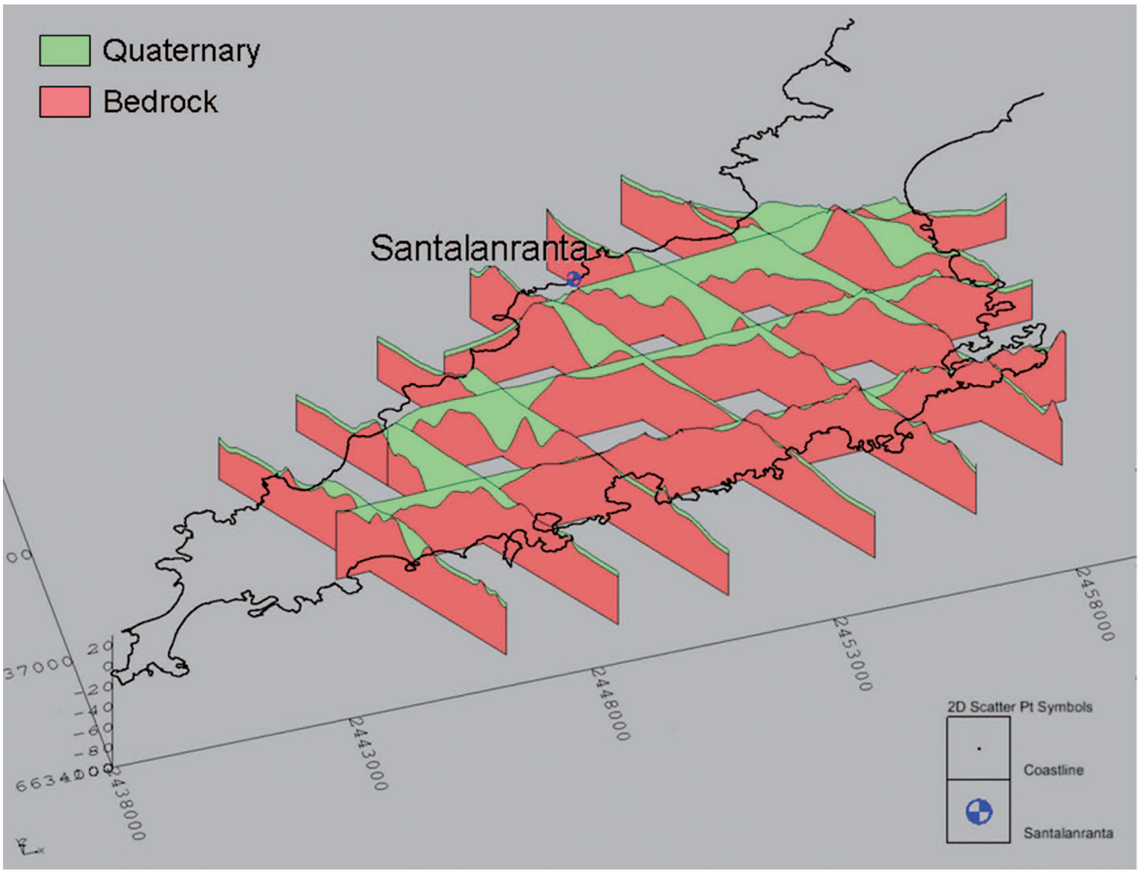

Figure 3. A solid model of Hanko aquifer showing Quaternary layers (green) lying on the crystalline bedrock (red) (Luoma 2010). At Santalanranta, in the vicinity of the wells supplying water to Hanko, the thickness of the aquifer (Quaternary layers) is about 15 m. Where the wells are located, the aquifer thickness is about 20 m.

CONCLUSIONS

As the presented examples show, geology is a modern science that is well placed to answer important emerging societal questions. Even though future climate change might not belong to the core tasks of geological research, geologists can support decision makers in analyzing climate change scenarios and the potential environmental and socio-economic impacts. Geology draws on a long history of climate (change) information; it thus enables assessments to be carried out based on experience and empirical data. Understanding the past is one key for future projections. For example, the fairly recent Pleistocene and Holocene geological changes reflect past climate change and provide references for projecting potential upcoming events. One important question rapidly arising in the cooperation with decision makers concerns the uncertainty of climate change scenarios. It is thus a great advantage for geologists to be able to draw on experiences and empirical data sets that can help to show the potential speed and impact of climatic changes. Moreover, it is clear that many current land use concepts are not reasonably adapted to the present climate, including its potential extreme events. Climate (change) adaptation must therefore begin with adaptation to the current climate to understand the nature and effects of extreme events. It has in fact often proven plausible to make overlays of past climates and evolving land use patterns to identify potential future challenges, such as changes to flood prone areas. Communication with planners has shown that multidisciplinary cooperation with geology is applicable in planning practices.

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GEOLOGICAL MODELLING OF THE BALTIC SEA AND MARINE LANDSCAPES

by
Aarno Tapio Kotilainen and Anu Marii Kaskela

Kotilainen, A. T. & Kaskela, A. M. 2011. Geological modelling of the Baltic Sea and marine landscapes. *Geological Survey of Finland, Special Paper 49*, 293–303, 5 figures.

The marine landscape maps developed for the Baltic Sea are an approach to a broad-scale, physical characterization of the marine environment. The seabed topographic features, one type of marine landscape, were developed from existing seabed substrate, bathymetry and visibility depth datasets using GIS methods. These features give a general picture of the physical complexity and the distribution of geomorphological structures of the Baltic Sea seafloor.

The marine landscape maps provide a practical, cost-effective tool for large-scale marine spatial planning. Marine landscapes can be used, for instance, in directing the use of marine resources such as marine wind farms to most suitable areas and in planning extensive nature reserve systems in order to ensure sustainable development. In addition, characterization of the marine landscapes provides information on the current environmental status and essential features of marine areas, which is needed to fulfil the demands of European Union Directives such as the Marine Strategy Directive.

Keywords (Georef Thesaurus, AGI): marine environment, submarine environment, marine landscapes, ocean floors, topography, marine sediments, models, marine geology maps, Baltic Sea

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INTRODUCTION

Almost half of the Earth's population lives within 200 km of a coastline (Creel 2003). The rapidly growing population and increased activities in coastal and marine areas have enhanced the use of the seas and seafloor worldwide. Such activities include fisheries, shipping, dredging, oil and gas exploitation, and more recently offshore wind farms and aquaculture. The latest studies indicate that at present more than 40% of the world's oceans are heavily affected by human activities (Halpern et al. 2008). This deterioration is also apparent in the Baltic Sea, a European inland sea and one of the world's largest brackish water areas (Figure 1). In addition, future climate change is likely to affect the marine environment. It has been estimated that the predicted climate warming could increase sea surface temperatures and winter precipitation in the Baltic Sea area, as well as reduce the length of the ice season in the Baltic Sea. Furthermore, changes in hydrography and biogeochemical processes could affect the whole Baltic Sea ecosystem (HELCOM 2007, Dippner et al. 2008).

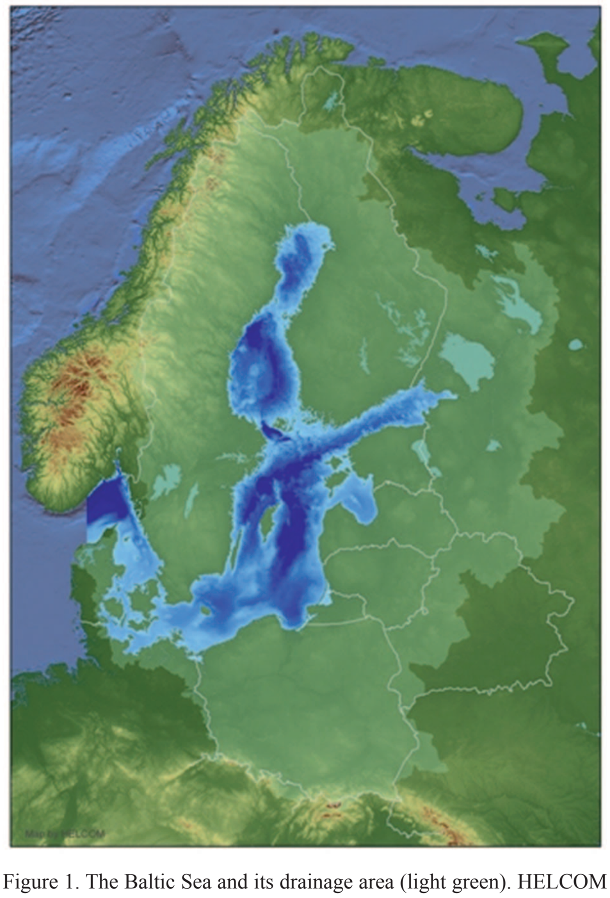

Figure 1. The Baltic Sea and its drainage area (light green). HELCOM map. The Baltic Sea is one of the largest epicontinental seas.

Increased activities in marine areas have led to various use conflicts in the marine environment. Massive constructions such as offshore wind farms, harbours and the North European Gas Pipeline from Russia to Germany through the Baltic Sea require an efficient transnational approach to management. This is a major challenge for successful marine spatial planning. To ensure the sustainable use of marine resources and health of the sea, ecosystem-based management is needed (e.g. Kappel, C. (lead author), 2006). Ecosystem-based management is an efficient science-based method that can be used in marine spatial planning. To properly implement these management tools for whole sea areas, however, a large amount of multidisciplinary information on the marine environment is needed. The Baltic Sea and its seafloor have been studied for decades, but information on the state and distribution of geo- and biodiversity is still scattered and insufficient in many places. In Finnish marine areas, including the Exclusive Economic Zone, less than 20% of seafloor geology is well known. Existing data, abiotic and biotic, is not adequate for planning and implementing effective management solutions for the sustainable use of marine resources and protection of the Baltic Sea's unique nature. Due to increased activities in marine and coastal areas, this lack of information is problematic. The urgent need for extensive marine information as well as common ocean management has been acknowledged in several national (e.g. the Baltic Sea Protection Programme) and international connections (EC Directives, HELCOM recommendations and related policy documents).

Another challenge is that the existing national and international data are very diverse in a multinational region such as the Baltic Sea region. Marine spatial data have been derived using different field techniques during the past decades (Al-Hamdani et al. 2007). Terminology and classifications also vary, since 10 separate circum-Baltic nations (Norway included) have interpreted their own data (e.g. seabed sediment) according to different national classification schemes. Harmonization of national categories into one classification scheme is essential for interoperability. International standards are needed for data collection and management. The importance of international standards for the harmonization of spatial data sets has been acknowledged in several international connections (e.g. the INSPIRE Directive). In fact, the EU has encouraged projects that seek to collate and combine existing marine datasets into uniform data layers.

Modelling is a valuable tool when the available data are limited. Biological data, in particular, often only cover small areas. Modelling is a cost-effective method that enables the data coverage area to be extended, e.g. by interpolating data on the basis of existing data points. If researchers use their expertise on the interaction between the physical and ecological environment, they can create models that characterize the marine environment a whole. This type of data serves ecosystem-based management and marine spatial planning.

MATERIAL AND METHODS

Marine landscape approach

Marine landscape (seascape) approach is a broad-scale physical characterization of the marine environment that also has ecological relevance (Roff & Taylor 2000). The approach is based on the fact that geophysical (e.g. seafloor geology) and hydrographical (e.g. depth) parameters of the sea play an important role in determining the distribution of marine life. They provide a cost-effective tool for marine spatial planning by describing large marine areas where biological data are often sparse. The marine landscape approach originates from Canadian sea areas where it was developed for marine spatial planning purposes (Roff & Taylor 2000). The approach has since also been used in the Irish Sea (Golding et al. 2004), UK seas (Connor et al. 2006), Norwegian Sea (Dolan et al. 2009, Thorsnes et al. 2009), Australian sea areas (Whiteway et al. 2007, Harris et al. 2008) and the Baltic Sea (Al-Hamdani et al. 2007, Al-Hamdani & Reker 2007, Kaskela et al. in review). The Geological Survey of Finland (GTK) has contributed to the development of the marine landscape approach in the Baltic Sea in several international and national projects such as BALANCE (Al-Hamdani et al. 2007, Al-Hamdani & Reker 2007, Kaskela et al. in review) and VALKO (Kotilainen et al. 2009).

Using the current marine landscape approach it has been possible to identify different types of marine landscapes such as coastal physiographic features, benthic marine landscapes and seabed topographic features (Vincent et al. 2004, Al-Hamdani & Reker 2007), which each describe different aspects of the seafloor. In this paper we focus on seabed topographic features of the Baltic Sea, as described in more detail by Kaskela et al. (in review). Seabed topographic features describe the geomorphological differences and structures of the seafloor. The approach described here was developed in the EU-funded BALANCE project (Al-Hamdani et al. 2007, Al-Hamdani & Reker 2007, Kaskela et al. in review).

Data collation and harmonization

Seafloor topographic features were identified using GIS analysis and geospatial modelling of existing bathymetry, visibility depth and seabed substrate datasets. Available bathymetric and seabed substrate data (e.g. maps) were collated from various institutes around the Baltic Sea in the BALANCE project. As the datasets originated from different sources and were in different formats, the collation and harmonization of the data was very challenging and time consuming (Al-Hamdani & Reker 2007). The datasets were reprojected to UTM34N and rescaled to 200 m raster grids in ArcGIS in order to ensure transnational coherence. However, it is noteworthy that the grid size used does not refer to, and not increase the resolution of the original input dataset; thus, the level of accuracy and confidence varies within datasets.

The sediment composition of the seafloor surface influences the biogeographical distribution of species (e.g. Whitlach 1981, Degraer et al. 2008, Post 2008). Basically, benthic species live either on top of the seafloor surface or within surface sediment. The surface material composition determines whether organisms are able to grow roots or burrow into the sediment. As a consequence, organisms living on marine rock surfaces differ from those living on mud surfaces (Beaman et al. 2005, Beaman & Harris 2007, Williams & Bax 2001). The Baltic Sea sediment map includes five substrate classes that were possible to translate from existing (national) substrate classification systems (Figure 2). The surface sediment classes are:

1) Bedrock (crystalline & sedimentary, bedrock covered with boulders).
2) Hard bottom composite, including complex, patchy hard surface and coarse sand (sometimes also clay to boulders).
3) Sand, including fine to coarse sand (with gravel exposures).
4) Hard clay, sometimes/often/possibly exposed or covered with a thin layer of sand/gravel.
5) Mud, including gyttja-clay to gyttja-silt.

Water depth is an important factor for marine biota. The amount of available light influences and structures the biological communities in the marine environment. Light is the driving force behind primary production by providing energy for photosynthesis. The depth of the photic zone, or euphotic zone, is often defined as the depth where 1% of the sunlight (of that at the sea surface) is available for photosynthesis (e.g. Lobban & Harrisson 1997, Nielsen et al. 2002). A value that was calculated by multiplying the measured Secchi depths (that is visibility depth, a measure of water transparency and clarity) by a factor of 1.9 (Al-Hamdani et al. 2007) was used in the present work. Based on the calculated irradiation depth, the photic zone was split into two intervals, the euphotic zone and the non-photic zone. These zones reflect the significant ecological difference between the shallow water environment (euphotic zone) where primary production takes place, and the deeper waters (non-photic zone) where species and biomass are dominated by fauna and bacteria (Al-Hamdani et al. 2007).

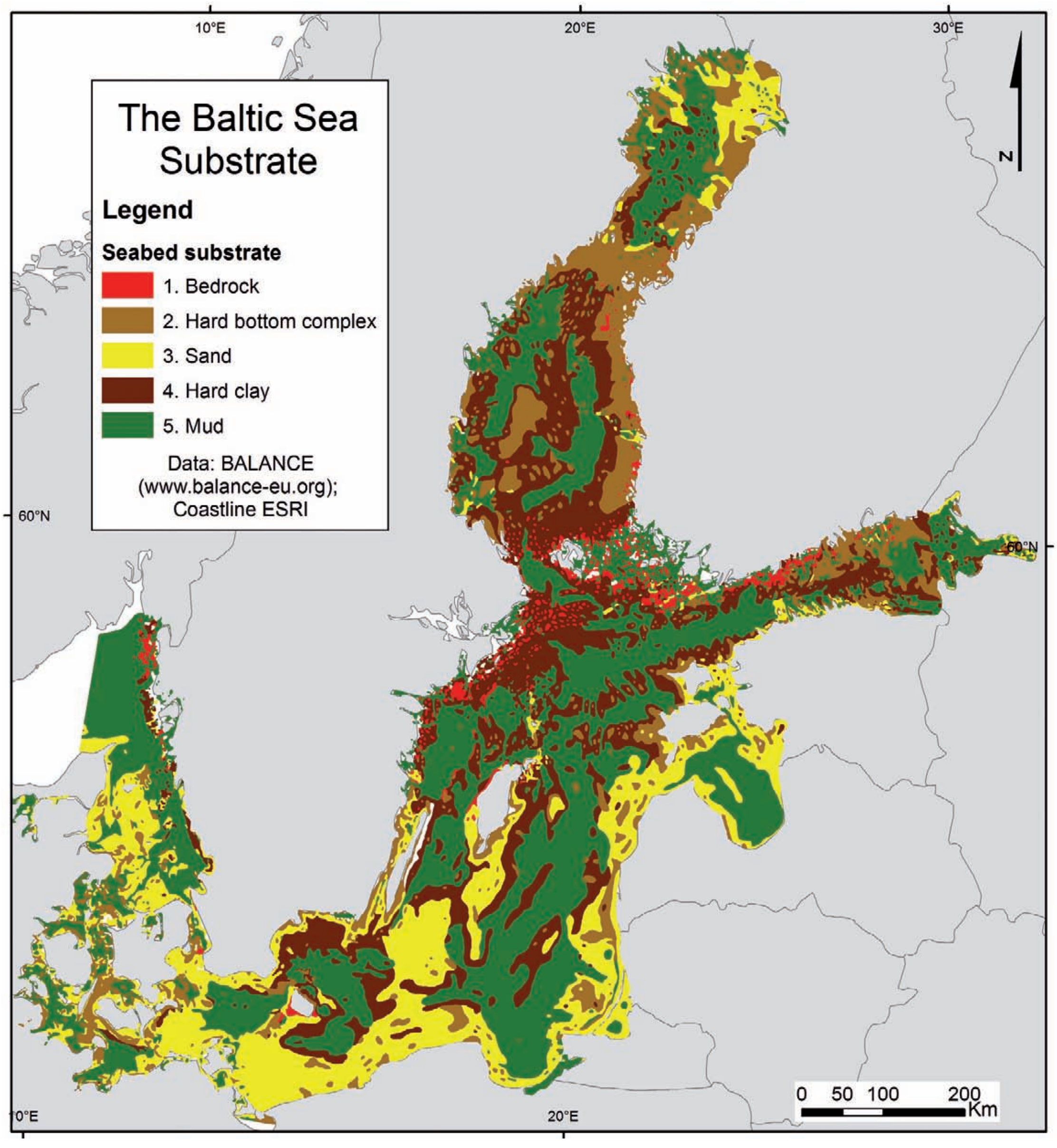

Figure 2. Substrate map of the Baltic Sea seabed. The map was collated and harmonised from substrate maps produced by institutes around the Baltic Sea in the BALANCE project.

Modelling of seabed topographic features

GIS modelling enables numerical and transparent analysis of the features that are also easily reproduced. It also ensures comparability of the features between regions. Seabed structures were modelled from the bathymetric data on the basis of relief/differences in heights using the ArcGIS extension Benthic Terrain Modeller (BTM). The BTM tool calculates a Bathymetric Position Index (BPI) from the bathymetric data (Lundblad et al. 2006). The tool was originally based on the Topographic Position Index (TPI) (Weiss 2001), but has been modified for the seafloor conditions (e.g. Wilson et al. 2007). The BPI is a measure obtained by comparing a referenced elevation of a cell to the mean elevation of the surrounding cells included within an annulus or ring of a selected specific diameter.

The slope of the seafloor was calculated using the ArcGIS Slope function. This calculates the maximum rate of change between each cell and its neighbours. Kaskela et al. (in review) classified Baltic Sea basin slope data into three classes: < 1% (flat), 1–4% (moderate) and >4% (steep). The classification of BPI-standardized values and the slope into BPI structures was modified and simplified from Lundblad et al. (2006). As a result, five BPI structures were generated: narrow depressions, basins, crests, flats and slopes. The BTM and BPI are valuable tools for defining topographic features, as the BTM provides much more information on seabed features than the bathymetric data alone, or even the bathymetric and slope data combined (see Figure 3).

The BPI structures (Lundblad et al. 2006) were combined with the substrate data and the photic zones (the euphotic and non-photic zones) in order to identify topographic features of the seabed. That was done using the ArcGIS Raster calculator tool by adding grid values. The definitions of current seabed topographic features are mainly adopted from "The Standardization of the Undersea Feature Names" (International Hydrographic Organization, 2001). For some seabed topographic features (such as basins, plains), substrates were combined into mud and clay substrate as well as coarse substrate (hard clay, sand, and complex) types in order to reduce the number of resulting classes. For the same reason, bedrock was also included in coarse substrates, although it provides a unique environment for biota (e.g. bedrock reefs). The identified seabed topographic features consisted of substrates and BPI structures. Some features (mounds) were further divided on the basis of the photic zone. The features identified indicate changes in the physical environment of the sea bottom and thus probably changes in biota.

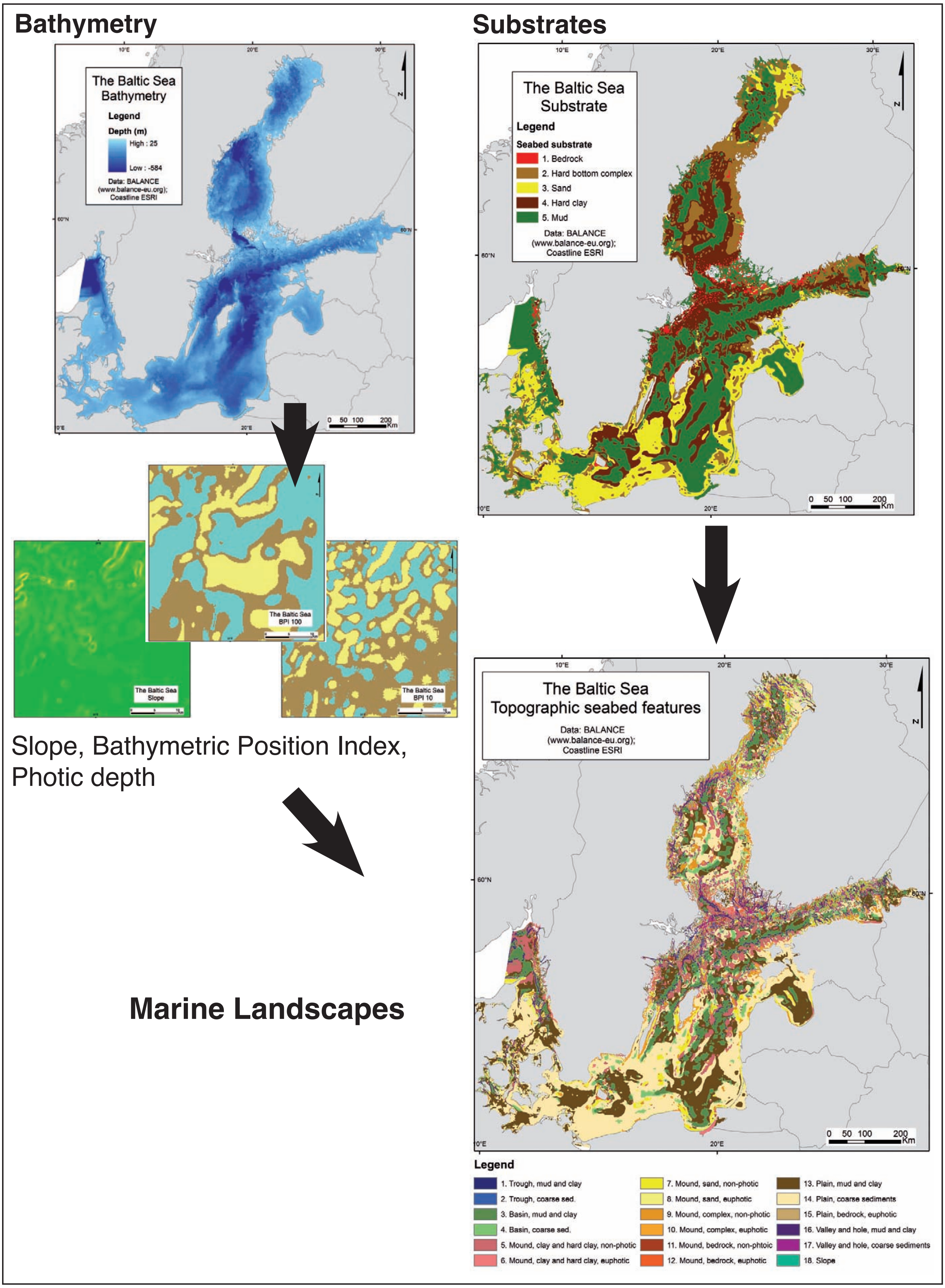

Figure 3. Topographic features of the seabed were defined through overlay analysis of the bathymetric dataset (and its derivatives), photic depth dataset (derived from visibility depth data) and the substrate dataset. The purpose was to describe the geomorphological differences and structures of the seafloor that most likely have ecological relevance. The work was done within the BALANCE project.

RESULTS AND INTERPRETATIONS

Seabed topographic features of the Baltic Sea

Kaskela et al. (in review) revealed a total of 18 unique seabed topographic features (i.e. marine landscapes) from the Baltic Sea and the Skagerrak (Figure 4). Plains with both coarse substrates and mud and clay are widespread throughout Baltic Sea. Coarse substrates plains, in particular, cover large areas. Basins, particularly with mud and clay, are also common. Plains and basins together cover two thirds of the seabed. Mud and clay areas (e.g. in basins and plains) include about one third of the seafloor. From these, mud areas represent the areas of actively ongoing sedimentation, as described by Winterhalter et al. (1981). Mounds with hard clay and clay are fairly typical throughout the Baltic Sea, but especially in the Skagerrak, the Åland Sea and the Archipelago Sea. Sand mounds are most frequent in the Kattegat, the Sound and the Belt Sea, the Gulf of Riga and in the Bothnian Bay, but still comprise less than 1/10 of the seabed in each zone. Mounds with complex sediments are characteristic features in the Kvarken area (Figure 5) in the northern Baltic Sea. Bedrock mounds are relatively typical in the Åland Sea and Archipelago Sea. Sea troughs are generally rare, but can also be found in the Åland Sea and Archipelago Sea (Kaskela et al. in review).

As the level of accuracy and confidence varied within the used datasets (bathymetry, visibility depth and seabed substrate), this reduces the confidence in the results. Thus, the features produced should be regarded as indicative of the physical environment. Future validation and confidence rating of the data layers and marine landscape maps will be necessary. In the future, the marine landscape approach will be further studied and especially adapted to Finnish marine areas.

Application of marine landscape maps

The marine landscape maps developed for the Baltic Sea are an approach to a broad-scale, physical characterization of the marine environment (Al-Hamdani et al. 2007, Al-Hamdani & Reker 2007, Kaskela et al. in revision). The topographic features of the seafloor provide, for the first time, an overall picture of the physical complexity, as well as the distribution of geomorphological structures on the Baltic Sea seafloor. A map of seafloor topographic features reveals the typical broad patterns of the seafloor for each sea area. The Kvarken area, where mounds with complex sediments are characteristic of the area, is one good example of such a distribution pattern (Figure 5).

The marine landscape maps have been used to assess the representativity of the network of marine protected areas (MPAs) within the Baltic Sea region (Andersson et al. 2008). This assessment revealed that some marine landscape types are missing or over-represented within the existing MPA network. This information can be used to evaluate whether the existing MPA network is protecting the marine diversity of the Baltic Sea region (Al-Hamdani et al. 2007). In addition, marine landscapes can be used in marine spatial planning to guide large-scale infrastructures, such as marine wind farms or gas pipelines, to suitable areas. Such information will allow us to avoid possible use conflicts of marine areas and ensure the sustainable use of marine resources.

The marine landscapes approach could be adapted as a tool for implementing various EU directives. Marine landscapes can be used: (1) as a strategic tool for planning future field surveys for mapping, e.g. Natura 2000 habitats under the EU Habitats Directive; (2) in the physical characterization of the marine environment for the implementation of the Marine Strategy Directive; and (3) as part of the typologies in the EU Water Framework Directive (Al-Hamdani et al. 2007). There is great potential to improve the marine landscape approach by adding a variety of other physical layers suggested by end-users (such as salinity and human pressures) to the model. The development of various types of marine landscape maps will provide valuable information to improve the management of the marine environment, in the Baltic Sea and in other sea areas around the world.

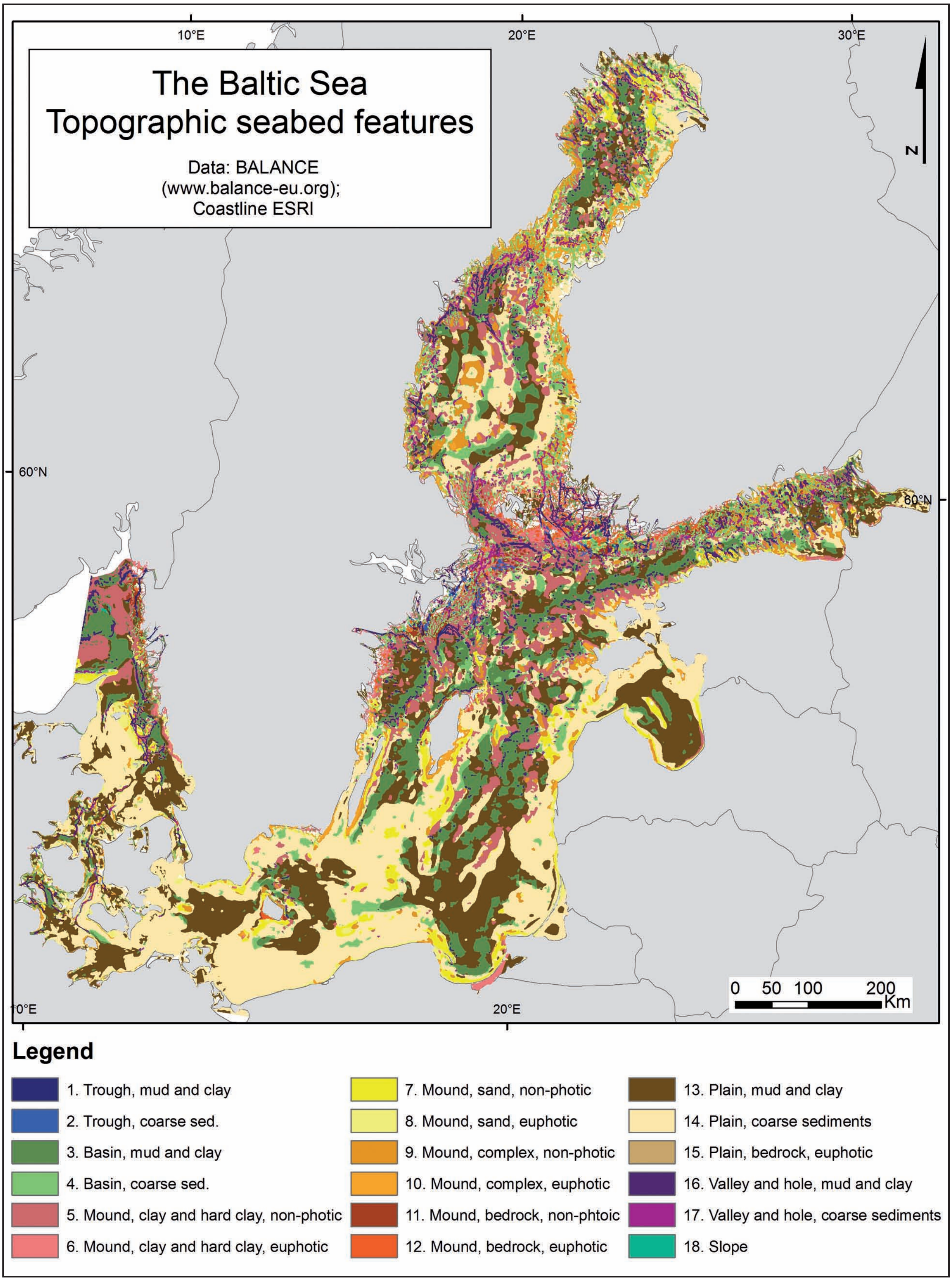

Figure 4. Topographic features of the Baltic Sea seabed (BALANCE project). Modified after Kaskela et al. (in revision). Plains and basis are widespread throughout the Baltic Sea. On average, other features such as mounds, valleys, holes and troughs are more locally characteristic.

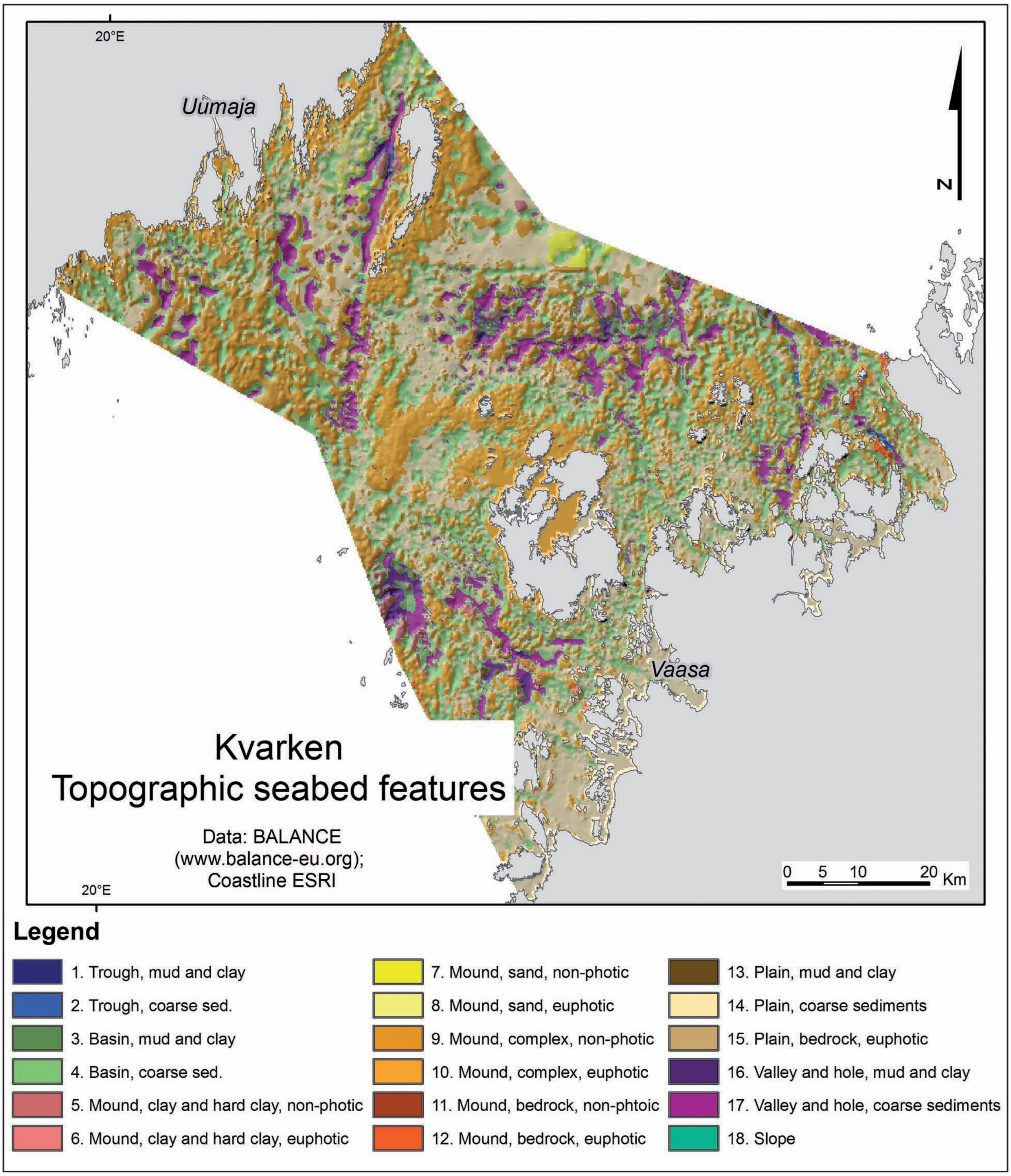

Figure 5. Seabed topographic features of the Kvarken archipelago, the northern Baltic Sea. The Kvarken archipelago is largely covered by moraines; DeGeer moraine fields are especially typical. This is also apparent from the distribution of seabed topographic features. The map reveals that complex mounds (in orange), which include moraines, are one of the most characteristic features of the area.

CONCLUSIONS

The topographic features of the seabed were determined from existing seabed substrate, visibility depth (that is Secchi depth) and bathymetric datasets using GIS methods (Kaskela et al. in review). These features enable the characterization and analysis of the physical environment of the whole Baltic Sea. They give a general picture of the physical complexity and the distribution of geomorphological structures of the Baltic Sea seafloor. The landscape maps provide a practical, cost-effective tool for large-scale marine management. Marine landscapes can be applied, for instance, in directing the use of marine resources such as marine wind parks to the most suitable areas and in planning extensive nature reserve systems in order to ensure sustainable development. They provide information on the current environmental status and essential features of marine areas, which is needed, for instance, to fulfil the demands of the EU's Marine Strategy (Directive 2008/56/EC).

Marine landscape mapping is a new approach in the Baltic Sea region. There are both needs and a potential to improve this approach in the future, which could be done by assigning confidence ratings to the landscape maps and improving the classification of data layers. Moreover, it is essential to provide sufficient practical examples on how this characterization can be applied in implementing EU legislation and the management of marine areas.

Supplementary information on the web:

The Baltic Sea Action Plan
http://www.helcom.fi/press_office/news_helcom/en_GB/BSAP_full/

European Commission Marine Strategy Framework Directive
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDF

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SEDIMENT GEOCHEMISTRY AND USE OF THE SEAFLOOR OF THE GULF OF FINLAND

by
Henry Vallius

Vallius, H. 2011. Sediment geochemistry and use of the seafloor of the gulf of Finland. *Geological Survey of Finland, Special Paper 49*, 305–313, 7 figures.

The Gulf of Finland has during the second half of the last century been under such stress as never seen before. Human activity in its catchment has introduced large amounts of harmful substances and nutrients into the water column. These substances can still be found in the offshore modern soft sediments of the Gulf of Finland. At the same time, all marine activities, except fishing, have expanded many-fold. The shift from the command economy of Soviet times to the current open market economy in Russia has increased marine activities many-fold, but at the same time it has initiated a slow recovery of the seafloor. The condition of the seafloor during the last two decades has clearly improved from the worst times in the early 1980s, but it takes a long time for the submarine environment to fully recover.

In particular, submarine works in connection with various types of new infrastructure, such as pipelines, cables, wind parks and submarine mining, are a new threat for the shallow and sensitive Gulf of Finland.

Keywords (GeoRef Thesaurus, AGI): environmental geology, marine pollution, marine sediments, geochemistry, heavy metals, human activity, Finland, Baltic Sea, Gulf of Finland

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INTRODUCTION

The Geological Survey of Finland (GTK) has a long tradition of marine geological investigations. Since the 1950s, staff from GTK have participated in numerous cruises, especially on the research vessel Aranda, and other research vessels of different nationalities, in the Baltic Sea as well as in other sea areas of the world. Dr Heikki Ignatius initiated marine geology in Finland after a stay in the United States in the mid-1950s. He was followed by Dr Boris Winterhalter, who also gained marine geological knowledge during a relatively long trip to the United States. After their pioneering work, these two initiators were followed by many other geologists specialized in marine geology. Perhaps because the Southern Finland office of the Geological Survey in Espoo, which close to the capital city, Helsinki, is located on the coast of the Gulf of Finland, the majority of the marine geological work has been conducted in the Gulf. The aim of this paper is to summarize the most recent studies on sediment geochemistry and sea floor infrastructure performed from the 1990s until today. These have included internal GTK studies and also national collaborative studies, as well as international collaborative projects such as SAMAGOL and TRANSIT, involving co-operation between GTK and the All-Russia Geological Research Institute (VSEGEI).

This paper summarizes information on the sediment chemistry of selected heavy metals and on the use of the seafloor of the Gulf of Finland, mainly through a review of earlier studies. The metal distribution is presented as composite case maps for nickel, cadmium, mercury and molybdenum, as their distribution is partly controlled by different factors. The data for the maps are from surveys carried out over a period of 7 years (2001–2008). This is a rather satisfactory time period considering the low accumulation rates of the offshore Gulf of Finland, as well as the short annual ship time and large sea areas to map for sampling, making it difficult to complete mapping of larger areas within shorter time periods. The area covered includes Finnish territorial waters and the Exclusive Economic Zone (EEZ) in the Gulf of Finland.

STUDY AREA: THE GULF OF FINLAND

The Gulf of Finland (Figure 1) is an estuarine-like, rather shallow eastward extension of the Baltic Sea. Its maximum longitudinal extent from the Hanko peninsula to the Neva Bay is some 350 km, while the width of the main gulf outside the Neva Estuary varies between 45 and 110 km. Its depth is slightly over 100 m at maximum and decreases from west to east. Surface salinity decreases from 6 psu to nearly freshwater conditions in the same direction. Because the Gulf of Finland is a direct continuation of the Baltic Proper, the saline water of the Baltic deep flows more or less freely into the Gulf, ensuring that the main hydrographical changes in the Baltic Proper are reflected there. A comparably high freshwater inflow, another important hydrographical factor, is guaranteed by several rivers draining to the Gulf. The most significant inflow is from the east, from the River Neva, which flows through the city of St Petersburg. During the last half century, the Gulf of Finland has been strongly affected by the activities of millions of inhabitants in its drainage basin. In 2002, over 12.6 million people lived in the area (Hannerz & Destouni 2006). Pollution and eutrophication have caused strong loading of harmful substances and nutrients to the seafloor sediments of this very shallow sea area (HELCOM 2007, 2009). The sediments act as reservoirs of emitted elements, recording the concentrations of metals and changes in emissions over the years.

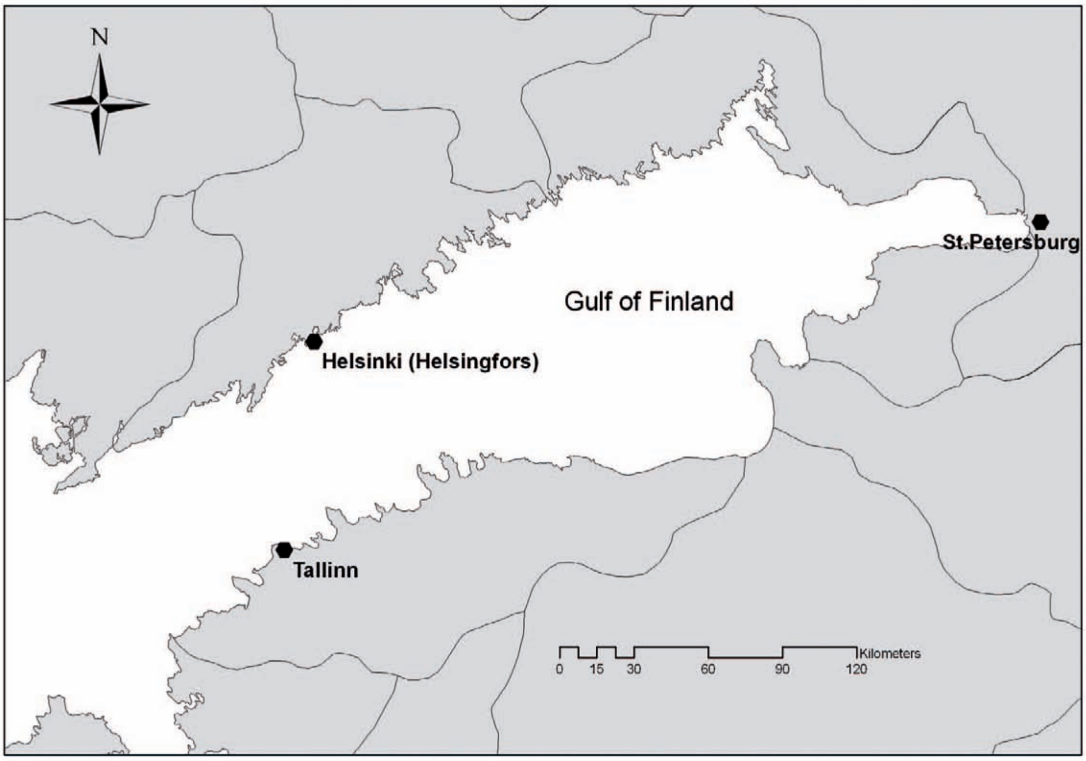

Figure 1. The Gulf of Finland with catchment areas indicated. Source: HELCOM.

EARLIER STUDIES

In several earlier studies, the distribution or accumulation of heavy metals in the Gulf of Finland has been reported (Jankovski & Pòder 1980, Ott & Jankovski 1980, Tervo & Niemistö 1989, Emelyanov 1995, Borg & Jonsson 1996, Leivuori 1996, Leivuori 1998, Vallius & Lehto 1998, Vallius & Leivuori 1999, Vallius 1999a,b, Leivuori 2000, Vallius & Leivuori 2003). The SAMAGOL project, a collaborative project between GTK and VSEGEI, St Petersburg, collected sediment information from the eastern Gulf of Finland in 2004 to 2006, which was published in a special report by GTK (Vallius 2007, Vallius et al. 2007).

Little has been published in the scientific literature on the infrastructure and the use of the sea floor in the Gulf of Finland. The TRANSIT project of GTK, a recent collaborative project between GTK and VSEGEI, St Petersburg, recognized this gap. The project mapped parts of the offshore sea floor and identified some other published data, in order to obtain a better overview of the situation of the offshore sea floor of the Gulf of Finland. This data will be presented in the final report of the TRANSIT project in 2011, but some data will be included in this paper.

CHEMISTRY OF MODERN MUDDY CLAYS

The modern soft sediments, muddy clays or muddy/silty clays, cover about one fourth of the sea floor of the Gulf of Finland (Kankaanpää et al. 1997). The distribution of such bottoms varies throughout the Gulf. Differences in basin size and shape correlate well with the number of islands and the complexity of the archipelago in the different sea areas. Small and isolated basins are usually to be found on the northwestern shores of the Gulf, where the archipelago is large and complex. The central northern coast is characterized by an almost complete lack of archipelago, which is reflected in very few sedimentation basins in the area. In the northeastern part of the Gulf, islands are scarce, rather large on average, and separated by larger distances of open sea. As a result of this, the sedimentation basins are usually larger.

The surfaces of these sedimentation basins are usually covered by a generally thin sheet of modern muddy clay with a rather high organic content. This material easily binds heavy metals and clearly reflects temporal changes in the anthropogenic input of harmful substances in the hydrosphere.

DISTRIBUTION OF NICKEL, CADMIUM, MERCURY AND MOLYBDENUM

The distribution of metals in the surface sediments is controlled by several factors, such as natural inputs, the anthropogenic load, hydrography and local physico-chemical conditions.

Natural inputs are rather strongly controlled by the chemistry of the local bedrock (Vallius 2009). Of all the heavy metals, nickel (Ni) perhaps best reflects the local natural input (Figure 2). It reflects the shale and amphibolite areas of the central coast, where these metals are present at slightly higher concentrations than in the surrounding rocks (Rasilainen et al. 2008). The soft sea floor sediments of the rapakivi area of the northeastern Gulf, on the other hand, seem to have slightly lower Ni concentrations.

Many heavy metals show clear anomalies, which are probably attributable to anthropogenic activity. Cadmium (Cd) has been found out to be present at rather high concentrations in the Gulf of Finland (Vallius 2009). Figure 3 illustrates the horizontal distribution of Cd in the study area. It shows a clear anomaly in the easternmost part of the area and some sites with slightly higher concentrations along the southern border of the Finnish EEZ (Exclusive Economic Zone). The rest of the northern Gulf seems to have lower and rather even Cd concentrations. As natural Cd concentrations are usually <0.2 mg kg^{-1} (Vallius 2007, Naturvårdsverket 1999), and only two surface samples in the study area were below this value, most sites in the Gulf of Finland have to be considered as relatively highly contaminated with Cd. Consequently, the distribution of Cd in the study area does not seem to correlate with any geological provinces, but instead with the availability of anthropogenically released Cd.

Mercury (Hg) is a special case in the eastern Gulf of Finland, as it is a significant contaminant of the sea floor off the outlets of the River Kymijoki. It has been known for decades to be present in high concentrations in the river environment, which is easily seen in the sea floor sediments outside the river outlets. The source of the Hg is release from industrial plants on the upper reaches of the river. The main contamination took place in the 1950s and 1960s, but the contaminated sediments are also a future source of Hg in the Gulf.

When looking at the map of Hg distribution in the northern Gulf of Finland (Figure 4), it can easily be verified that the River Kymijoki, with outlets between the longitudes of 26.4 degrees and 27 degrees east, is the main source of Hg. Sites near the Finnish–Russian border also show slightly higher concentrations compared to the western Gulf of Finland, which implies that these sites might have another source of Hg in the east, as the concentrations slightly increase towards the border.

Molybdenum is a metal usually present in rather low concentrations in modern sea floor sediments. Mean and median values of 2.47 mg kg^{-1} and 1.64 mg kg^{-1}, respectively, have been reported from the Gulf of Finland (Vallius 2009). The majority of the samples in the present dataset are close to those values, but there is an anomaly at the Finnish–Russian border and some strongly anomalous sites along the southern border of the Finnish EEZ (Figure 5).

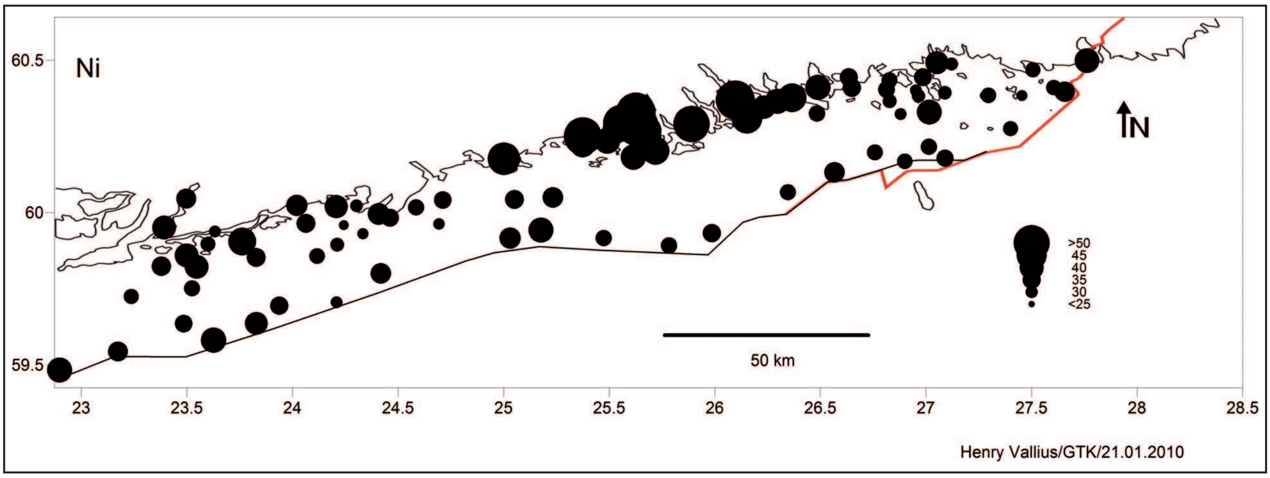

Figure 2. Circular symbol map of nickel concentrations in the soft surface sediments of the Gulf of Finland. Concentrations in mg kg-1 DW.

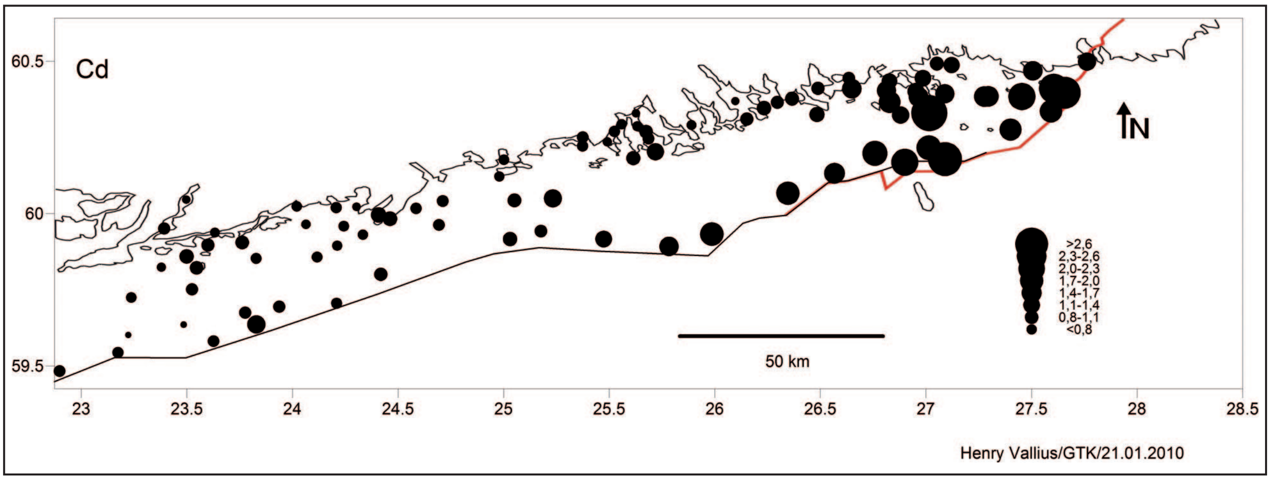

Figure 3. Circular symbol map of cadmium concentrations in the soft surface sediments of the Gulf of Finland. Concentrations in mg kg-1 DW.

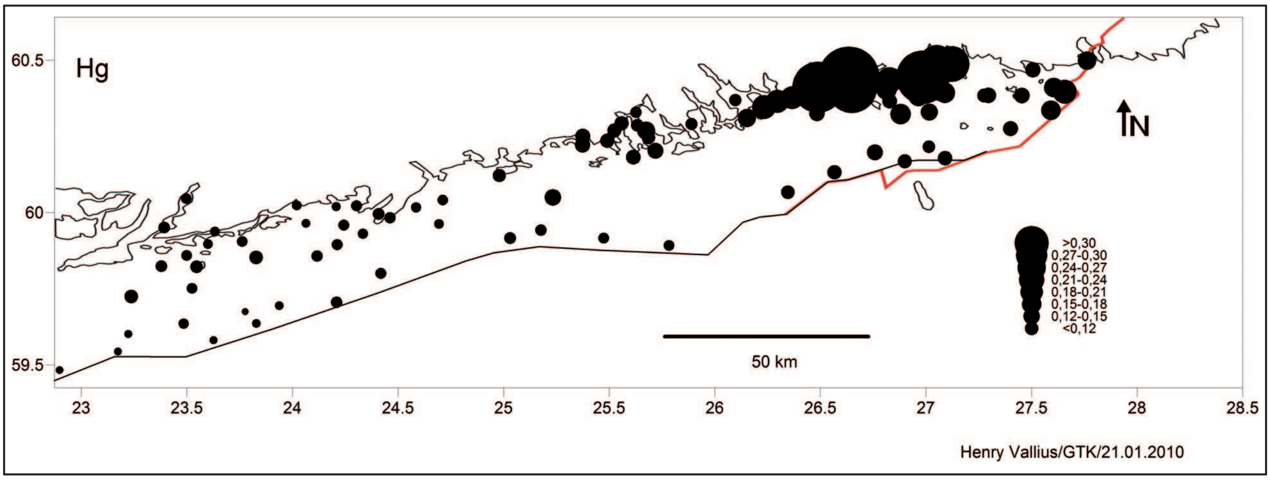

Figure 4. Circular symbol map of mercury concentrations in the soft surface sediments of the Gulf of Finland. Concentrations in mg kg-1 DW.

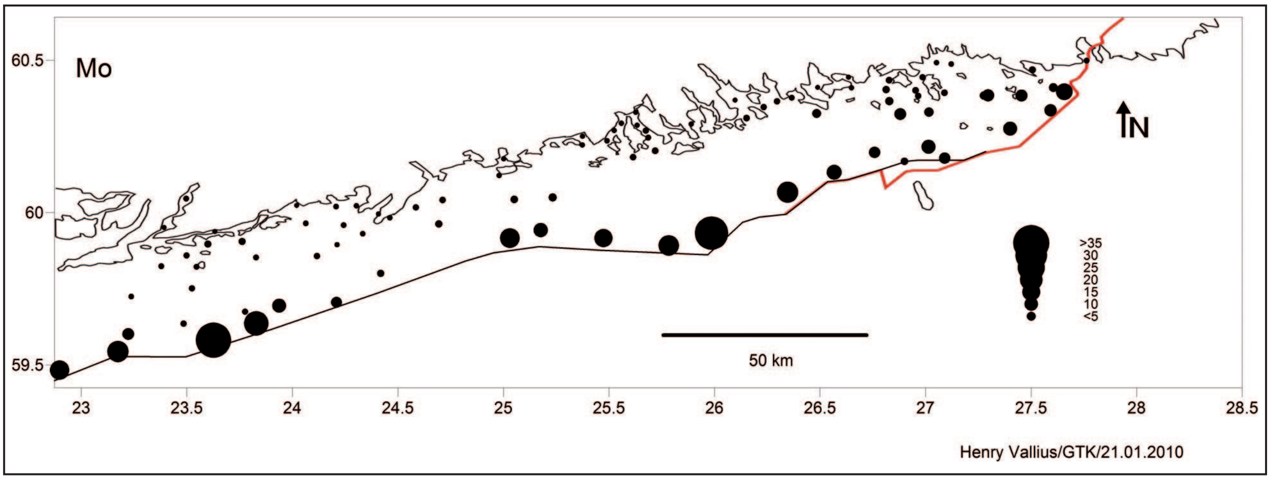

Figure 5. Circular symbol map of molybdenum concentrations in the soft surface sediments of the Gulf of Finland. Concentrations in mg kg-1 DW.

The anomaly in the east is difficult to explain, but is most certainly of anthropogenic origin, and the Mo at least partly originates in Russia. The anomalous sites along the EEZ border are very interesting and perhaps easier to explain. There is a more or less permanent halocline in the Gulf of Finland at a depth of about 60 m, which hinders water exchange from upper oxidized water layers to the bottom layers. This easily leads to oxygen depletion and hypoxic/anoxic bottoms below the halocline. Some bottoms above the halocline also suffer from hypoxia, as most bottoms in the Gulf of Finland suffer from seasonal oxygen depletion. In many cases, periods of water exchange from surface layers to these bottoms are too short to promote life. Mo is widely regarded as an anoxia indicator (Hallberg 1974). When plotting Mo concentrations of the present study against with the depth of the sampled station, an interesting pattern is seen (Figure 6). Higher levels of Mo (> 10 mg kg^{-1}) start to be found in bottom sediments at depths of 50 m or more, and the concentrations increase with depth. At the same time, no concentrations below 15 mg kg^{-1} are to be found at depths of over 80 m. As virtually all the bottoms of over 50 m depth suffer from poor oxygen conditions, and the deepest bottoms probably from permanent anoxia, the correlation between Mo content and anoxia seems to be rather clear. However, as there have been no actual oxygen measurements from these sampling sites, the relationship is still speculative. On the other hand, all samples of this study have undergone thorough macroscopic investigation to provide a description of the cores. Virtually all samples from the deep sites have shown black surfaces indicating anoxia, often reeking of hydrogen sulphide and often even covered with a white bacterial mat, indicating reducing conditions. The Pearson correlation coefficient between bottom depth and the Mo content of the 90 samples is 0.72.

Of the metals discussed here, two are strongly controlled by anthropogenic loading and sources (Cd and Hg), while Ni is controlled by the anthropogenic load but also rather strongly by the natural input. Molybdenum, on the other hand, is an element that is strongly controlled by local physico-chemical conditions, and the input source is of secondary importance.

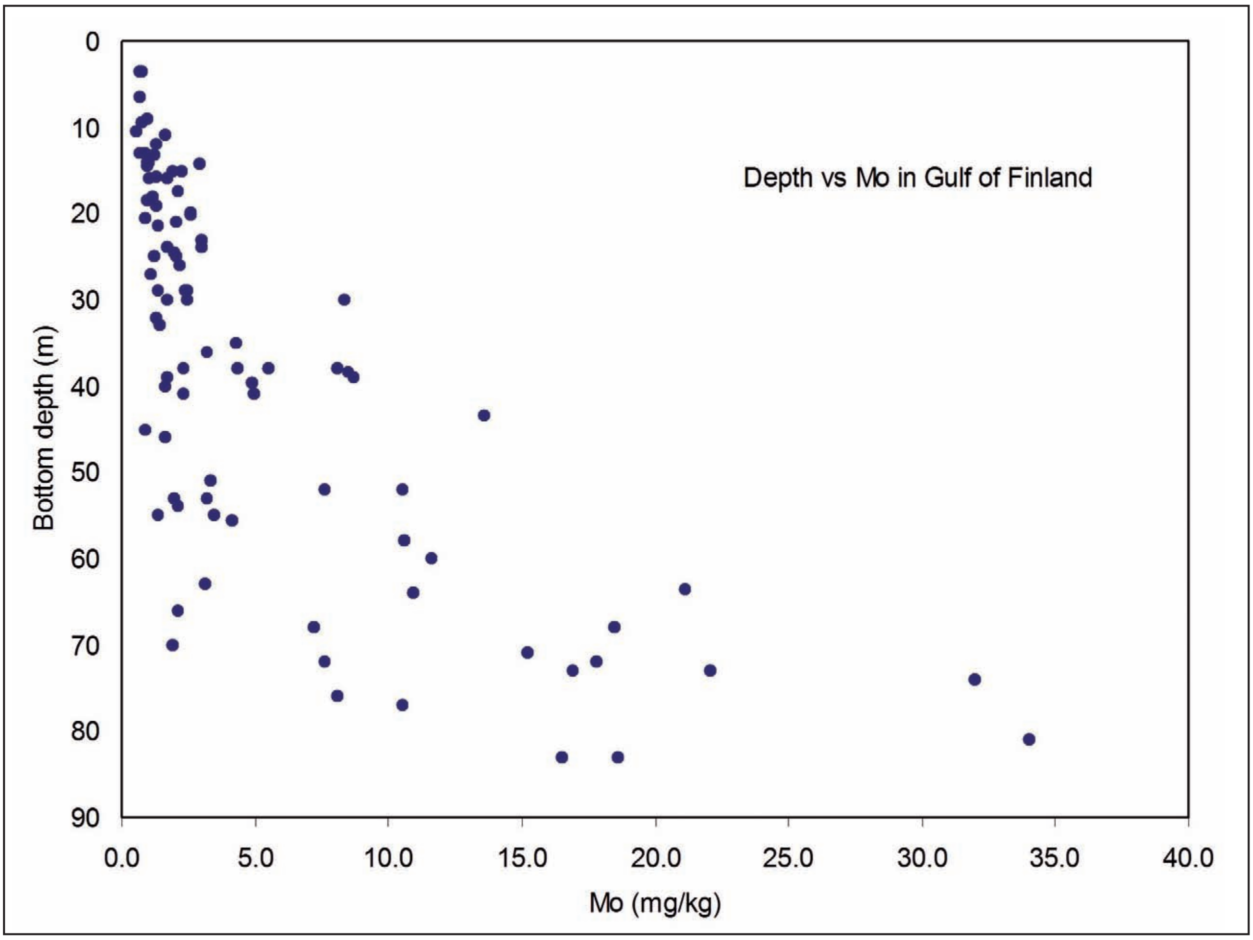

Figure 6. Molybdenum concentrations in relation to depth in the Gulf of Finland.

TEMPORAL TRENDS IN HEAVY METAL ACCUMULATION

Based on older studies (Vallius & Lehto 1998, Vallius 1999 a,b, Vallius & Leivuori 1999, Vallius et al. 2007), it is known that the concentrations of heavy metals in the soft surface sediments have declined from the highest levels of the early 1980s. There are several reasons for the decrease, but increasing environmental awareness together with improved environmental legislation has played the most important role here. A clear decrease in the concentration of Pb and Zn was already observed during the 1990s throughout the Gulf of Finland, but especially in the eastern Gulf (Vallius & Leivuori 1999). In the same data, Cd showed a rather clear decrease in the western Gulf of Finland, but an uncertain decrease in the eastern Gulf of Finland (Vallius & Leivuori 1999). However, according to the report from the SAMAGOL project, Cd concentrations seem to have been slowly decreasing in the easternmost part of Finnish territorial waters (Vallius et al. 2007). The offshore Gulf of Finland has also been rather well sampled during the ongoing TRANSIT project. Preliminary data from this project show that a similar decreasing trend is still going on and new samples (August 2009) from Russian territorial waters show that in addition to other heavy metals, Cd is also decreasing in the eastern Gulf of Finland. This is a very welcome finding from an area not so easily or often accessed. Figure 7 illustrates the vertical distribution of Cd, Pb, and Zn from a short surface core taken at station F40, 25 km ENE of the island of Seiskari (Seskar), in the outer Neva estuary just 80 km from the shores of St Petersburg. According to the chemistry data from this core, the highest concentrations are still very close to the sediment surface, at a depth of only 6–8 cm, but the surface concentrations are clearly lower.

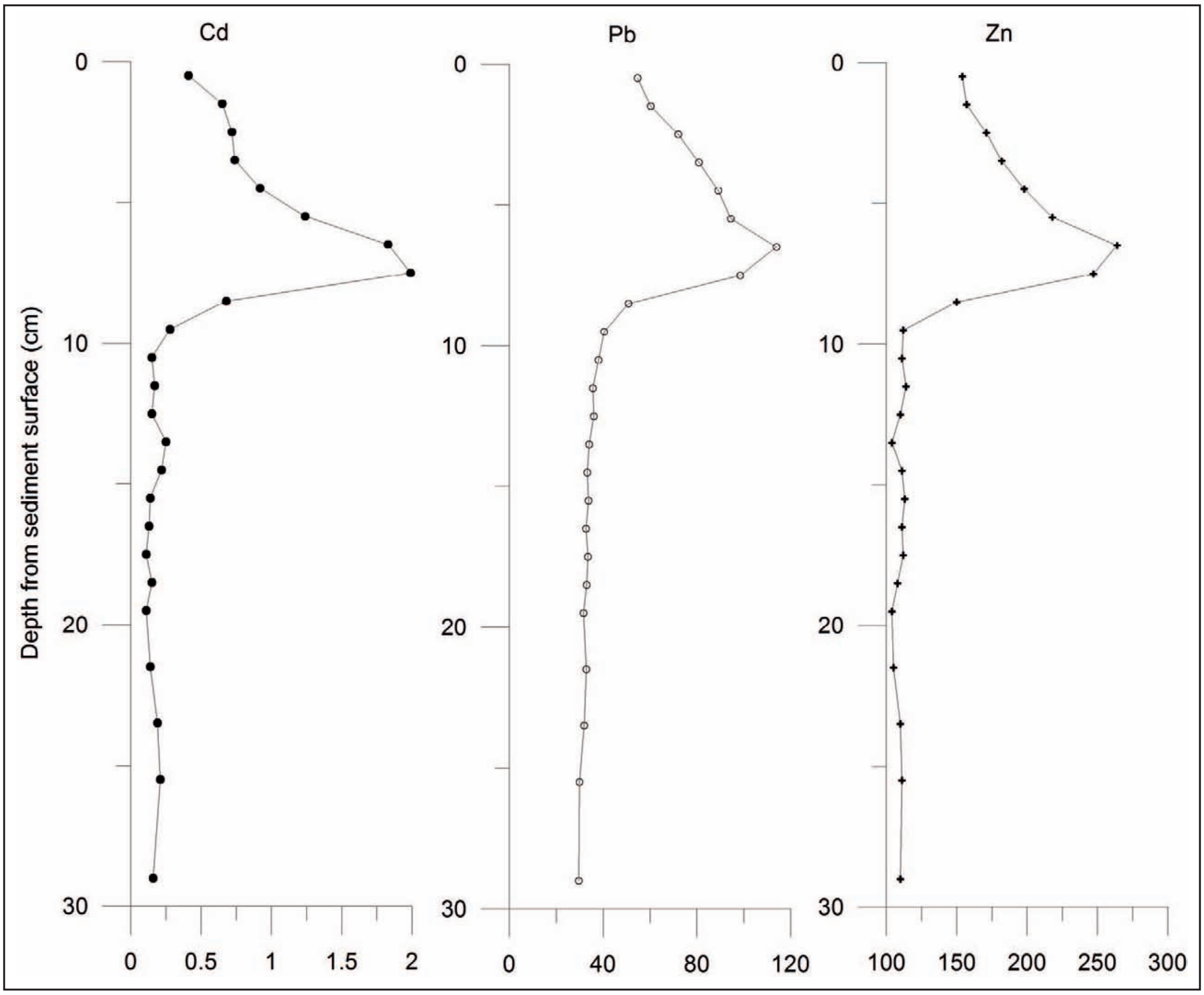

Figure 7. Vertical profiles of cadmium, lead, and zinc at site F40 in the eastern Gulf of Finland, Russian territorial waters.

INFRASTRUCTURE AND USE OF THE SEA FLOOR OF THE GULF OF FINLAND

The Gulf of Finland is currently affected by many types of human activity on a magnitude never seen before. Shipping and various offshore infrastructures are considerably increasing. During investigations of the sea floor in connection with the Nord Stream gas pipeline, an inventory of offshore infrastructure was published (Nord Stream Espoo Report 2009). In the Finnish EEZ, a total of 10 cables were found in the pipeline corridor, all of which are in use. Nine of them are communications cables and one, the Estlink between Finland and Estonia, is a power cable. In addition to these, several unidentified cables were found. Most of the cables are situated in the western Gulf of Finland, crossing the Gulf in a north–south direction.

While old activities in the Gulf of Finland, such as fishing and hunting, are declining, it is clear that the Gulf will in the future be even more exploited in the sense of infrastructure. Already today there are ongoing or planned pipeline projects, in Russia the Fe/Mn concretions are being mined and wind parks will certainly be constructed in the near future. Marine sand and gravel extraction, especially in the Russian sector, has been a threat to the marine environment, as it has caused coastal erosion especially along the northern coast of the Neva estuary. Clear signals of increased human activity also include the large harbours that have recently been built, especially in Russia, but also in Finland and Estonia. Increasing ship traffic with larger vessels and especially off-shore anchorage is affecting the sea floor. At the same time, risks of ship collisions and other marine accidents are increasing alarmingly. Any larger accident would have severe impacts on the seafloor and ecosystems of this shallow and sensitive sea.

CONCLUSIONS

The Gulf of Finland has suffered from strong human activity during the past century. Intense industrial activity has caused pollution and the accumulation of harmful substances on the seafloor. The magnitude of accumulation of such substances, as well as their concentration in the soft surface muddy clays, has recently started to decrease. This positive trend has continued for the last two or three decades. The reason is probably the better awareness of the sensitive nature of our shallow sea, followed by environmentally-friendly legislation and regulations. The shift from the Soviet command economy to the current market economy in Russia probably forced many of the worst polluting industrial plants to shut down, while many marine activities have increased considerably.

During the last two decades, marine activities in the Gulf of Finland have grown many-fold. Ship traffic is accelerating as never seen before, new harbours are being constructed in all countries surrounding the Gulf, and large infrastructure projects are being realized. At the same time, however, fishing is in decline. It seems that the Gulf of Finland of today serves mankind more as a means of transportation than as a source of food.

As the Gulf of Finland is so shallow and affected by the activities of more than 12 million people living in its catchment area, it is very important to consider all new planned activities in relation to what the sensitive sea and its ecosystems can withstand.

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GEOLOGICAL CONTROLS ON SUBARCTIC CONIFER DISTRIBUTION

by
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Sutinen, R., Närhi, P., Middleton, M., Kuoppamaa, M., Juntunen, V., Hyvönen, E., Hänninen, P., Teirilä, A., Pänttäjä, M., Neuvonen, S., Äikää, O., Piekkari, M., Timonen, M. & Sutinen, M.-L. 2011. Geological controls on subarctic conifer distribution. *Geological Survey of Finland, Special Paper 49*, 315–325, 7 figures.

Scots pine (Pinus silvestris L.) is found to be suited to well-drained tills on felsic terrains in Finnish Lapland, but an excess soil water content $\theta_v > 0.27$ cm^{3}cm^{-3} ($\varepsilon > 15$) constitutes an edaphic constraint for pine. Norway spruce (Picea abies L. Karst.) is a dominant conifer on the glacial drift of the Greenstone Belt, but a low soil solute content ($\sigma_a < 0.5$ mS/m) is constraining for spruce. On the basis of the present spruce forest line in the transition between the mafic Tanaelv Belt and felsic Lapland Granulite Belt, we argue that spruce has not been a ubiquitous member of the Holocene tree succession sequence in northern Fennoscandia. Both Scots pine (polar) and Norway spruce (alpine) forest lines have significantly expanded in the 20th century. The northward expansion pattern of Scots pine during the last 400 years may be associated with solar periodicities.

Keywords (GeoRef Thesaurus, AGI): soils, forest soils, till, physicochemical properties, bedrock, tree line, Pinus sylvestris, Picea abies, Lapland, Finland

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INTRODUCTION, MATERIALS AND METHODS

The site requirements of cold-hardy conifers, Scots Pine (*Pinus silvestris* L.) and Norway spruce (*Picea abies* L. Karst.), are significantly different with respect to soil water and nutrient regimes. Geological and soil physical-chemical factors predominantly govern the species-specific distributions in the subarctic, such that Scots pine is best suited to well-drained soils derived from felsic rock types such as granites and granulites, whereas Norway spruce dominates on nutrient-rich soils derived, for instance, from the mafic rock types of the Lapland Greenstone Belt (Sutinen et al. 2002a, 2005).

During the Holocene, climatic fluctuations have contributed to continental shifts in the conifer forest lines. Based on radiocarbon (^{14}C) dating as well as tree-ring master series of conifers, the past distribution of pine and spruce during the Atlantic maximum is still well above the present conifer forest lines (Eronen 1979, MacDonald et al. 2000, Sutinen et al. 2007a). Due to the current global change, both polar and alpine forest lines have shifted northwards and onto higher elevations, for instance in Fennoscandia and the Polar Urals of Russia (Hagberg 2001, Juntunen et al. 2006, Kullman 2007, Shiyatov et al. 2007, Middleton et al. 2008). These shifts are to a great extent associated with local lithologies, such that the expansion of spruce may only occur on mafic regimes, whereas Scots pine can strengthen its dominance on felsic terrains (Sutinen et al. 2005). Even though the ongoing global change will eventually affect conifer distributions, no predictive models are yet available to estimate how the subarctic forest composition or the forest lines will change in the future. We have investigated Holocene and recent shifts in the forest lines with regard to lithology and the physical-chemical properties of the soil, and we here summarize present knowledge on the influence of soil physical-chemical properties on conifer distributions over the diverse lithological provinces of Finnish Lapland.

Lithological provinces

The major lithological provinces of Lapland are the mafic Lapland Greenstone Belt (LGB) in the south, felsic Lapland Granulite (LG) and Hetta Granite (HG) in the north and the Tanaelv Belt (TB) in the transition between the LGB and LG (Figure 1; Marker 1985, Lehtonen et al. 1998). Fertile glacial tills of the LGB are typically covered with forests dominated by Norway spruce (Hyvönen et al. 2003, Närhi 2010a). The transition between LG and the arc-shaped TB (Marker 1985), similar in lithological composition to the LGB, demarcates the spruce timberline in NE Fennoscandia (Sutinen et al. 2005). The terrain of HG north of Pallastunturi (P) fell is typified by acidic and nutrient-poor glacial tills only supporting forests dominated by Scots pine (Hagberg 2001, Sutinen et al. 2007b). LG is composed of felsic garnet gneisses and the derived sandy drift is dry and acidic and is occupied by Scots pine forests (Salmela et al. 2001). Podzol (Spodosol) is the main soil type, although the types may range from Typic Haplocryods to Skeletic Podzols (Sutinen et al. 2007b). Some of the sites from our investigations are presented as examples, such as Vaalolehto (V in Figure 1), which is underlain by chlorite-amphibole schist and is a part of the LGB. Sandy drift of the Juolkusselkä (J in Figure 1) site is derived from granite gneiss and hosts mature (>150-year-old) Scots pine stand. Lommoltunturi (next to Pallastunturi, P in Figure 1), as a part of the LGB and composed of Mg-tholeiitic metavolcanites, provides a good opportunity to investigate the role of physical-chemical properties of the soil on the alpine shift of the Norway spruce forest line (Middleton et al. 2008).

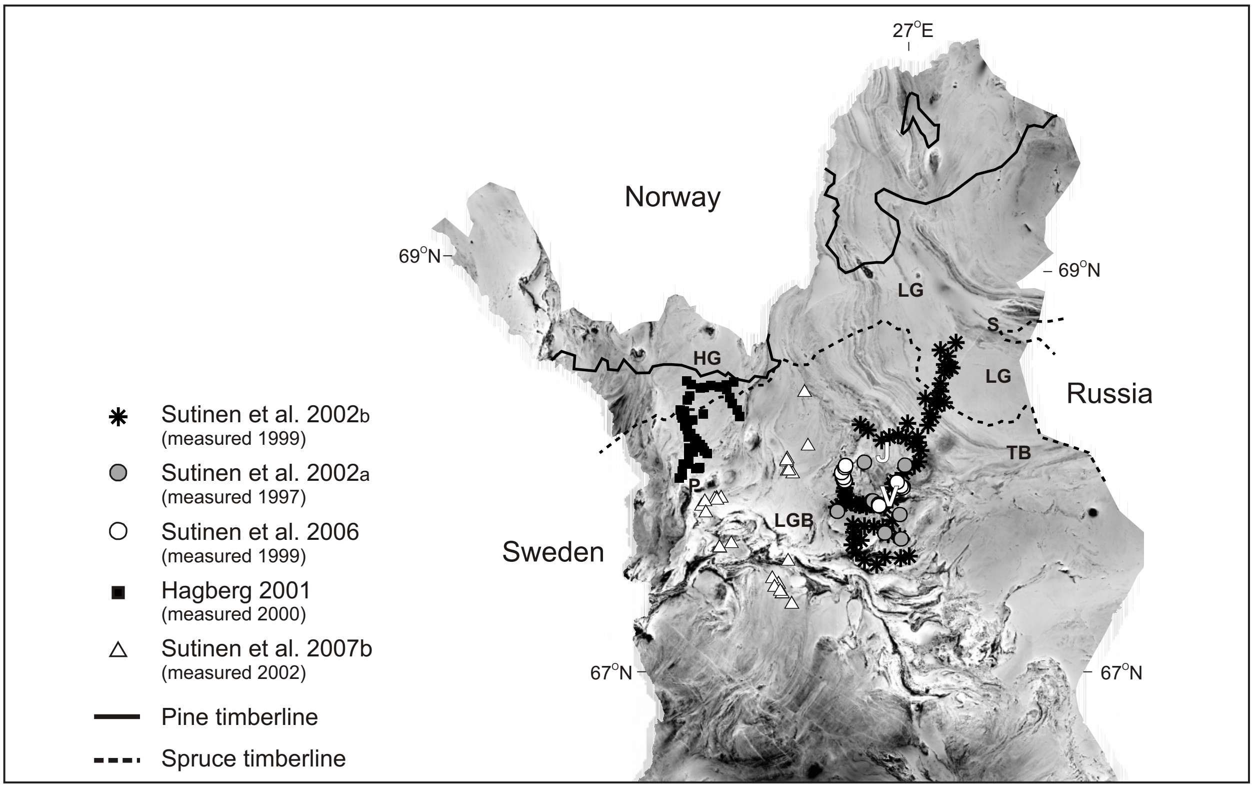

Figure 1. Airborne magnetic total intensity map of northern Finland. Norway spruce timberline (dashed line), pine timberline (solid line). Lithological provinces: LGB = Lapland Greenstone Belt, TB = Tanaelv Belt, LG = Lapland Granulite, HG = Hetta Granite, P = Pallastunturi fell, J = Juolkusselkä, V = Vaalolehto, S = Sarmituntur fell. Study sites shown by symbols. (Adopted from Sutinen et al. 2007b, with permission from the Scandinavian Journal of Forest Research).

Measurements

We applied soil electrical conductivity (σ_a) as a measure of the solute content and soil dielectric permittivity (ε) as a measure of the soil volumetric water content to examine the differences in site requirements between Scots pine and Norway spruce over diverse lithologies in Finnish Lapland (Hänninen 1997, Penttinen 2000, Sutinen et al. 2002a, 2009a, Närhi et al. 2010b). The soil σ_a was measured using a conductivity fork, a four-electrode Wenner configuration with 15-cm steel rods and 16-cm spacing (Geological Survey of Finland; model Puranen), or using electromagnetic (EM) induction with an EM38 (Geonics, Mississauga, Ont. Canada). Simultaneously with σ_a, the soil ε was measured with an electrical capacitance probe (Adek Ltd., Tallin, Estonia) or TDR (Tektronix 1502B, Beaverton, Or, USA). In grid measurements of the soil ε, we applied a two-antenna radar (GSSI, North Salem, NH, U.S.A.) configuration, known as the radar surface arrival detection (RSAD; Hänninen 1997) technique. The regional soil water regimes were assessed using airborne gamma-ray data from the Geological Survey of Finland, which were referenced in the field with a portable GS-256 gamma spectrometer (Geofyzika Brno, Czech; Hyvönen et al. 2003).

At permanent monitoring stations in Lapland, we measured the soil water content with CS615/616 probes and soil temperature with T107 sensors. Climatic variables, namely air temperature, snow temperature and snow depth, were simultaneously recorded. Snow depth was measured with (SR50A) sonic range sensors (Campbell Scientific, Logan, UT, USA) and apparent snow water (ASW) with dielectric leaf wetness sensors (Decagon Devices Inc, Pullman WA, USA). All parameters were automatically logged with Campbell CR1000 data-loggers (Campbell Scientific, Logan, UT) (Sutinen et al. 2008, 2009b). Mineral soil was analyzed for concentrations of chemical elements, extractable with 1 M ammonium acetate (NH_4OAc) at pH 4.5, using inductively coupled plasma atomic emission spectrometry (ICP-AES) on a Thermo Electron iCAP 6500 Duo ICP Emission Spectrophotometer (Thermo Fisher Corp., Cambridge, UK). Concentrations of total carbon (C_{TOT}) and nitrogen (N_{TOT}) were analyzed on a Vario MAX CN analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) (Närhi et al. 2010a).

RESULTS AND DISCUSSION

Soil hydrological regimes

Our results indicate that the seasonal soil water content (θ_v) is significantly lower in the sandy tills of Scots pine stands compared to the silty tills of Norway spruce stands, and that an excess soil $\theta_v > 0.27$ $cm^3\,cm^{-3}$ ($\varepsilon > 15$) constitutes an edaphic constraint for Scots pine (Figure 2; Sutinen et al. 2002a). Inter-seasonal dielectric monitoring of the soil θ_v has indicated that the magnitude of variation in the soil θ_v is site- and texture-specific, but with snowmelt as a major contributor to the water content in glacial tills (Hänninen 1997, Sutinen et al. 1997, 2007b). Soil saturation $\varepsilon > 30$ ($\theta_v > 40$ $cm^3\,cm^{-3}$) of silty tills may last 2–8 weeks after disappearance of the snow cover in Lapland, but that of sandy tills is either totally lacking or lasts only a few days (Sutinen et al. 1997, 2007b; Figure 3). When two sites (Vaalolehto and Juolkussekä; see locations in Figure 1) with similar climatic conditions but with contrasting lithologies (chlorite amphibole schist vs. granite gneiss) were compared, the soil θ_v was clearly site-specific, such that seasonal soil θ_v (soil ε in Figure 3) was significantly lower in sandy till (Juolkusselkä) than that in silty till (Vaalolehto). Even the maximum soil θ_v at the Juolkusselkä site was low in comparison to the minimum at the Vaalolehto site for the growing seasons (Jun–Sep) 1999–2003 (Figure 2). It was found that the mean inter-seasonal $\varepsilon = 7.0 \pm 1.36$ ($0.12 < \theta_v < 0.14$ $cm^3\,cm^{-3}$) applies to Juolkusselkä and $\varepsilon = 24.4 \pm 6.56$ ($0.3 < \theta_v < 0.49$ $cm^3\,cm^{-3}$) to Vaalolehto, respectively (Sutinen et al. 2007b).

We found that spatial patterns in the soil water content can be assessed through both airborne gamma and dielectric measurements (Hyvönen et al. 2003, Sutinen et al. 2007c). Although soil θ_v varies over time and according to the location in field, the pattern of spatial variability does not change with time when the observations are ranked according to the magnitude of the soil θ_v (Vachaud et al. 1985). This temporal stability of spatial patterns, referred to as time stability, for field-measured soil θ_v has been attributed to the soil texture and topographic curvature in agricultural soils (Vachaud et al. 1985). We tested the time stability concept for fine-grained glacial tills (clay fraction content 7%, fine fraction content 55%) derived from greenstones and mafic volcanites in central Finnish Lapland at a site formerly covered by a mature (>150 yr) Norway spruce stand (Sutinen et al. 2007c). We found that soil texture and topographic curvature were secondary to the coarse fragment content of the tills in contributing to the spatial persistence of the soil dielectric properties (ε), i.e. soil θ_v. The TDR measurements of the soil ε, analyzed with Spearman's rank correlation analysis, displayed significant time stability ($r_s = 0.83$-0.93; $P < 0.01$) of the soil water content for the whole season (from 31 May to 1 October 2001) (Sutinen et al. 2007c). Therefore, the time stability of glacial tills implies that airborne gamma ray measurements, particularly γ_K, can be applied to assess soil water regimes in the forest compartment and at regional scales (Hyvönen et al. 2003).

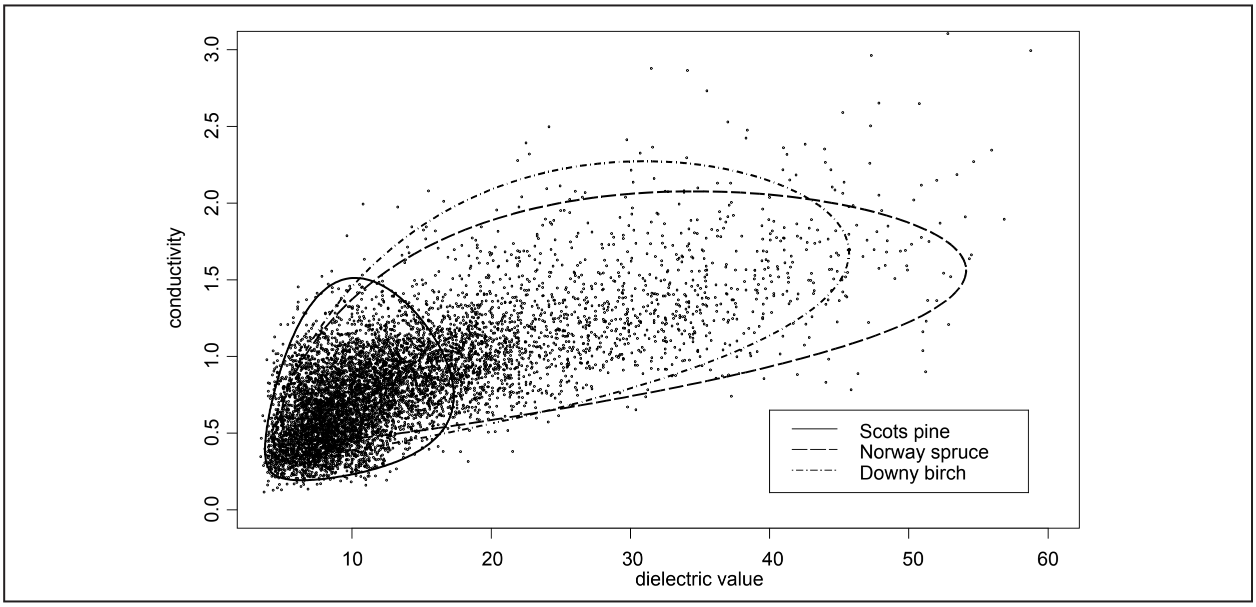

Figure 2. A scatter plot of the dielectric values and electrical conductivity (mSm^{-1}) of soil in mature forest in Finnish Lapland. The 95% confidence ellipses are estimated for log-transformed data for Scots pine (n = 3258), Norway spruce (n = 2818), and downy birch. (Adopted from Sutinen et al. 2002a, with permission from the Canadian Journal of Forest Research).

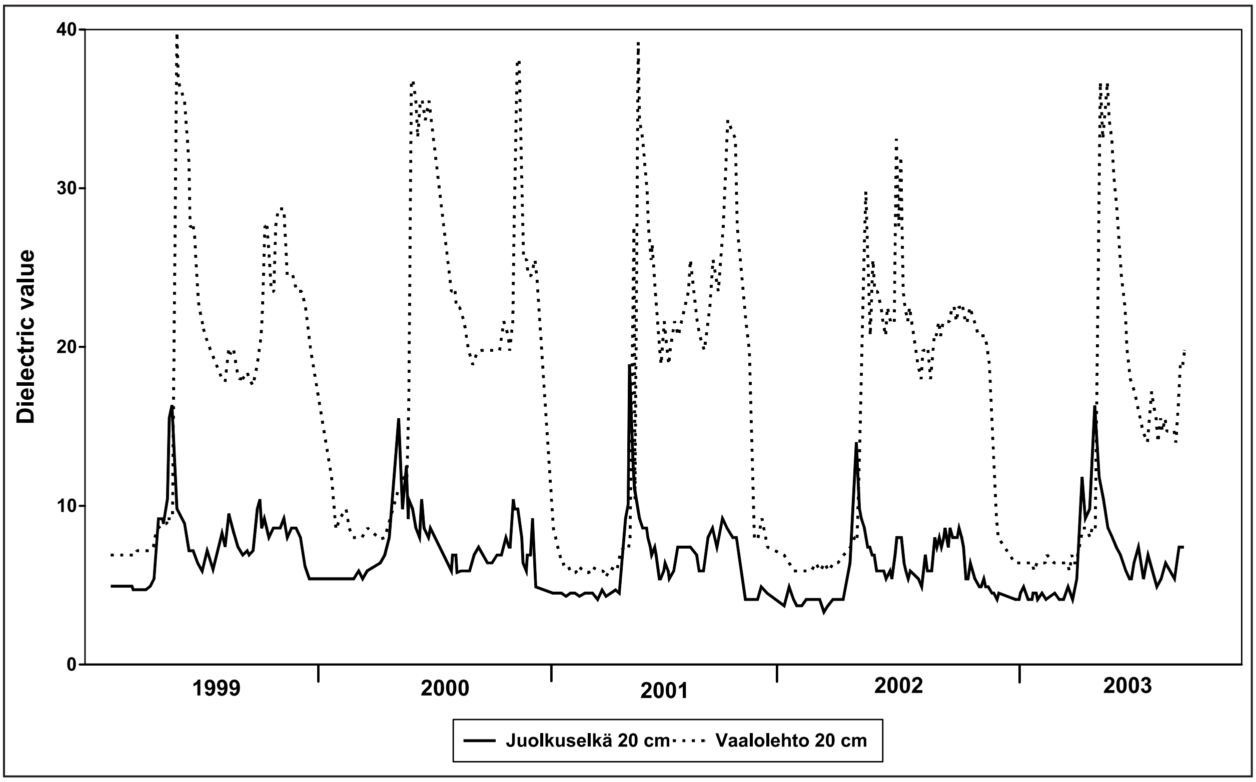

Figure 3. Inter-seasonal variation (1999–2003) in the dielectric values (20 cm depth) of sandy till occupied by a mature stand of Scots pine (Juolkusselkä) and silty till occupied by a Norway spruce-downy birch stand (Vaalolehto; locations shown in Figure 1). (Adopted from Sutinen et al. 2007b, with permission from the Scandinavian Journal of Forest Research).

Soil temperature regimes

Our results indicate that the snowpack provides a necessary shelter for conifer root systems in winter. As an example, the extreme cold event T_{AIR} = –49 °C in January 1999 resulted in soil freezing (at 10-cm depth) down to T_{10} = –26 °C at a snow-free site, but beneath the 50-cm-thick snowpack the soil temperature was only T_{10} = –0.5 °C (Sutinen et al. 2009a). The snowpack has a low thermal conductivity, hence making it a good insulator, such that a thick snowpack can even prevent the formation of soil frost. Our observations of glacial tills ranging from sandy to silty matrix have indicated that the soil temperature (20 cm depth) is above or close to 0 °C under the snow cover in the subarctic climate of northern Finland (Hänninen 1997, Sutinen et al. 1997). According to Hänninen (1997), an organic soil surface may experience soil temperatures down to –4.5 °C due to fluctuations at the snow-atmosphere interface, but the soil temperature of silty till may only change from T_{20} = +0.8 °C to +0 °C during the period from December–June.

Snowmelt timing is a critical factor for tree growth at high latitudes, such that root-zone soil water availability in spring is concomitant with an air temperature rise notably above 0 ˚C (Sutinen et al. 2009a, 2009b). As an example, in spring 2008 we measured the snowpack thickness, apparent snow water (ASW), air and soil temperature, as well as the soil water content (θ_v) at Mustavaara fell (67˚59’N, 24˚06’E), Finnish Lapland (next to Pallastunturi; see location in Figure 1). Before the onset of the snowmelt (on 16 April), the snowpack was 104 cm thick at the forest line, whereas the soil temperature (20 cm depth) remained below 0 ˚C until 1 June. Due to the air temperature rise notably above 0 ˚C on 27 April, the onset of snowmelt was seen as a rise in ASW (29 April) two days later and a rise in θ_v (30 April) three days later, hence suggesting that snowmelt water infiltrated rather unimpeded through the partially frozen soil (Figure 4; Sutinen et al. 2009b). At the forest line, snow disappeared almost a month later than when the maximum soil water content was reached. We contend that i) snowmelt infiltration through partially frozen soil significantly contributes to ground water reserves and ii) soil water availability, rather than soil temperature, is pivotal for the start of the height increment of trees in northern boreal conditions (Sutinen et al. 2009a, 2009b)

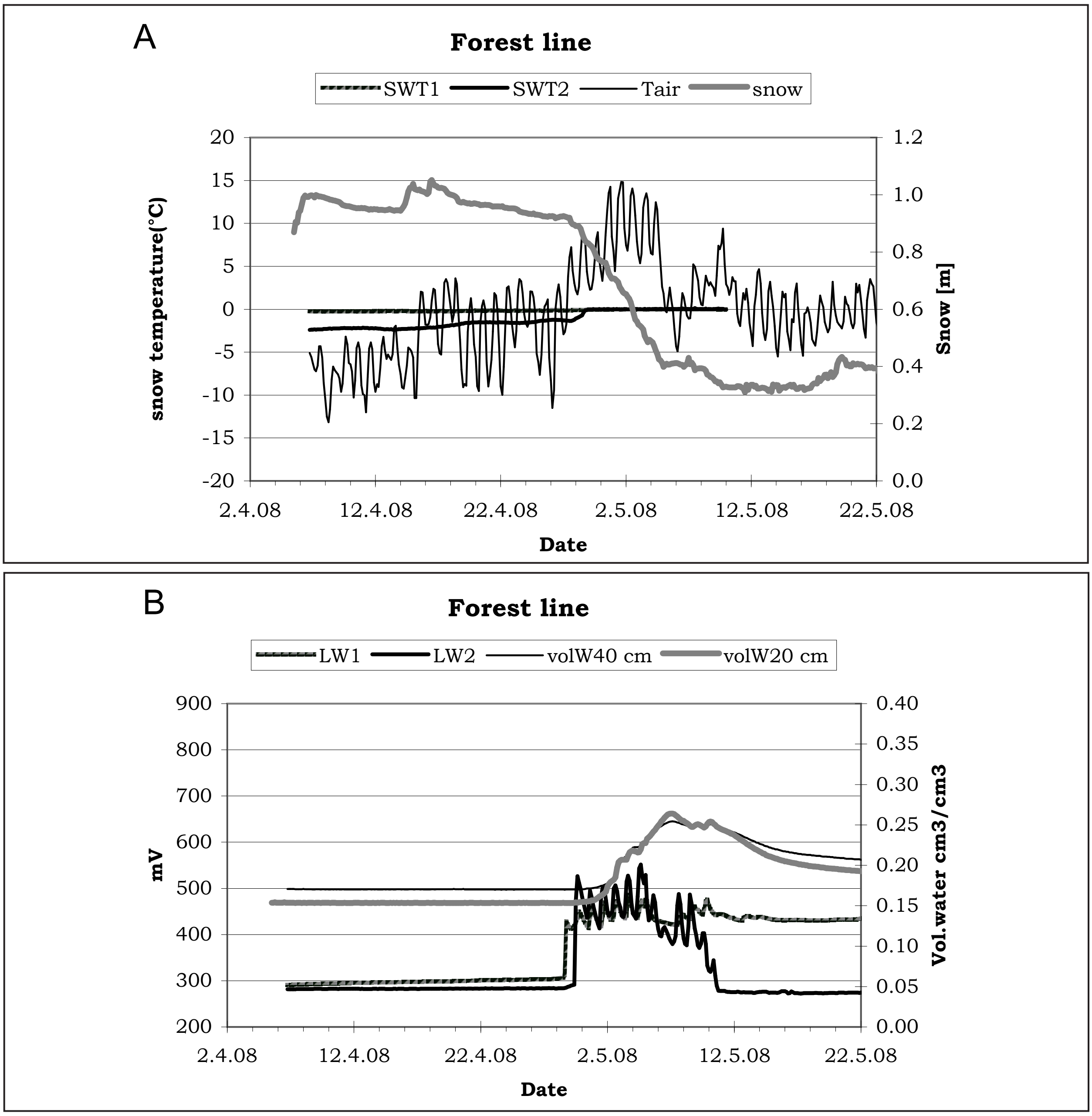

Figure 4. Changes in climatic variables and soil properties at a forest line site on Mustavaara fell (447 m a.s.l.) during late spring 2008. A. Snow temperature on the ground surface (SWT1) and 30 cm above the ground surface (SWT2), air temperature (Tair) as well as thickness of the snowpack (snow). B. Apparent snow water on the ground surface (LW1) and 30 cm above the ground surface (LW2), as well as soil water content at 20 cm depth (volW20cm) and 40 cm depth (volW40cm). (Adopted from Sutinen et al. 2009b, with permission from Geophysica).

Soil nutrient regimes

Our results indicated that Norway spruce is the dominant conifer on the glacial drift of the Greenstone Belt in Lapland (Hyvönen et al. 2003). However, a low soil solute content (σ_a< 0.5 mS/m) is a constraint for Norway spruce (Figure 2; Sutinen et al. 2002a). Based on the measurements of soil gamma radiation, electrical conductivity and dielectric properties, the artificial neural network (ANN) classification indicated that the forest line of Norway spruce is geologically controlled at the transition between the mafic Tanaelv Belt and felsic Lapland Granulite (Sutinen et al. 2005, see lithology in Marker 1985, Lehtonen et al. 1998; Figure 1). Scots pine is the only conifer on tills derived from felsic rocks of Hetta granite (HG) and Lapland granulite (LG). Norway spruce dominated on tills derived from the mafic rocks of the Lapland Greenstone Belt (LGB), but the tills of LG and HG constitute a dispersal barrier for spruce (Sutinen et al. 2005, 2007b). It should be noted that no macrofossil evidence has been presented to demonstrate the presence of spruce beyond the TG-LG transition. The importance of geology has been well demonstrated at Sarmitunturi fell (see Figure 1), where the forest line is formed by spruce underlain by tills derived from diorites (Sutinen et al. 2007b). We therefore argue that spruce has not formed a part of the forest succession on LG (see discussion of forest fire dynamics and shade-tolerance of spruce in Sutinen at al. 2005 and references therein).

The sampling design covering the main lithological provinces in Lapland, based on the KALPEA database of the Geological Survey of Finland, revealed significant differences in soil geochemistry as well as conifer distributions (Närhi et al. 2010a). We found a strong correlation between the field-measured soil σ_a and soil attributes associated with forest productivity, such as exchangeable Ca and Mg (Närhi et al. 2010a, see McBride et al. 1990). In the LGB, the soils are Ca-rich and characterized by high Mg, pH and soil electrical conductivity, but by low concentrations of soil Al, S, Zn and C:N, (Närhi et al. 2010a). LG is characterized by high concentrations of soil Al, but is low in water-soluble nutrients, particularly base cations Ca and Mg (Närhi et al. 2010a). We therefore argue that the geochemical composition of parent tills has fundamentally contributed to the conifer distributions in Lapland.

Besides the soil forming processes during the Holocene (10 Kyr), soils in Lapland have been subjected to human impacts, such as reindeer herding and forestry practices. Site preparations have been applied to alter soil conditions, but failures in pine plantations have been recorded at sites with an excess soil water content and formerly covered by stands dominated by Norway spruce (Hansson and Karlman 1997). Our results indicate that mechanical site preparation, e.g. with ploughing (Marttiini), is not able to amend the soil θ_v to meet the site requirements of Scots pine at former spruce sites (Sutinen et al. 2002b). Instead, ploughing tends to result in a reduction in the soil nutrient supply such that untreated control σ_a>tilt σ_a>trench σ_a (Figure 5). The degradation of soil conditions, through the leaching of soil nutrients, may even hamper the natural regeneration of spruce at sites formerly covered by spruce-dominated stands (Sutinen et al. 2006, 2010a).

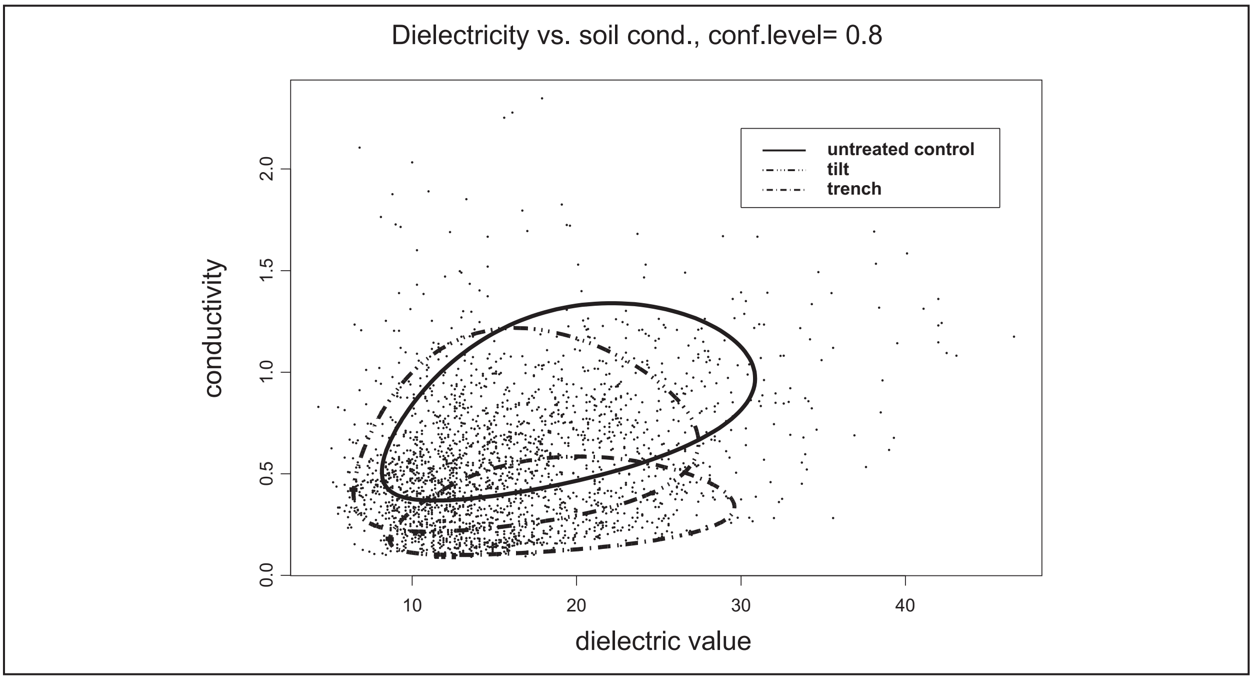

Figure 5. A scatterplot of the electrical conductivity (mSm^{-1}) and dielectric values of the soil at former Norway spruce sites in Finnish Lapland 8–23 years post-ploughing. The 80% confidence ellipses are estimated for log-transformed data for untreated control, tilt and trench. (Adopted from Sutinen et al. 2006, with permission from Geoderma).

Holocene forest lines of conifers

The northernmost polar forest line in Eurasian Russia was formed by spruce (*Picea abies* ssp. Obovata) ~9 000–8 000 yr BP (MacDonald et al. 2000), whereas in northern Fennoscandia the northernmost forest line was formed by Scots pine ~8 000–7 000 yr BP (Eronen & Zetterberg 1996). We found subfossil pine logs at the Pousujärvi site (68°51'N, 21°10'E) in northernmost NW Lapland (Kilpisjärvi area), ranging from ^{14}C ages of 5 000 ± 40 to 5 110 ± 60 yr BP (5 730 to 5 900 cal. yr BP) to tree-ring ages of 6 006 to 6 054 cal. yr BP (Sutinen et al. 2007a). On the basis of tree-ring analysis, the oldest pine logs yielded dates of 6 006 to 6 054 cal. yr BP and the youngest 4 698 to 4 369 cal. yr BP. Hence, pine had been present in Kilpisjärvi between ~6 000–4 400 yr BP. Our results are similar to those presented by Eronen and Zetterberg (1996), who reported the time window for the presence of pine (68°57'N, 20°57'E) to range from 6 000 to 4 085 cal. yr BP. However, no macrofossil evidence has been found to indicate presence of Norway spruce during the Atlantic period in the felsic terrain of Finnish Lapland (see Sutinen et al. 2005).

After the gradual retreat of the forest lines by ~4 000–3 000 yr BP (Eronen 1979, MacDonald et al. 2000, Sutinen et al. 2007a), no evidence of marked advances in the forest line has been presented. Our results from Karesuvanto, western Finnish Lapland (68°30'N, 22°30'E), suggest that after the retreat of pine to its present position, the pine forest line may have been rather stable (Sutinen et al. 2007a). The forest lines and migration patterns of Fennoscandian and Eurasian spruce and pine species are in reverse order (MacDonald et al. 2000, Sutinen et al. 2005). Since spruce and pine have distinctly different site requirements with respect to soil water availability and nutrients (Sutinen et al. 2002a), the reverse order may be associated with differences between the soils derived from the rocks of the Baltic Shield and those derived from Cambrian sedimentary rocks in subarctic Siberia.

Alpine forest line of Norway spruce and global change

We investigated recent shifts in the forest lines with regard to the snowpack, soil physical-chemical properties as well as tree species canopy coverage and the age chronology along the elevation gradient (380–557 m a.s.l.) of the Lommoltunturi fell (next to Pallastunturi, location in Figure 1). Change detection and object-based image analysis of present false colour (2003) and past panchromatic (1947) aerial photographs demonstrated a spatial expansion pattern for Norway spruce (Middleton et al. 2008; Figure 6). Validated with field data on tree and sapling ages, the spruce forest is young (<165 yrs). Norway spruce was found to have migrated uphill approximately 100 m in distance (55 m in elevation) within the past 60 years (Middleton et al. 2008). In accordance with the birch-pine-spruce succession concept, forest tundra stands formerly dominated by downy birch have now been replaced by Norway spruce (Figure 6). We did not find soil water availability, soil temperature or N to be limiting factors in the expansion of spruce forest on Lommoltunturi fell, but a surplus of soil Al relative to base cations may be unfavourable to spruce at some sites in the tundra. Evidence from ground penetrating radar surveys indicated that the snowpack thickness is spatially variable in the tundra, whereas a thick and even snowpack is typical of the forest. We found no evidence of fire disturbances or of old stumps or logs, and we hence conclude that the forest has expanded onto formerly treeless tundra. Based on tree-ring indices, the growth of spruce has positively correlated with the June–July temperature, but the data demonstrated climatic periodicity, suggesting that the 30- to 33-year (Bruckner) solar forcing (see Stocker 1994) has impacted on the alpine forest-tundra in Lapland (Sutinen et al. 2010b).

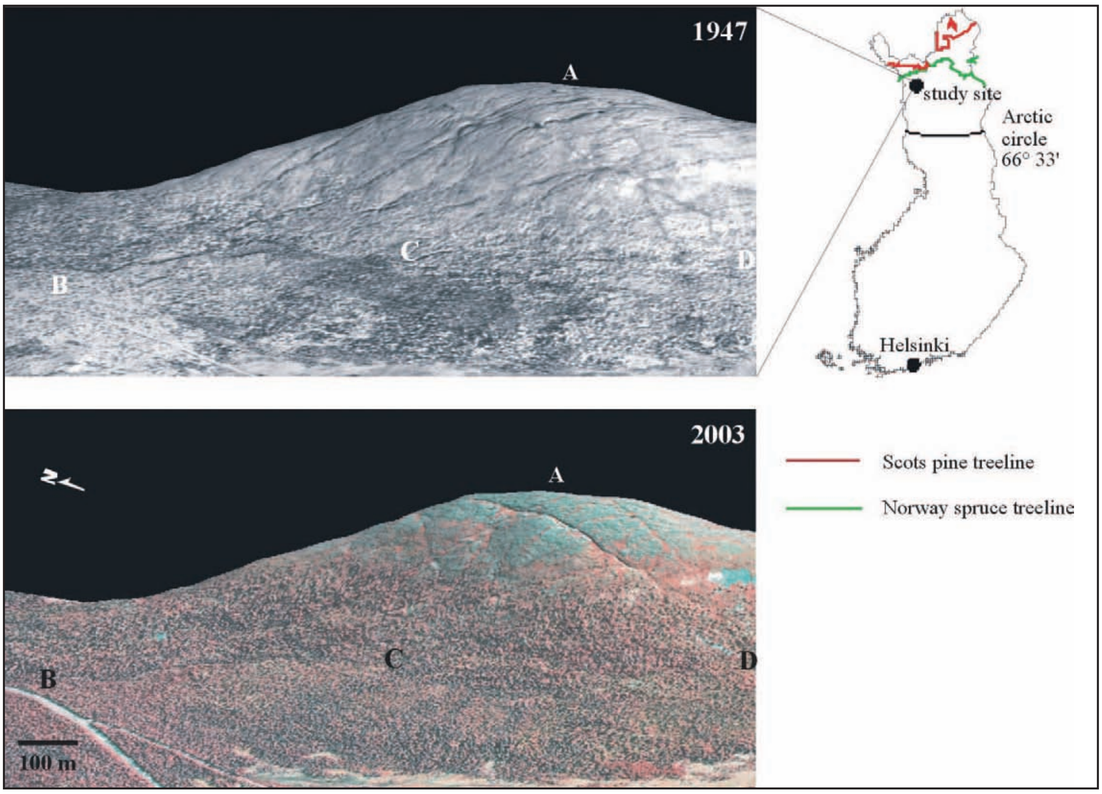

Figure 6. Panchromatic (year 1947, upper) and false colour (year 2003, lower) aerial photographs of the west slope of Lommoltunturi fell west slope draped over digital elevation model. Field data were acquired along transects A-B, A-C and A-D. The red and green lines in the index map represent the Scots pine and Norway spruce forest lines, respectively. Aerial photographs from the Finnish Defence Forces Topographic Service © and Blom-Kartta Oy ©.

Polar forest line of Scots pine and global change

Our results indicate that since the 1890s, Scots pine has migrated ~20 km northwards (about a 100 $d.d._5$ change in Figure 7) on felsic Hetta granite terrain (Hagberg 2001, Juntunen et al. 2006). Scots pine individuals were established on sites underlain by well-drained sandy till (Hagberg 2001). None of the stabilized pines were found at sites with $\varepsilon_r > 15$ ($\theta_v > 0.27$ cm^3cm^{-3}). The expansion of Scots pine into harsher conditions (i.e. higher latitude and altitude) was rapid during the whole 20th century (Figure 7; note, top of the Y-axis refers to lowest temperature sum, i.e. most harsh climatic conditions). The 1960s was an exceptional decade, with the lowest temperature sum being 515 d.d. (in 1962). In comparison, the lowest temperature sum of 489 d.d. was recorded in the 1950s (1952). In the 1980s and 1990s, pines established on sites with the lowest temperature sums (428 d.d.).

Within the ongoing project “Forest soils and global change” we will address the hypothesis that the spatial changes in forest lines may be linked to solar periodicity. Preliminary analysis of the data acquired on the Hetta granite terrain (see location of pine forest line in Figure 1) has revealed some similarities in the expansion of Scots pine (Figure 7) and solar centennial-decadal fluctuations, particularly with respect to Gleissberg (88 years) and de Vries (205 years) periodicities (see solar cycles in Peristykh & Damon 2003). With our sampling design (all accessible ATV trails north of the forest line; Hagberg 2001, Juntunen et al. 2006), the chronology starts in the 1630s. The retarded expansion appears concurrent with the Gleissberg-de Vries superposition minima in the 1670–80s (Maunder minimum ~1645–1715). The Santorini eruption in 1628 may also have contributed to climatic forcing in the Northern Hemisphere. The Gleissberg-de Vries superposition exhibited its maximum in ~1770–90s (note Dalton minimum ~1790–1820), which may be delayed (maximum in 1817) or even reversed in our Scots pine data (Figure 7). After the 1810s, the again retarded pine expansion (1817 to 1848; Figure 7) seemed coincidental with the declining trend in the Gleissberg-de Vries superposition. This retardation may eventually also have been forced by the massive eruption of Tambora in Indonesia (10 April 1815), bringing an epoch of global climatic cooling. Even if climatic forcing has a crucial impact on the expansion or retreat of the forest, the lithological diversity will drive the spatial distribution patterns of future forest lines of Scots pine (felsic lithologies) and Norway spruce (mafic lithologies) in Finnish Lapland (Sutinen et al. 2010c).

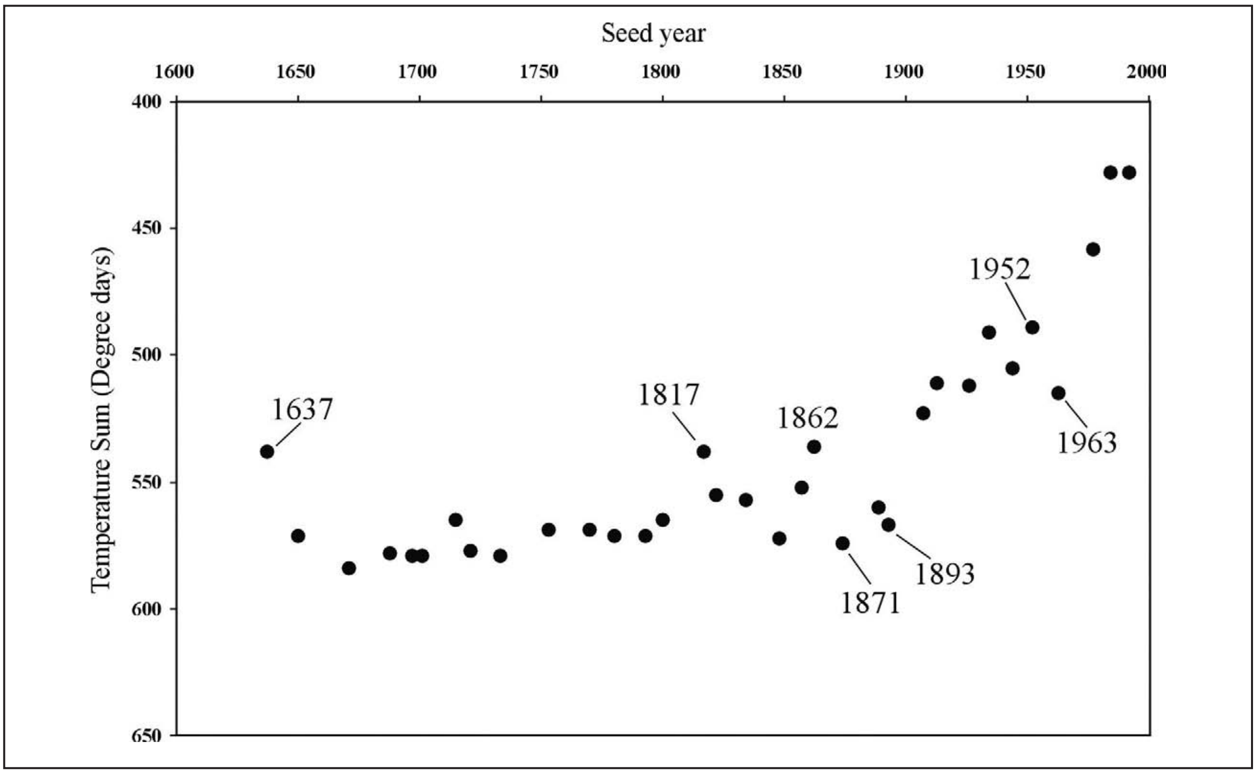

Figure 7. Expansion of Scots pine to harsher conditions in Hetta granite terrain, western Finnish Lapland. The temperature sum (y-axis; over +5 °C threshold) is used as a surrogate variable for the harshness of the growing season, combining the effects of latitude and site altitude. The points refer to pines established in the harshest climate for each decade from the 1630s to the 1990s. Note the reverse temperature sum axis.

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4 Geodata management and database development

From the field to databases and stakeholders – digitally and effectively. (Photo: Jari Väätäinen, GTK)

4 GEODATA MANAGEMENT AND DATABASE DEVELOPMENT

Introduction

The Geological Survey of Finland (GTK), like all long-established geological surveys with a mission to contribute to the economy and the quality of life of society, is facing the same challenge: how to fulfil its mission. Vast amounts of geological data have been gathered and distributed in conventional formats such as printed geological maps, reports and publications. This, however, has its limitations. The traditional products are hardly understandable by non-professionals and a considerable amount of invaluable data has remained hidden in archives, while new societal needs have evolved, also calling for new products and services.

The revolution in information technology, pressures for greater responsiveness to customer groups, and the push for greater organizational efficiency are drivers that have brought geology and the surveys alike into the digital era. This, for sure, has also provided a real stroke of luck] to the surveys. The present sophisticated information and communications technologies (ICT) allow the management of different datasets in ways never seen before, creating new possibilities to respond to diversified and changing end-user expectations.

Modern ICT provides the technological basis for "remaining relevant", but is not enough. Close dialogue with clients is needed to understand their needs. The change from the "old" GTK into a modern GTK has demanded considerable resources and skills and new ways of working. A distinct breakthrough occurred two years ago, when we were able to introduce our centralized information management system into effective use.

However, the work is not over. Our present focus is on careful analysis of work flows and the development of web services to ensure effective processes from the field to end-users. Increasing pressures to resolve cross-border issues also call for the development of international exchange languages and the harmonization of datasets in geology. The INSPIRE directive, aiming to create an EU spatial data infrastructure, provides the frame for this work.

The first article of this section describes our unique and coherent information system architecture, which allows easy maintenance of the system as well as effective data management and distribution. An article on GTK's bedrock databases summarizes the change from "paper to digital" and describes GTK's unique solution of a seamless map database linked to a stratigraphic unit database. Finland was the first country in the world to be covered by low altitude airborne geophysical mapping. The final article provides an overview of this effort, describes various applications of the results, and finally, extends to a global view of magnetic anomalies.

Hannu Idman

Geoscience for Society
125th Anniversary Volume
Edited by Keijo Nenonen and Pekka A. Nurmi
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THE IMPLEMENTATION OF GTK'S MANAGEMENT AND DISTRIBUTION SYSTEM FOR GEOSCIENCE DATA

by
Niina Ahtonen, Katja Lalli, Esa Kauniskangas and Jouni Vuollo*

Ahtonen, N., Lalli, K., Kauniskangas, E. & Vuollo, J. 2011. The implementation of GTK's management and distribution system for geoscience data. *Geological Survey of Finland, Special Paper 49*, 329–334, 5 figures.

Geologian tutkimuskeskus (GTK) aims to be the national centre of excellence for geoscience data management and analysis. Millions of records of geological bedrock, soil and mire observation data have been aggregated, harmonised and migrated to centralised data storages and made available to the end users. User applications for data capture, visualisation, querying and extraction have been programmed and customised at GTK and are in production use in the main data capture and analysis processes. The coherent information system and data architecture have created new possibilities to produce different kinds of services for customers.

Keywords (GeoRef Thesaurus, AGI): geology, data management, data acquisition, data storage, data bases, data retrieval, Finland

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INTRODUCTION

Geologian tutkimuskeskus (GTK) has been developing as the national centre of excellence for geological data management and analysis. A significant amount of resources has been used to create centralized information systems and tools for storing, managing and distributing geological data concerning bedrock, soil and mires, which have been collected during more than 100 years by GTK and other organisations. An extensive amount of archived data in different formats has been digitized, aggregated and harmonized during past years in several data management projects.

Two different information systems have been developed for the management of geoscience data. Geotietoydin is based on a database management system where dynamic, nationwide and spatially seamless data are stored. Geodata is based on a distributed file system and is used to store static, map sheet or individual project data.

The main components of the complete data management and distribution system are (Figure 1):

- A relational database and geodatabase belonging to Geotietoydin;
- The distributed file system of Geodata;
- Field data capture applications and procedures for bedrock, soil and peat surveys;
- Data distribution and visualization tools;
- A metadata editor; and
- Map and interface services.

The coherent system architecture makes the maintenance and management of the system and data flows, as well as the distribution of data and the production of services more effective.

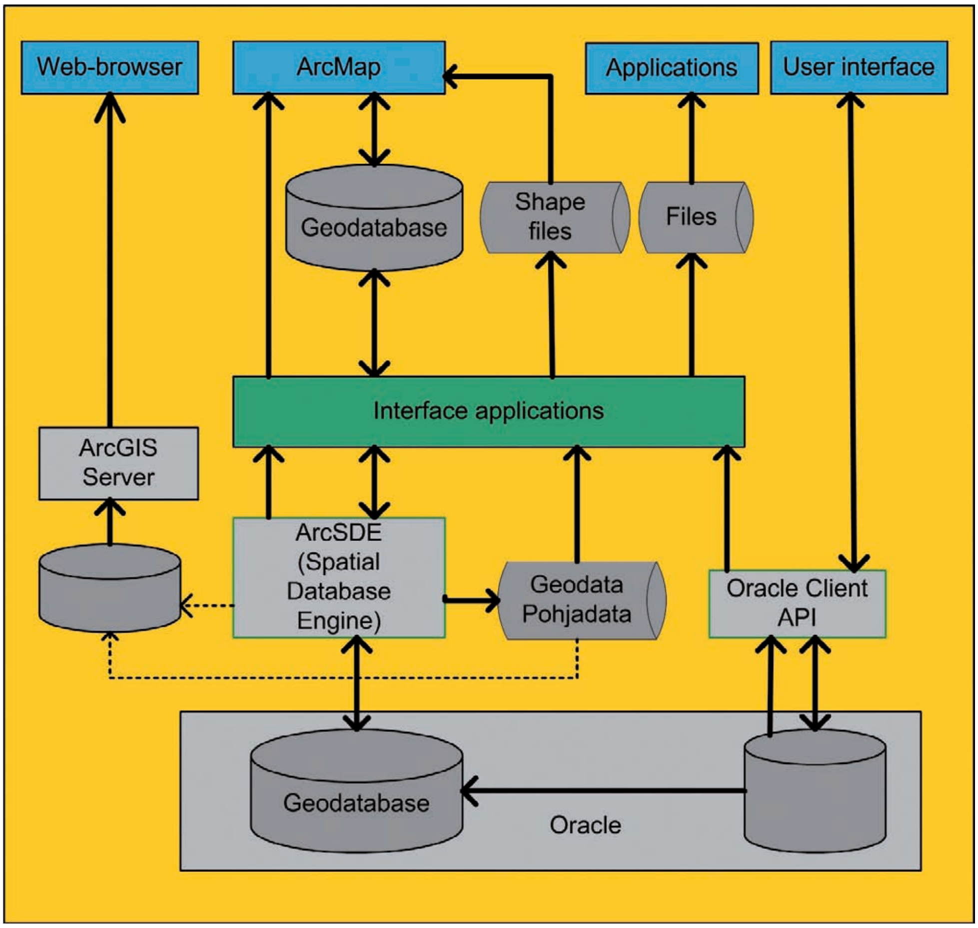

Figure 1. A simplified scheme of the system architecture of GTK's data management and distribution system. Dark grey shapes represent data storages such as databases and files systems, the green box represents interface applications for querying and extracting data from the database for different applications, and the blue boxes are client software.

GEOTIETOYDIN

The Geotietoydin system contains a geographical information system with a spatial geodatabase and a system for data without geometry, which is based on a relational database. The geographical information system is mainly constructed using Esri's ArcGIS products (www.esri.com). The geodatabase structure makes it possible to store both the correct geometry and the attributes of features in the same database. Field data are no longer divided into separate formats and systems. In the 1990s, spatial geological data layers were digitized in the map production system and the attributes of geological features were separately stored in different kinds of databases or data files. Typically, there were no dynamic links between geometry and attribute data. Today, observation data are collected digitally in the field using GIS. Seamless nationwide map databases are produced based on field data and other spatial data sets such as previously produced geological maps, geophysical data and topographical maps.

The large sets of data collected during past decades in several data capturing processes have been successfully migrated to the subsystems of Geotietoydin (Figure 2). For example, the geodatabase contains data for 14 600 mires, including 680 000 stratigraphic study points and more than 700 000 depth study points. The bedrock data sets consist of more than 390 000 bedrock observations and nearly 30 000 boreholes migrated to the geodatabase. Intranet users can obtain all the data freely for background use without limitations between subsystems. This is the most significant strength of Geotietoydin. Data editing is limited by access rights. The current use of the GTK's geodata management system in data capturing processes has been described by Vuollo et al. (2011) and Palmu (2011).

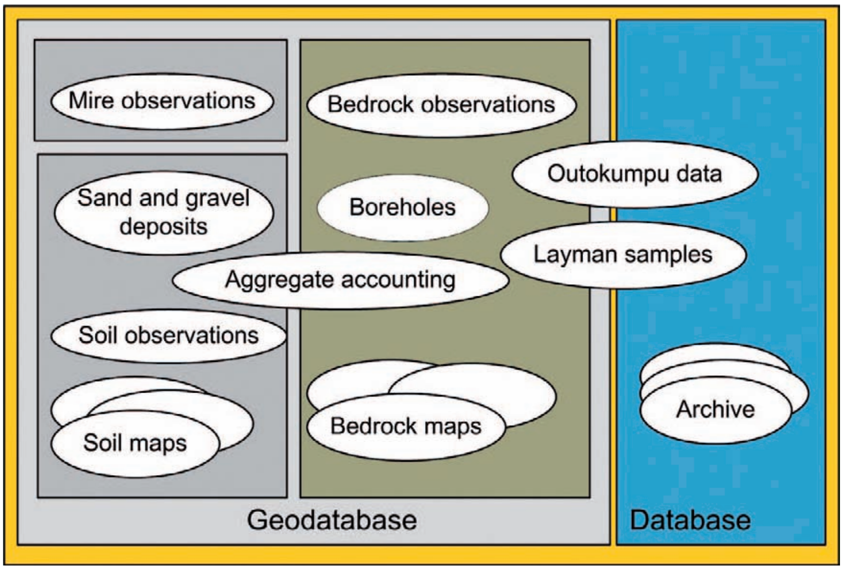

Figure 2. The subsystems of Geotietoydin.

FIELD DATA CAPTURE

GTK has been developing digitalized field data capturing processes during the past five years for peat surveying, sand and gravel deposit mapping, soil observation and mapping and bedrock mapping. Field data capture is carried out using rugged tablet PCs (Figure 3). All base maps, geophysical maps, previous observations and so on are in digital format and fully usable in the GIS software during fieldwork. Field observations are stored using the standard ArcMap tools and attribute editors programmed at GTK. The database structure for field work is extracted from the central geodatabase. Data models and database structures for geological data are complex: each capturing process uses several layers and tables, one geological feature can have dozens of attributes and database tables have many relationships.

After a field season, the data are uploaded to the central geodatabase of Geotietoydin. This is carried out using a software component customized at GTK. When necessary, data can be extracted for editing with the same tool.

Figure 3. A tablet PC for field work. Photo: Perttu Mikkola.

GEODATA

Geodata is a distributed file system in which the master server is replicated to the other regional offices every night. There is a data server in all four regional offices and the client uses the closest available server. Geodata is an intranet disk space that can be read by all GTK employees. Copyrights are restricted and managed by the service manager.

There are 11 folders on the top level of Geodata (Figure 4), one for each data entity. At the moment, there are folders for geophysics, geochemistry, bedrock, soil, ArcGIS layer files, marine geology, reports, photos, digital products and external projects. The contents of the folders are supervised by data managers and the service manager. Geodata is often used as a storage place for data and formats unfit for the Geotietoydin system, mainly vector files, raster images, photos, pdf files, and so forth. A similar distributed file system called Pohjadata is also available for topographic and administrative data.

METADATA

GTK's aim is to produce metadata for all relevant data sets. Metadata are stored using a custom-made metadata editor. The production of metadata is managed by GTK's metadata profile, where the ISO 19115:2003 standard and the requirements of the INSPIRE directive have been adopted. So far, GTK's metadata can only be accessed via the intranet.

DATA MANAGERS

A total of 34 data managers have been designated in GTK. The data managers are process experts having comprehensive knowledge of the data and management of the dataset in question. For major data sets, there are data managers in each regional office. Data managers have a key role in producing metadata, advising on the maintenance of the data and further development of data sets, as well as on the content of the data.

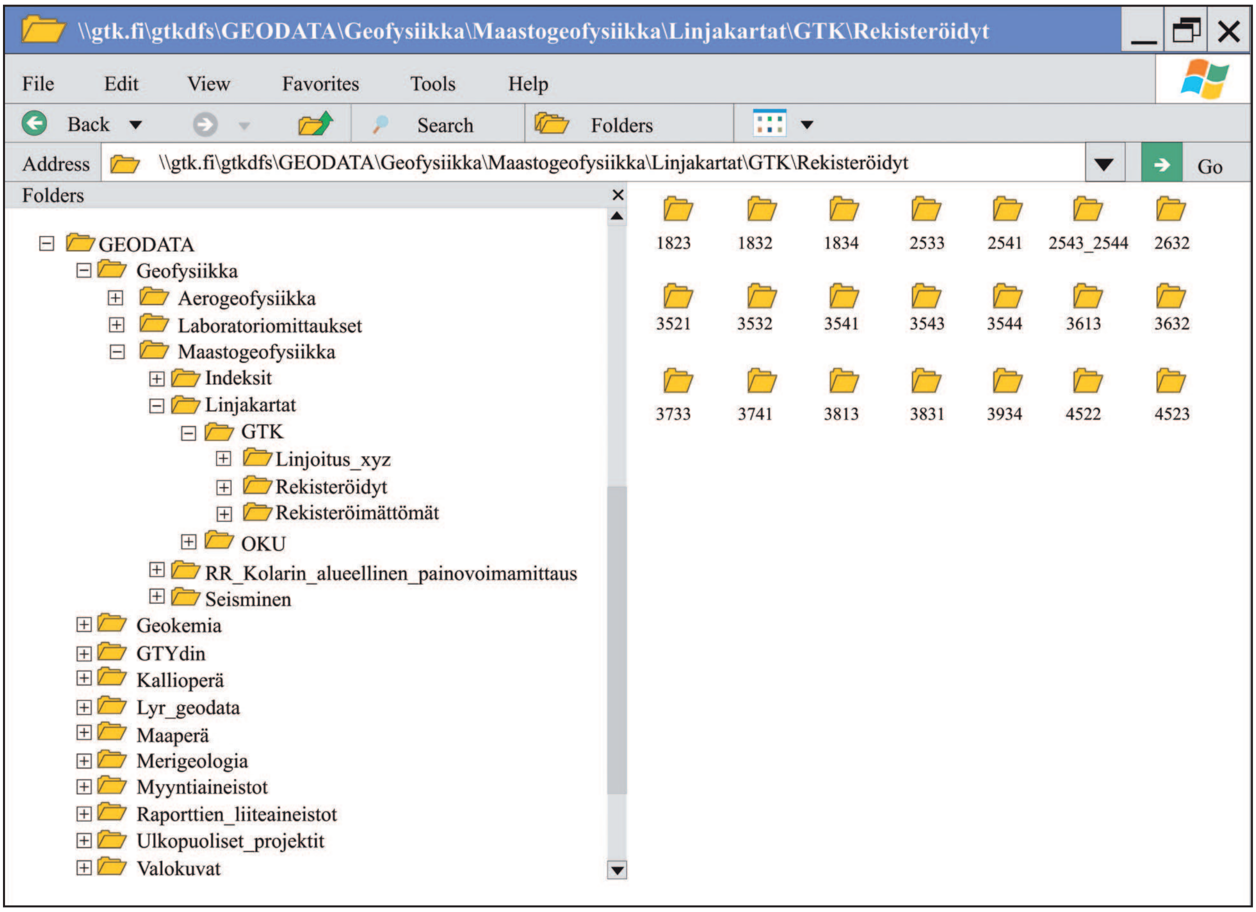

Figure 4. The top-level directory structure of Geodata.

DISTRIBUTION OF DATA

The distribution of data among the intranet clients is organized using custom-made query and data extraction applications. In this way, data delivery is much easier and more effective than using out-of-the-box toolsets. GTK's software development group has put a lot of effort into producing applications for end users to obtain data from the databases and file system for further background use, editing and modelling. The Haavi application extracts data from the geodatabase with the customer's predefined selection, such as the map sheet or spatial extent. A security component checks the user's access rights when data are being accessed for editing. Data in certain restricted structures and formats required for geochemical and bore hole modelling can also be extracted by a custom-made solution that makes data extraction rapid and easy, because end users do not need to prepare data sets by themselves. Two-dimensional peat profiles showing the peat type and humification distributions are printed out from the geodatabase with software programmed at GTK.

The replication service guarantees that the folder structure and contents of the Geodata file system are always identical in all GTK offices. This enables the development of GIS services. For intranet ArcGIS Desktop users, a GisData toolbar is available (Figure 5). The GisData toolbar is based on ArcGIS layer files stored in the Geodata system. Source data for the layer files are stored in the Geodata and Geotietoydin systems. The aim of the GisData service is to provide data from several sources in a simple way for end users, because complicated file names, file paths and database connections are hidden inside the service.

Map services have been developed for both intranet and Internet customers. The purpose of intranet services is to run customized geoprocessing or reporting tasks on a server to accelerate working processes. The geo.fi service (www.geo.fi) contains geological data and functionality destined for companies, authorities, educational institutes and citizens. WMS interfaces are offered, for example to the One Geology Europe portal.

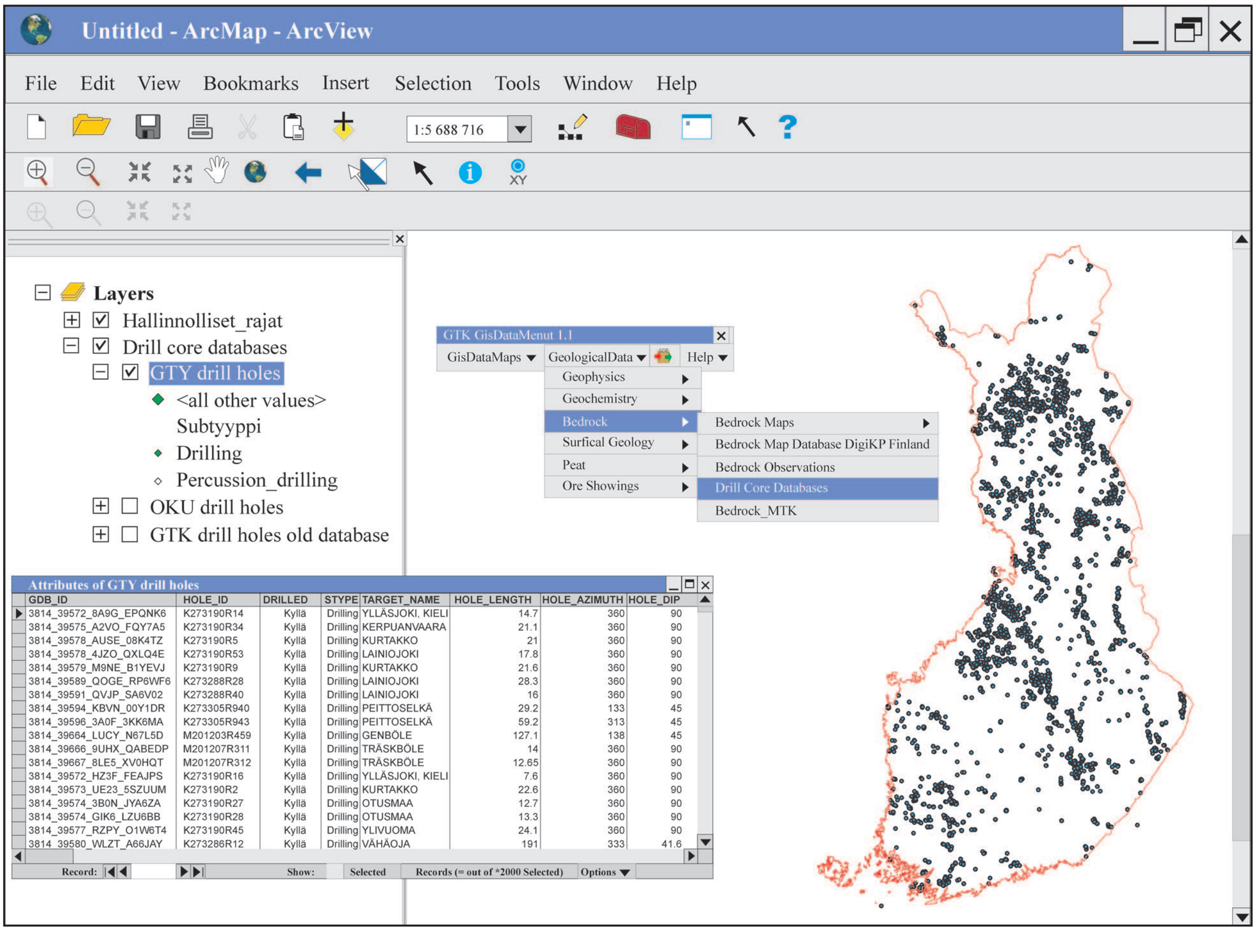

Figure 5. GisData menu for ArcGIS Desktop users.

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Vuollo, J., Luukas, J., Nironen, M., Ahtonen, N. & Kauniskangas, E. 2011. Bedrock databases – a step toward standardized geological information. In: Nenonen, K. & Nurmi, P. A. (eds.) Geoscience for Society. 125th Anniversary Volume. Geological Survey of Finland, Special Paper 49.

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BEDROCK DATABASES – A STEP TOWARD STANDARDIZED GEOLOGICAL INFORMATION

by
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Vuollo, J., Luukas, J., Nironen, M., Ahtonen, N. & Kauniskangas, E. 2011. Bedrock databases – a step toward standardized geological information. *Geological Survey of Finland, Special Paper 49*, 335–344, 4 figures.

For more than 100 years, geological surveys all over the world have been collecting their data sets as paper documents – notes, sketches, maps etc. For the last thirty years however, almost all the surveys have collected their mapping data sets into distinct and/or different databases. GTK also started to construct its first computerized bedrock databases at in the early 1980's, and all the bedrock processes, such as bedrock mapping, mineral exploration and urban mapping, have their own databases and standards for the storing of data.

The revolution in information technology (GIS and www services) led geological surveys to start developing methods in the mid-1990s for government geological mapping in accordance with the demands of the post-paper map era. In order to address these IT challenges, GTK also started its "Legacy data" and "Geokernel" projects at the beginning of 2000 for the purpose of recording new bedrock data (e.g. observations and map data) in databases constructed according to a consistent format, and it has now proceeded to adapt its early sets of survey material to the same database structures. Similarly, it has switched over to the use of rugged PCs for data acquisition purposes and adopted a uniform classification system for all its user interfaces.

GTK's bedrock mapping has moved over from its use of traditional map sheets to a single seamless bedrock map database (DigiKP), one essential part of which is a register of geological bedrock units (Finstrati) covering the entire country. A seamless bedrock map to a scale of 1:200 000 based on the DigiKP and Finstrati databases was released as an online product in March 2010. Both databases observe international stratigraphic standards and employ IUGS/GCI vocabularies.

Work on developing the bedrock databases will continue for a long time to come even after the old data, e.g. observation, commodity and map data, have been transferred to the new databases, because the increased dissemination of information at home and abroad is creating new demands (INSPIRE–GeoSciML–EarthResourceML).

Keywords (GeoRef Thesaurus, AGI): bedrock, mapping, data management, data bases, survey organisations, Finland

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INTRODUCTION

Where generations of earth scientists have summarised the results of their fieldwork and research in map form and field notebooks, geological survey agencies all over the world are now developing methods for government geological mapping in the post-paper map era. The Geological Survey of Finland (GTK), like most long-established surveys, is in the process of renewing its mapping strategies in the light of the revolution in information technology. Pressures for greater responsiveness to customer groups and the push for greater organizational efficiency are the main drivers behind this process. Web-based approaches are increasing in importance as they make it possible to query and exchange geoscientific information internationally.

GTK took its first steps towards the digital era in the mid-1980s, with the MS-DOS based PC-Kalpea and PC-Kaira user interfaces (Haavikko 1989, Kairakari 1989), which were the first observationdatabase software products adopted for bedrock and raw material mapping. Later, in the 1990s, some other processes, such as dimension stone, aggregate and urban mapping acquired user interfaces of their own. At the beginning of the 2000s, these PC interfaces were converted to the Windows environment and the database solution was RDB. More than 400 000 field observations have been stored in GTK's bedrock databases (Kalpea–Raki–Kiva–Taajama) over the last two decades.

GTK has a long history of constructing ore deposit databases. The first version was created in the mid-1970s (Saltikoff 1976), and many versions have been developed after that. Currently, GTK is using separate Access-based ore deposit databases for several metals and minerals (http://en.gtk.fi/ExplorationFinland/Commodities/).

All surveys have had different kinds of mapping programs in the course of their history, mainly ones based on map sheet partition. Systematic geological bedrock mapping has been going on at GTK for more than 100 years with different map scales and variable degrees of coverage:

- 1:400 000 – first map published in 1900 and the last in 1980 (100%)
- 1:100 000 – first map published in 1949 and the last in 2007 (57%)

Mapping at GTK was traditionally based on lithology, and it is only in the last 15 years that some map sheets have been based on geological units and lithology (e.g. Laajoki 2006). GTK has produced various 1:1 million scale geological maps during its 125-year history (Simonen 1980, Korsman et al. 1997) and GTK has published many digital map products during the last 15 years (e.g. Koistinen et al. 2001, Nironen et al. 2002, Räsänen et al. 2004).

Common to all GTK's historical geological data sets (digital or analogue) is that they have to a greater or lesser extent employed different data models and vocabularies (or have lacked any systematic vocabulary). The era of Information Technology (IT) that began in the last quarter of the 20th century changed the world of geosciences totally and irrevocably. As Loudon (2000) pointed out: "IT influences the way in which scientists investigate the real world, how they are organized, how they communicate, what they know and what they think. We are just at the dawn of that era."

Each geological organization has its own starting point, depending on its previous data management systems and mapping processes. Many surveys had plans to build seamless map databases for surficial and bedrock purposes. One significant planning project that started in the late 1990s at U.S. Geological Survey was for a seamless map of the USA. The key result of this planning process has undoubtedly been the North American Data Model – A Conceptual Model for Geologic Map Information (NADMSC 2004) – http://www.nadm-geo.org/). Several other surveys launched data model planning efforts and web-based data delivery services at much the same time, and finally, in 2005, many surveys came to recognize the importance of cooperation. This marked the starting point of the global activity coordinated by the IUGS (International Union of Geological Sciences)/CGI working group (Commission for the Management and Application of Geoscience Information), with the development of a conceptual geoscience data model mapped to a common interchange format, which was also demonstrated by the IUGS-CGI group (GeoSciML and OneGeology portal – see more info http://www.cgi-iugs.org/).

BEDROCK DATABASES

In order to address these IT challenges, GTK instigated the "Legacy data" and "Geokernel" projects at the beginning of the new century. The history of the "Geokernel" project is presented elsewhere in this special paper (Ahtonen et al. 2011). The idea of the project was that GTK should in the future have mapping capabilities that encompass the entire process from fieldwork and data capture to final map production and services. Another task was to evaluate the old "legacy data" and "unharmonised" databases and then migrate to new database structures. The largest issues to be tackled in the renewal process relate to data models and architecture, data capture and acquisition and the dissemination and delivery of information. The process has called for considerable resources and demands a wide variety of skills.

GTK's original plan, dating back a decade, featured centralized data storage based entirely on ESRI's Geodatabase data structure (Oracle/ArcSDE platform). Recently, the architecture has been divided into spatial (Oracle/ArcSDE) and non-spatial parts (Oracle, without SDE). The present bedrock database structure is illustrated in Figure 1.

This paper describes our achievements in the bedrock data management process during the first decade of 21st century. Examples of the significant changes that have occurred include filed data capture and interfaces with standardized domain lists, old data migration, a seamless bedrock map database with geological units and hierarchical vocabularies (according to IUGS/CGI GeoSciML lists – see http://www.geosciml.org/).

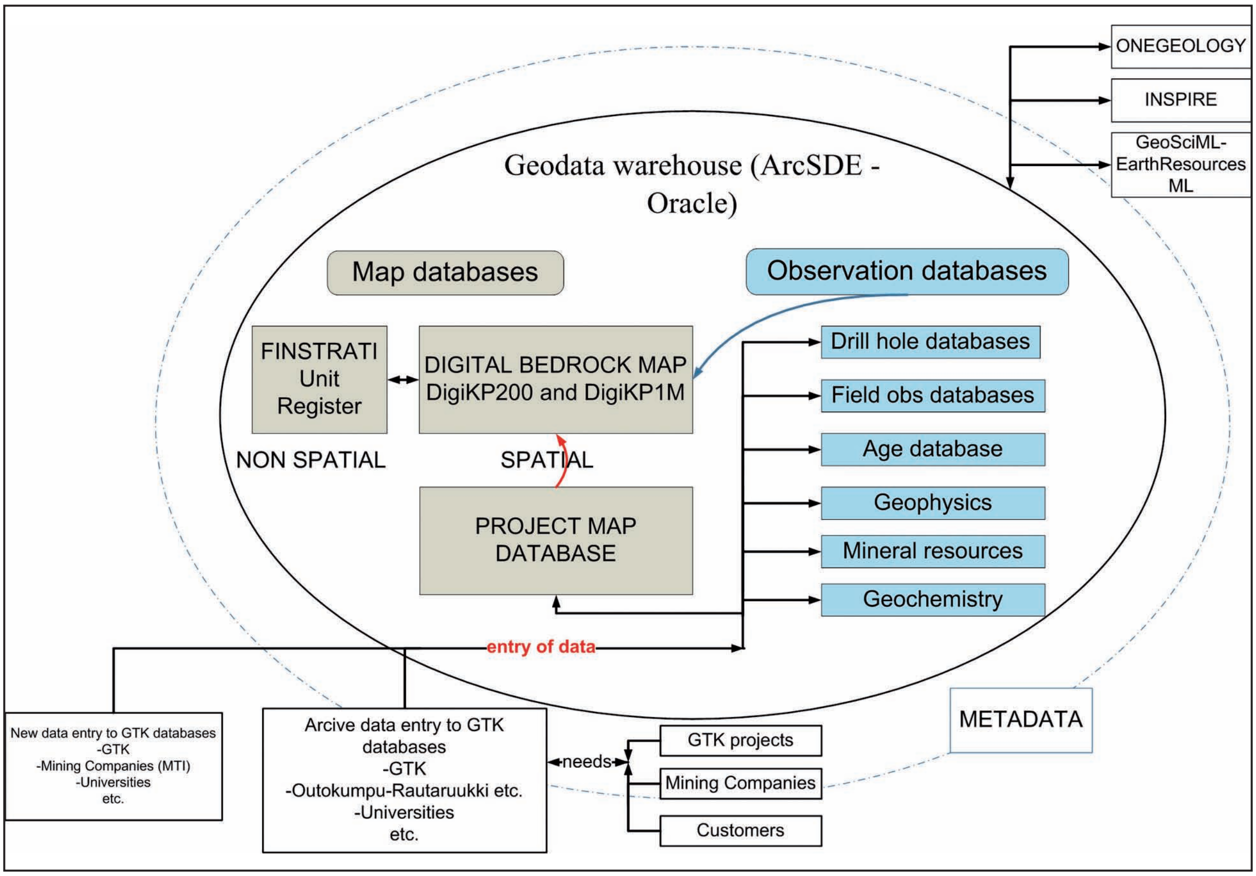

Figure 1. GTK's bedrock database structure. New data and maps – from archives and fieldwork – will be stored in observation and map databases. These can be used to update the harmonized seamless geology map database and map products to scales of 1:200,000 and 1:1 million that are linked to a non-spatial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

The GTK field data capture solution – 2010

GTK has had many mapping processes during its history. All the previous data sets were collected in paper note books and on forms. Now we have created a new environment for the bedrock mapping process – to encompass the entire process from fieldwork and data capture to centralized database storage. In the future, GTK will implement a uniform, international standard data model updated to meet national demands with respect to field observations. One significant change compared with the past will be that all the processes have the same user interface, with uniform pick-up lists for bedrock outcrop and boulder data (Figure 2) and another for drill core logging data. The data model for bedrock observations covers such sub-processes as regional bedrock mapping, exploration, natural stone investigations and urban geology for construction purposes.

Field data capture will also be of importance for GTK in the future. As the data models used by GTK are complicated, we have focused especially on attribute editor development in software programming. Attribute editors are programmed on top of ArcGIS. Field data capture in the bedrock mapping process takes place by means of portable tablet PCs. Base maps, geophysical maps, previous observations, etc. are in digital format and can be used together in GIS software in the field. Bedrock observations are stored using standard ArcMap tools and customized editors.

GTK has digitalized (over 400 000) old field observations in various databases over the last twenty years, but these have mainly been saved in their native format, which means variable data structures and classifications. It has been a challenging process to convert all these old data sets to a new structure! The migration process will take up considerable resources and time, but it is these old data sets that will form the foundation of the new Finnish geological database which GTK and its customers will be using far into the future.

One good example of the challenges encountered during the conversion process concerns GTK’s old outcrop observation database (KALPEA) and its quality problems. Almost all the data fields in the KALPEA database were saved as free text and only few data fields had specific domain lists. One key data field was of course rock name, and when migration started there were nearly 4000 such names to cope with (Figure 3a). In the course of the migration, all misspellings of the names were corrected and abbreviations were replaced with complete terms. Finally, all of these corrected rock names were transferred to the “Field Name” column, so that now there are only 2760 field rock names in the new database! Another example is rock colour – there were originally about 4600 colour names for rock types (Figure 3b), and now there are 179 left. The descriptions were first harmonized and then split during the migration process, after which the data were transferred and adapted to the new database structure and value lists (gcvd_Colour and gcvd_Colour attributes – Figure 3c).

GTK has transferred nearly all the field observation data sets to its new database structure during the last two years, marking the first step towards standardized geological data. This step will make our observation data much easier to use for various purposes in the future (e.g. www services).

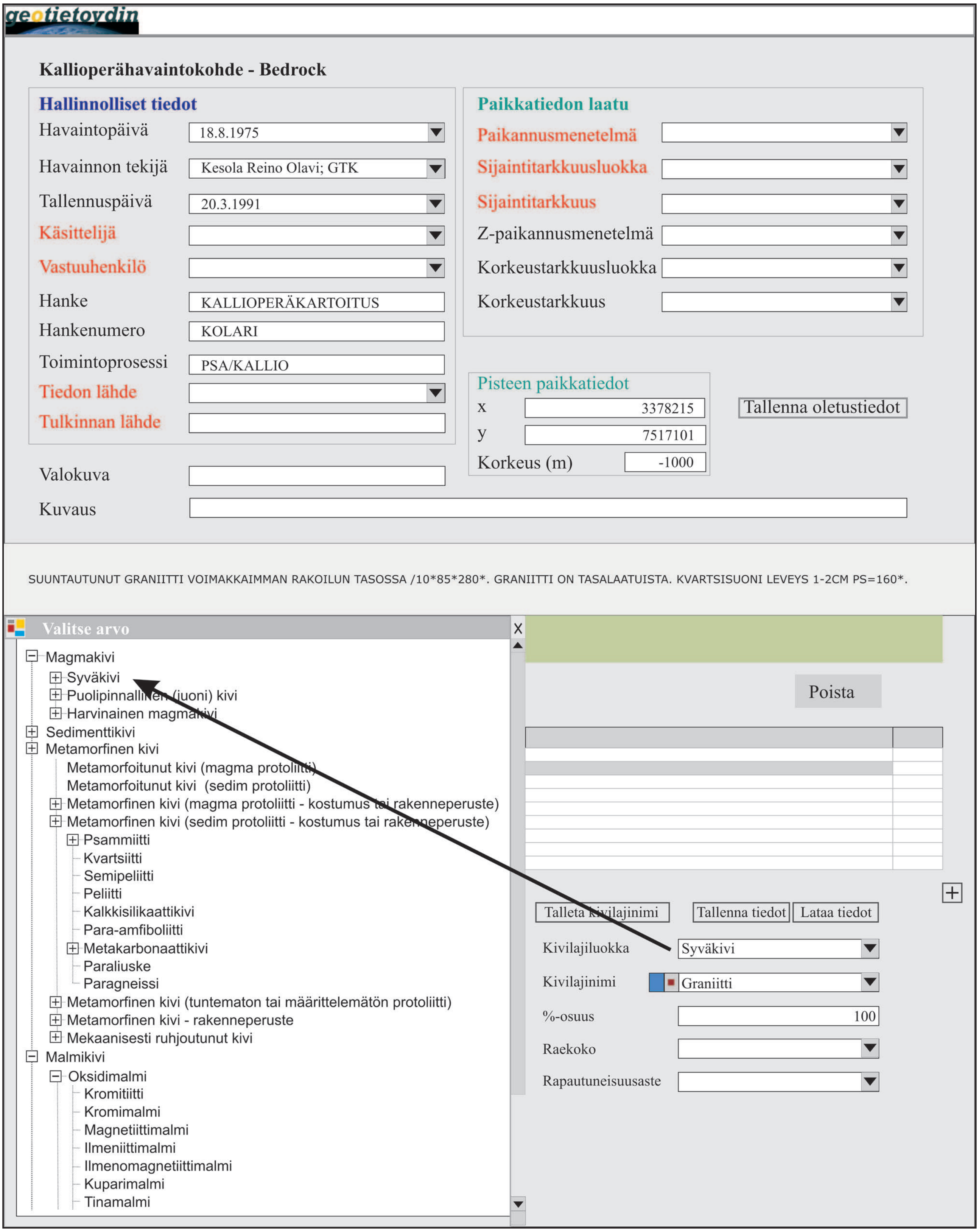

Figure 2. Part of the bedrock outcrop and boulder data capture interface "Kapalo" and the pick-up list of classified rock groups.

Kivilajit:Table

LKM	KIVILAJINIMI	KIVILAJINIMI_KORJATTU
1	AMFBOLIITTI	AMFIBOLIITTI
2	AMPHIBOLITE	AMFIBOLIITTI
1	AMFIBOLIITTI-KIVI	AMFIBOLIITTI
2	AMFIBOLIITTTI	AMFIBOLIITTI
1	AMFIBOLIITTIRAITA	AMFIBOLIITTI
3	PARA-AMFIBOLIITTI	AMFIBOLIITTI
1	SÄDEKIVI AMFIBOLIITTI	AMFIBOLIITTI
2	AMFFIBOLIITTI	AMFIBOLIITTI
1	AMFIBOLIITTI KERROS	AMFIBOLIITTI
21391	AMFIBOLIITTI	AMFIBOLIITTI
1	AMFIBOLIITI	AMFIBOLIITTI
1	AMFIBIOLIITTI	AMFIBOLIITTI
1	AMFIBOLIITTI.	AMFIBOLIITTI
2	AMFIBOLITTI	AMFIBOLIITTI
2	AMFIBOLIITTI(EMÄKSINEN VULKANIITTI)	AMFIBOLIITTI
84	AMFIBOLIT	AMFIBOLIITTI
1	AMFIBOLIIITTI	AMFIBOLIITTI
7	AMFIBOLIITTI/DIABAASI	AMFIBOLIITTI/DIABAASI
2	AMFIBOLIITTI/DIORIITTI	AMFIBOLIITTI/DIORIITTI
1	AMFIBOLIITTI/GABRO	AMFIBOLIITTI/GABRO
2	AMFIBOLIITTI/METADIABAASI	AMFIBOLIITTI/METADIABAASI
1	AMFIBOLIITTI/MEDIABAASI	AMFIBOLIITTI/METADIABAASI
2	AMFIBOLIITTI/ PERIDOTIITTI	AMFIBOLIITTI/PERIDOTIITTI
2	AMFIBOLIITTI/PERIDODIITTI	AMFIBOLIITTI/PERIDOTIITTI
3	AMFIBOLIITTI/SARVIVÄLKEGNEISSI	AMFIBOLIITTI/SARVIVÄLKEGNEISSI
1	AMFIBOLIITTI JA BIOTIITTIGNEISSI	AMFIBOLIITTI-BIOTIITTIGNEISSI
1	AMFIBOLIITTI-BIOTIITTILIUSKE	AMFIBOLIITTI-BIOTIITTILIUSKE
8	AMFIBOLIITTIBREKSIA	AMFIBOLIITTIBREKSIA
1	AMFIBOLIITTI-GABRO	AMFIBOLIITTI-GABRO
29	AMFIBOLIITTIGNEISSI	AMFIBOLIITTIGNEISSI

Record: 13 of 2537

A

Kivilajit väri:Table

LKM	VARI	VÄRI_KORJATTU
5	HAALEANPUNERTAVA	VAALEANPUNERTAVA
2	HAARMAA	HARMAA
1	HAARMAAN PUNAINEN	HARMAANPUNAINEN
2	HAMAA	HARMAA
1	HAMRAA	HARMAA
1	HAR	HARMAA
3	HAR.RUSKEA	HARMAANRUSKEA
3	HAR.RUSKEHTAVA	HARMAANRUSKEA
1	HARAMAA	HARMAA
1	HARAMAA-RUSKEA	HARMAANRUSKEA
1	HAREMAA	HARMAA
1	HARHAA	HARMAA
1	HARHAA, RUOSTEINEN	HARMAA
1	HARHAHTAVA	HARMAA
4	HARM.	HARMAA
4	HARM. PUNAINEN	HARMAANPUNAINEN
3	HARM. PUNERTAVA	HARMAANPUNERTAVA
1	HARM. PUNERTAVAA	HARMAANPUNERTAVA
1	HARM. RUSKEHTAVA	HARMAANRUSKEA
1	HARM. SININEN.	HARMAANSININEN
1	HARM. VIHERTÄVÄ	HARMAANVIHREÄ
1	HARM. VIHREÄ	HARMAANVIHREÄ
1	HARM./PUNAINEN	HARMAANPUNAINEN
1	HARM./VIHERT. ?	HARMAANVIHREÄ
1	HARM.+PUN.	HARMAANPUNAINEN
5	HARM.KIRJAVA	HARMAANKIRJAVA

Record: 1 of 4559

B

A	B	C	D	E	F	G	H
Koodi	**Arvo**	**Domainin nimi**	**Tietotyyppi**	**Koodi**	**Arvo**	**Domainin nimi**	**Tietotyyppi**
-1	Ei arvoa	gcvd_Colour	int	-1	Ei arvoa	gcvd_Colour_attributes	int
1	Vihreä	gcvd_Colour	int	6	Punaisen	gcvd_Colour_attributes	int
2	Harmaa	gcvd_Colour	int	7	Sinisen	gcvd_Colour_attributes	int
3	Keltainen	gcvd_Colour	int	95	Valkoisen	gcvd_Colour_attributes	int
4	Violetti	gcvd_Colour	int	96	Punertavan	gcvd_Colour_attributes	int
5	Musta	gcvd_Colour	int	97	Mustan	gcvd_Colour_attributes	int
6	Oranssi	gcvd_Colour	int	98	Keltaisen	gcvd_Colour_attributes	int
7	Punainen	gcvd_Colour	int	99	Vihertävän	gcvd_Colour_attributes	int
8	Ruskea	gcvd_Colour	int	22730001	Vaalean	gcvd_Colour_attributes	int
9	Sininen	gcvd_Colour	int	22730002	Tumman	gcvd_Colour_attributes	int
10	Tumma	gcvd_Colour	int	22730003	Harmaan	gcvd_Colour_attributes	int
11	Vaalea	gcvd_Colour	int	22730004	Puna-	gcvd_Colour_attributes	int
12	Valkoinen	gcvd_Colour	int	22730005	Kelta-	gcvd_Colour_attributes	int
13	Kirjava	gcvd_Colour	int	22730006	Sini-	gcvd_Colour_attributes	int
93	Vaaleahko	gcvd_Colour	int	22730007	Vihreän	gcvd_Colour_attributes	int
94	Tummahko	gcvd_Colour	int	22730008	Ruskean	gcvd_Colour_attributes	int
95	Ruskehtava	gcvd_Colour	int	22730009	Lilan	gcvd_Colour_attributes	int
96	Harmahtava	gcvd_Colour	int	22730010	Oranssin	gcvd_Colour_attributes	int
97	Lila	gcvd_Colour	int	22370098	Musta-	gcvd_Colour_attributes	int
98	Punertava	gcvd_Colour	int	22730099	Valko-	gcvd_Colour_attributes	int
99	Vihertävä	gcvd_Colour	int				

C

Figure 3a. The Kalpea database – primary field name (*kivilajinimi*) and corrected field name.
Figure 3b. The Kalpea database – primary colour (*väri*) and corrected colour (*värikorjattu*).
Figure 3c. Domain lists (gcvd_Colour/ and gcvd_Colour_attributes) in the new database.

THE GTK SEAMLESS BEDROCK MAP DATABASE – 2010

Another important component of the bedrock database design has been a seamless bedrock map database for Finland. The idea of GTK's seamless map database goes back to the beginning of the 2000s, but the actual work on building the database started in 2005. The decision to put an end to GTK's 1:100 000 bedrock mapping programme and the need to achieve a uniform presentation of the bedrock of Finland led to the implementation of a digital bedrock map database project called *DigiKP*, the aim of which was to produce a uniform seamless vector bedrock map to a scale of 1:200 000. The project was active in 2006–2009 and practically all the bedrock geologists in the GTK were involved in it.

The first plans for the database structure were based on traditional lithological mapping. However, even with careful planning, the process has not been straightforward. The first plan was replaced with a new approach at 2007. A new data model based on the NADM-C1 (NADMSC 2004) definition and supplemented according to national needs. The original plan for centralized storage based on an ESRI Geodatabase data structure (Oracle/ArcSDE platform) has also been revised and the databases are now divided into spatial (Oracle/ArcSDE) and non-spatial parts (Finstrati, the geological unit register with attribute data in relational databases). The idea of a divided architecture came from the plan of Geoscience Victoria of Australia (GSA) for a map database solution. Their primary plan was to store everything in an ESRI Geodatabase, but after an evaluation process a combination of RDBMS and GIS technology was selected (Simons et al. 2005).

The 1:100 000 bedrock map sheets of Finland were the most important source of data for the new map, especially where Southern and Central Finland were concerned. The areas without such maps were covered by 1:200 000 and 1:400 000-scale maps, and more detailed data (scale 1:4000–1:10 000) were available for some areas. A large number of maps (scale 1:10 000–1:20 000) produced by the Outokumpu company were also used as source data. For some areas in northern Finland, the relevant maps were lacking and were interpreted and digitized on the basis of outcrops and low-altitude airborne geophysical data.

Because of the great variety in the scale of the source data, the original idea of a map database to a scale of 1:200 000 was exchanged for a seamless map database without any specific scale. The product, termed DigiKP, is intended to be GTK's primary bedrock map database and will be updated regularly in the future. The products based on this primary map database will be maps to scales of 1:200 000 and 1:1 000 000. The former is a product that will be available for customers in the form of specified map sheets and data and also as an Internet map service (Figure 4a – http://www.geo.fi/en/bedrock.html), while the latter will be a simplified bedrock map database covering the entire area of Finland.

A database of stratigraphic geological units (Finstrati) was also developed during the DigiKP project by extending the division of the bedrock into stratigraphic units that had formerly been in use only in Northern Finland to cover the whole country. Almost 2000 lithostratigraphic or lithodemic units were generated and described. The units were first stored with an MS Access-based system and will subsequently be incorporated into the GTK geodatabase. The nomenclature was generated according to international rules (North American Commission on Stratigraphic Nomenclature 2005) and in co-operation with the Stratigraphic Commission of Finland. Most of the database value lists (e.g. unit, contact_type, process, environment and event – Figure 4b) are based on hierarchical classifications vocabularies and have been adopted from IUGS–CGI work. These classifications will facilitate our plans to use the database for interoperability purposes in the future (e.g. INSPIRE–OneGeology–GeoSciML–EarthResourceML)

Stratigraphic codes are included in the map database as attribute data. This is a huge improvement on earlier bedrock maps, which had only lithology coding. In the first stage (version 1.0), the bedrock map database in the Geokernel system (Finn. *Geotietoydin*) is composed of polygonal geological units, source data and quality layers together with a line-based structure layer, but there are plans to add dyke, metamorphic, structural analysis and ore potential maps, among others, to the database in the future. Both the map database and the stratigraphic unit database will be updated regularly.

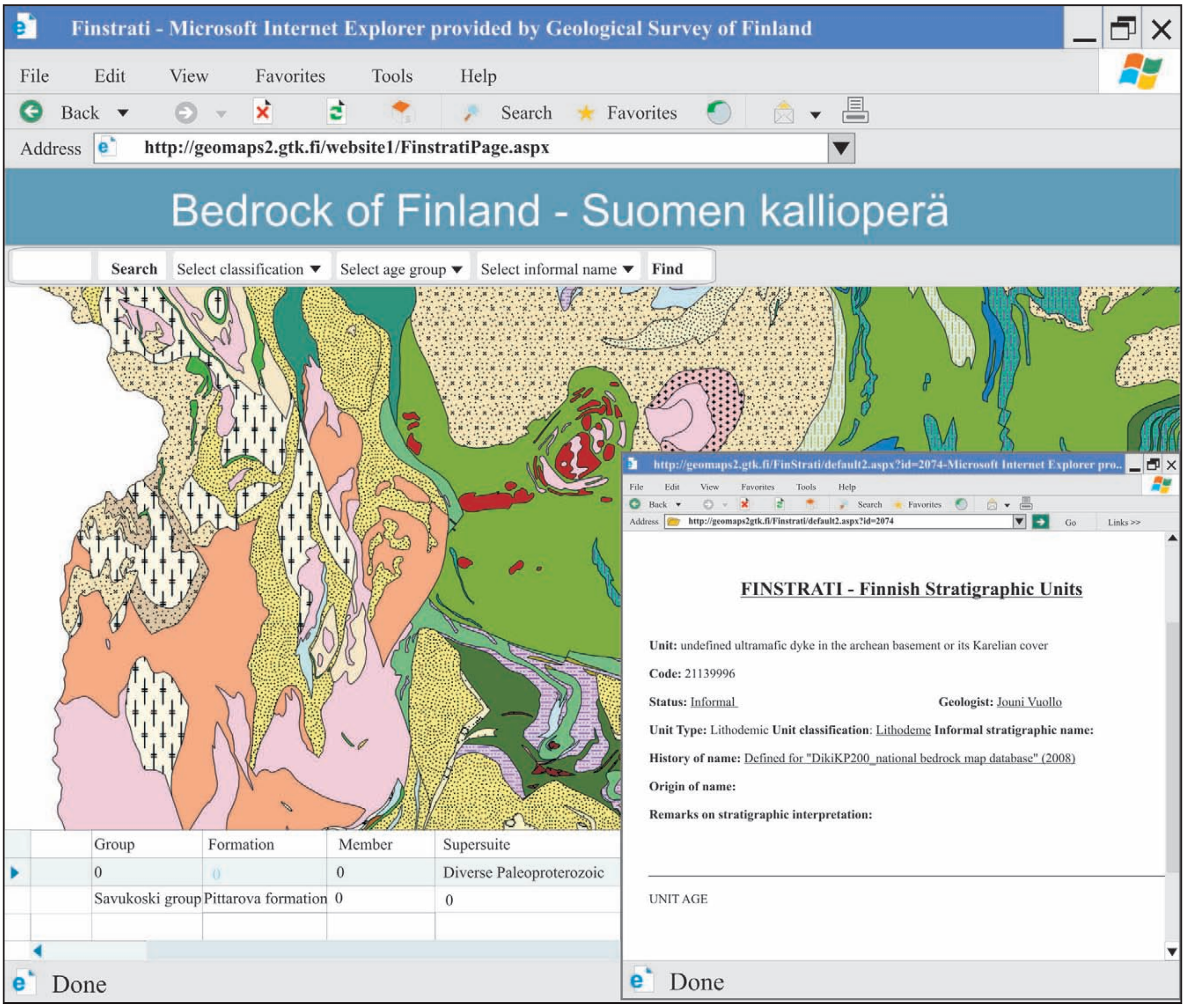

Figure 4a. Snapshot from "Bedrock of Finland" – the service opened on 5.3.2010.

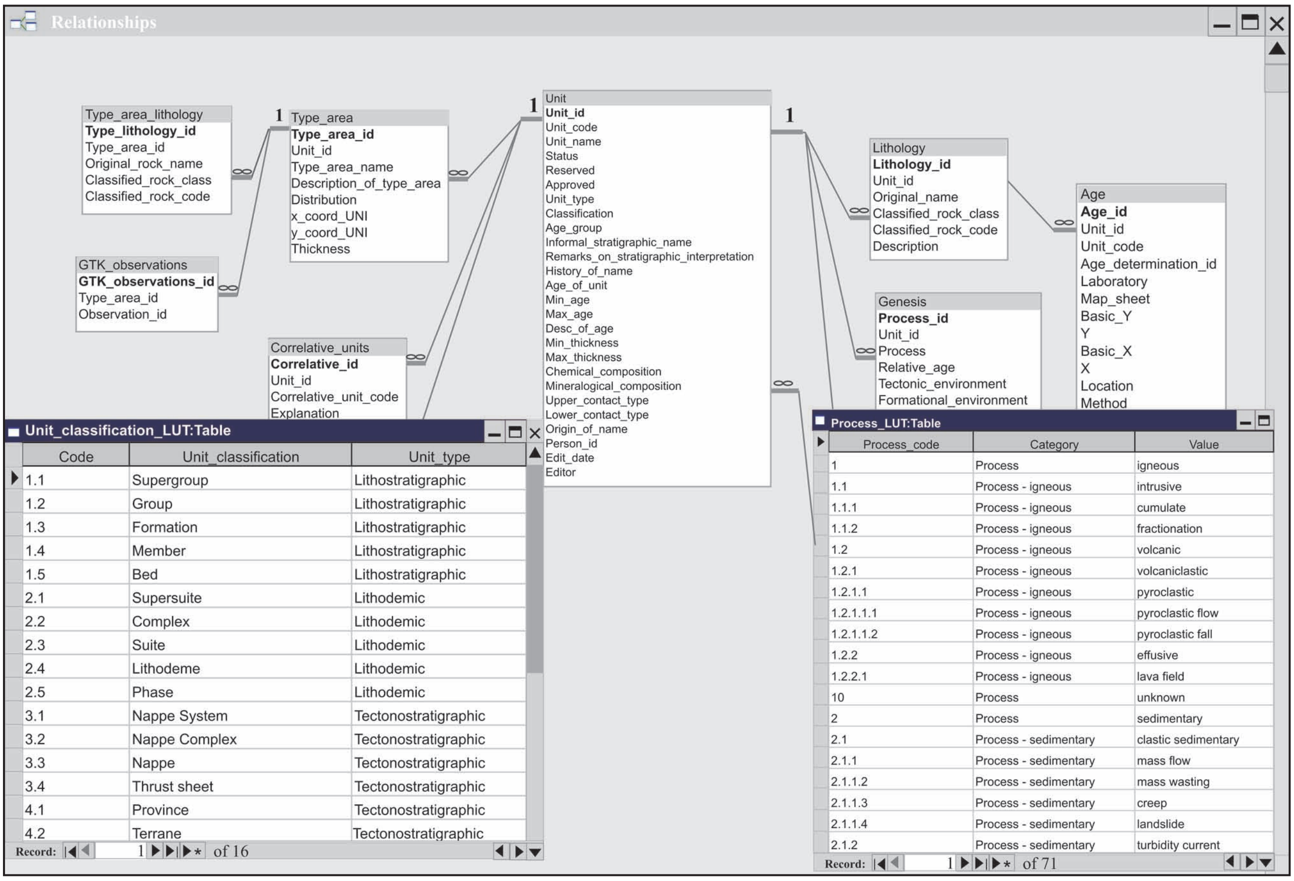

Figure 4b. The data model and code lists for Finstrati.

FUTURE PLANS

Many factors that constrained our predecessors no longer exist. Modern computing systems (GTK's new databases, GIS and Internet tools) allow us to store, retrieve and present far more information and knowledge than we could ever show on two-dimensional paper maps. The whole data capture process has changed in the last few years with the introduction of rugged PCs and GPS receivers, and all data sets can also be made available in the field. At the same time, web services and the needs for interoperability impose new challenges. These changes have created a totally new range of possibilities and challenges for our geological databases – in terms of structure, standardization and above all data quality. Examples of the challenges include the questions of how to manage the workflow from project maps and other data sets in GTK's seamless bedrock map database (DigiKP) and how to create a workable updating process for this database and its products.

GTK´s vision is of being a national geoinformation centre finding ways to make numerical datasets accessible, relevant, and easy to use. Interoperability in Europe due to the EU's INSPIRE directive (http://www.inspire-geoportal.eu/) and global collaboration (OneGeology; http://onegeology.org/) requires normative conceptual data models, classification systems, and common geological terminology. For this purpose, GTK is moving towards harmonized databases, governed largely by the recommendations of the INSPIRE directive and the technical specifications contained in the emerging data transfer standard e.g. GeoSciML (http://www.geosciml.org/)–EarthResourceML (http://www.earthresourceml.org/). International networking, for instance with the IUGS–CGI [http://www.cgi-iugs.org/], NADM [http://nadm-geo.org/] and GeoSciM–EarthResourceML teams, plays a significant role in this harmonization process.

Supplementary information on the web:

http://en.gtk.fi/ExplorationFinland/Commodities/
http://www.cgi-iugs.org/
http://www.geosciml.org/
http://www.earthresourceml.org/
http://www.geo.fi/en/bedrock.html
http://www.inspire-geoportal.eu/
http://onegeology.org/

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Geological Survey of Finland, Special Paper 49, 345–348, 2011

COLLECTION, MANAGEMENT AND DISTRIBUTION OF DATA ON SURFICIAL DEPOSITS

by
Jukka-Pekka Palmu

Palmu, J.-P. 2011. Collection, management and distribution of data on surficial deposits. *Geological Survey of Finland, Special Paper 49*, 345–348, 1 figure.

The mapping and management of data on superficial deposits have evolved into a streamlined, efficient process during the last ten years. The traditional mapping workflow, using paper maps, notebooks and so on, has been replaced by a solution based on rugged and powerful field computers with GPS and GI software. Mapping information is inputted using a pen on a touch-sensitive screen.

Various primary data (e.g. topographic basemaps, digital aerial photographs, lidar-based digital elevation models) are loaded into the field computer and are also accessible during the new mapping process, speeding it up and making it more accurate.

Ongoing international standardisation work in the fields of both GI (INSPIRE) and geology (GeoSciML) is also increasingly important for Finland and the Geological Survey of Finland (GTK).

Keywords (GeoRef Thesaurus, AGI): surficial geology, soils, mapping, data acquisition, data management, data bases, Finland

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INTRODUCTION

During recent years, the emphasis in the collection and management of data on superficial deposits has shifted towards a user demand-based approach. For data on superficial deposits, this change has created a need to collect new types of data that were not required in the past. There is also a growing need for the data to be more location-accurate compared with what has traditionally been the accuracy considered relevant for geological mapping data.

At the same time, the revolution in geological data collection possibilities (GPS, field computers etc.) has caused a transformation in the mapping and data collection process. There has been heightened emphasis on the accuracy and relevancy of the collected data. This makes the development and management of the data collection process a demanding task. Consequently, the above-mentioned new tools are vitally needed to maintain and improve efficiency.

A large amount of older field observation data and other data, for example from test pits, boreholes, sedimentary units and seismic profiles, are often highly relevant and need to be made more readily accessible. Analogue profiles have to be scanned and linked with locational information in GI systems. This work already started in the 1980s and will continue, using an order of data importance approach.

Background

In Finland, the mapping of superficial deposits was originally undertaken as part of a geological mapping programme that began in the 1860s. The geological map combined information on both the superficial deposits and bedrock. Polygon data on the superficial deposits were already classified into a combination of genetic and material classes.

In the late 20th century, the mapping programme was divided and the mapping scale was changed from 1:200 000 to 1:400 000. Books providing map explanations were also produced. This mapping continued into the 1930s and the mapped area covered southern and central parts of Finland.

After the Second World War, the mapping programme for superficial deposits continued in the northern part of the country at the scale of 1: 400 000. For the southern parts of the country, a mapping programme at the scale of 1:100 000 was started.

The actual mapping process was originally mainly based on field observations, notes being collected and mapped units being drawn on field maps, from which material the printed maps were produced by the usual mapping data compilation. From the early 1960s, especially for the mapping of Lapland, aerial photograph interpretation was introduced. The mapping process was based on a morpho-litho-genetic approach and field notes were systematically collected. Map explanations were produced for each map, based on the mapping data and field observations.

In the 1970s, a superficial deposits mapping programme started at the scale of 1:20 000. The mapping was carried out in cooperation with the National Land Survey until 1995. Institutes in the agricultural and forestry sector were also involved in this work. This mapping programme mainly produced maps and less emphasis was placed on field note collection.

The first large-scale use of data management with computers in the mapping and collection of data from superficial deposits started in the early 1970s in connection with peat resource investigations, and during the same timeframe geochemistry data management was also computerised. For the core process of mapping superficial deposits, a data register for data management was introduced in the late 1970s, initially for the observations and borehole data management.

FINGIS software was introduced for map production purposes in the late 1980s. This software is still useful for digitizing. The data file formats of the system can be transferred into a true GI system. The ArcInfo GI system was selected after an exhaustive selection process and was brought into use during the early 1990s.

During the 1990s, the advantages of using of a GI system became increasingly appreciated. However, at the same time it was noted that the efficient use of a GI system, and indeed, an efficient geological mapping and data collection process, requires a comprehensive data management solution. For this purpose, a development project started in the late 1990s. This project has evolved during the 2000s and now covers not only the spatial data-based GI system information, as in our geodatabase in Geotietoydin (GeoKernel), but also the various databases and other components that together comprise the current and further evolving Geodata warehouse (Figure 1).

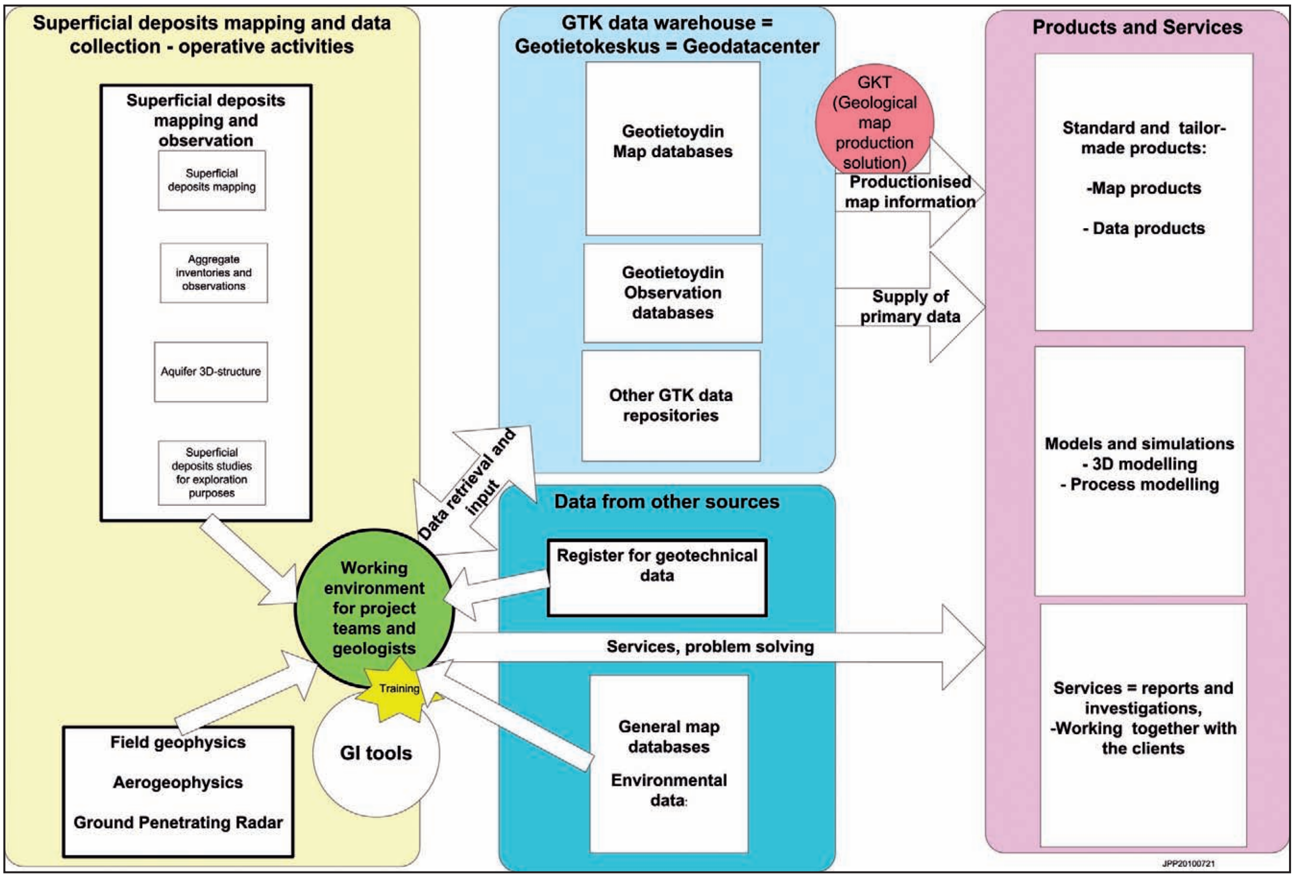

Figure 1. The superficial deposits data flow chart. The data collection and edition components are on the left, in the middle are the data warehouse parts and on the right are the output client-servicing components.

DATABASES

For the mapping data on superficial deposits, a scale-reliant approach has been chosen. Currently, the most accurate database is at the scale of 1:20 000, partly at the scale of 1:50 000 (http://geomaps2.gtk.fi/geo/, guide (in Finnish): http://weppi.gtk.fi/aineistot/mp-opas/). These mapping data cover about one-third of Finland and will be developed and transferred to the new coordinate system and map base, at the scale of 1:25 000.

The coarsest superficial deposits map database has a scale of 1:1000 000. The newest map database (http://geomaps2.gtk.fi/geo/ or http://geomaps2.gtk.fi/activemap/), at the scale of 1:200 000, covers the whole country and currently consists of a soil (grain size based) information layer. This map database is under development and will in the future also include proper layers for superficial deposits (geological units), an overburden thickness theme and themes dealing with deglaciation and glaciodynamics, as well as a shoreline height through time theme.

A new 1:10 000 scale map database is under consideration. It will especially be used for new mapping and will emphasise the accuracy of data and 3D information management. It will include the use of Lidar data and the types of areas to be mapped will probably be, at least in the beginning, areas of intensive land use and the most important groundwater areas, eskers and end moraines, such as the Salpausselkäs.

For the observation data, a module has been developed in ArcSDE. It contains old data transferred from an earlier observation data management system, the latest of which was Maakanta, an Oracle database. Considerable resources were needed to repair and unify the old data before the transfer could be carried out.

For borehole data management, a two-fold solution has been chosen. In the Geotietoydin Profile point structure we can manage interpreted borehole data, with the data interpreted as geological units. The other data management solution is based on the Infra standard for borehole and other geotechnical data developed in the 2000s in Finland. The survey has Oracle-based software for this data management. In the future we will integrate these two borehole data management solutions by developing interfaces for interoperability.

For field geophysics data, a database solution is under development. The initial emphasis is on field data management (measurements etc.), but will later also include interpretation.

FIELD DATA CAPTURE AND MANAGEMENT SOLUTION 2010

For the mapping and observations of superficial deposits, an ArcMap-based solution, Maapeli, is currently in use. The field observer or mapper can choose the grain size classification and collect the data for both the map (ultimately map data = points, lines and polygons) and/or collect the basic observational data. The software can be used for both the fieldwork stage and also for data editing in the office. The SDE approach gives the choice of using existing mapping, observations and borehole data as background data, or updating the data, and the third possibility is to use the data structure (empty database) as a basis for new data collection.

For sand and gravel (aggregate) resources in superficial deposits (http://geomaps2.gtk.fi/Kiviainestilinpito/) there is a separate database and interface, Maali. It uses the same principles as the other main data management component of the Geotietoydin.

Another important component in the data management system is the Geodata file management system and the GISDataMenu interface for the efficient use of the various geological and other GI data. This interface is linked to both the core database (ArcSDE) and also to other, non-GI databases and registers in order to provide access to project data and other nonstandardised data.

FUTURE PROCESS IMPROVEMENT

In the future, the field mapping solution, including the collection of observational data, will probably evolve towards a net-centric approach, with high-speed, low-cost wireless connections. Both corporate data and also the common GI databases could then be accessible in real time. This would free the fieldworker from time-consuming preliminary GI data preparation.

Another possibility is to update the main GI databases without the time lag that is inevitable when using the existing approach. In most cases, the timing of geological fieldwork data management is probably not critical, so this solution might only become common later on.

Providing the geological data to the various end users in various data forms is one of the key challenges for the geological surveys in the future. Steps have already been taken to serve the users and their demands, but a lot is still to be done. The INSPIRE directive is also affecting data policies and is guiding the development of process and data management work in the surveys.

In the future, the data management solution will comprehensively integrate the standardisation work carried out internationally, for example in the GeoSciML development. The management will move towards using international standards and will include a geological unit management approach. For superficial deposits, the basic unit will be a morpho-litho-genetic unit, similar to what British Geological Survey is using (BGS Rock Classification Scheme - Vol 4 – Superficial, 1996). For the units, databases similar to the FinStrati database will be used, as in bedrock data management.

Supplementary information on the web:

GeoSciML
http://www.geosciml.org/, also:
http://www.cgi-iugs.org/tech_collaboration/geosciml.html

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AIRBORNE GEOPHYSICAL DATA MANAGEMENT AND INTERPRETATION

by
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Airo, M.-L., Hautaniemi, H., Korhonen, J. V., Kurimo, M. & Leväniemi, H. 2011. Airborne geophysical data management and interpretation. *Geological Survey of Finland, Special Paper 49*, 349–358, 6 figures.

Nationwide airborne geophysical surveys undertaken by the Geological Survey of Finland (GTK) were completed in 2007 and altogether covered about 1.90 million line kilometres. Magnetic, radiometric and multi-frequency EM survey data were systematically acquired at 200 m line spacing and 30 m nominal terrain clearance, along north-south or east-west trending flight lines. Consistent countrywide data grids have been generated at a 50 m grid cell size and incorporate GIS-compatible source data for integration with other geoscience data in mapping, exploration and for environmental purposes. Airborne geophysical data archives include both survey line data and grid products. Throughout the 35 years of surveying, direct first-pass interpretation of these data has been carried out on a map sheet basis. Rock samples from the entire country have been gathered for physical property determinations to establish a petrophysical database. An interpretation package has been introduced for accessing detailed geological and geophysical information, and map compilations of larger areas have formed the basis for understanding regional geology. Interpretation is in progress to deliver countrywide geophysical imagery for ArcGIS applications. These could be used to further customize interpretation and ground surveys for local investigation, as well as predictive targeting using neural networks. GTK's expertise in aeromagnetic mapping and map compilation of diverse datasets is acknowledged in an international project that is compiling the first magnetic anomaly map of the world (2007) at the scale 1:50 000 000. The project is a joint effort between numerous scientific organizations including the IAGA, CGMW and world geological surveys. The project at GTK is planned to be extended until 2011 to allow the compilation and release of a new edition of the map and databases.

Keywords (GeoRef Thesaurus, AGI): geophysical surveys, airborne methods, data management, interpretation, petrophysics, magnetic anomalies, aeromagnetic maps, Finland

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INTRODUCTION

Finland has been covered by airborne geophysical measurements in two successive mapping programmes. The first, so-called 'high-altitude' mapping programme started in the early 1950s and lasted for about 20 years. It was followed by more high-resolution surveys of the so-called 'low-altitude' mapping programme. The Geological Survey of Finland (GTK) conducted these programmes in a systematic way with the goal to create constant countrywide airborne geophysical databases to be used as a reference in geological mapping and exploration.

The first two chapters in this report describe the data collection and the techniques adopted in the integrated interpretation. A characteristic of GTK surveys is the '3-in-1' approach: simultaneous measurement of magnetic, electromagnetic (EM) and radiometric data. In particular, GTK has focused on developing the frequency-domain EM method, which is well suited to mapping electrically conductive sulphide deposits close to the surface. Typical applications of '3-in-1' surveys nowadays include bedrock mapping, environmental monitoring and raw-material investigations. The combination of '3-in-1' data and the national petrophysical database offers a unique resource for geophysical and geological modelling and GIS-compatible interpretation. The high quality and resolution of GTK's aerogeophysical datasets allow the application of statistical and neural network approaches to encourage data mining processes and mapping of the mineral potential.

One of the original aims of countrywide airborne geophysical surveys was to create a general picture of geophysical anomalies in Finland. These data also enable the integration of Finnish data into cross-national aeromagnetic datasets. The third chapter of this report describes how local aeromagnetic datasets have been integrated into multi-national and global magnetic anomaly maps.

This report provides a brief description of GTK's airborne geophysical databases, their maintenance and interpretation. Articles providing more detailed information and further references can be found in Airo (2005).

LOW-ALTITUDE AIRBORNE GEOPHYSICAL DATA COLLECTION

The National Airborne Geophysical Mapping Programme

During 1972–2007, the Geological Survey of Finland (GTK) conducted a systematic programme of high-resolution, low-altitude airborne geophysical mapping of the entire country (Hautaniemi et al. 2005). The methodology was based on the experience and know-how acquired during the first national airborne geophysical programme in 1951–1972. The low-altitude mapping programme and resulting countrywide maps have been summarized by Moore (2008).

Methodology

The geophysical system included three geophysical methods: magnetics, electromagnetics (EM) and gamma-spectrometry. The key points in ***magnetic surveys*** were 1) the use of two sensor systems (horizontal gradiometry) as a wing-tip installation to improve data interpolation between flight lines and 2) systematic levelling of all surveys to the reference year 1965 by a survey base station and two geomagnetic observatories in Finland, and then subtracting of IGRF-65. The ***frequency domain EM*** system was designed and built entirely in-house at GTK, and the 3 kHz frequency was selected to meet the demands of exploration for base-metal bearing sulphide deposits in Precambrian shield areas. The ***radiometric*** data face challenges with the thick overburden spread out during glacial periods.

Data collection

The whole country was covered by a strict systematic survey during a 36-year period. The flight line spacing was fixed to 200 metres and the mean terrain clearance to 30 metres. The survey areas were selected according to the Finnish map sheet system. Throughout the survey period, the geophysical parameters were basically kept constant.

The selection of the annual survey area was based on GTK needs and the fact that the survey season is very limited in northern Finland (Figure 1). The flight season was started in the south after the snow had melted; in midsummer, flights were then carried out in the north, slowly returning to the south in the autumn. The annual survey flight hours were maximized with two full flights daily and a 6- to 7-day working week (Figure 2). The safety of low altitude flying was carefully considered, and often two pilots were accompanied by a navigator. The aircraft was leased from an aviation company with long-term agreements to ensure the safety and professional skills of the pilots.

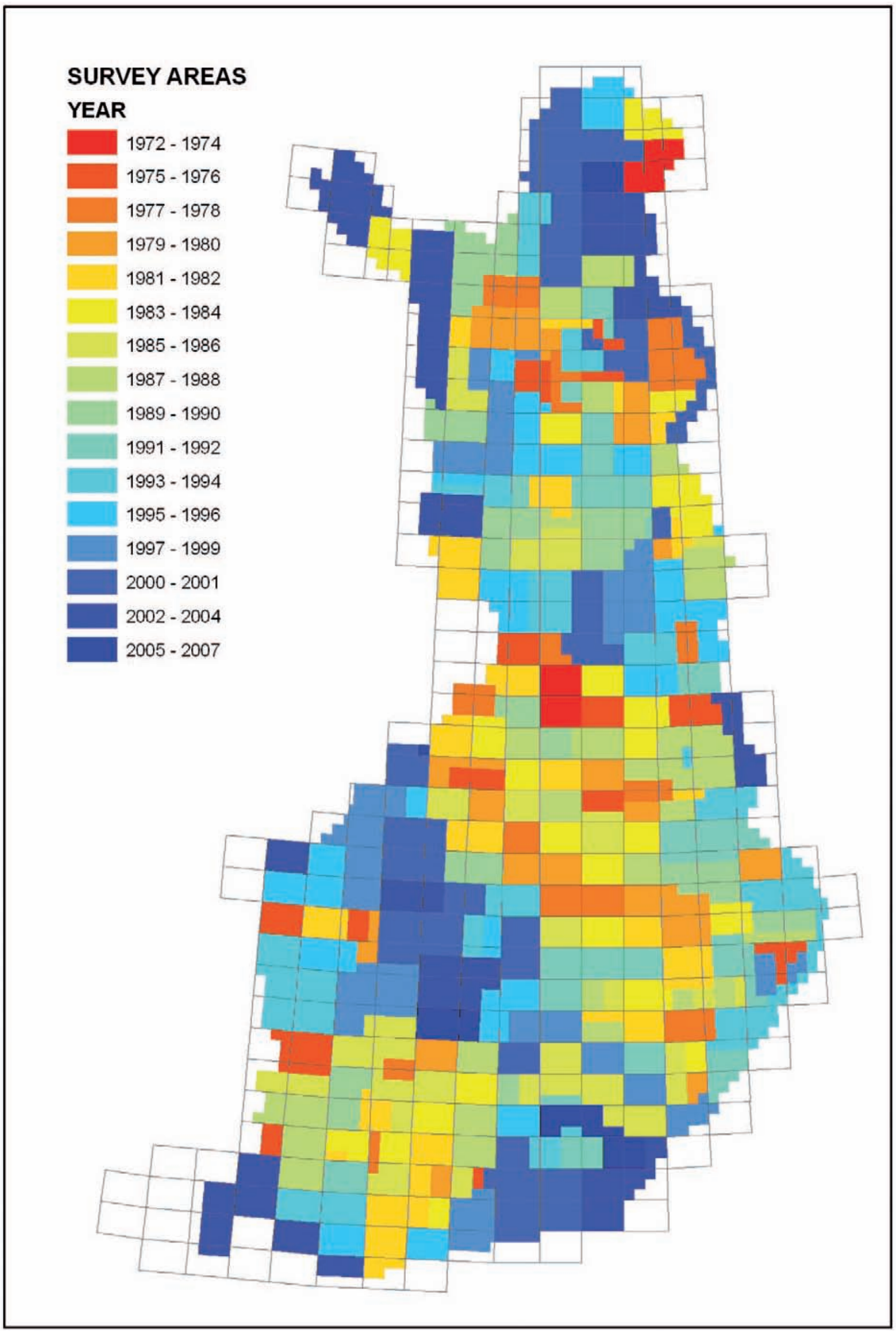

Figure 1. Annual survey areas of the National Mapping Project.

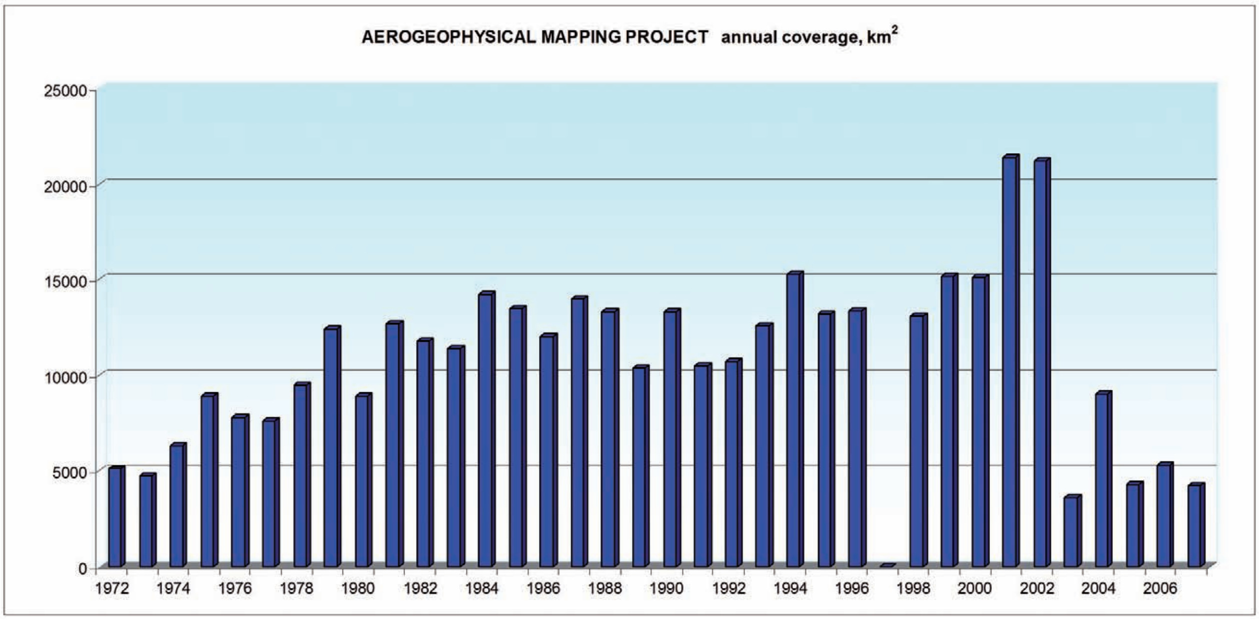

Figure 2. The annual survey coverage of the National Mapping Project.

The quality of measured data was carefully monitored during the survey, and after the flight the data were checked as soon as possible. At first, the daily flight tapes were sent by air freight to the GTK office; later, the data were checked in the field immediately after each flight. The annual calibrations were carried out using constant calibration areas, above a deep part of the Baltic Sea for EM and a permanent calibration line near Helsinki for radiometrics.

The instruments were upgraded and modernized continuously. For the radiometrics, the crystal size was increased from 27 litres to 41 litres and the number of spectrometer channels from 36 to 256. The magnetometer accuracy improved when proton sensors were replaced with caesium sensors and the resolution was increased from 2/s to 10/sec. The EM development steps included the adding of a second frequency in 1996 and the implementation of a four-frequency system in 2006 (Leväniemi et al. 2009). In 1993, navigation accuracy was improved by GPS. The processing software was under continuous development, the most important steps being during the 1990s with data visualization and field laptops.

The raw data from the aircraft and base station, with positioning and other auxiliary information, were collected daily and archived. The geophysical data were methodologically corrected with calibration and positioning data, as described in Hautaniemi et al. (2005). All filtering was avoided in order to keep the data as original as possible. EM levelling is always problematic, and the methodology has been developed together with increased technical capabilities.

The final results include digital, corrected data in two formats: corrected data along true flight lines in ASCII XYZ format and with original sampling intervals, and interpolated grids with a 50 metre cell size.

Data maintenance and archiving

The quality of the early data is variable and computer and software technology during the 1970s and 1980s had limitations. The calibrations were inadequate in comparison to current standards. Three different aircraft and two coil configurations in EM were used in data collection, causing a challenge in the combining of the data. The amount of data is huge, comprising over 300 separate flight areas, about 53 500 flight lines and ca.1.90 million line kilometres of magnetic, radiometric (Tot, K, U, Th), EM (1–4 frequencies) and apparent resistivity data.

The first-phase radiometric correction included re-levelling, the correction of a few malfunctions, false anomalies and coordinate problems. Radiometric components are often presented as ratio maps and their efficient use requires the further fine tuning of re-levelling, as well as radon verification and removal for the entire data (U, Tot).

The first phase of correcting the 3 kHz EM data was carried out in 2009. The zero levels were re-levelled for the first time throughout the entire country (real and imaginary components, and apparent resistivity, Figure 3). The approximated coefficients for the oldest non-calibrated data will then be determined and a second levelling carried out on the whole dataset. The high noise levels are also a problem for some areas. Coordinate errors and malfunctioning of equipment also need to be corrected for in many areas.

The entire magnetic data set will also be corrected in the near future, mainly by re-levelling the data and recalculating the secular corrections.

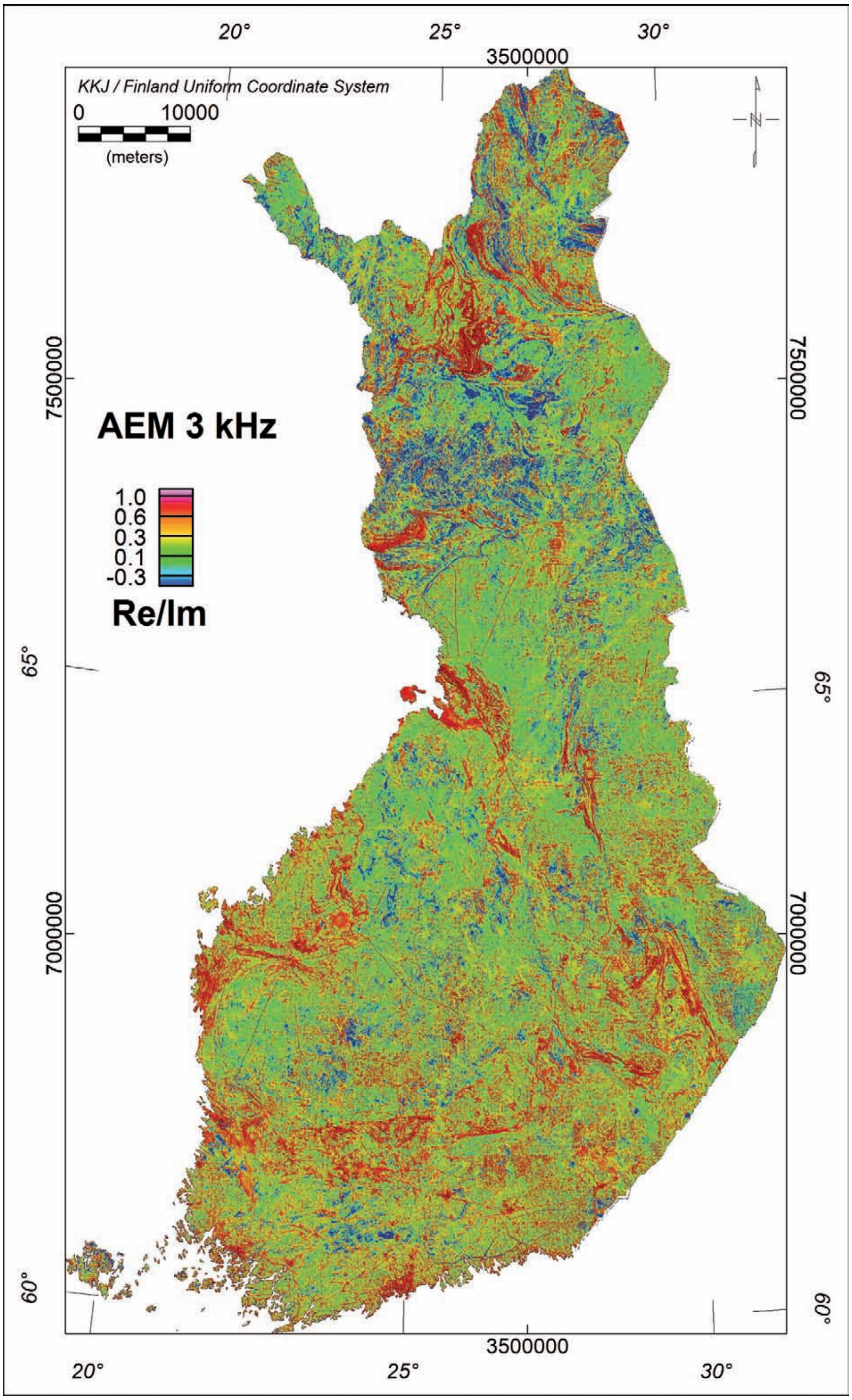

Figure 3. The calculated ratio of real and imaginary components of the airborne electromagnetic field (3 kHz).

INTEGRATED INTERPRETATION ASSISTED BY PHYSICAL ROCK PROPERTIES

Interpretations of airborne geophysical survey data are carried out on an integrated basis, correlating geological, petrophysical or geochemical data, and incorporating terrain data and satellite imagery. Interpretations aim at finding geological reasons for geophysical anomalies and at explaining the survey results and the calculated models based on them. Depending on the objective of the interpretation, airborne data are used in data and grid analysis for surface mapping and characterization, or 2D and 3D modelling to add a depth dimension and to understand the subsurface geometry.

Mapping and monitoring

GTK's airborne geophysical dataset contains extensive and versatile geophysical and geological information to be used in mapping and characterizing the survey area and in identifying features that may be critical for resource exploration. In some areas, airborne surveys have been conducted repeatedly and comparison of the datasets from different years may be valuable in environmental monitoring. Various tools, filtering and enhancement methods are applied in grid texture analysis, lineament and edge detection, and the classification of geological provinces possessing different geophysical properties. A variety of processed airborne geophysical images are used to characterize the lithology and locate structures of interest, to describe the configuration of rocks or soils and structures in the ground and to extend the known geological features to areas where the outcrop information is limited.

When looking for local features, the analysis of profile data from flight lines may provide access to more detailed analysis. For example, subtle local magnetic intensity variations related to fracture and joint settings have been highlighted by directional trend analysis and discontinuity structure detection of magnetometer data along survey lines (Airo & Wennerström 2010). The local radiometric response attributed to hydrothermal alteration associated with mineralization may also require detailed analysis of flight line data (Airo 2007).

To help in the utilization of the wide range of airborne geophysical datasets, an ***interpretation package*** has been developed for lateral mapping of surface geophysics. The package provides a general picture of the variation in the lithology and soil in the study area and formulates a first-pass interpretation that helps in the selection of targets for more detailed investigations. The interpretation package introduces processed easy-readable geophysical images: the example in Figure 4 is from southern Finland. Classification of radiometric and AEM datasets is represented as overlays on aeromagnetic images: either total magnetic intensity (TMI) or derivative data. The radiometric classification shows the highest K, Th and U radiation counts as cut-off values. Some of the radiometric anomalies reflect the bedrock, but soil and infrastructure strongly disturb the geological response. The AEM colour categories in Figure 4 are based on analysis of in-phase (**Re**al) and quadrature (**Im**aginary) components and are related to the variation in the electrical conductivity of the ground. The negative in-phase response in frequency-domain AEM data is related to high magnetic permeability due to an abundant magnetite concentration. The map compilation of the AEM **Re/Im** ratio for the whole of Finland in Figure 3 demonstrates the distribution of high electrical conductivity associated with schist belts and high magnetic susceptibility mainly associated with igneous rock rich in magnetite. In particular, granitoid areas and ultramafic rock sequences are emphasized in Finnish Lapland. In southern Finland, the gabbro intrusion of Hyvinkää and the highly magnetic granitoids in the Häme region are distinguished by their negative EM real component.

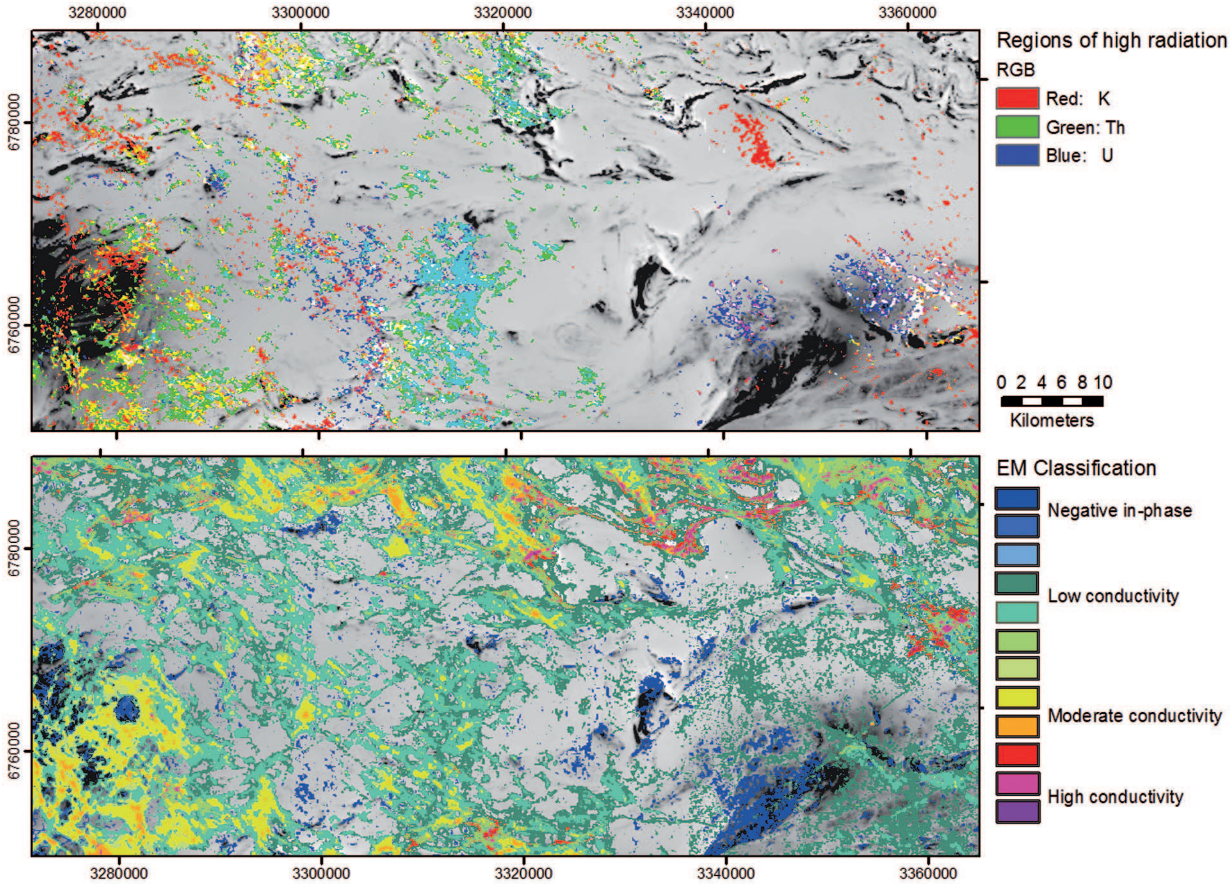

Figure 4. The interpretation package. Geophysical 'easy-reading' interpretation images: an aeromagnetic grey-scale image as the background, with high-radiation regions (top panel) and AEM categories (bottom panel) as overlays.

Modelling

Supplementary petrophysical rock parameters improve the modelling when creating numerical estimates of the depth and the dimensions of the anomaly sources. Creating conceptual models of the subsurface involves the quantification of geophysical properties and matching of properties to rock types, mineralization types or ore grades. Investigation of the magnetic signature, i.e. the magnetic anomaly texture and intensity variation, may be of key importance in resource exploration, because rock magnetic properties record the magnetic – and the geological – history of rock. The remanent and induced magnetizations play a role in producing the magnetic signature and describe the magnetic mineralogy of rock. Remanent magnetization correlates with grain size and induced magnetization depends on the ferrimagnetic mineral content. Figure 5 compares remanent and induced magnetizations determined in the laboratory for samples representing different rock types. A predominance of induced magnetization causes a soft, consistent magnetic anomaly signature, often related to magnetite. Prevailing high remanence causes sharp, discontinuous magnetic anomalies and may indicate monoclinic pyrrhotite or fine-grained magnetite. Hydrothermal alteration or other geological processes related to mineralization affect the magnetic mineralogy and thereby the magnetic properties (Airo & Mertanen 2008). The interpretation and identification of alteration zones also incorporates radiometric and EM signatures.

For data mining and predictive targeting based on statistical or neural network methods, GTK's airborne geophysical datasets provide an endless resource. Interpretation is in progress to classify geophysical clusters with similar spectral signatures in different geological provinces in Finland and to create prospectivity models for different mineralized areas. Classification and prospectivity modelling have been applied to GTK's survey data collected in international airborne geophysical projects.

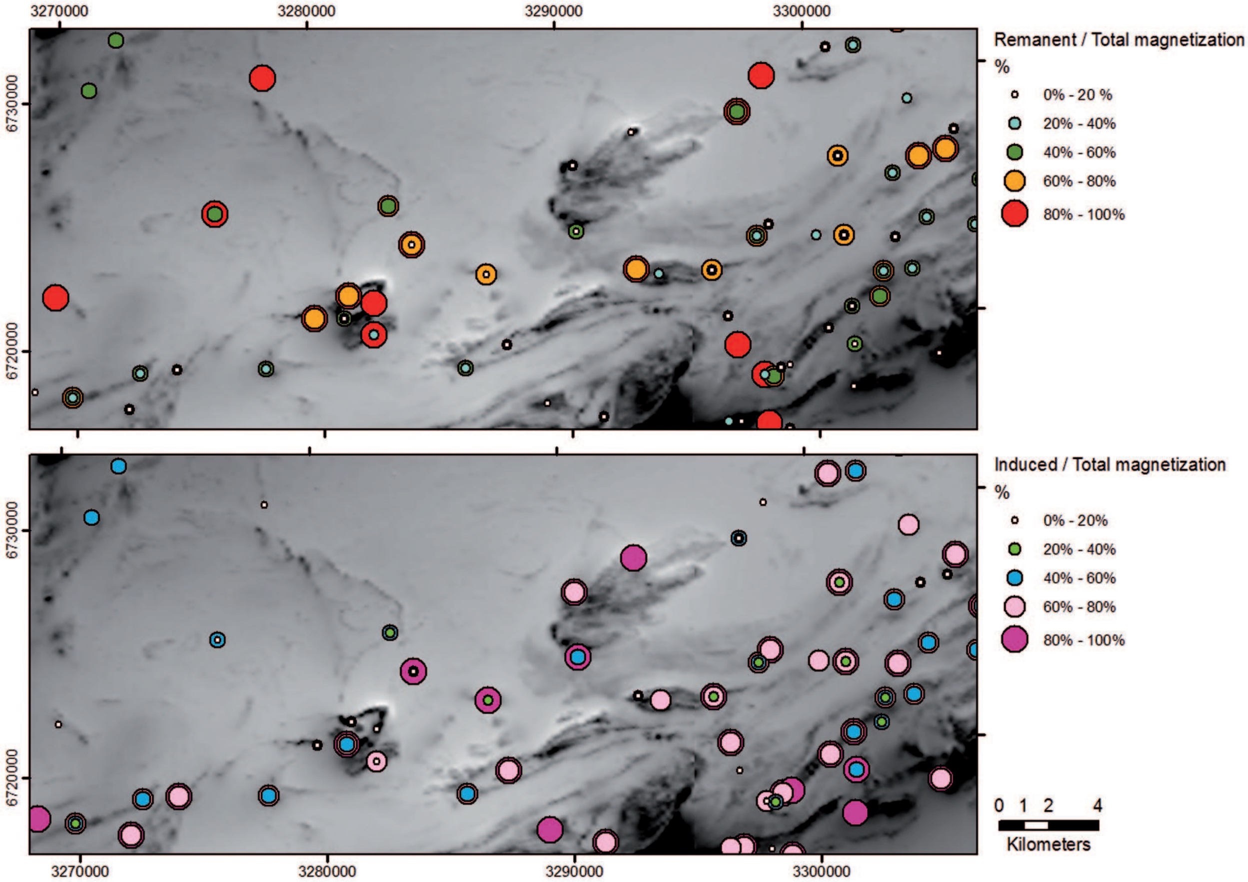

Figure 5. Physical rock property data (total magnetization) from the petrophysical database. The background image is TMI. Comparison of magnetization components: warm colours indicate a predominance of remanent magnetization (top panel) or induced magnetization (bottom panel).

A MULTINATIONAL AND GLOBAL VIEW OF MAGNETIC ANOMALIES

For almost two decades, Finnish aeromagnetic surveys were based on analog data processing and drafting methods. The numerical work was begun by digitizing hand-drawn anomaly maps and by measuring long, digital tie lines across the country in 1968–69. This led to two branches of aeromagnetics at GTK: new digital national airborne mapping at a lower altitude and digital compilation and interpretation of magnetic anomalies from regional to international scales (Hautaniemi et al. 2005, Korhonen 2005).

The Finnish high altitude aeromagnetic map set at the scale of 1:20 000 was digitized to a 1 km x 1 km grid. The aim was to prepare an overview of the magnetic anomalies of the country, and to facilitate using Finnish aeromagnetic data jointly with neighbouring and global datasets. In ten years the first Finnish aeromagnetic summary was ready (Korhonen 1980). A printed anomaly map was presented to IGC26 for geological studies and a numerical grid to the IAGA for the European and global compilation of anomaly grids. During the following decades, GTK developed co-operation with neighbouring countries, finally compiling and providing access to a joint magnetic (1 km x 1 km) and gravity (2.5 km x 2.5 km) anomaly set on the Fennoscandian Shield and its close margins (Korhonen et al. 2002). A geological result of sub-continental scale was that the shield borders could not be outlined from either of the sets. Hence, it was concluded that the present exposure of the crystalline rock units is not solely due to the properties of the Precambrian units of the basement, but for an essential part due to later balancing of the lithosphere.

The Finnish anomaly grid was the first national grid to be reported for the IAGA World Magnetic Anomaly Map in 1981. At the end of this work in 2003, GTK was given the responsibility to co-ordinate the final stage of the map compilation, which was jointly carried out with several scientific teams and data owner organizations. The map was published and grid and data sets released at the 2007 IUGG General Assembly in Perugia, 30 years after the first IAGA resolutions to create the map

(Korhonen et al. 2007). The second edition of the global magnetic anomaly map is in preparation by complementing the datasets and reduction methods. A basis for the third edition is being established by preparing for the launch of the SWARM satellite constellation by ESA.

The global magnetic anomaly map clearly outlines major geological units on the sub-continental scale. Figure 5 presents a European and North Atlantic window to the map. The youngest, Cenozoic part of the Earth's crust of the Atlantic Ocean floor causes a well known striped signature of magnetic anomalies, mainly due to the varying direction of total magnetization (left). The oldest, Precambrian lithosphere causes a more irregular and stronger pattern of magnetic regional anomalies above the East European basement area, mainly due to variation in the intensity of total magnetization between major geological units (upper right). The crust in Central and Southern Europe is younger, magnetically thinner and less magnetized (from the centre to the lower edge of the figure). This anomaly picture presents anomalies at an elevation of 5 km above the geoid, and the widest parts of the anomalies (> 2 600 km) have been removed by the anomaly definition of the map. To represent these missing wider features, a global magnetization model of the Earth's lithosphere would be required. This task is one of the future challenges of the scientific geological and geomagnetic communities.

To explain the geological sources of magnetic anomalies in Finland, petrophysical measurements of bulk density, magnetic susceptibility, the intensity of remanent magnetization, and to minor extent its direction, have been carried out for decades. A general conclusion is that a considerable proportion of the smooth anomalies are due to sources in the deeper part of the crust, above the Curie isotherm of magnetite, and some are influenced by the direction of remanent magnetization, different to that of the present main field. A view has been presented that geological interpretation of the sources of the anomalies, and the establishment of sets of numerical models to work out the results of future studies should be among the key tasks in applying aeromagnetics in Finland, as well as internationally.

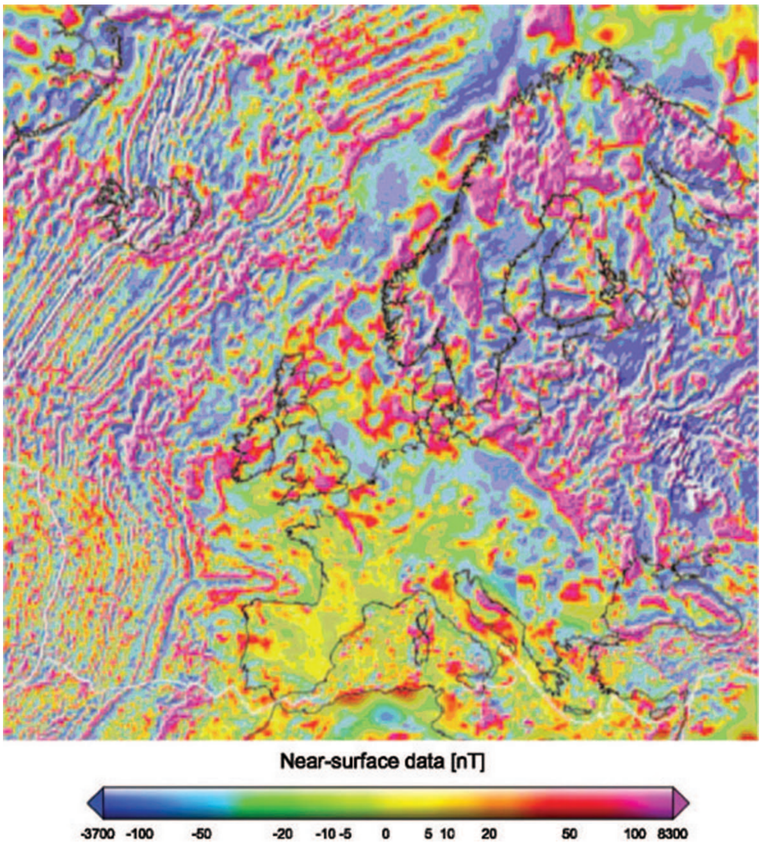

Figure 6. Atlantic-European window to the World Digital Magnetic Anomaly Map 2007 (WDMAM 2007, Korhonen et al. 2007, available at: http://projects.gtk.fi/WDMAM/). The upright dimension of the window (N-S) corresponds to 3200 km of arc length.

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This 125th Anniversary Publication of the Geological Survey of Finland (GTK) aims at elucidating, through 33 short articles, the current focus of research and development at GTK. We have defined our current strategy to cover three areas of societal impact: (1) mineral resources and raw material supply, (2) energy supply and the environment, and (3) land use and construction, which also form the subsections of this anniversary publication, in addition to a section on geodata management and database development.

In reaching the milestone of 125 years, we can state that our anniversary slogan, “forever young”, is justified by the vitality and increasing societal impact of the organization and our research focusing on sustainable development of our society. GTK is currently the centre of geoinformation and applied geoscientific expertise in Finland, and we have very active international co-operation and project export worldwide.

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