by Reijo Salminen¹, Anne Kousa¹, Rolf Tore Ottesen², Olle Selinus³, Eiliv Steinnes⁴, Timo Tarvainen¹, and Björn Öhlander⁵

Environmental Geology

¹ Geological Survey of Finland, P.O. Box 96, FIN-02151 Espoo, Finland. E-mail: reijo.salminen@gtk.fi

² Geological Survey of Norway, N-7491 Trondheim, Norway. E-mail: rolf.ottesen@ngu.no

³ Geological Survey of Sweden, P.O. Box 670, S-75128 Uppsala, Sweden. E-mail: olle.selinus@sgu.se

⁴ Institutt for Kjemi, Norges teknisk-naturvitenskapelige universitet N-7491 Trondheim, Norway. E-mail: eiliv.steinnes@chem.ntnu.no

⁵ Luleå University of Technology, SE-97187 Luleå. E-mail: bjorn.ohlander@ltu.se

The mining environment, medical geology and urban geochemistry form a group of related scientific disciplines that have developed strongly during recent years in the Nordic countries. Modern legislation controls the environmental issues. Close co-operation of researchers and legislators has improved the quality and safety of life in the societies of the Nordic countries. In mining environmental studies, methods that are suitable in Arctic conditions have been developed; in medical geology, the input from the Nordic countries has made it an appreciated scientific discipline throughout the world, and in the case of the urban environment, methods developed by our geochemists have especially improved the health conditions, particularly of children.

Introduction

Environmental geology deals with many issues closely related to the life of human beings. Many disciplines of environmental geology are strongly developed in the Nordic countries. Sub-arctic conditions with long winters and thick snow cover provide special challenges in e.g. environmental management of mine wastes. On the other hand, environmental problems connected with volcanism and earthquakes hardly exist in the Nordic countries, except on Iceland. In this paper, we selected three special topics: the mining environment, medical geology and urban geochemistry to introduce some highlights of environmental research in the Nordic countries. In mining environmental studies, methods suitable in Arctic conditions have been developed; in medical geology, successful input from the Nordic countries has been a key issue, and applications developed by our geochemists have improved the health of citizens living in urban areas. Some other topics are discussed in other papers in the present volume.

Urban geochemistry

Urban soil is a key environmental topic considering the increasing urbanisation of our world. Processes that lead to urban soil pollution pose serious challenges to the management of urban environments. Cities and towns have been affected by the inward migration of large numbers of inhabitants during the last century, largely because of the concentration of goods and services that cities offer. Now, 70–80 per cent of the population in the Nordic countries lives in cities or towns. The urban environment is affected by a wide variety of anthropogenic activities (e.g., Berglund et al., 1994; Birke et al., 1992; Ahlgren, 1996; Mielke, 1999; Ottesen et al., 2000a; Mielke et al.,

2005). In general, most products we use in our daily life pollute our environment during their production, use and disposal as waste. Typically, the urban soils are used and reused several times and a chemical imprint from each generation can be found.

Soil types within towns and cities vary greatly, ranging from relatively undisturbed natural soils, similar in some respects to their rural counterparts, to completely man-made products. Artificial landscaping and imported topsoil are a common feature within cities. For example, the inner city of Trondheim, Norway has, on average, two meters of man made soils (Ottesen et al., 2000b). Soils act as reservoirs for heavy metals and organic micro-pollutants from various sources. Human activity may create pathways from these reservoirs to the urban populations, thus, influencing human health.

Geochemical mapping, pollution sources and the dynamics of urban soil

Systematic geochemical mapping based on sampling and analysis of surface soils (0–2 cm) has been carried out in several Norwegian cities since 1994 (Ottesen et al., 1995); in other Nordic countries the systematic work started some years later (Salla, 1999; Peltola, 2005; Salonen and Korkka-Niemi 2007; Lax and Selinus, 2005; Ljung et al., 2006). Typically the soils in the oldest parts of the cities are polluted with metals (especially Pb) and polycyclic aromatic hydrocarbons (PAH). Surface soils in the younger suburban parts of the cities normally show lower concentrations of these compounds (Ottesen et al., 1999a; Jartun et al., 2002); however, polychlorinated biphenyls occur there (Andersson et al., 2004). The arsenic concentrations in soils at child day-care centres were often found to be higher than those in soil with other land use. Cu-Cr-As (CCA) impregnated wood has proved to be the pollution source in day-care centres and play-grounds (Langedal and Hellesnes, 1997). A number of other sources, such as traffic, flaking paint, building wastes, city fires, waste incinerators, hospital incinerators, crematoriums, and industrial activity contribute to the pollution of the urban environment. The natural content of arsenic, metals and organic pollutants in the urban environment has been documented by analysis of 4–5 m deep soil samples (Ottesen et al., 2000; Langedal and Ottesen 2001), samples of bedrock (Ottesen et al., 1999b; Jartun et al., 2002), samples of overbank sediments (Ottesen et al., 1995), and by collecting samples from similar soil types around cities (Salla, 1999; Tarvainen et al., 2006; Salonen and Korkka-Niemi, 2007). The levels of the observed concentrations of contaminants in urban soils are of concern for human health.

Land use changes with time. It is now very common to develop dwelling areas in city centres and on old industrial sites. Changes in land use result in large volumes of surplus soils, after excavation. Ottesen and Haugland (2003) calculated the total volume of excavated masses from the polluted inner parts of four Norwegian cities in 2001 (Table 1). That year, 3.8 Mm³ soil was re-dug up and moved in the four investigated cities. 1.2 Mm³ were from older parts of the cities and therefore were probably polluted. Uncontrolled transportation of surplus soil is a very efficient method for spreading pollution.

Table 1 Data on volumes of excavated soil in four Norwegian cities in 2001.

Cities	Total amount of excavated masses (m ³)	Amount of polluted excavated masses from inner city (m ³)	Amount of polluted excavated masses delivered to approved landfill (m ³)
Oslo	1 612 000	850 000	16 000
Bergen	947 000	241 000	4 000
Trondheim	715 000	77 000	27 600
Tromsø	530 000	35 000	0

In addition to health risk evaluation, the urban geochemical data is used as background information in remediation of contaminated land sites. The Geological Surveys of Finland and Sweden have a programme in which they produce geochemical baseline data in the surroundings of the major cities.

Soil pollution in day-care centres and playgrounds

Studies of metal concentrations in playground dust ingested by children via the hand-to-mouth pathway have been carried out in a number of places (Calabrese et al., 1997). There is substantial evidence that a high Pb level in the environment can affect Pb levels in children's blood, thereby influencing their intelligence and behaviour (Mielke, 1991; Mielke et al., 2005).

Based on the results from systematic geochemical mapping, it was early realized that special focus must be directed towards soils in

day-care centres and playgrounds. More than 75% of Norwegian children spend a long day in day-care centres. In four cities, a geochemical mapping and remediation program was initiated and conducted from 1996 until 2006. Surface soils (0–2 cm) were preferably collected from places where bare soil was visible, e.g., close to playing equipment, in areas where grass lawns had been worn down, in holes dug by the children, etc. The health risk evaluation was primarily focused on estimating the element exposure from soil through the three exposure routes:

skin, oral and respiratory. To evaluate whether the soil pollution could contribute significantly to the children's health, the exposure from soil was compared with allowable intakes and background exposure levels from other sources (food and drinking water). Health risk evaluations have so far been carried out for As, Cd, Cr⁶⁺, Hg, Ni, Pb, PAH_{sum16}, benzo(a)pyrene and PCB_{sum7} and the Norwegian Institute of Public Health has developed quality criteria for these components in soils in day-care centres and playgrounds.

The first project was carried out in Trondheim in 1996, where the CCA-impregnated wood in playing equipment was well documented. Later it was detected that the soil in all day-care centres in Tromsø was polluted with As due to use of CCA-impregnated wood. After these observations a process was initiated to ban this product and eventually it was banned in 2002 in Norway. In the inner city of Bergen, 45 out of 87 day-care centres were polluted to a degree that required remediation mainly due to concentrations of As, Pb and

benzo(a)pyrene exceeding the recommended action levels. In Oslo, 34% of 700 day-care centres had to renovate the soils, due mainly to As, Pb and B(a)P, and to a smaller extent, Hg, Cd, Ni and PCB. Figure 1 illustrates the mean content of benzo(a)pyrene in 700 day-care centres in Oslo.

These projects convinced the present Norwegian government that soil pollution in day-care centres and playgrounds is an important health issue. The government presented an action plan in 2006, for mapping and, if necessary, remediation of all 6000 day-care centres and 40 000 playgrounds in Norway. The work started in ten cities and five industrial towns in 2007. Ten samples of surface soil (0–2 cm) are collected from each locality and analysed for As, metals, 16 PAHs and 7 PCBs. Samples from the industrial towns have an extended analytical program. The Geological Survey of Norway has developed routines for the mapping (field-, laboratory- and reporting- manuals) and is responsible for quality control. These ten cities and five industrial towns will be mapped during 2008 and necessary remediation completed before the summer of 2010. A proposal for an action plan to handle the day-care centres and playgrounds in the rest of Norway will be developed within the same time limit.

Urban geochemistry in land use planning

Concurrently with reorganizing the geological mapping programmes in the late 1990s, urban geochemistry projects were initiated in Sweden. The city planners and city environmental authorities are involved in urban geochemical projects and the results are adapted to the needs of the planners in Sweden and Finland. Typically these projects include sampling of surface soils, deeper soils, water, and other media. All types of geological information were mapped and used in this programme. In Gothenburg, the completion of the project was marked by the publication of an atlas (Selinus et al., 2001), which includes information on heavy metals, organic compounds, and natural background values

Figure 1 Content of benzo(a)pyrene in urban soils from day-care centers in Oslo, Norway. The symbol represents the mean value of 10 sample in each of 700 day-care centres (Geological Survey of Norway, unpublished data, 2007).

in different sample media. Since then, Västerås and Stockholm have been completed and seven other large cities in Sweden will be covered before 2009. In Finland, a pilot project was carried out in Porvoo and the next target is the district surrounding Helsinki (Tarvainen, 2003; Tarvainen, 2006).

These programmes were largely focused on the analysis of soil by sampling within the cities and their nearest surroundings. A representative set of undisturbed, natural soils is sampled, both from the C-horizons (variable depth, mostly >0.6 m) and top soil samples (sampling depth, 5–25 cm). The parameters analysed are the same as in the regional mapping programmes, which facilitates comparison with samples collected from sites subject to no or extremely weak diffuse pollution. Sampling density is higher than for regional mapping and depends on the size of the urban area, the geology, and the sampling media. Topsoil samples are collected regardless of the type of Quaternary deposit, with a maximum sampling density of 1 sample/2.5 km².

Biogeochemical methods are also a part of the urban geochemistry programme in Sweden. Since natural vegetation usually is scarce or lacking in urban areas, transplants of *Fontinalis antipyretica* are used. Adapting a method recommended by the Swedish EPA (Naturvårdsverket, 1999), the transplants consist of sub-samples collected from an unpolluted site that have been stored in pure water for a few weeks prior to exposure to the water of investigated streams.

Site selection in urban areas is based on avoidance of known contaminated sites. Planning therefore involves contacts with relevant authorities, and most sampling is conducted in “green” areas, like parks, etc. Surrounding rural areas are also sampled to find the local natural background values of elements. The higher sampling density allows a statistical approach in order to verify visually interpreted diffuse pollution. Experience has shown that some samples have been subject to point source contamination; anomalous levels of element associations, typically not present in geological media, are sometimes encountered.

Geology and health in Scandinavia

Geologic factors play key roles in a range of environmental issues that impact the health and well-being of billions of people worldwide (Figure 2). But there is a general lack of understanding of the importance of these factors on animal and human health among the general public, the biomedical/public health community, and even within the geoscience community. The Scandinavian countries have been very active in this field for decades, have made important scientific contributions and have helped to raise awareness of these issues.

Two tracks in Scandinavia: medical geology and geomedicine

The first track is **Medical Geology**. In 1996, the IUGS commission COGEOENVIRONMENT established an International Working Group on Medical Geology led by Olle Selinus (Selinus, 2002a, b; Skinner and Berger, 2000; Bowman et al., 2003). In 2000, the International Geological Correlation Programme (IGCP) established a new project “IGCP 454 Medical Geology”, chaired by Olle Selinus with co-chairs Peter Bobrowsky (Canada) and Ed Derbyshire (UK). This initiative was developed into the IUGS Medical Geology Working Group. Its main activity during the recent years has been to provide short courses on medical geology to developing countries

Figure 2 Examples of effects of geology on the human body (Finkelman, R. B.).

where there are critical medical geology problems. These courses have now been presented on 33 occasions all over the world and have been attended by thousands of students and professionals. A textbook on Medical Geology (Selinus et al., 2005) with c. 60 authors, (about 50% geoscientists and 50% medics, veterinarians and other scientists) has been granted three distinguished international awards. The International Medical Geology Association (IMGA) was finally launched in January 2006 (www.medicalgeology.org) with councillors and regional divisions established all over the world (Finkelman et al., 2004).

The second track is in **Geomedicine**, defined as the relation between natural environmental factors and health. In addition to the composition of rocks, soils, and water, this field considers factors related to climate and radiation, and deals with human as well as animal health. This scientific discipline was first defined by Professor Jul Låg, Agricultural University of Norway, and is described in his book *Geomedicine* (Låg, 1990). In the Norwegian Academy of Science and Letters, the “Committee on Information and Research in Geomedicine” (www.dnva.no/geomed) has been active since 1984. Norwegian scientists (Jul Låg and Eiliv Steinnes) have promoted geomedicine as a subject in the International Union of Soil Sciences.

Examples of research

In Sweden, research started in the 1960s on coronary heart disease and hard water. Later, a large study was carried out on Diabetes type 1 in children, which resulted in evidence for a correlation between high contents of Zn in drinking water and this type of diabetes (Haglund et al., 1996). In the 1980s, when thousands of moose died in Sweden, close collaboration between veterinarians and geochemists showed that this disease was found to be the result of liming of acidified areas (Selinus and Frank, 2000; Selinus et al., 1996). The liming mobilizes molybdenum in bedrock and soils, causing a disturbed Cu/Mo ratio which is important for the health of ruminants. Much attention has also been focused on the health effects of radon and, in recent years, on the effects of natural arsenic in drinking water (Selinus et al., 2005). There has also been a focus on a serious genetic disease, Morbus Gaucher, with links to the old mining activities in the mountain areas of northern Sweden in the 17th century (Hillborg, work in progress). Research is also carried out on the effects of the Chernobyl disaster (Tondel, 2007) and currently on the

links between geology and *Multiple Sclerosis* (Eliaeson, work in progress). These are just a few examples of research activities in medical geology in Sweden. It is important to stress that all this research has been undertaken as a close collaboration between geochemists and medical scientists, epidemiologists, toxicologists, veterinarians, etc.

In Norway, problems of geomedical character have been known for a long time in human as well as veterinary medicine. As an example, the connection between iodine deficiency and goiter, most prevalent in areas situated far from the ocean, was known already in the 1920s (Låg, 1990).

A number of investigations have been performed over the years on deficiency problems in animal husbandry related to low abundance of essential trace elements in pasture soils. Currently a large-scale geographical study is being carried out on the status of essential trace elements in grazing domestic ruminants in Norway, and the factors that determine this status (T. Sivertsen et al., work in progress).

At the Geological Survey of Norway, geomedical research has been carried out since 1971. This activity has included multi-element countrywide geochemical mapping and correlation of spatial distributions of geochemical and other types of natural data with the epidemiology of endemic human diseases. An example of this work is a comparison of the composition of drinking water from the main water works all over Norway with the geographical distributions of various types of cancer and other diseases (Flaten and Bölviken, 1991). Interesting regional distributions of elements were disclosed, although no strong correlations were evident between the chemical and corresponding epidemiological data. A novel method for spatially moving correlation has been developed. By the application of this method, several geomedical associations were revealed, including significant correlations for rates of the occurrence of *Multiple sclerosis* with Rn in indoor air (positive) and atmospheric deposition of marine salts (inverse) (Bölviken et al., 2003). By considering data in the literature, strong associations were observed in China for rates of *nasopharyngeal carcinoma* with the soil contents of Th and U (positive) and Mg (inverse).

In Finland, during the past few decades, studies of the effect of selenium, arsenic, radon and certain other substances such as asbestos, on human health have been carried out (e.g. Koljonen, 1975; Lahermo et al., 1998; Kurttio et al., 1999; Nikkarinen et al., 2001; Kokki et al., 2001; Kurttio et al., 2006; Piispanen, 2000; Szalay et al., 1981). There were also recent studies of environmental risk assessment and the spatial variation of certain chronic diseases in relation to the geological or geochemical environment (<http://www.eracnet.fi>; Kousa et al., 2004). GIS and geo-referenced data allow studies that benefit from a flexible geographical scale, for example grid cells instead of administrative boundaries. During the last ten years, the Geological Survey of Finland (GTK) and the National Public Health Institute (KTL) have carried out studies of the spatial variation of acute myocardial infarction (AMI) (Kousa et al., 2006) and the incidence of childhood type 1 diabetes (T1DM) in relation to the geochemistry of local groundwater (Moltchanova et al., 2004). Results of recent studies have suggested that water hardness, especially magnesium, in well water has an inverse relationship with geographical variation of AMI risk in Finland. The incidence of T1DM was not associated with the concentration of nitrate or zinc in well water at the population level.

Environmental risk assessment methods are increasingly applied to investigate small- and large-scale environmental problems and their impact on human health. GTK, KTL and the University of Kuopio have recently founded the Environmental Risk Assessment Centre (ERAC) to conduct scientific research and to develop new projects (<http://www.eracnet.fi>). The ERAC is based on multidisciplinary networking and co-operation, ranging from geochemistry, geology, biogeochemistry and ecology to environmental sciences, toxicology, epidemiology, risk analysis and the political sciences. One objective of ERAC, in co-ordination with The Finnish Cancer Registry, is to investigate relationships between cancer risk and exposure to natural elements in soil. Another multidisciplinary pro-

ject, FINMERAC (Integrated Risk Assessment of Metals), improves risk analysis methodology using two selected metal industry areas and one mining target area as examples of environmental pollution, thus providing different challenges for risk assessment and management (<http://www.eracnet.fi>). Application of the Rapid Inquiry Facility (RIF), developed by Imperial College London together with international partners, operates with ArcGIS software, making possible the study of local and national scale health concerns, such as occurrence of cancer cases near particular industrial plants (or near all similar plants in the country). Partners of the FINMERAC project are GTK, KTL, the University of Kuopio, and the Finnish Environment Institute.

It can be concluded that the Nordic countries have been very active in research on geology and health for many years. This has resulted in close collaboration between geoscientists and the medical authorities, many publications including several books, as well as international recognition and leadership in this discipline.

Mining and the environment

Mining of metals has long and rich traditions in the Nordic countries, particularly in Finland, Norway and Sweden. Falun copper mine, in south central Sweden, where hard rock mining is thought to have commenced already during the Viking era around 800 A.D., is the oldest known metal mine in the Nordic countries; production continued until 1992. The mining industry is still very important for Finland and Sweden, where the European Union's most promising areas for finding new ore deposits are located.

Mining operations require large areas of land and associated conflicts arise that are primarily related to competing land use, fugitive dust, vibrations and, inevitably, large amounts of mine waste. The largest copper mine in Europe, at Aitik in northern Sweden (Figure 3), has an average copper concentration of c. 0.4 %; 99.6 % of the ore has to be deposited as waste after processing. Gold is mined in deposits with a grade as low as a few g/t., thus the major parts of the ores will be waste. During 2003, all the metal mines in Sweden together generated 58.9 Mt (million tonnes) of waste, 24.8 Mt of tailings and 34.1 Mt of waste rock (Höglund et al., 2004). However, the main environmental problem with mine waste is not the volume, but

Figure 3 The Aitik copper mine with the open pit, with waste rock dumps in the foreground and the tailings impoundment in the background (photo by Boliden Mineral).

the acid drainage waters (AMD) which often have high concentrations of dissolved metals.

The Swedish biologist Carl von Linné observed, already in the 18th century, that the Falu river was polluted by drainage waters from the Falun copper mine. However, it was not until a few decades ago that it was realised that AMD causes serious damage to the environment. Today, the Nordic mining industry and public organisations are in the forefront of the research concerning the mitigation of pollutants from metal mining, and the geosciences play a leading role.

Methods to mitigate the environmental impact of mine waste

Mine waste needs to be managed by using principles that control the environmental impact in both short and long term, the latter being a factor of particular importance. Neutralizing AMD by liming is common, but this generates a sludge rich in iron oxyhydroxides and heavy metals, thus generating a new type of metal-rich waste. The environmental authorities and the mining industry in the Nordic countries prefer remediation methods that will last for very long times (to the next glaciation) with a minimum of maintenance.

Actions to prevent the formation of acid drainage from mine waste deposits are usually directed towards reducing the amount of oxygen reaching the waste. The most common methods are to apply dry covers consisting of several different layers, usually including various soil types; alternatively, the waste can be covered with water (Figure 4). Both dry cover and water cover methods are based on the solubility and diffusivity of oxygen being much lower in water than in air. Soil covers therefore in most cases contain a sealing layer with low hydraulic conductivity, which is aimed at having a high degree

of water saturation. The sealing layer then functions as a barrier against oxygen intrusion also in cases where the groundwater surface is far below the cover.

Various types of dry covers have been studied (e.g. Höglund et al., 2004). One conclusion is that, although dry covers may be effective, they are expensive to construct. A type of dry cover often used by the Nordic mining industry consists of a sealing layer of clayey till with low hydraulic conductivity, and a superimposed protective layer of unclassified till. Modelling based on extensive lab- and field studies has shown that the oxygen flux through this type of dry cover will be about one mole O_2/m^2 per year, implying a very strong reduction compared to the pre-remediation conditions (Höglund et al., 2004).

Other materials such as cement-stabilized fly-ash and organic waste (paper mill sludge and sewage sludge) have also been used as sealing layers. The organic waste is intended to function not only as physical barrier, but also by consumption of oxygen during decay of the organic matter. Sewage sludge is used for establishment of vegetation on covered waste and on tailings impoundments lacking cover.

Since 2000, the Geological Survey of Finland has investigated the environmental impact of mine waste, and has tested innovative remediation methods such as the use of magnesite tailings from a talc operation as the sealing layer in dry cover (Räisänen et al., 2005), and the utilization of natural reactions in wet-land treatments for collecting heavy metals from AMD (Räisänen, 2003). Geophysical methods have been used for characterizing tailings impoundments, related dam constructions, and underlying bedrock and soil structures (Vanhala et al., 2004).

Water cover reduces the rate of oxygen transport to a level that often is acceptable. Water coverage is achieved by underwater disposal of tailings during production, either in natural lakes or in tailings ponds that are deep enough. Conventionally operated impound-

Figure 4 Illustration of some basic alternatives for remediation of mine tailings. The last alternative is not feasible if the tailings are potentially acid generating (from Höglund et al., 2004).

ments, with discharge along a beach, may also be permanently protected by a water cover after mine closure by raising the dam walls along existing impoundments. Another possibility in complex mining areas is to deposit tailings in pit lakes, which may have anoxic bottom waters. Water cover is generally regarded as one of the most cost-effective methods for the mitigation of acid-generating mine tailings. Among the benefits of using water cover is the reasonably low maintenance required and beneficial side effects such as the prevention of dust formation. A major drawback of the method involves the construction of dams and dikes that often need maintenance and monitoring for long time periods. It remains to be proven that dams built at reasonable cost are effective for time scales of hundreds to thousands of years. This effectiveness includes both the geotechnical stability of the dam structures, and the long-term water balance for the water cover. According to the current policy of the Swedish Environmental Protection

Agency, it is extremely difficult to get permission to use natural lakes for disposal of mine waste, which in many respects would be the best solution. They also consider it to be impossible to construct dams that will stand for very long time periods without maintenance, and therefore prefer dry cover as the remediation method for mine waste.

Norwegian researchers did some pioneering studies on the use of water cover (Arnesen, 1993; Arnesen et al., 1997). In the Hjerkinntailings pond, sulphur-containing tailings from a Cu-Zn mine were deposited subaqueously between 1968 and 1993. The area of the tailings pond was 1 km². The minimum water depth was 1 m, which is considered not sufficient to prevent re-suspension. After deposition ceased, the water quality has been considerably improved. In another Norwegian tailings pond, situated at Løkken, tailings were deposited from 1974 to 1987. The minimum water cover depth was 1 m. Mine waste seepage was pumped into an underground mine, where heavy metals and suspended solids settled to the bottom. The Cu concentration in the outlet water from the mine was 99% lower than in the inlet water.

A well-known and well-studied mine site where water cover has been used is Stekenjokk, a stratabound volcanogenic Zn-Cu deposit of Caledonian age, situated in northern Sweden close to the Norwegian border. During the operations of Boliden Mineral from 1976 to 1988, 8.08 Mt were mined mainly by underground cut and fill operations. Mining left some 4.4 Mt of tailings containing about 20% sulphur, mainly occurring as pyrite (FeS₂). A decommissioning programme based on flooding was completed in 1991. Flooding was achieved by raising the water level in the tailings and clarification pond by raising the existing dykes. A breakwater system was built to prevent re-suspension from the tailings surface. The pond has an area of 1.1 km² and a water volume of about 2 Mm³. Water depth is on average about 2 m. Field studies have shown that pond water is well mixed and oxic the whole year round, and has low metal concentrations. Layers rich in iron and manganese oxyhydroxides have been developed close to the tailings surface, and a layer of natural sediments rich in organic material has developed on the tailings surface since the flooding. The oxyhydroxides adsorb and/or co-precipitate metals and function as a trap for metals released at the interface between tailings and pond water. This illustrates that it is possible even in northerly areas for a deposit of flooded tailings to quickly reach a state when it functions almost as a natural lake, with Fe- and Mn-oxyhydroxide layers controlling the diffusion of metals into the overlying pond water (Holmström and Öhlander, 2001).

For very large deposits of mine waste, both dry cover with a sealing layer and water cover may be unrealistic. At the Aitik mine (Figure 3) in northern Sweden, operated by Boliden Mineral, the ore is mined in an open pit at a production rate of 18–19 Mt of ore per year, resulting in up to 36 Mt of waste (Lindvall, 2005). At a mean production level of 25 Mt/year, the mine will be in production at least to 2020. The depth of the final pit will be close to 600 m. Chalcopyrite (CuFeS₂) is the copper source, at an average concentration of 0.4 % Cu. The ore further contains Au (0.2 g/t) and Ag (3.5 g/t).

The waste rock is deposited in dumps with an area of c. 400 ha. Around 300 Mt of waste rock have currently been deposited. At the time of closure, at least 750 Mt of waste rock will have been produced. The dumps are located on c. 10 m thick glacial till with low permeability. Almost all water infiltrating through the dumps is collected as toe drainage in drainage ditches and used in the milling process. The tailings pond, occupying an area of 11 km², is delimited by the natural topography and four dams. The tailings are pumped as slurry from the concentrator to the discharge area along the upstream dam and distributed onto a 5 km long and 2 km wide beach. Tailings layers have reached the 40 m level. The free water volume in the tailings pond is normally around 2 Mm³, covering 20% of the pond area. The 160 ha clarification pond has a holding capacity of 15 Mm³ and constitutes the final water treatment step and a reservoir for mill process water. In a normal year, approximately 6 Mm³ of water are discharged, resulting in a Cu load to the recipient typically below 50

kg. The concentrator operates exclusively on recycled water from the clarification pond.

About 20% of the waste rock is reactive (Lindvall, 2005). Old dumps containing so-called marginal ore, identified as the main metal source, have been removed and processed. Large quantities of non-reactive waste rock are managed in a separate mass flow, allowing them to be a source for construction aggregates. Existing dumps of mixed waste rock, i.e., containing both reactive and non-reactive components, will be covered by a 0.5 m compacted till layer and a 0.5 m topsoil of till and some sewage sludge to establish vegetation and prevent erosion. The oxygen inflow is estimated to decrease to 1% of the level prior to application of the cover.

The future

The Nordic metal mining industry is very profitable, and there are still good possibilities to find new ores. Environmental standards are set high, and research aiming at development of cost-efficient technologies for prevention of environmental problems related to mining and remediation of mine waste is constantly going on. A new challenge facing the mining industry is that large areas with good potential in national parks and in other protected areas are excluded from industrial activities. National parks are completely protected, but in other restricted areas the environmental impact of mining should be compared with natural metal flows from mineralized bedrock to make it possible for society to take the right land use decisions.

References

- Ahlgren, M. 1996, Undersökning i Falun av markblyets biotilgänglighet. Uppsala Universitet, Ekotoxikologiska avdelingen nr 42, 86 pp. and measured copper and zinc concentrations at three Norwegian underwater tailings disposal sites: Proc. IV Int. conf. on Acid Rock Drainage, May 31–June 6, 1997, Vancouver, B.C., Canada. 15 pp.
- Andersson, M., Ottesen, R.T., and Volden, T., 2004, Building materials as a source of PCB pollution in Bergen Norway: Science of the Total Environment, v. 325 pp. 139–144.
- Arnesen, R.T., 1993, Subaqueous Disposal of Tailings, Hjerkinntailing Dam.
- Arnesen, R.T., Bjerkeng, B., and Iversen, E.R., 1997, Comparison of model predicted.
- Berglund, M., Fahlgren, L., Frelund, M., and Vahter, M. 1994, Metaller i mark i Stockholms innerstad och kranskommuner – förekomst och hälsorisker för barn. Institutet för miljömedicin, Karoliska Institutet i samarbete med Miljöförvaltningen i Stockholm stad: IMM-rapport 2/94. 46 pp.
- Birke, M., Rauch, U., and Helmert, M. 1992, Umweltgeokemie des Ballungsraumes Berlin-Schöneide: teil 1: Bearbeitungsmethodik – Elementverteilung in Böden und Grundwassern: Zeitschrift für angewandte geologie, v. 38, pp. 37–66.
- Bølviken, B., Celius, E.G., and Nilsen, R., 2003, Radon: A possible risk factor in multiple sclerosis: Neuroepidemiology, v. 22 pp. 87–94.
- Bowman, C., Bobrowski, P.T., and Selinus, O., 2003, Medical Geology: New relevance in the Earth Sciences: Episodes, v. 26 (4), pp. 270–278.
- Calabrese, E.J., Stanek, E.J., James, R.C., and Roberts S. M., 1997, Soil ingestion: a concern for acute toxicity in children: Environmental Health Perspectives, v. 105 pp. 1354–1358.
- Finkelman Robert B., Centeno Jose A., and Selinus Olle, 2004. The Emerging Medical and Geological Association: Transactions of the American Clinical and Climatological association.
- Flaten, T.P., and Bølviken, B., 1991, Geographical associations between drinking water chemistry and the mortality and morbidity of cancer and some other diseases in Norway: Science of Total Environment, v. 102, pp. 75–100.
- Haglund, B., Ryckenberg, K., Selinus, O., and Dahlqvist, G., 1996, Evidence of a relationship between childhood-onset type 1 diabetes and low groundwater concentration of Zinc: Diabetes Care, v. 19 (8), August 1996.
- Hjerkinntailing Dam, Løkken: NIVA-Report, O-92186. Serial No.: 2962, 49 pp (in Norwegian).
- Höglund, L.-O., Herbert, R., Lövgren, L., Öhlander, B., Neretniks, I., Moreno, L., Malmström, M., Elander, P., Lindvall, M., and Lindström, B., 2004, MiMi - Performance assessment: Main report. MiMi-report 2003:3.

- Holmström, H., and Öhlander, B., 2001, Development of layers rich in organic matter and Fe- and Mn-oxyhydroxides in flooded mine tailings: A possible trap for trace metals: *Journal of Geochemical Exploration*, v. 74, pp. 189–203.
- Jartun, M., Ottesen, R.T., Volden, T., Jensen, H., Andersson, M. and Alexander, J., 2002, Forebyggende arbeid – Jordforurensning I små barns utelekemiljø I Tromsø: NGU-rapport 2002.053.
- Kokki, E., Ranta, J., Penttinen, A., Pukkala, E. and Pekkanen, J., 2001, Small area estimation of incidence of cancer around a known source of exposure with fine resolution data: *Occup Environmental Medicine*, 58 (5), pp. 315–20.
- Koljonen, T., 1975, The behavior of selenium in Finnish soils: *Annales Agriculturae Fenniae*, v. 14, pp. 240–247.
- Kousa, A., Havulinna, A.S., Moltchanova, E., Taskinen, O., Nikkarinen, M., Eriksson, J., and Karvonen, M., 2006, Calcium:magnesium ratio in local groundwater and incidence of acute myocardial infarction among males in rural Finland: *Environmental Health Perspectives* 114 (5), pp. 730–734.
- Kousa, A., Moltchanova, E., Viik-Kajander, M., Rytönen, M., Tuomilehto, J., Tarvainen, T., and Karvonen, M., 2004, Geochemistry of ground water and the incidence of acute myocardial infarction in Finland: *Journal of Epidemiology and Community Health* 58 (2), pp. 136–139.
- Kurtio, P., Salonen L., Ilus T., Pekkanen J., Pukkala E., and Auvinen A., 2006, Well water radioactivity and risk of cancers of the urinary organs: *Environmental Research* 102 (3), pp. 333–338.
- Kurtio, P., Pukkala, E., Kahelin, H., Auvinen, A., and Pekkanen J., 1999, Arsenic concentrations in well water and risk of bladder and kidney cancer in Finland: *Environ Health Perspect* 107 (9), pp. 705–710.
- Låg J., ed., 1990, *Geomedicine*: CRC Press, Boca Raton.
- Lahermo, P., Alfthan, G. and Wang, D., 1998, Selenium and arsenic in the environment in Finland: *Journal of Environmental Pathology, Toxicology and Oncology*, 17(3-4), pp.205–216.
- Langedal, M., and Ottesen, R.T. 2001, Plan for forurensset grunn og sedimenter i Trondheim. Trondheim kommune, Miljøavdelingens rapporter, TM 01/03, 15 pp.
- Langedal, M., and Hellesnes, I., 1997, Innhold av tungmetaller i overflatejord og bakterier i sandkasser i barnehager i Trondheim. Trondheim kommune, Miljøavdelingen, TM 97/03.
- Lax, K., and Selinus, O., 2005, Geochemical mapping at the Geological Survey of Sweden. *Geochemistry: Exploration, Environment, Analysis*, v. 5 (4), pp. 337–346.
- Lindvall, M., 2005, Strategies for remediation of very large deposits of mine waste; the Aitik mine, Northern Sweden. Luleå University of Technology, Licentiate Thesis 2005: 72.
- Ljung, O., Otabbong, and Selinus O. 2006, Natural and anthropogenic metal inputs to soils in urban Uppsala: Sweden. *Environmental Geochemistry and Health*.
- Ljung, K., Otabbong, E., and Selinus, O., 2006, Natural and anthropogenic metal inputs to soils in urban Uppsala, Sweden: *Environmental Geochemistry and Health*, v. 28, pp. 353–364.
- Mielke, H., 1999, Lead in inner cities. *American Scientist*, v. 87, pp. 62–73.
- Mielke, H.W., Berry, K.J., Mielke P.W., Powell, E., and Gonzales, C., 2005, Multiple metal accumulation as a factor in learning achievements within various New Orleans elementary school communities: *Environmental Research*, v. 97, pp. 67–75.
- Moltchanova, E., Rytönen, M., and Kousa, A., Viik-Kajander, M., and Karvonen M., 2004, Zinc and nitrate in the ground water and the incidence of type 1 diabetes in Finland: *Diabetic Medicine*, v. 21, pp. 256–261.
- Naturvårdsverket, 1999, *Bedömningsgrunder för miljökalité, sjöar och vattendrag*. Report 4913 (in Swedish): Swedish Environmental Protection Agency.
- Nikkarinen, M., Aatos, S., and Teräsvuori, E., 2001., Asbestin esiintyminen ja sen vaikutus ympäristöön Tuusniemellä, Outokummussa, Kaavilla ja Heinävedellä. Summary: Occurrences of asbestos minerals and their environmental impact in the area of municipalities of Tuusniemi, Outokumpu, Kaavi and Heinävesi, eastern Finland: Geological Survey of Finland, Report of Investigation, v. 152. 41 pp+2 app.
- Ottesen R.T., Volden T., Finne T.E., and Alexander J. 1999a., Undersøkelse av polyklorete bifenyl (PCB) i jorden i skolegården ved Hellen skole. NGU rapport 99.062.1999.
- Ottesen, R.T., and Haugland, T., 2003, Trygg disponering avrivede og anleggsmasser: Norwegian Pollution Control Authority Report TA-1932/2003, 32 pp. (in Norwegian).
- Ottesen, R.T., Almklov, P., and Tijhuis, L., 1995, Innhold av tungmetaller og organiske miljøgifter i overflatejord fra Trondheim. Miljøavdelingens rapporter 95/06.
- Ottesen, R.T., Volden, T., Finne, T.E., Aalexander, J., Langedal, M., and Eide, L., 2000, Soil pollution in Norwegian cities—State of pollution, sources and health risk, in Burghart, W., and Dornauf, C., eds., First International Conference on Soils of Urban, Industrial, Traffic and Mining Areas. International Union of Soil Sciences (IUSS), University of Essen, Germany, pp. 555–559.
- Ottesen, R.T., Volden, T., Finne, T.E., and Alexander, J., 1999b, Jordforurensning i Bergen – Undersøkelse av barnehager, barnepark og lekeplasser på Nordnes, Jekteviken og Dokken. Helseisikovurdering. Norges geologiske undersøkelse. Report 99.077, 52 pp.
- Peltola, P., 2005, *Multielement Urban Geochemistry – Exploring the Expected, Unexpected and the Unknown*. Kalmar: Univeristy of Kalmar. 55 pp + 5 app.
- Piispanen, R., 2000, Radon and lung cancer in Finland: are there signs of radiation hormesis? *Environmental Geochemistry and Health* 22 (2), 113–130.
- Räisänen, M.L., 2003, Rehabilitation options for tailings impoundments—case studies of “wet” cover and wetland treatment, in C. Hebestreit, J. Kudelko and J. Kulczycka (eds). *Mine Waste Management Best Available Techniques*. CBPM Cuprum, Wroclaw and MEERI PAS, Krakow, pp. 141–150.
- Räisänen, M.L., Heikkinen, P., Pulkkinen, K., Korkka-Niemi, K., and Salonen, V.-P., 2005, Finland – Mine water quality in some abandoned and active Finnish metal sulphide mines: *Mine Water and the Environment*, 24, Supplementary material, 7–10.
- Salla, A., 1999, Maaperän haitta-aineiden taustapitoisuudet Helsingissä. Eräiden alkuaineiden ja orgaanisten yhdisteryhmien luontaisten ja ihmäperäisten pitoisuuksien summatt Helsingin maaperän pintakerroksissa. (Baselines of certain potentially harmful elements in Helsinki, Helsingin kaupungin ympäristökeskuksen julkaisuja 15/99. 25 pp.+7 app. (in Finnish).
- Salonen, V.-P., and Korkka-Niemi, K., 2007, Influence of parent sediments on the concentration of heavy metals in urban and suburban soils in Turku, Finland: *Applied Geochemistry*, v. 22, pp. 906–918.
- Selinus, O., Rundqvist, R., and Johansson P., 2001. Göteborgsprojektet. *Geokemi i Göteborgs kommun* (in Swedish): Geological Survey of Sweden.
- Selinus, O., and Frank, A., 2000. *Medical Geology*, in *Environmental Medicine*, ed L Möller, pp 164–183 ArbSkNämnden.
- Selinus, O., 2002, *Medical Geology: Method Theory and Practice*, in *Geoenvironmental mapping*, ed., P Bobrowsky, pp 473–496. Balkeema press.
- Selinus, O., Alloway, B., Centeno, J.A., Finkelman, R.B., Fuge, R., Lindh, U., and Smedley, P. eds, 2005, *Essentials of Medical Geology*: Elsevier, Amsterdam, 820 p.
- Selinus, O., Frank, A., and Galgan, V., 1996, Biogeochemistry and metal biology – An integrated Swedish approach for metal related health effects. in: *Environmental geochemistry and Health in Developing Countries*, ed. Appleton, D., Fuge, R., and McCall, J., Special Publication, Geological Society of London, v 113, pp 81–89: Chapman and Hall.
- Skinner, C., and Berger, A., eds, 2000, *Geology and Public Health – Closing the Gap*: Oxford Press.
- Szalay, A., Salminen, R., and Sámsoni, Z., 1981, Investigations into the micronutrient deficiency of North Karelian bedrocks with regard to health problems of the population: *Acta Alimentaria* 10 (4), pp. 417–424.
- Tarvainen, T., Hatakka, T., Kumpulainen, S., Tanskanen, H., Ojalainen, J., and Kahelin, H., 2003, Alkuaineiden taustapitoisuudet eri maalajeissa Porvoon ympäristössä: *Geologian tutkimuskeskus, raportti S/41/3021/2003/1*. 56 pp.+1 app.
- Tarvainen, T. (ed.), Eklund, M., Haavisto-Hyvärinen, M., Hatakka, T. Jarva, J., Karttunen, V., Kuusisto, E., Ojalainen, J., and Teräsvuori, E., 2006, Alkuaineiden taustapitoisuudet pääkaupunkiseudun kehyskuntien maaperässä. Summary: Geochemical baselines around the Helsinki metropolitan area. Geological Survey of Finland: Report of Investigation 163. 40 pp. ISBN: 951-690-968-X. (in Finnish).
- Tondel, Martin, 2007, Malignancies in Sweden after the Chernobyl accident in 1986: Linköping University medical dissertations 1001, ISSN 0345-0082.
- Vanhala, H., Räisänen, M.L., Huotari, T., Valjus, T., Lehtimäki, J., and Suppala, I., 2004, Characterizing tailings impoundment at the closed Hammaslahti Cu-Zn mine, Finland. Near Surface 2004 – 10th European Meeting of Environmental and Engineering Geophysics, Utrecht, The Netherlands, pp. 1–11.

Reijo Salminen is Research Professor at the Geological Survey of Finland, Espoo, Finland. His speciality is in geochemical mapping and environmental geology. He is a regional co-ordinator for Europe in IUGS/IAGC Working Group on Global Geochemical Baselines. He has conducted large geochemical mapping projects in Europe, Russia and Africa. Active in promoting geology as an important factor to policy and decision makers.

Eiliv Steinnes is Professor in Environmental Science since 1980 at NTNU, Trondheim where he served as Rector, College of Arts and Science 1984–1990. He worked 1964–1979 at the Norwegian reactor centre, where he made developments in nuclear analytical methods for which he received the Hevesy medal 2001. He has around 600 publications. He holds several honorary degrees and is a member of several academies. His main scientific interest is sources and pathways of trace elements in terrestrial and aquatic systems and their uptake in foodchains.

Anne Kousa is Research Scientist at Geological Survey of Finland, Kuopio, Finland. She has a MSc in public health and is currently a PhD-student in Kuopio University. She has studied connection between geochemistry of local groundwater and heart diseases.

Timo Tarvainen is a senior researcher at GTK, and holds a docentship from the University of Helsinki. He has been working for GTK since 1986, mainly for development of geological databases and environmental applications of geochemical data. He has taken part in environmental indicator development and environmental reporting at the European Topic Centre for Terrestrial Environment of the European Environment Agency. In the FOREGS geochemical baseline programme he is responsible for database management.

Rolf Tore Ottesen is a professor and team leader in environmental geochemistry, working with the Geological Survey of Norway, Trondheim, Norway. He has over 30 years of professional experience starting with medical geology and prospecting in Norway and in the Arctic. Later in environmental research developing methods to distinguish natural and anthropogenic sources of metals in soils, historical pollution, and air, water and soil pollution in the urban environment. He has worked as Environmental Director in the City Administration of Trondheim and is also teaching in the Norwegian University for Science and Technology since 2000.

Björn Öhlander is Professor, and Head of the Division of Applied Geology and Dean of the Faculty of Engineering at the Luleå University of Technology, Luleå, Sweden. His professional experience and research interests are concentrated in environmental geochemistry, especially in mining waste problems, geochemistry of natural weathering, and analytical and isotope geochemistry.

Olle Selinus is a senior geologist working with the Geological Survey of Sweden, Uppsala, Sweden. He started his career in mineral exploration and since the beginning of the 1980s his research work has been focused on environmental geochemistry, including research on medical geology. He serves as President of the International Medical Geology Association. He has received several international awards and has been appointed Geologist of the Year in Sweden because of Medical Geology.