Geoscience for Society
125th Anniversary Volume
Edited by Keijo Nenonen and Pekka A. Nurmi
Geological Survey of Finland, Special Paper 49, 91–102, 2011

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

by
Päivi M. Kauppila[1)], Tommi Kauppila[1)], Jari Mäkinen[1)],*
Susanna Kihlman[2)] and Marja Liisa Räisänen[1)]

Kauppila, P. M., Kauppila, T., Mäkinen, J., Kihlman, S. & Räisänen, M. L. 2011. Geochemistry in the characterisation and management of environmental impacts of sulfide mine sites. *Geological Survey of Finland, Special Paper 49*, 91–102, 8 figures.

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

[1)] Geological Survey of Finland, P.O. Box 1237, FI-70211 Kuopio, Finland
[2)] Department of Geology, University of Turku, FI-20014 Turku, Finland / Geological Survey of Finland, P.O. Box 96, FI-00251 Espoo, Finland

Corresponding author: P. M. Kauppila (née Heikkinen).

[*] E-mail: paivi.kauppila@gtk.fi

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.

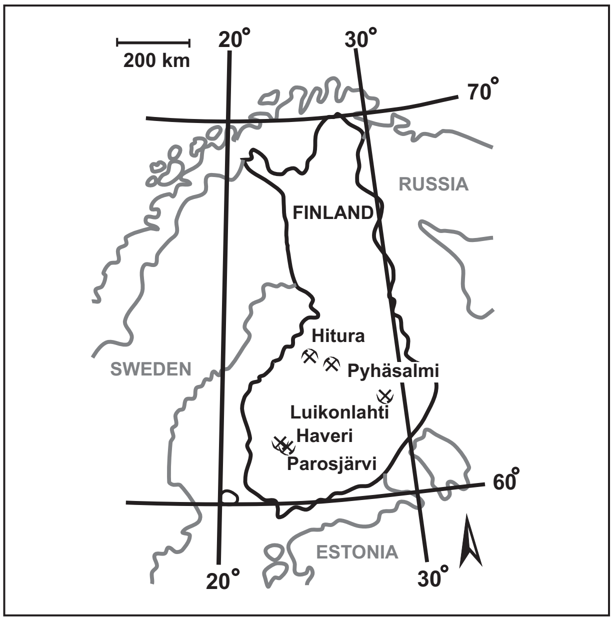

Figure 1. Locations of the mine sites referred to in the paper.

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.

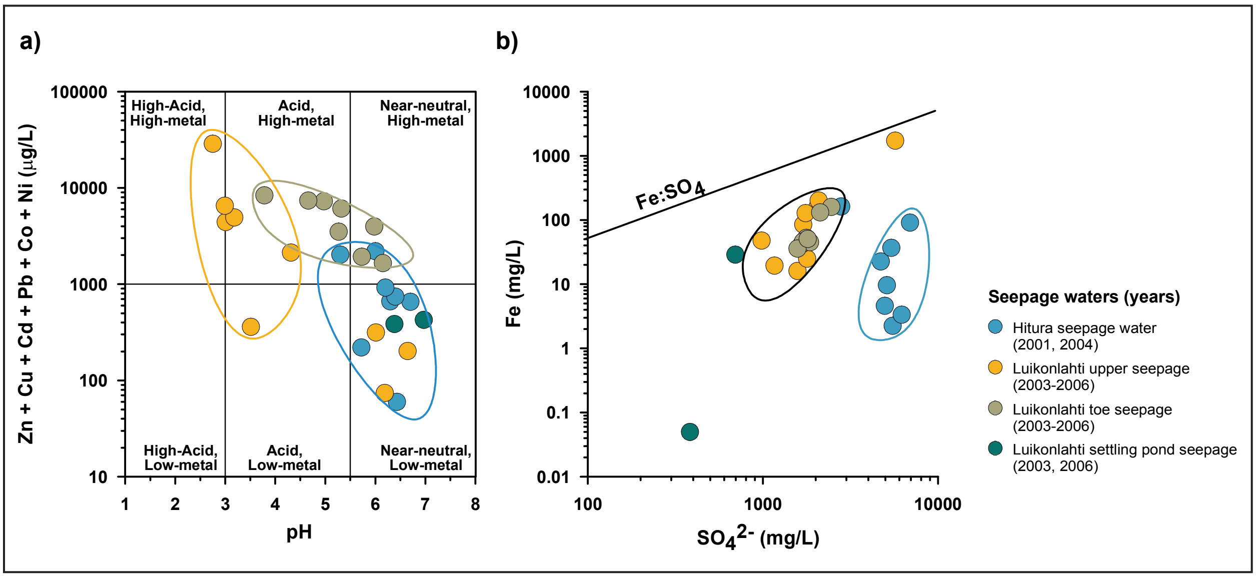

Figure 2. a) Variation in the seepage water quality from neutral to acid mine drainage in the low-sulphide Hitura tailings and the high-sulphide Luikonlahti tailings presented with a Ficklin diagram (Plumlee et al. 1999) showing the sum of dissolved heavy metals (µg/L) plotted against pH; b) Diagram 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).

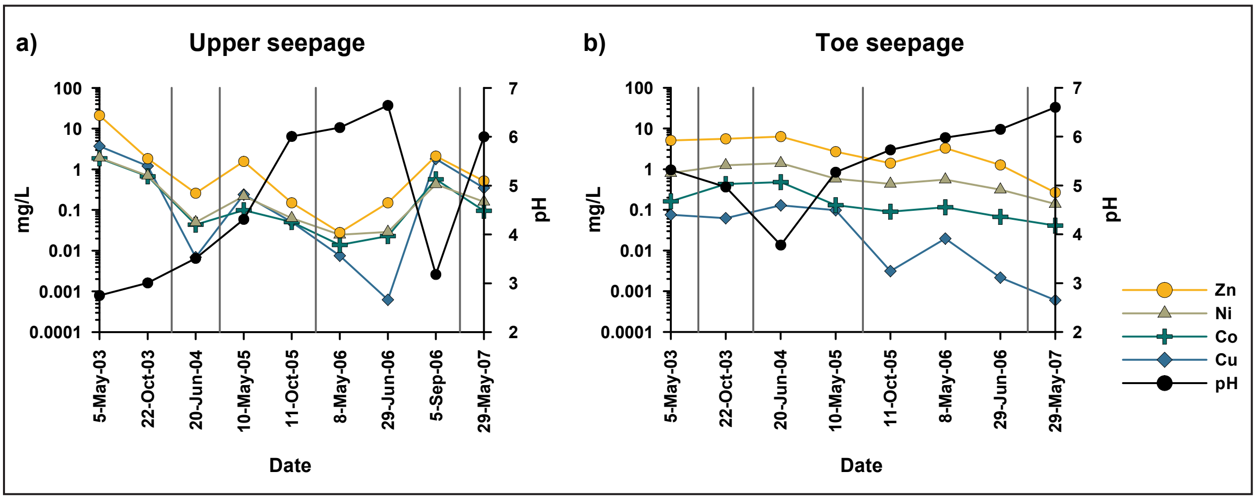

Figure 3. Diagram showing an example of the effect of local hydrological conditions and structural changes in the tailings impoundment seen in the metal concentrations (mg/L) and pH in the Luikonlahti tailings seepage waters between May 2003 and May 2007. a) 'Upper seepage' from the upper section of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

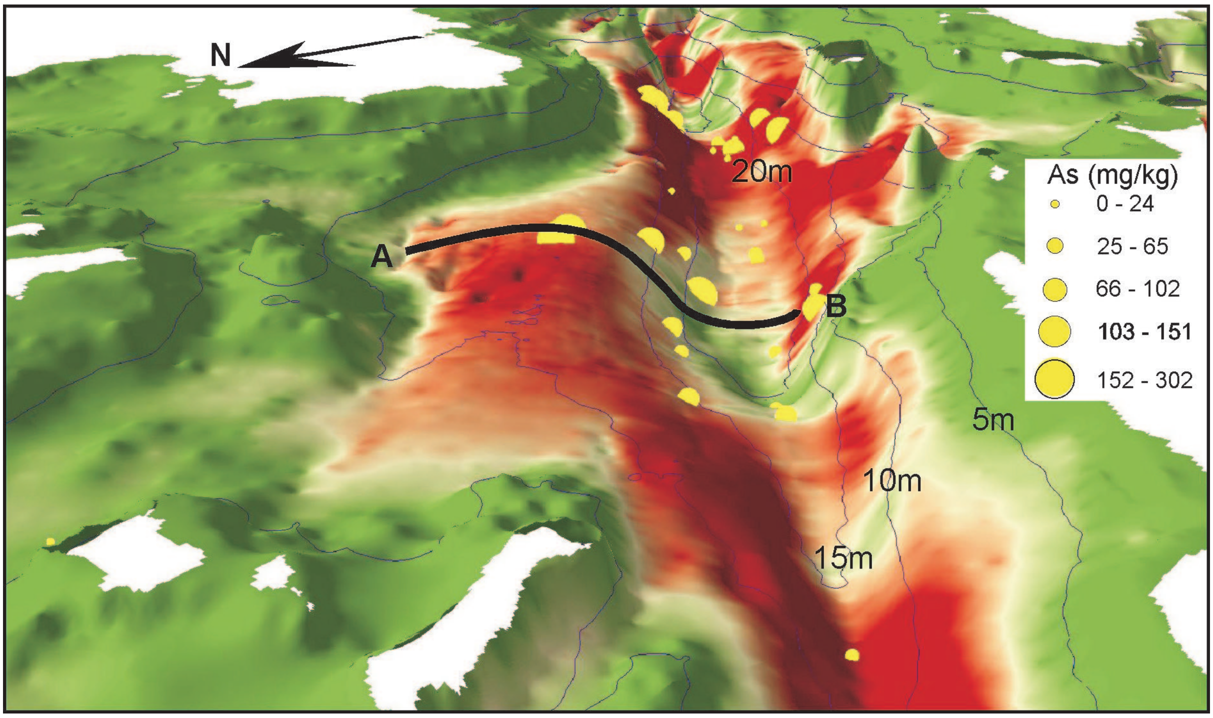

Figure 4. Diagram showing the relationship between maximum As concentrations (yellow circles) in the top sediment profile (< 10 cm; see Figure 6b) and sediment dynamics in the central part of Lake Pyhäjärvi. Sediment thickness is presented in a 3D view with 35 times vertical exaggeration. The green colour 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.

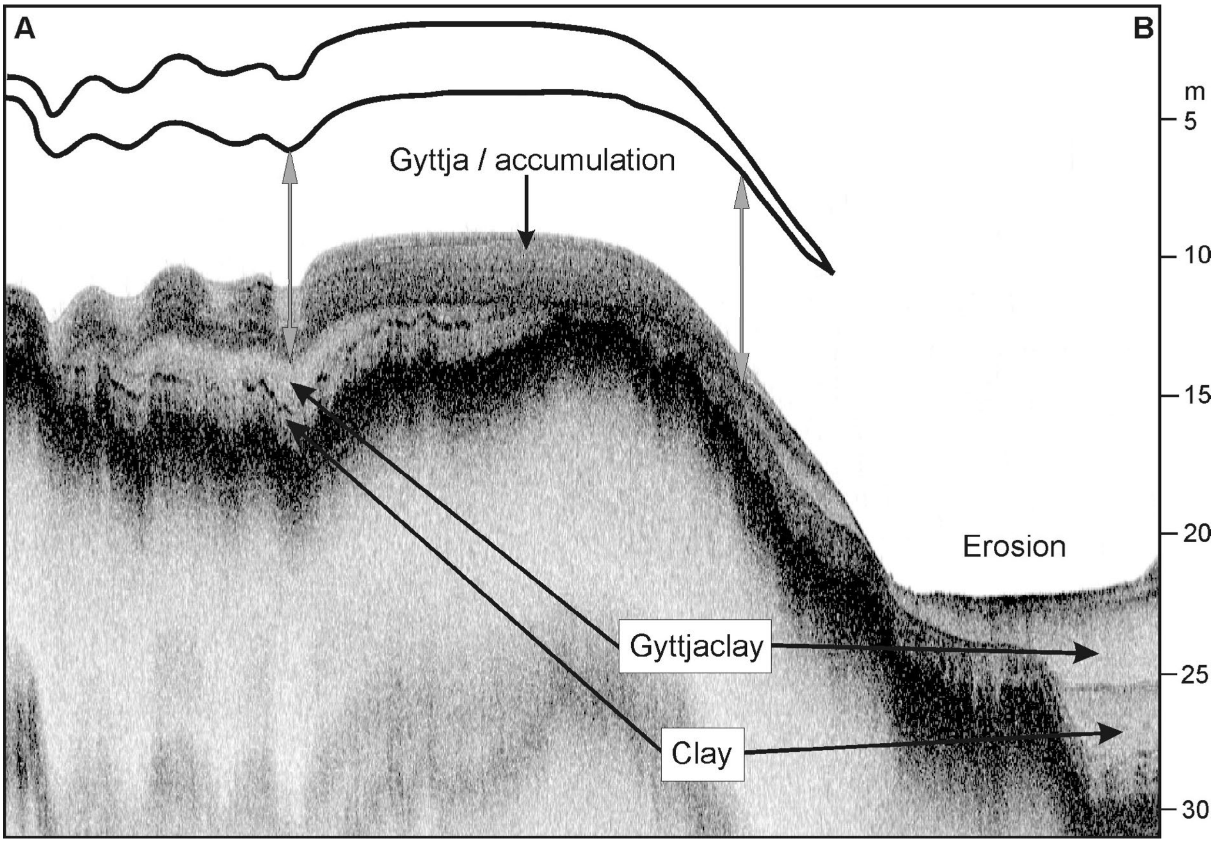

Figure 5. Cross section of the echo soundings of sediment thickness in the central part of Lake Pyhäjärvi (location is presented in Figure 4) showing the accumulation and erosion zones. The accumulation area is located at 10–15 m depth, whereas the erosion zone is at > 20 m depth.

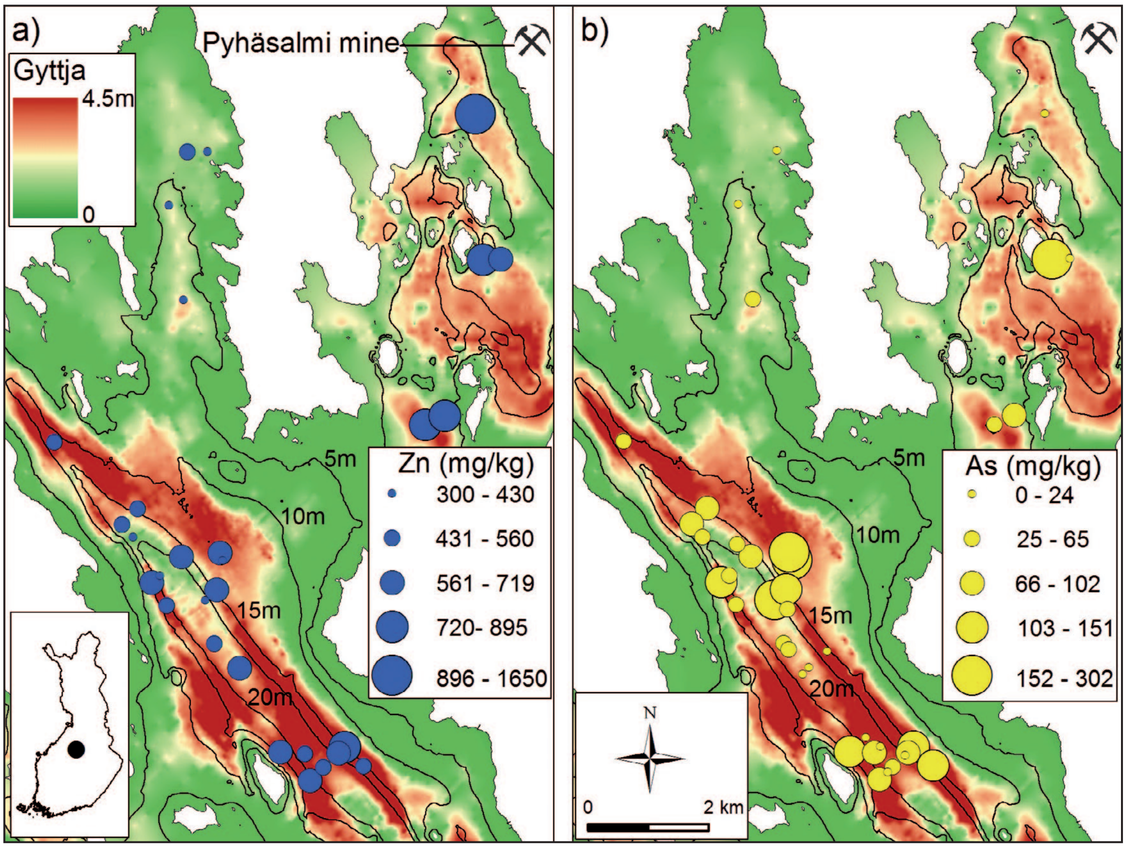

Figure 6. The spatial distribution of a) maximum Zn concentrations and b) maximum As concentrations in the top sediment profile (< 10 cm) of Lake Pyhäjärvi. The outfall of the lake is NW from the Pyhäsalmi mine. The thickness of the gyttja layer is expressed as a coloured surface and water depth as contours. 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).

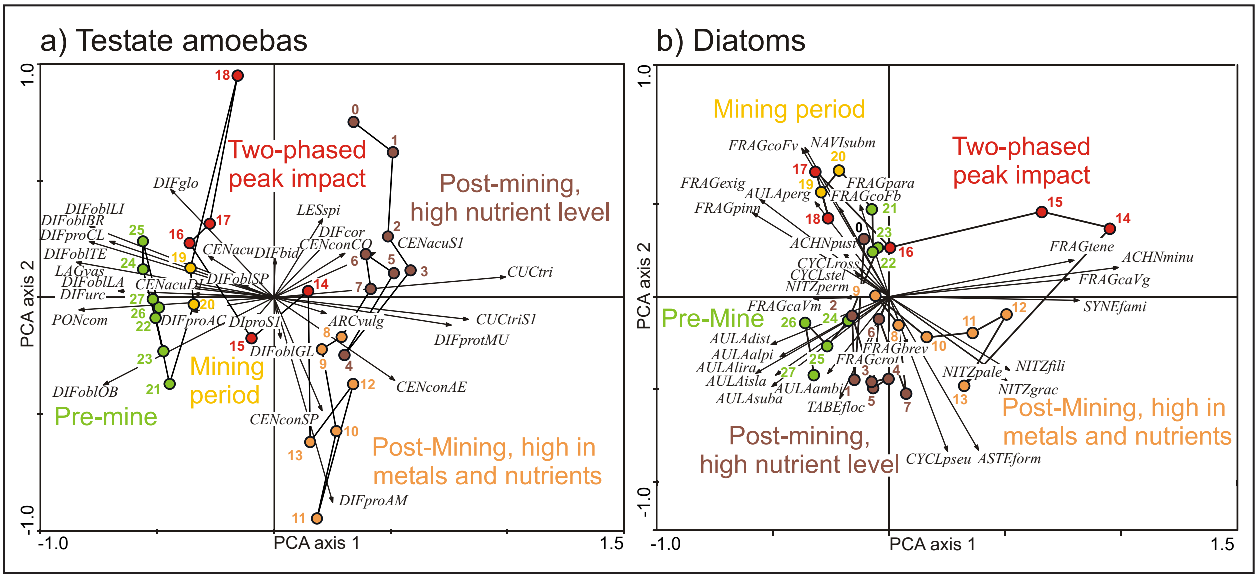

Figure 7. A principal components analysis (PCA) ordination plot summarizing the temporal evolution of mine impact seen in the species assemblages of a) testate amoebas and b) diatoms. Different types of mine drainage result in distinct species compositions. Sediment core from Lake Kirkkojärvi, Haveri.

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.

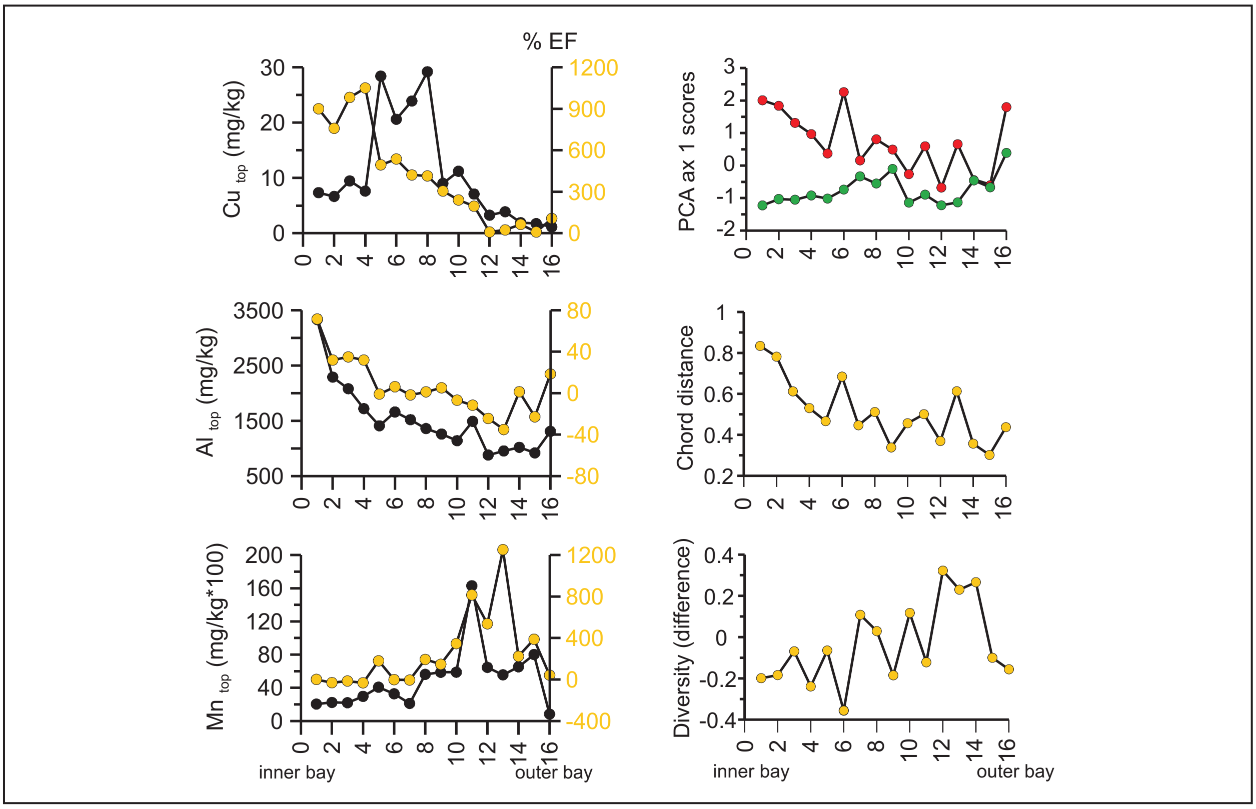

Figure 8. Selected geochemical gradients in the top sediments of the Petkellahti Bay at Luikonlahti (left) and the associated pre- to post-disturbance shifts in sediment testate amoeba assemblages (right). EF = top-bottom enrichment factors. Green dots = pre-disturbance PCA Axis 1 scores, red dots =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

REFERENCES

Alakangas, L., Öhlander, B. & Lundberg, A. 2010. Estimation of temporal changes in oxidation rates of sulphides in copper mine tailings at Laver, Northern Sweden. Science of the Total Environment 408, 1386–1392.

Blowes, D. W. & Jambor, J. L. 1990. The pore-water geochemistry and the mineralogy of the vadose zone of sulfide tailings, Waite Amulet, Quebec, Canada. Applied Geochemistry 5, 327–346.

Blowes, D. W., Ptacek, C. J. & Jurjovec, J. 2003. Mill tailings: hydrogeology and geochemistry. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds.) Environmental aspects of mine wastes. Mineralogical Association of Canada, Short Course Series, Vol. 31, 95–116.

Cattaneo, A., Couillard, Y. & Wunsam, S. 2008. Sedimentary diatoms along a temporal and spatial gradient of metal contamination. Journal of Paleolimnology 40, 115–127.

Chapman, B. M., Jones, D. R. & Jung, R. F. 1983. Processes controlling metal ion attenuation in acid mine drainage streams. Geochimica et Cosmochimica Acta 47, 1957–1973.

Chapman, P. M. 1996. Hazard identification, hazard classification and risk assessment for metals and metal compounds in the aquatic environment. International council on metals and the environment. Ottawa. 31 p.

DeVos, K. J., Ritchie, D. G. & Bocking, K. A. 1999. Practical considerations for covering sulphidic tailings deposits situated above the groundwater table. In: Goldsack, D., Belzile, N., Yearwood, P. & Hall, G. (eds.) Mining and the environment II. Conference proceedings, Sudbury '99, Volume 1, 291–300.

Håkanson, L. & Jansson, M. 1983. Principles of Lake Sedimentology. Heidelberg: Springer-Verlag. 316 p.

Hedin, R. S., Nairn, R. W. & Kleinman, R. L. P. 1994. Passive Treatment of Coal Mine Drainage. U.S. Bureau of Mines, Information circular 9389. 38 p.

Heikkinen, P. M. 2009. Active sulphide mine tailings impoundments as sources of contaminated drainage: controlling factors, methods of characterisation and geochemical constraints for mitigation. Espoo: Geological Survey of Finland. 38 p.

Heikkinen, P. M., Korkka-Niemi, K., Salonen, V.-P. & Lahti, M. 2002. Groundwater and surface water contamination in the area of the Hitura nickel mine, Western Finland. Environmental Geology 42, 313–329.

Heikkinen, P. M. & Räisänen, M. L. 2008. Mineralogical and geochemical alteration of Hitura sulphide mine tailings with emphasis on nickel mobility and retention. Journal of Geochemical Exploration 97 (1), 1–20.

Heikkinen, P. M. & Räisänen, M. L. 2009. Trace metal and As solid-phase speciation in sulfide mine tailings – indicators of spatial distribution of sulfide oxidation in active tailings impoundments. Applied Geochemistry 24, 1224–1237.

Heikkinen, P. M., Räisänen, M. L. & Johnson, R. H. 2009. Geochemical Characterisation of Seepage and Drainage Water Quality from Two Sulphide Mine Tailings Impoundments: Acid Mine Drainage versus Neutral Mine Drainage. Mine Water and the Environment 28, 30–49.

Jambor, J. L. 1994. Mineralogy of Sulfide-rich Tailings and Their Oxidation Products. In: Jambor, J. L. & Blowes, D. W. (eds.) The Environmental Geochemistry of Sulfide Minewastes. Mineralogical Association of Canada. Short Course Handbook, Vol. 22, 59–102.

Johnson, R. H., Blowes, D. W., Robertson, W. D. & Jambor, J. L. 2000. The hydrogeochemistry of the Nickel Rim mine tailings impoundment, Sudbury, Ontario. Journal of Contaminant Hydrology 41, 49–80.

Kauppila, T. 2006. Sediment-based study of the effects of decreasing mine water pollution on a heavily modified, nutrient enriched lake. Journal of Paleolimnology 35, 25–38.

Kauppila, T., Kihlman, S. & Mäkinen, J. 2006. Distribution of arcellaceans (testate amoebae) in the sediments of a mine water polluted bay of Lake Retunen, Finland. Water, Air and Soil Pollution 172, 337–358.

Kihlman, S. & Kauppila, T. 2009a. Mine-water-induced gradients in sediment metals and arcellacean assemblages in a boreal freshwater bay (Petkellahti, Finland). Journal of Paleolimnology 42, 533–550.

Kihlman, S. M. & Kauppila, T. 2009b. Spatiotemporal effects of an active metal mine on lacustrine arcellaceans and sediment geochemistry in Lake Pyhäjärvi, central Finland. 11th International Paleolimnology Symposium, December 14.–16. 2009, Guadalajara, Jalisco, Mexico, Abstract volume, p. 83.

Kihlman, S. M. & Kauppila, T. 2010. Tracking the aquatic impacts of a historical metal mine using lacustrine protists and diatom algae. Mine water and the Environment 29, 116–134.

Kumpulainen, S., Carlson, L. & Räisänen, M. L. 2007. Seasonal variations of ochreous precipitates in mine effluents in Finland. Applied Geochemistry 22, 760–777.

Lahermo, P., Väänänen, P., Tarvainen, T. & Salminen, R. 1996. Suomen geokemian atlas, osa 3: Ympäristögeokemia – purovedet ja -sedimentit = Geochemical atlas of Finland, Part 3: Environmental geochemistry – stream waters and sediments. Espoo: Geological Survey of Finland. 149 p.

Legendre, P. & Legendre, L. 1998. Numerical ecology. Developments in environmental modelling 20. Amsterdam: Elsevier. 853 p.

Lindström, M., Håkanson, L., Abrahamsson, O. & Johansson, H. 1999. An empirical model for prediction of lake water suspended particulate matter. Ecological Modelling 121, 185–198.

Lottermoser, B. G. 2007. Mine Wastes. Characterization, Treatment, Environmental Impacts. Second edition. Berlin–Heidelberg: Springer-Verlag. 304 p.

Mäkinen, J. 2004. Arseeni järvisedimenteissä. Summary: Arsenic in lake sediments. In: Loukola-Ruskeeniemi, K. & Lahermo, P. (eds.) Arseeni Suomen luonnossa, ympäristövaikutukset ja riskit. Espoo: Geological Survey of Finland, 73–88.

Parviainen, A., Vaajasaari, K., Loukola-Ruskeeniemi, K., Kauppila, T., Bilaletdin, Ä., Kaipainen, H., Tammenmaa, J. & Hokkanen, T. 2006. Anthropogenic arsenic sources in the Pirkanmaa region in Finland. Espoo: Geological Survey of Finland. 72 p.

Patterson, R. T. & Kumar, A. 2000. Assessment of arcellaceans (thecamoebian) assemblages, species, and strains as contaminant indicators in James Lake, Northeastern Ontario, Canada. The Journal of Foraminiferal Research 30, 310–320.

Plumlee, G. S., Smith, K. S., Montour, M. R., Ficklin, W. H. & Mosier, E. L. 1999. Geologic Controls on the Composition of Natural Waters and Mine Waters Draining Diverse Mineral-Deposit Types. In: Filipek, L. H. & Plumlee, G. S. (eds.) The Environmental Geochemistry of Mineral Deposits. Part B: Case Studies and Research Topics. Reviews in Economic Geology, Vol. 6B, 373–432.

Räisänen, M. L. 2009. Capability of natural and constructed wetlands to mitigate acidic leakage from closed mine waste facilities – cases in Eastern Finland. Conference Proceedings Securing the future, Mining, metals and society in a sustainable society and 8th ICARD International Conference on acid rock drainage Skellefteå, Sweden June 22–June 26 2009. 10 p. (Electronic publication)

Räisänen, M. L. & Juntunen, P. 2004. Decommissioning of the old pyritic tailings facility previously used in a talc operation, eastern Finland. In: Jarvis, A. P., Dudgeon, B. A. & Younger, P. L. (eds.) International Mine Water Association Symposium. Proceedings of the Symposium: Mine water 2004 – Process, Policy, and Progress. University of Newcastle, Newcastle upon Tyne, UK 19–23 September 2004. Volume I, 91–99.

Räisänen, M. L., Heikkinen, P., Pulkkinen, K., Korkka-Niemi, K. & Salonen, V. P. 2005. Finland – Mine Water Quality in some Abandoned and Active Finnish Metal Sulphide Mines. In: Wolkersdorfer, C. & Bowell, R. (eds.) Contemporary Reviews of Mine Water Studies in Europe, Part 2. Mine Water and the Environment 24, 5–7.

Reinhardt, E. G., Dalby, A. P., Kumar, A. & Patterson, R. T. 1998. Arcellaceans as pollution indicators in mine tailing contaminated lakes near Cobalt, Ontario, Canada. Micropaleontology 44, 131–148.

Rowan, D. J., Kalff, J. & Rasmussen, J. B. 1992. Estimating the mud deposition boundary depth in lakes from the wave theory. Canadian Journal of Fisheries and Aquatic Sciences 49, 2490–2497.

Schaller, T. & Wehrli, B. 1997. Geochemical-focusing of manganese in lake sediments – an indicator of deep-water oxygen conditions. Aquatic Geochemistry 2, 359–378.