Studia Quaternaria, vol. 21: 197–205.

DEPTH DISTRIBUTION OF HEAVY METALS IN LAKE SEDIMENTS FROM LIGNITE MINE PIT LAKES OF LUSATIA (GERMANY)

Kurt Friese

UFZ-Centre for Environmental Research, Department Lake Research, Brückstr. 3a, D-39114 Magdeburg,
phone: +49 391 8109 200, fax: +49 391 8109 150, e-mail: kurt.friese@ufz.de

Abstract

Mine pit lakes from lignite mining in Lusatia posses a great environmental problem due to very low pH (< 4) and high acidity of more than 100 of these lakes. To study the range and penetration of possible contamination of the sediments of these lakes by heavy metals the depth distribution of aluminium, iron, manganese, zinc, copper, lead, nickel and chromium were determined in four lakes (pit lake B, pit lake Felixsee, pit lake F, pit lake Waldsee) covering a broad range in pH (2.7–8.0), lake size (0.3–230 ha) and lake depth (5–17.5 m). According to the different acid status and history of the lakes the level of contamination is quite different for the four lakes investigated, especially for aluminium (1,800–39,000 mg/kg), iron (13,000 mg/kg – 45.7 wt-%) and manganese (28 – 1,095 mg/kg). In general, the mass concentrations for zinc, copper, lead, nickel and chromium are low (< 100 mg/kg for zinc and < 50 mg/kg for copper, lead, nickel and chromium) although varying among and within the four pit lakes.

Key words: mine pit lakes, sediments, heavy metals

INTRODUCTION

A major environmental problem of several mining sites is water acidification caused by pyrite and marcasite oxidation. This effect is very well known as acid mine drainage (AMD) from nearly all varieties of ore mines but is still an observation in many surface coal mines (Alpers, Blowes 1994). The reason is the widespread occurrence of pyrite and marcasite minerals in form of concretions or fine-dispersed as a common accompanying mineral of most ore and coal rocks. If the substrate or host rocks are brought under aerobic conditions weathering and oxidation of the FeS-minerals took place yielding highly acidic oxidation products (Singer, Stumm 1970, Lowsen 1982, Nordstrom 1982, Alpers, Blowes 1994). Several techniques were developed in the past 20 years to prevent the environment from the strong acid streams and seepages which leaves the mine sites (Hedin *et al.* 1994, Klapper *et al.* 1996, 1998, Wendt-Potthoff, Neu 1998, Totsche, Steinberg 2003, Wilscher 2003).

The situation in Germany is somewhat different from this scenario. Ore mining is not longer existent in Germany and never covered relevant areas and hard coal mining is performed by subsurface mining exclusively. Nevertheless acid outflow of closed underground mines (including uranium mines) and seepages draining heaps and dumps of ore and hard coal mines containing high concentrations of metals and acidity are still a problem (e.g. Zänker *et al.* 2000, 2002a, b; Schmid, Wiegand 2003, Wennrich *et al.* 2004).

Surface mining in Germany is solely related to soft (brown) coal mining in three main districts, the Rhenish district near Cologne, the Central-German district around Leipzig and the Lusatian district around Cottbus. In east Germany, the former GDR power generation was based on brown coal up to 90% (maximum output in 1988). A total lignite output of 300 million tons in 1989 was decreased to 116 million tons in 1993 after the reunification of Germany. 23 surface mines were closed from 1990 to 1993 based on economic aspects leaving an area of about 60,000 ha abandoned landscape. Due to the used mine techniques the groundwater level was reduced over an area of 3200 km^2 in an intensive manner. The total water deficits is about 21 billion mł. In the residual hollow forms of the open-cast mining the water deficit accumulates to 6.5 billion mł (Möbs, Maul 1994). The open-cast basins of the abandoned mine sites are filled by the rising water table and/or by riverine water. Beside this newly created lakes several lakes from former reclamation and recultivation measures exist. In general, mining lakes in the lignite district around Cottbus are characterized by very low pH (2–3) due to the release of H_2SO_4 as a drainage product of pyrite dissolution (Pietsch 1979). Accompanying high iron and sulfate concentrations and increased concentrations of elements like Al, Mn and Zn are further characteristics (Klapper, Schultze 1995, Schultze, Geller 1996,). Life conditions are extreme and research in an interdisciplinary manner is required for the development of new remediation concepts in an ecological acceptable way (Geller *et al.* 1996).

Since 1993 the Department Lake Research of the UFZ-Centre for Environmental Research performs limnological research in the Lusatian district starting with a survey of 15 lakes (Klapper, Schultze 1995, Schultze, Geller 1996, Friese

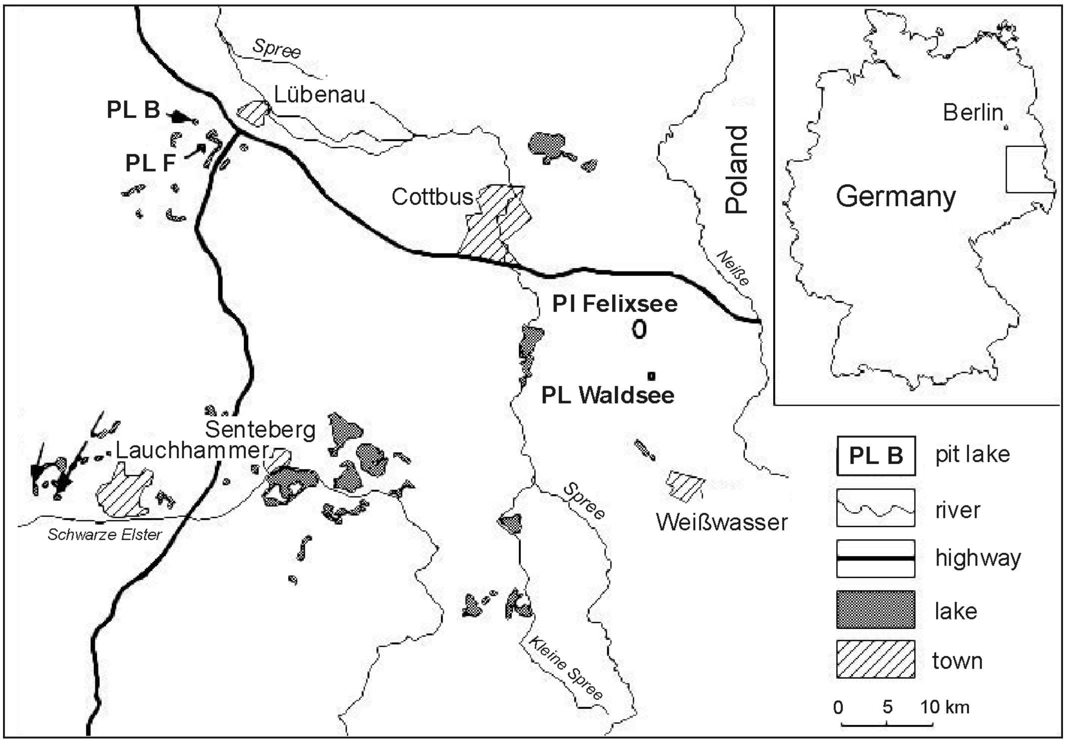

Fig. 1. Geographical setting of the mine pit lakes PL B, PL Felixsee, PL F and PL Waldsee in the lignite mine district of Lusatia. PL B and PL F are part to the local mining district “Schlabendorf-Nord”.

Table 1

Historical and morphometric data from the four pit lakes (PL B, PL Felixsee, PL F, PL Waldsee; all data from Nixdorf *et al.* 2001

	PL B	PL Felixsee	PL F	PL Waldsee
Mining period	1960-1963	1850-1933	1959 -1977	manual
Time of formation (filling)	1963/64	1933	1984	approx. 1900
Size [ha]	24	13	230	0.3
Max. Depth [m]	10.5	17.5	31*	5

*At the time of sampling in September 1994 the maximum depth was 8 m

et al. 1998). Four of these pit lakes (PL B, PL Felixsee, PL F, PL Waldsee) covering the whole pH-range observed (Fig. 1, Table 1) were selected for a preliminary investigation including lake sediment chemistry. Sediment chemistry and their controlling factors are important for the chemical and biological development of the pit lakes (*e.g.* Belzile, Morris 1995). The unstable and reactive milieu in the top layer of the sediments is related to settling of biotic and abiotic particles, microbial decomposition of organic matter, precipitation and dissolution of minerals and diffusion of dissolved components along concentrations gradients. Therefore investigations of pit lake sediments are an essential part of research for restoration and remediation measures.

This paper describes the depth distribution of heavy metals and aluminium in sediment cores from four very different mine pit lakes (PL) from the Lusatian lignite mining district in East Germany.

MATERIAL AND METHODS

Sampling and chemical analyses were performed according to the techniques listed in Table 2. The sediment samples were taken at the point with the greatest depth (see Table 1) in August 1994 (PL B, PL Felixsee, PL Waldsee) and September 1994 (PL F). Before sampling pH, temperature (T), oxygen concentration and saturation (O2) and electric conductivity (EC) were measured in the water column in steps of 1 m and water samples for a base measure of water chemistry were taken from the epi-and hypolimnion. For each pit lake one grab sample was taken as a reference sample for an integrated geochemical bulk analyses by X-ray fluorescence spectrometry (XRF) (for methodology see Morgen-

Table 2

Preparation and analytical methods for the sediment investigations

	Sampling	Preparation	Method of determination
Organic content	Ekman grab	1 g, ceramic oven	Loss on ignition (550°C)
Bulk analyses	Ekman grab	6-10 g: molten glass discs for main and pressured pellets for trace elements;1 g, aqua regia	XRFICP-OES
Depth profiles	Mondsee Corer: 10 cm cores (6 cm inner diameter	Segmentation in 2 cm steps0.5 g, aqua regia	ICP-OES

Fig. 2. Burkhard Scharf preparing the "Mondsee-Corer".

stern *et al.* 2001) and for comparison of conventional digestion with aqua regia. Core samples of the top 10 cm were taken by a modified Kajak gravity corer ("Mondsee Corer", Niederreiter, Austria) with polycarbonate tubes of 6 cm inner diameter (Fig. 2) and sliced in 2 cm steps in the field immediately after sampling. Only the sediments from PL F were cut into pieces of 1 cm thickness. The segments were stored and transported in plastic bags and refrigerated within one days. This procedure could not avoid first quick oxidation processes but gives reliable results for more integrated approaches. All samples were freeze dried prior to analyses.

The core and grab samples were digested by aqua regia following the National German Standard Methods (DIN 38414 /7). Concentration measurements for aluminium (Al), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni) and lead (Pb) were performed using ICP-OES technique (Optima 3000; Perkin Elmer, Germany). For quality assurance standard reference material (NBS 2704 'Buffalo river sediment') was proceeded in an identical way. Due to very low sample weights an adaptation of the DIN-Method which normally requires 1 g of dry mass was necessary. Standard deviations given in the tables and figures are results of triplicate analyses of the sample solution. To be able to estimate the degree of digestion by aqua regia which is not a total digestion method XRF analyses of the bulk material were performed in comparison.

RESULTS AND DISCUSSION

Lake water chemistry

The four lakes investigated spread a broad range in pH values, lake size, lake depth and living conditions (Table 1, Table 3). A recent overview about the base limnological status of most mine pit lakes in Germany is given by Nixdorf *et al.* 2001. Table 3 summarizes the water chemical data obtained during the sampling in August and September 1994. Figure 3 displays the results for the limno-physical measurements.

The neutral status of PL B (pH 8) presumably is a result of local variations in the soil composition of the surrounding rocks. The ionic composition is dominated by calcium and sulfate which indicates pyrite/marcasite oxidation in the lignite and substrate horizons. The adjacent acidity is then buffered by more calcareous and loamy soil. Due to a hypolimnion below 8 m depth with nearly anoxic conditions (Fig. 3) reductive processes at the sediment surface lead to enhanced concentrations of iron and manganese in the hyolimnetic water (Friese *et al.* 1998).

Table 3

Main and trace element concentration of water chemistry in the Epilimnion (Epi) and hypolimnion (Hypo) for calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulphate (SO4), chloride (Cl), inorganic carbon (IC), Al, Fe, Mn, Zn, Cu, Pb, Ni, and Cr in the four investigated pit lakes (PL)

	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	SO4 mg/L	Cl mg/L	IC mg/L	Al mg/L	Fe mg/L	Mn mg/L	Zn mg/L	Cu mg/L	Pb mg/L	Ni mg/L	Cr mg/L
Epi	295	20.3	10.2	4.1	433	19.2	21	0.014	0.025	0.009	<10	<2	<2	<2	<2
Hypo	194	18.8	11.3	3.7	429	19.4	24	0.049	0.25	0.45	<10	<2	<2	<2	<2
Epi	67	5	3.44	2.8	220	2.4	<1	3.2	0.28	0.46	100	3.8	<2	26	<2
Hypo	64	5.3	2.88	2.9	225	2.1	<1	3.3	0.41	0.46	110	9.6	<2	26	<2
Epi	315	70	16.4	3.4	1450	88	2.4	3.2	130	6.5	540	12	<2	135	7.7
Hypo	339	68	17.5	3.7	1650	130	2.6	3.2	160	6.7	480	11	<2	120	7.8
Epi	87	21	9.9	15	354	3.5	10	0.135	7.3	1.2	36	3.1	<2	<2	<2
Hypo	84	24	11	16	326	4.3	90	0.18	222	1.2	36	3	<2	<2	5.2

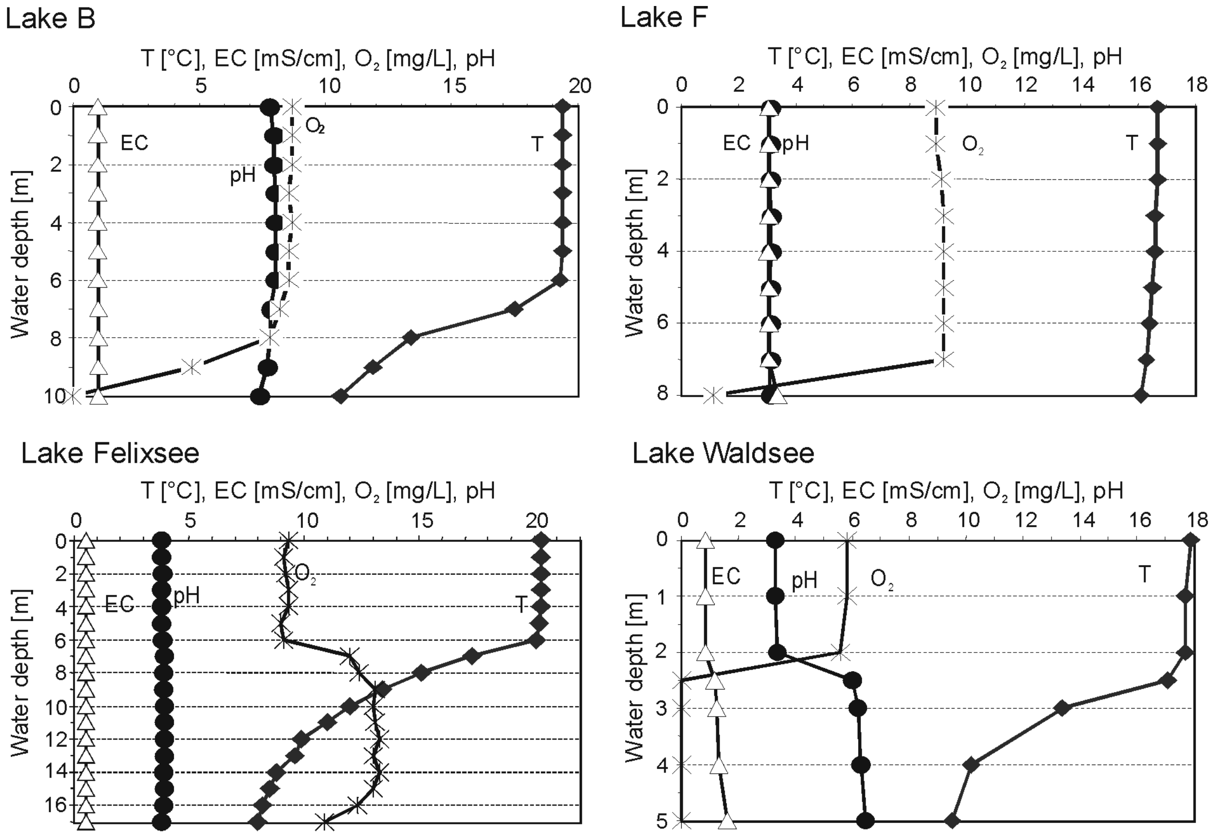

Fig. 3. Depth profiles of temperature (T), pH, electric conductivity (EC) and oxygen concentration in the water column of the four mine pit lakes (PL B, PL Felixsee, PL F, PL Waldsee).

Pit lake 'Felixsee' occupies a middle position of the investigated lakes concerning the pH-value of about 4. This pit lake is buffered within the Al-buffer as clearly indicated by the anomalous high dissolved Al concentrations in the lake water (about 3 mg/L). Due to high biological activity below 6 m water depth oxygen concentration increase from about 9 mg/L O2 in the epilimnion to about 13 mg/L O2 in the hypolimnion yielding an oxygen saturation of 126% at maximum. PL Felixsee also exhibits also high concentrations of dissolved Zn within the water column (100 µg/L) which seems to be related to the high amounts of aluminium.

The water chemistry of PL F is a typical example of an acid lignite mine pit lake as described for example in Klapper, Schultze 1995, Schultze, Geller 1996, Friese *et al.* 1998. The pH of 2.7 is buffered by the iron buffer with concentrations of 130 to 160 mg/L of dissolved iron. Beside the high concentrations of iron, calcium (315–340 mg/L) and sulphate (1450–1650 mg/L) the concentrations of the heavy metals Mn (6.5–6.7 mg/L), Zn (480–540 g/L), and Ni (120–135 µg/L) and of Al (3.2 mg/L) in the lake water are also very high.

Although the PL Waldsee is permanently stratified indicated by pH (3.3 and 6.3 in the epi- and hypolimnion, respectively), electric conductivity (0.85 and 1.3 mS/cm in the epi- and hypolimnion, respectively), and oxygen concentration (5.8 and 0 mg/L in the epi- and hypolimnion, respectively) only for iron (7.3 mg/L in the epilimnion and 222 mg/L in the hypolimnion) and for the inorganic carbon (10 mg/L and 90 mg/L in the epi- and hypolimnion, respectively) are occurring remarkable differences in the water column (Table 3).

General observations on sediments

All samples are fine grained clays, very muddy and fluffy reaching water contents up to 90% in the top 5 cm. Sediments of PL B show coarse grained sand below 8 cm depth.. Sediments of the acidic Lake 'RL-F' and Lake 'Waldsee' are rich in organic matter expressed as the loss on ignition (17% and 21% LOI, respectively). For Lake 'RL-F' (pH 2.7) this observation can be attributed to the extreme living conditions lowering the microbial degradation of the organic matter, especially under oxic conditions. This lake has a elongated form and is affected by wind and storm events resulting in a well mixed water body and oxygen saturation over the whole year. Lake 'Waldsee' is a very small meromictic lake, strongly stratified over the whole year with an anoxic neutral monimolimnion. In contrast, the epilimnion is still acidic (pH 3.0), which decreases the aerobic degradation of the organic matter during settling time. Organic matter is only destroyed partly by anaerobic bacteria in the lower part of the water column.

Bulk analyses

The results of the bulk geochemical analyses by XRF of the four grab samples are given in Table 4. From these results

Table 4

Results of bulk geochemical analyses by XRF for the four grab sediment samples of the pit lakes (PL B, PL Felixsee, PL F, PL Waldsee)

	PL B	PL Felixsee	PL F	PL Waldsee
SiO_2 [%]	51	51	40	7.7
Al_2O_3 [%]	14.7	15.6	13.6	1.69
TiO_2 [%]	0.736	0.683	0.61	0.117
Fe_2O_3 [%]	4.34	2.98	19.7	28.1
MgO [%]	0.76	0.52	0.6	0.86
CaO [%]	0.79	0.28	0.47	29.0
Na_2O [%]	0.223	0.159	0.233	0.01
K_2O [%]	2.03	1.75	1.75	0.08
P_2O_5 [mg/kg]	733	537	1063	2072
Mn [mg/kg]	206	79	150	770
S [mg/kg]	2000	1500	5500	63000
Cl [mg/kg]	35	30	120	100
As [mg/kg]	15	14	28	55
Ba [mg/kg]	379	294	490	365
Br [mg/kg]	5	4	9	4
Co [mg/kg]	8	6	4	8
Cu [mg/kg]	12	9	22	36
Cr [mg/kg]	68	62	67	23
Ni [mg/kg]	22	16	20	13
Pb [mg/kg]	26	22	29	18
Rb [mg/kg]	83	62	75	12
Sr [mg/kg]	72	54	104	530
V [mg/kg]	84	80	90	12
Zn [mg/kg]	54	35	46	47
LOI [%]	9.5	8.6	17.2	21
Sum [%]	**83**	**80**	**92**	**95**

PL Waldsee clearly separates from PL B and PL Felixsee whereas PL F shows an intermediate position. By the mass concentrations of SiO_2, Al_2O_3, TiO_2, CaO, Na_2O, K_2O, and Mn PL F groups together with PL B and PL Felixsee. In contrast PL Waldsee shows the lowest values for SiO_2, Al_2O_3, TiO_2, Na_2O, K_2O and the highest mass concentrations for CaO and Mn. Regarding the mass concentrations of Fe_2O_3, P_2O_5, and S, PL F shows more similarities with PL Waldsee which exhibits the highest values of these compounds.

From Figure 4 it is obvious that the digestion with Aqua Regia following the procedure given in the DIN 38414 / Part 7 is not able to release all amounts (< 50%) of Al and Cr to the solution (with the exception of Lake Waldsee). Mainly silicates (clay minerals and mica) are probably not dissolved by this technique (Heinrichs, Herrmann, 1990). Surprisingly, for Lake B and Lake Felixsee the digestion with Aqua Regia and determination by ICP-OES yielded higher mass concentrations for Pb and Ni whereas in Lake F and Lake Waldsee Pb and Ni were only detectable by XRF analyses. These observations are to be taken into account when discussing the results of the core sediments (see following chapter).

Sediment cores

Pit Lake B

Although PL B exhibits a neutral pH in the lake water its origin as a pit lake from lignite mining is clearly shown by the water composition e.g. with sulfate as the major anion. This

Fig. 4. Comparison of XRF bulk analyses (black bars) and ICP-OES determination after Aqua Regia digestion (grey shadowed bars) of four grab sediment samples (error bars are 2 10% standard deviation). Mn, Zn, Pb, Ni, Cu, and Cr are given in [mg/kg], Fe and Al are given in [g/kg].

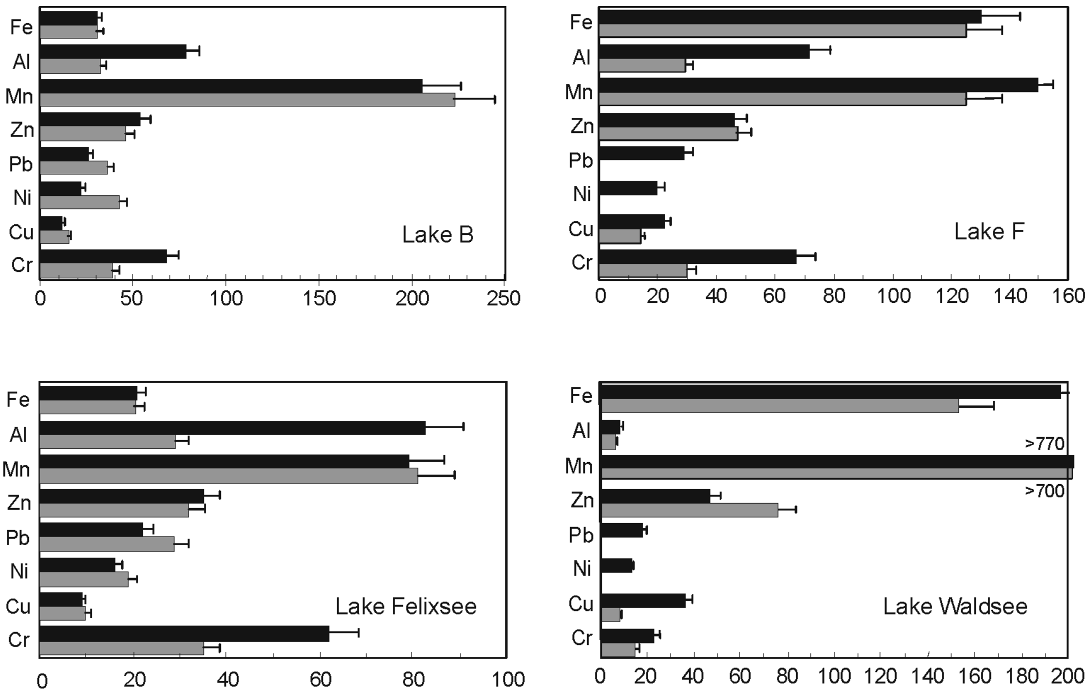

Table 5

Depth distribution of mass concentrations of Fe, Al, Mn, Zn, Cu, Pb, Ni and Cr in core sediments from the four investigated lakes determined by IC-OES after aqua regia digestion

Depth/Unit	Fe [g/kg]	Al [g/kg]	Mn [mg/kg]	Zn [mg/kg]	Cu [mg/kg]	Pg [mg/kg]	Ni [mg/kg]	Cr [mg/kg]
PL B								
0-2 cm	52	37	520	88	21	40	41	51
2-4 cm	53	39	427	87	21	42	44	52
4-6 cm	48	36	392	78	19	39	39	49
6-8 cm	39	35	341	71	18	36	35	46
8-10 cm	28	29	244	42	12	29	24	36
PL Felixsee								
0-2 cm	15	26	28	28	8	21	12	35
2-4 cm	14	23	31	19	8	17	10	32
4-6 cm	13	21	28	12	7	19	10	29
6-8 cm	19	29	34	30	10	25	13	41
PL F								
0-1 cm	364	7.2	134	18	4.0	6	20	13
1-2 cm	457	2.2	131	20	2.4	<2	21	9.8
2-3 cm	451	1.8	114	20	2.4	<2	18	9.4
3-4 cm	419	6.2	113	25	3.7	3	21	10
4-5 cm	342	18	170	104	8.1	11	36	18
5-6 cm	308	16	169	93	8.5	13	35	21
6-7 cm	243	28	143	49	9.9	17	32	33
7-8 cm	114	39	128	31	12.3	31	23	39
8-9 cm	109	40	126	30	13.0	30	23	39
PL Waldsee								
0-2 cm	269	5.7	581	26	7.0	17	20	14
2-4 cm	66	4.7	953	13	4.7	5	8	9
4-6 cm	51	5.0	1095	11	4.9	4	9	8
6-8 cm	65	5.4	830	15	5.0	5	11	8
8-10 cm	199	6.0	382	33	7.3	29	20	14
10-12 cm	274	7.7	227	37	9.0	34	22	16

origin can also be demonstrated by the high values of iron and aluminium in the sediment decreasing from top to down. The observation of decreasing mass concentrations is valid for all the elements analysed (Table 5). In the top 8 cm of the sediment core the decreasing in mass concentration is slight followed by a more pronounced decrease in the last 2 cm of the core (specially for Mn and Zn). This more pronounced decrease in element mass concentration might be the result of the change to the original unpolluted sandy bottom sediment of the unfilled void after excavation of the lignite seam before mining was ceased and the void was filled by the rising water table. The top 8 cm of the lake sediment represents sedimentation within the final pit lake by internal particle production due to the biological activity of the neutral lake (Packroff *et al.* 2000), by internal mineral precipitation and by run-off. Since Lake B is estimated to exist since 30 years at the time of sampling a sedimentation rate of about 0.27 cm per year can be calculated which is in good agreement to a sediment dating of the sediments of Lake B by Treutler *et al.* (1999) giving a sedimentation rate of 0.2 to 0.3 cm/y. Within the top 8 cm of the sediment an enrichment towards the surface for all elements analysed is observed. This might be due to an accumulation of the elements which are related to the former mining process and still be introduced into the lake by run-off and seepage or groundwater infiltration. Additionally, it is highly probable that compaction by loss of water and/or increasing grain size with depth result in the measured distribution of mass concentrations of the elements. This assumptions will be verified in the future sediment investigations.

Pit Lake Felixsee

From PL Felixsee it was able to retrieve only a short core of 8 cm length. All element mass concentrations are much lower than for the neutral pit lake B. Nevertheless, the mass concentrations for Fe and Al (1.3 to 1.9 wt-% and 2.1 to 2.9

wt-%, respectively) are much higher than in natural lakes of glacial origin in northern Germany and a clear evidence of the artificial mining origin of the pit lake. The depth distribution of the mass concentrations of the elements analysed is less clear as for pit PL B but the highest values are found at the end of the core. Towards the top of the sediment core first a decrease of the mass concentrations is observed but afterwards again an increase of the values in the top layer (with the exception of Mn). A careful interpretation assuming a similar sedimentation rate as for PL B is the assumption that the depression of element mass concentrations between 2 and 6 cm sediment depth is the result of a liming action which probably was undertaken in the time period between 1940 and 1970 (oral communication of nearby inhabitants).

Pit Lake F

The sediments from PL F show the highest mass concentrations of iron throughout the four investigated lakes with values from 10.9 to 45.7 wt-%. PL F is a typical example of an acid mine pit lake from the lignite mining in East Germany (Klapper, Schultze 1995, Schultze, Geller 1996, Friese *et al.* 1998, Nixdorf *et al.* 2000). The lake received high loads of iron, sulfate and acidity on a regular base during the time of its existence by seepage water, groundwater infiltration, and run-off. Since the acid products of the pyrite oxidation are not buffered due to missing calcareous material in the surrounding soils the pH of PL F is constantly low (< pH 3) and the main acid products iron and sulphur are stored in the sediment. From the depth distribution of the mass concentrations of the elements analysed (Table 5) a sharp change at a depth of 4 cm is indicated. With the exception of Fe, all elements exhibit an increase of mass concentration. For Mn, Zn, and Ni this increase in mass concentration is restricted to the depth of 4 to 6 cm sediment depth; further downwards the mass concentrations decrease to values similar as at the surface of the sediment core. The mass concentrations of Al, Cu, Pb, and Cr increase continuously from 4 to 9 cm sediment depth. Iron shows an accumulation of mass concentration at a sediment depth of 1 to 3 cm and a continuously decrease below the boundary at 4 cm sediment depth. The accumulation of iron between 1 and 3 cm sediment depth is accompanied by a depression of Al, Cu and Pb in this zone.

One probable explanation for the complex pattern of depth distribution of the heavy metals and Al is a higher sedimentation rate of about 0.4 cm/year in the time period from 1984 to 1994 which would explain the boundary at 4 cm depth as the bottom and starting point of lake sedimentation. The sediment part between 4 and 9 cm depth which is macroscopically clearly distinguishable from the upper part by a deep black colour might be explained a human introduction of sediment material from the nearby dumps while flatten the shore of the mine pit before filling with groundwater. Alternatively, high erosion and inflow of material in the first year after filling the mine pit by the rising water table due to steep slopes could be another explanation for the element depth distribution. In both cases, the actual sediment depth of 4 to 6 cm depth was the active interface zone between the lake water and the bottom sediment of the new pit lake in the first years after creation. This might be reflected by the accumulation or release of the redox sensitive elements Fe, Al, Mn, Zn, and Ni due to anoxic conditions where for example Zn and Ni sulphide precipitation have occurred (Friese *et al.* 1998).

Pit Lake Waldsee

Since PL Waldsee posses a very unique and special situation by having a stable monimolimnion although the small lake surface and shallow water depth normally would provide thorough mixing of the whole water column at least once a year the sediment composition is also quite unusual. Although the monimolimnion in the deepest part of the lake shows a circum-neutral pH value of about 6 accompanied by high concentrations of alkalinity also very high concentrations of dissolved iron (about 200 mg/L) and sulphate (about 330 mg/L) are observed in the water. Because the monimolimnion is strongly anoxic reductive conditions prevail the whole year (Eh approx. 150 mV) resulting in high concentrations of reduced species of iron (Fe^{2+}) and manganese (Mn^{2+}).

In the sediments of PL Waldsee the highest mass concentrations of Mn were detected (1095 mg/kg, see Table 5) among the investigated lakes showing a zone of enrichment within a sediment depth of 2 to 8 cm. All other metals measured exhibit a decrease of mass concentration within this zone or in other words an enrichment of mass concentrations in the top 2 cm of the sediment core and similar or even higher values below 8 cm sediment depth. A careful explanation for the unusual picture of heavy metal behaviour might be seen in the huge amounts of CaO (29 wt-%), S (6.3 wt-%) and OM (21 wt-%) in the bulk sample to which all of them manganese has positive relationships. Since there is no bulk chemical data available in the vertical resolution it will be highly speculative to assume a similar depth distribution of these three parameters like as for Mn.

SUMMARY

According to the different environmental conditions (local geology, limnology and history) of the four investigated mine pit lakes the mass concentrations and depth distribution of heavy metals and aluminium varies between and inside of the pit lakes. Nevertheless especially the mass concentrations of iron and aluminium are very high in all four pit lakes in the range of g/kg to wt-% for iron (PL F and PL Waldsee). In contrast the mass concentrations of the heavy metals are unexpected low being below critical values of any kind of the most used “lists” (*e.g.* Eikmann-Kloke list 1992, “Holland list” Anonymous 1994, BBodSchV 1999). For PL B the more or less uniform decrease of all heavy metals and aluminium with depth can be best explained by compaction and accumulation of the elements at the sediment surface and/or by increasing grain size from clay to silt in the top 8 cm (grain size effect). For PL Felixsee only small variations in the depth distribution of the elements were observed. Moreover, the sediment of PL Felixsee exhibit the lowest mass concentrations of heavy metals and aluminium among the four pit lakes which might be attributed to a liming action. But there are no other evidences of this liming than only oral communications of nearby inhabitants. The sediments of PL F show very high mass concentrations of iron up to 45 wt-% typical for acid mine pit lakes of Lusatia (Friese *et al.* 1998). The depth distribution of the elements exhibits a clear boundary at 4 cm depth which is also indicated macroscopically by a change from a red-brownish colour in the upper part to a deep black colour in the lower part. All elements with the exception of iron have lower mass concentrations in the upper 4 cm. Mn, Zn, and Ni show an accumulation between 4 and 6 cm depth. In PL Waldsee sediments the highest mass concentrations for Mn were found (1 wt-% at maximum). Whereas Mn shows an enrichment in a sediment depth between 2 and 8 cm depth iron is depleted within this zone. The mass concentrations of all other elements are relatively low compared to the other three mine pit lakes.

Acknowledgements

I am very thankful to Burkhard Scharf for his great help and support in introducing geochemical and limnological lake sediment investigations into the former GKSS-Institute for Inland Water Research in Magdeburg in 1994. Since that time we have been good friends and Burkhard as the practical man introduced me into the tips, tricks and special technical knacks of sediment sampling with different devices.

Peter Morgenstern from the UFZ-Department for Chemical Analyses performed the XRF analyses and Dorothee Ohlwein from the UFZ-Department Lake Research was responsible for the ICP-OES analyses of the heavy metal mass concentrations in the sediment cores. Many thanks to Gabi Packroff, Corinna Völkner, Claudia Wende, Peter Herzsprung and Michael Herzog for their great help and support during field and lab-work. All colleagues of the subsequently starting project “LENAB – Leitbilder für naturnahe Bereiche” are greatful acknowledged for their good collaboration.

REFERENCES

Alpers C.N., Blowes D.W. 1994. Environmental geochemistry of sulfide oxidation. *American Chemical Society*, Washington, DC.

BBodSchV 1999. Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV) vom 16.07.1999, BGBl. I, Bonn.

Belzile N., Morris J.R. 1995. Lake sediments: sources or sinks of industrially mobilized elements. In Gunn J.M. (ed), *Restoration and recovery of an industrial region*, 183–193. Springer Verlag, New York.

DIN 38414–7. Aufschluß mit Königswasser zur nachfolgenden Bestimmung des säurelöslichen Anteils von Metallen. In Wasserchemischen Gesellschaft -Fachgruppe in der Gesellschaft Deutscher Chemiker in Gemeinschaft mit dem Normenausschuß Wasserwesen (NAW) im DIN Deutsches Institut für Normung e.V. (Hrsg.), *Deutsche Einheitsverfahren zur Wasser-, Abwasser- und Schlammuntersuchung,* Wiley-VCH, Weinheim.

Eikmann T., Kloke A. 1992. Ableitungskriterien für nutzungs- und schutzgutbezogene Orientierungswerte für (Schad-)Stoffe in Böden. *Müll und Abfall* 24, 789–805.

Evangelou V.P. 1995. *Pyrite oxidation and its control*. CRC Press, New York.

Friese K., Hupfer M., Schultze M. 1998. Chemical characteristics of water and sediment in acid mining lakes of the Lusatian lignite district. In Geller W., Klapper H., Salomons W. (eds.), *Acid Mining Lakes - Acid Mine Drainage, Limnology and Reclamation*, 25–46. Springer-Verlag, Berlin.

Geller W., Klapper H., Salomons W. (eds.) 1998. *Acidic mining lakes - Acid mine drainage, limnology and reclamation*. Springer Verlag, Berlin.

Heinrichs H., Herrmann A.G. 1990. *Praktikum der analytischen Geochemie*. Springer Verlag, Berlin.

Herzsprung P., Friese K., Packroff G., Schimmele M., Wendt-Potthoff K., Winkler M. 1998. Vertical and annual distribution of ferric and ferrous iron in acidic mining lakes. *Acta hydrochimica et hydrobiologica* 26, 253–262.

Hölting B. 1989. *Hydrogeologie – Einführung in die Allgemeine und Angewandte Hydrogeologie*. Enke Verlag, Stuttgart.

Klapper H., Friese K., Scharf B., Schimmele M., Schultze M. 1998. Ways of controlling acid by eco-technology. In Geller W, Klapper H., Salomons W. (eds.), *Acid Mining Lakes - Acid Mine Drainage, Limnology and Reclamation*, 401–416, Springer Verlag, Berlin.

Klapper H., Geller W., Schultze M. 1996. Abatement of acidification in mining lakes in Germany. *Lakes and Reservoirs: Research and Management* 2, 7–16.

Klapper H., Schultze M. 1995. Geogenically acidified mining lakes - Living conditions and possibilities of restoration. *Internationale Revue der gesamten Hydrobiologie* 80, 639–653.

Lowsen R.T. 1982. Aqueous oxidation of pyrite by molecular oxygen. *Chemical Review* 82, 461–497.

Möbs H., Maul C. 1994. Sanierung der Braunkohlegebiete in Mitteldeutschland und in der Lausitz. *Wasserwirtschaft-Wassertechnik* 4, 12–18.

Morgenstern P., Friese K., Wendt-Potthoff K., Wennrich R. 2001. Bulk chemistry analysis of sediments from acid mine lakes by means of wavelength dispersive X-ray fluorescence.- *Mine Water and the Environment* 20, 105–113.

Nixdorf B., Hemm M., Schlundt A., Kapfer M., Krumbeck H. 2001. Braunkohletagebauseen in Deutschland - ein Überblick. *Texte Umweltbundesamt* 35/01, 519 S, Umweltbundesamt, Berlin.

Nordstrom DK 1982. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. *Soil Science Society America Special Publication* 10, 37–57.

Packroff G., Blaschke W., Herzsprung P., Meier J., Schimmele M., Wollmann K. 2000. Limnologie und Gewässerchemie von ausgewählten, geogen schwefelsauren Tagebauseen der Niederlausitz. In Wiegleb G., Bröring U., Mrzljak J., Schulz F. (Hrsg.), *Naturschutz in Bergbaufolgelandschaften – Lanschaftsanalyse und Leitbildentwicklung*, 314–330, Physica Verlag, Heidelberg.

Pietsch W. 1979. Zur hydrochemischen Situation der Tagebauseen des Lausitzer Braunkohlen-Reviers. *Archiv Naturschutz und Landschaftsforschung* 19, 97–115.

Schmid S., Wiegand J. 2003. Radionuclide contamination of surface waters, sediments, and soil caused by coal mining activities in the Ruhr district (Germany). *Mine Water and the Environment* 22, 130–140.

Schultze M., Geller W. 1996. The acid lakes of lignite mining district of the former German Democratic Republic. In Reuther R. (ed.), *Geochemical approaches to environmental engineering of metals*, 89–105. Springer-Verlag, Berlin.

Singer P.C., Stumm W. 1970. Acid mine drainage: the rate determining step. *Science* 167, 1121–1123.

Treutler H.-J., Freyer K., Friese K. 2000. Datierung der Sedimente von Tagebaurestlöchern mit 137Cs und 210Pb. In Friese K., von Tümpling W.Jr. (eds.), *Biologische und chemische Entwicklung von Bergbauseen*. UFZ-Report 26/2000; 177–182. UFZ-Umweltforschungszentrum Leipzig-Halle.

Wendt-Potthoff K., Neu T.R. 1998. Microbial processes for potential in-situ remediation of acidic lakes. In Geller W., Klapper H., Salomons W. (eds.), *Acidic mining lakes - Acid mine drainage, limnology and reclamation*, 269–284. Springer Verlag, Berlin.

Wennrich R., Mattusch J., Morgenstern P., Freyer K., Treutler H.-C., Stärk H.-J., Brüggemann L., Paschke A., Daus B., Weiss

H. 2004. Characterization of sediments in an abandoned mining area; a case study of Mansfeld region, Germany. *Environmental Geology* 45, 818–833.

Wilscher S. 2003. Lösungsansätze zur Minderung der Umweltbelastung durch saure Grubenwässer: II. Methoden der passiven und semi-passiven Behandlung. *Vom Wasser* 100, 61–84.

Zänker H., Richter W., Brendler V., Nitsche H. 2000. Colloid-borne uranium and other heavy metals in the water of a mine drainage gallery. *Radiochimica Acta* 88, 619–624.

Zänker H., Moll H., Richter W., Brendler V., Hennig C., Reich T., Kluge A., Hüttig G. 2002a. The colloid chemistry of acid rock drainage solution from an abandoned Zn-Pb-Ag mine. *Applied Geochemistry* 17, 633–648.

Zänker H., Richter W., Hüttig G., Moll H. 2002b. Colloid-borne uranium in mine waters. In Merkel B.J., Planer-Friedrich B., Wolkersdorfer C. (eds.), *Uranium in the aquatic environment*, 399–406. Springer Verlag, Berlin Heidelberg.