

Pilot scale studies of different dry covers on sulphide-rich tailings in Northern Sweden

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Abstract

Pilot scale studies of different dry covers with low permeability barrier can be performed during realistic conditions to reasonable costs narrowing the gap between field and laboratory studies. Most cover studies have been performed on tailings left open for oxidation and weathering for many years. Therefore, a project was initiated with studies of different types of dry covers on unoxidised sulphide-rich tailings in pilot scale test cells. Six 5*5*3 m³ concrete cells constructed at the Kristineberg mine site, Northern Sweden, were filled with sulphide rich mine tailings. Clayey till, sewage sludge, Trisoplast (a mixture between a polymer, bentonite and tailings sand) and fine-grained apatite are used as sealing layers and on top of that a protective cover of unspecified till was applied. In one reference cell, uncovered tailings have been left open. Measurements during late 2003 and 2004 showed average oxygen intrusions by diffusion in the range of 0.3-2.7 mole, m⁻², year through the different sealing layers. The water infiltration was relatively high, c. 0.3 m³, m⁻², year, probably due to the lack of natural run-off. The oxygen intrusion by infiltrating water was less than 10% of the total oxygen intrusions. The constantly lowest oxygen concentration beneath the sealing layer occurred in the cell with sewage sludge. Chemical analyses of the pore and drainage waters indicate that the process water still influences the pH (near neutral). Low dissolved iron content was probably due to the high pH and the relatively oxygenated water. High sulphur concentration indicates that sulphide oxidation occurred but in its initial phase. Measurements of oxygen concentrations and water chemistry will continue to obtain knowledge of the long-term efficiency of the different covers.

Introduction

In waste from mining, varying amounts of ore-associated sulphides that are not extracted during concentration processes may be exposed to the atmosphere when deposited. Sulphides such as pyrite (FeS₂) and pyrrhotite (Fe_{1-x}S) will oxidise in the presence of oxygen and water in acid-producing reactions. The acid produced increases weathering of others minerals and mobilises metals such as Cu, Pb, Zn, Cd and Co. The resulting acid drainage to the recipient may therefore have high concentrations of metals. Remediation of sulphide mine waste and prevention of metal-rich acid drainage is, therefore, an important topic. In Sweden, and also in other countries, remediation of sulphide-rich tailings are mainly carried out using water covers (Feasby et al. 1997; Öhlander et al. 1997; Holmström et al. 1999; Holmström and Öhlander 1999; Öhlander and Holmström 2000; Eriksson et al. 2001; Widerlund et al. 2001) or soil covers (Lundgren 1997; Holmström et al. 2000; Lundgren 2001; Börjesson 2002). The major reasons for covering tailings are to minimize the infiltration of water (soil cover) and decrease the oxygen intrusion into the tailings.

The application of a soil cover including a low permeability barrier has become an established reclamation method for mine waste deposits in Sweden, preferred by the Swedish Environment Protection Agency. However, there are still considerable uncertainties regarding the optimization of soil covers with regard to long-term performance and cost-efficiency. The most common method in Sweden is to use a sealing layer with low hydraulic conductivity, usually a compacted clayey till, and on top of that 1-1.5 m of unclassified till as protective layer (Höglund et al., 2005.). Within the Swedish MiMi program, this type of till cover has been studied in detail in field scale at the Kristineberg mine site (Höglund et al., 2005).

Pilot scale studies have proven useful for various types of dry covers (Aubertin et al. 1997; Simms and Yanful, 1999). Such studies also narrow the commonly observed gap between field and laboratory studies. Another advantage with pilot-scale test cells is that they enable studies of various types of covers to reasonable costs during realistic conditions. Most studies of the effects of applying till cover on tailings have been performed on tailings that have been left open for oxidation and weathering for many years. This was also the case for the MiMi studies. The most favorable case, however, when applying cover on unoxidised waste to minimize sulphide oxidation has not been studied to the same extent. Therefore, this project was initiated, with studies of different types of dry covers on unoxidised sulphide-rich tailings. Regular measurements of the oxygen concentration above and beneath the sealing layers have been performed. Chemical analyses and pH measurements of the infiltrating water and drainage water have been performed regularly, which enable estimations of the sulphide oxidation rate. The first results are presented here.

Description of the test cells

Ten concrete cells (surface 5x5 m², depth 3 m) (fig.1) were constructed during the summer of 2001 at the Kristineberg mine, owned by the mining company Boliden. An inert HDPE-liner covers the concrete inner walls and floor from possible acid produced by the pyrite oxidation, which could attack the concrete. The cells were also insulated from the outside in an attempt to avoid horizontal freezing. Six of the cells were filled with sulphide rich tailings from the Boliden concentrator. Various types of covers were applied on five of the cells whereas the sixth cell was uncovered to be used as a reference for tailings exposed to fully oxidizing conditions (fig.1).

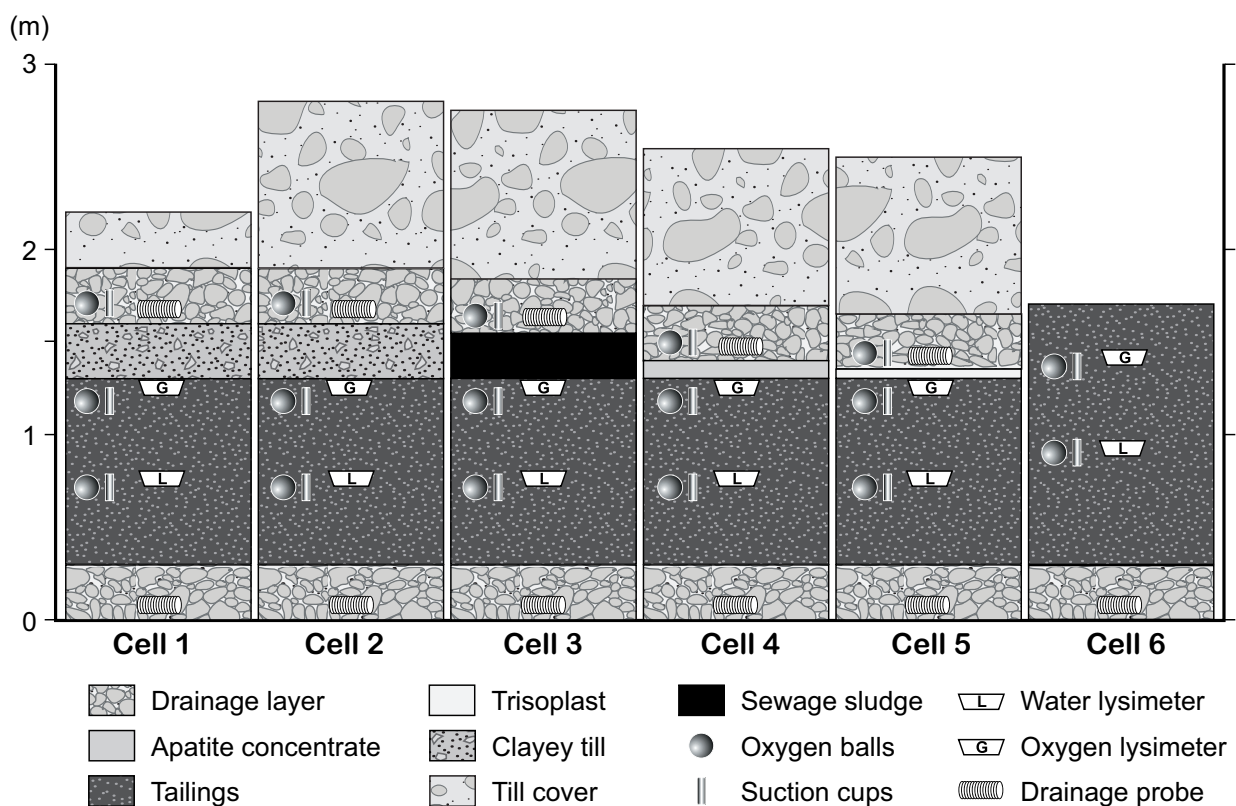


Figure 1. A schematic picture of the different layers in the different test cells at Kristineberg, Northern Sweden

All cells have a 0.3 m thick drainage layer at the bottom followed by tailings (1.0 m in cells 1-5 and 1.4 m in cell 6) (fig. 1 and 2). For the covered cells a sealing layer (different in different cell), another drainage layer (0.3 m) and finally a protective cover of unclassified till at the top were added. The thickness of the protective cover is 0.6m thick in cell1; whereas the other cells have a thickness of 1.2m. The till is similar to the till used by Boliden for the remediation of tailings impoundments at Kristineberg (Lindvall et al. 1999; Carlsson, 2002).

The sealing layers consist of; 0.3m of clayey till in cells 1 and 2; 0.25m sewage sludge in cell 3; 0.1m of apatite concentrate in cell 4 and finally 0.05m of Trisoplast (mixture of 0.2 % polymer, 11.8 % bentonite and 88.0 % tailings) in cell 5. The apatite concentrate are waste from the Kiruna iron mine and the aim with this layer are to study possible immobilization of heavy metals such as Pb and Cd due to formation of solid phosphates with low solubility.

Methods

Oxygen balls and lysimeters

Oxygen lysimeters (fig.2) were used for studies of oxygen diffusion and placed just below the various sealing layers (fig. 1 and 2), and at 0.3 m depth in cell 6. The lysimeters have a volume of $1 \times 1 \times 0.2 \text{ m}^3$ and are filled with quartzite which gives a porosity of 54%. The lysimeters are covered upwards with geotextile to avoid material from the sealing layer. The sides are sealed with bentonite to avoid oxygen consuming surroundings. Three pipes are attached to the lysimeters; one at the bottom (water outlet) and two probes upwards to the surface (oxygen sampling).

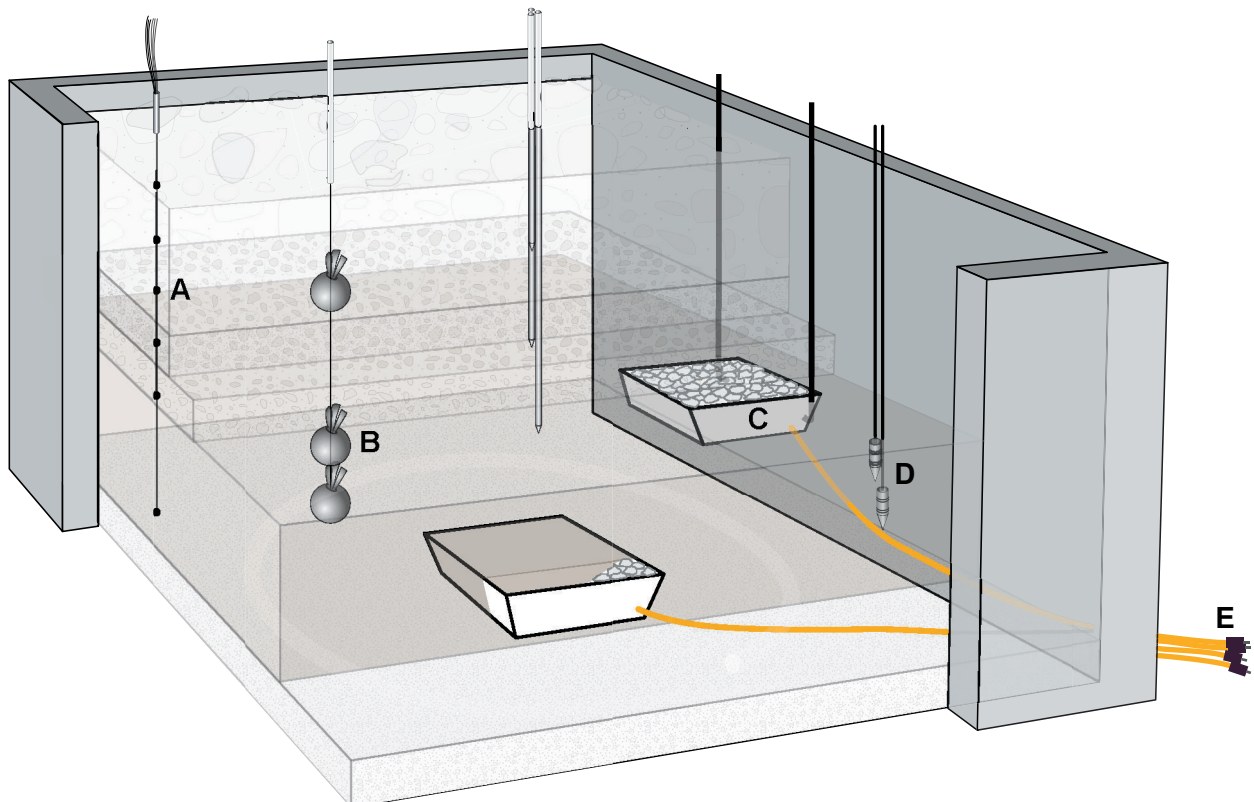


Figure 2. Location of installed equipment; A. thermistors, B. oxygen balls, C. oxygen lysimeters, D. suction cups, E. water outlets

Gas concentrations above and beneath the sealing layer were sampled from oxygen balls, consisting of geotextile filled with quartzite into which a tube has been inserted and extends to the surface. The balls were installed 0.1 m above and 0.1 m and 0.5 m beneath the sealing layer in each cell (fig.1 and 2). The oxygen balls are situated 0.5 m and 0.9 m beneath the surface in cell 6.

Water collection

Water for chemical analysis could be sampled in all cells from the bottom and from above the sealing layers through drainage probes (fig. 1 and 2). Water could also be sampled through water lysimeters (0.5m beneath the sealing layer) and oxygen lysimeters (just beneath the sealing layer) through outlets outside the cells. Pore water could be pumped up through suction cups installed 0.1m and 0.5m beneath the sealing layer, in cell 3 and 4 also in the sealing layer (fig. 2). In cell 6 the suction cups are located 0.5 m and 0.9 m beneath the surface, respectively.

Gas concentration measurement

Gas concentrations of oxygen, carbon dioxide and methane in the oxygen balls and in the lysimeters were analyzed using Maihak S710 (Boo-instrument, 2005). Prior to each gas sampling occasion the lysimeter has been emptied on water. The measurement values ranged as follows; oxygen (0-20.950vol %) carbon dioxide and methane (0-5vol %). Prior to measurements the analyzer was zero calibrated with nitrogen for oxygen, methane and carbon dioxide. The higher level was calibrated with the actual oxygen atmospheric concentration and with specific gas concentration of 3.998vol% and 3.13vol% for methane and carbon dioxide, respectively. To enable zero oxygen concentration in the beginning of the measurement periods, the oxygen lysimeters are flushed with nitrogen once during the autumn and once during the spring. During the winter, problems with frozen probe connections limit the oxygen sampling occasions.

Water concentration measurement

Water samples were collected and immediately filtrated by HNO₃ acid-washed syringes through HOAc acid-washed 0.22 μm Millipore membrane filters. The filter-passing phase was analysed using ICP-AES to determine Ca,K, Mg, Na, S, Si, Ba, Co, Mn, Sr and Zn and ICP-SFMS to determine Fe, Al, As, Cd, Cr, Cu, Mo, Ni, P and Pb.

Calculation of oxygen diffusion coefficient

The effective oxygen diffusion coefficient (D_{eff}) is a measure of how penetrable a soil is for oxygen (m^2, s^{-1}). The value of D_{eff} decreases as the water saturation in the soil increases (Elbering, 1996) since the diffusion coefficient for water ($D_w = 2.1 \cdot 10^{-09} m^2, s^{-1}$) is lower than for air ($D_{Air} = 1.78 \cdot 10^{-05} m^2, s^{-1}$). Therefore calculations of the effective diffusion coefficient are commonly calculated based on the water saturation and porosity of the soil (Schaefer, 1997; David and Nicholson, 1995; Stuparyk, 1995; Elbering B, 1996). In this case data of the water saturation is lacking. The diffusion coefficient is instead calculated using the data from the lysimeters situated just beneath the sealing layer. By using a mass balance were the change of the oxygen mass (dC_{lm}) in the lysimeters with volume, V, during time, t_0 and t_x , should be equal to the mass rate of oxygen ($F_{lm} \cdot A$) into the lysimeters (equation 1) (Cussler, 1984).

$$F = -D_{eff} \left(\frac{\Delta c}{\Delta z} \right) \quad (1)$$

F_{lm} = Oxygen flux into the lysimeters (mol, m^{-2}, s^{-1})

A = Cross-section area of the lysimeters (m^2)

V_v = Volume of the lysimeters (m^3)

dC_{lm} = Oxygen concentration differences between two sampling occasions in the lysimeters($mole, m^{-3}$)

dt = Time between the sampling occasions (s)

The flux (F_{lm}) should be equal to oxygen flux, F , (mole, year, m^{-2}) from the atmosphere into the soil which could be expressed by Fick's first law if steady-state are assumed.

$$F_{lm} = \left(\frac{V_v}{A} \right) \frac{dC_{lm}}{dt} \quad (2)$$

D_{eff} = Effective value of the diffusion coefficient in layer (m^2/s)

ΔC = Oxygen concentration difference, C_0, C_x

C_0 = Atmospheric concentration above a layer (mole, m^{-3})

C_x = Oxygen concentration beneath a layer

Δz = Thickness of the layer (m)

An approximate value of the diffusion coefficient could then be expressed if F_{lm} equals F :

$$-D_{eff} \left(\frac{\Delta c}{\Delta z_c} \right) = \left(\frac{V_v}{A} \right) \frac{dC_{lm}}{dt} \quad (3)$$

Integrating equation 3, using the initial condition with zero concentration in the lysimeters immediately after flushing the lysimeters with nitrogen at $t=0$ and $C_{lm}(0)=0$, then following equation could be expressed

$$D_{eff} = \ln \left[\frac{C_0}{C_0 - C_{lm}(t)} \right] \frac{V_v \Delta z_c}{At} \quad (4)$$

By using the oxygen concentration from the oxygen balls just above the sealing layer instead of atmospheric oxygen concentration in equation 4, the diffusion coefficient for the sealing layer alone could be estimated. Eventually volume changes due to water infiltration have not been regarded in the calculations of the effective diffusion coefficients, since the lysimeters have been emptied prior to the sampling occasions.

Results and discussion

The transports of oxygen into the tailings results in oxidations of sulphide minerals. The oxygen enters the tailings primarily by diffusion and by the infiltrating water. The oxygen diffusion is lower in water filled pores than in air filled. The diffusion therefore decreases as the water saturation in the soil increases. The fluctuations of the oxygen diffusivity during the year are therefore related to varying water saturation related to seasonal variation of precipitation and evaporation. The Swedish climatic conditions, with rather regularly distributed precipitation over the year results in that the sealing layers are water saturated most part of the year if protective covers are applied above. Estimations of the influences on the water saturation in sealing layers by periodically dry periods showed that the drying of the sealing layers are insignificant, but a decrease of the water saturation from 95% to 80% could increase the oxygen intrusion significantly (Moreno and Neretnieks, 2004).

The sealing layers are assumed to have high degree of water saturation due to the finer grain size distribution compared to the protective covers. The diffusion coefficients (D_{eff}) for the sealing layers and for the protective layers are therefore assumed to range between several orders of magnitude (Moreno and Neretnieks, 2004). However, the oxygen diffusivity between the protective layers and the sealing layers (table 1) differs only two orders of magnitude in the cells, which suggests that the difference in water saturation is small. Cell 1 have a thinner protective

cover than the other cells, but the average D_{eff} for the protective till covers are rather similar in cells 1, 2, 4 and 5.

The sealing layers are the oxygen diffusion controlling layers and the water saturation should be >0.95 to be effective. Cells 1 and 2 have similar protective covers and sealing layers as in the field at Kristineberg, which was selected as a base case in the calculation of oxygen intrusion performed by MiMi (Moreno and Neretnieks, 2004). Calculation of oxygen intrusion suggests a D_{eff} of $1.0 \cdot 10^{-9} \text{m}^2/\text{s}$ in the sealing layer when the water saturation is 0.95 (Moreno and Neretnieks, 2004). The D_{eff} in cell 2 showed similar value, which suggests a high degree of water saturation of this sealing layer. The sealing layer in cell 1 had a high D_{eff} of $1.21 \cdot 10^{-8} \text{m}^2/\text{s}$, which correspond to a lower water saturation (Moreno and Neretnieks, 2004), which could be due to low compaction when the sealing layer was applied. So far, the sealing layer consisting of apatite concentrate showed the lowest average D_{eff} , and it was also low during the whole sampling period. All sealing layers except for the apatite layer showed D_{eff} varying in the range of two orders of magnitude during the sampling period. The apatite layer is only 10 decimetres thick and was not expected to have this property as an oxygen barrier. Further investigations of the apatite material are necessary to explain this property. The physical characterisations such as water retention capacity, grain size distribution and hydraulic conductivity of the different materials are under investigation. Continuous outtake of water from above the sealing layers during 2004 in cells 2 and 4 supports that the sealing layers have been water saturated to high degree. This was, however, not the case for cell 5

The water infiltration rates in the cells were as follows: cell 1, 0.3; cell 2, 0.24; cell 3, 0.27; cell 4, 0.25; cell 5, 0.28 and cell 6, 0.16 $\text{m}^3/\text{m}^2 \cdot \text{a}^{-1}$, which corresponds to oxygen intrusions by infiltrating water of 0.05-0.09 mole, $\text{m}^{-2} \cdot \text{year}^{-1}$. The water infiltrations are relatively high, but the oxygen intrusions by water are insignificant compared to the oxygen intrusions by diffusion (0.3-2.7 mole, $\text{m}^{-2} \cdot \text{year}^{-1}$). The highest oxygen intrusion by diffusion was observed in cell 1 (2.7 mole, $\text{m}^{-2} \cdot \text{year}^{-1}$). For cells 2, 4 and 5 the oxygen intrusion by diffusion, and calculated D_{eff} :s for the sealing layers, agreed very well with calculated values from field data (Moreno and Neretnieks, 2004).

Table 1. Average effective oxygen diffusion coefficients (D_{eff}) calculated for the test cells at Kristineberg for 2004, shown separately for the whole cover (protective cover and sealing layer), protective layer and for the sealing layer only.

<i>Cell nr with type of sealing layer and field</i>	<i>D_{eff} (m^2/s)</i>		
	<i>Whole cover</i>	<i>Protective till cover</i>	<i>Sealing layer</i>
Cell 1 (Clayey till)	2.35E-08±3.01E-08	9.32E-08±1.36E-07	1.02E-08±1.17E-08
Cell 2 (Clayey till)	2.77E-08±5.02E-08	8.94E-08±1.62E-07	6.2174E09±1.13E-08
Cell 3 (Sewage sludge)*			
Cell 4 (Apatite concentrate)	9.74E-09±8.63E-09	6.77E-08±6.23E-08	8.06E-10±7.04E-10
Cell 5 (Trisoplast)	7.48E-08±1.2E-07	3.51E-07±6.56E-07	3.86E-09±5.7E-09
Cell 6 (Unremediated)*			

- Cell 6 (only tailings) and cell 3 (sewage sludge) contain oxygen consuming materials. Therefore diffusion coefficients could not be calculated with the method outlined above (eq.1-4).

The relatively high water infiltrations through the covers are probably mainly due to the lack of natural run-off. Continuous outtake of water from above the sealing layers indicate that the covers could have been water saturated most part of the year. However, high amounts of water have only been collected during the snowmelt from above the sealing layers. The lack of natural run-off influences the water saturation in the soils, to which extent this affect the water infiltration and oxygen intrusion is not known yet. The high water infiltration rates could also be due to damages of the sealing layers by e.g. freezing.

The oxygen concentrations in the oxygen balls beneath and above the sealing layers vary during the seasons (fig. 3). During parts of May the water from the snowmelt made oxygen measurement impossible. Except for some occasions, the oxygen concentrations have been lower beneath the sealing layer than above in all cells. 0.1m above the sealing layer there has been almost atmospheric oxygen concentration during the whole sampling period, except for cell 3. The cell with sewage sludge shows most variation of the oxygen concentration above the sealing layer, with periods of low concentrations. 0.5m beneath the sealing layer of sewage sludge the oxygen concentrations are constantly low. There has been some problem with the oxygen probes at 0.1m beneath this sealing layer but there is probably similar oxygen concentration as at 0.5m depth. The sewage sludge cell shows lowest oxygen concentration beneath the sealing layer.

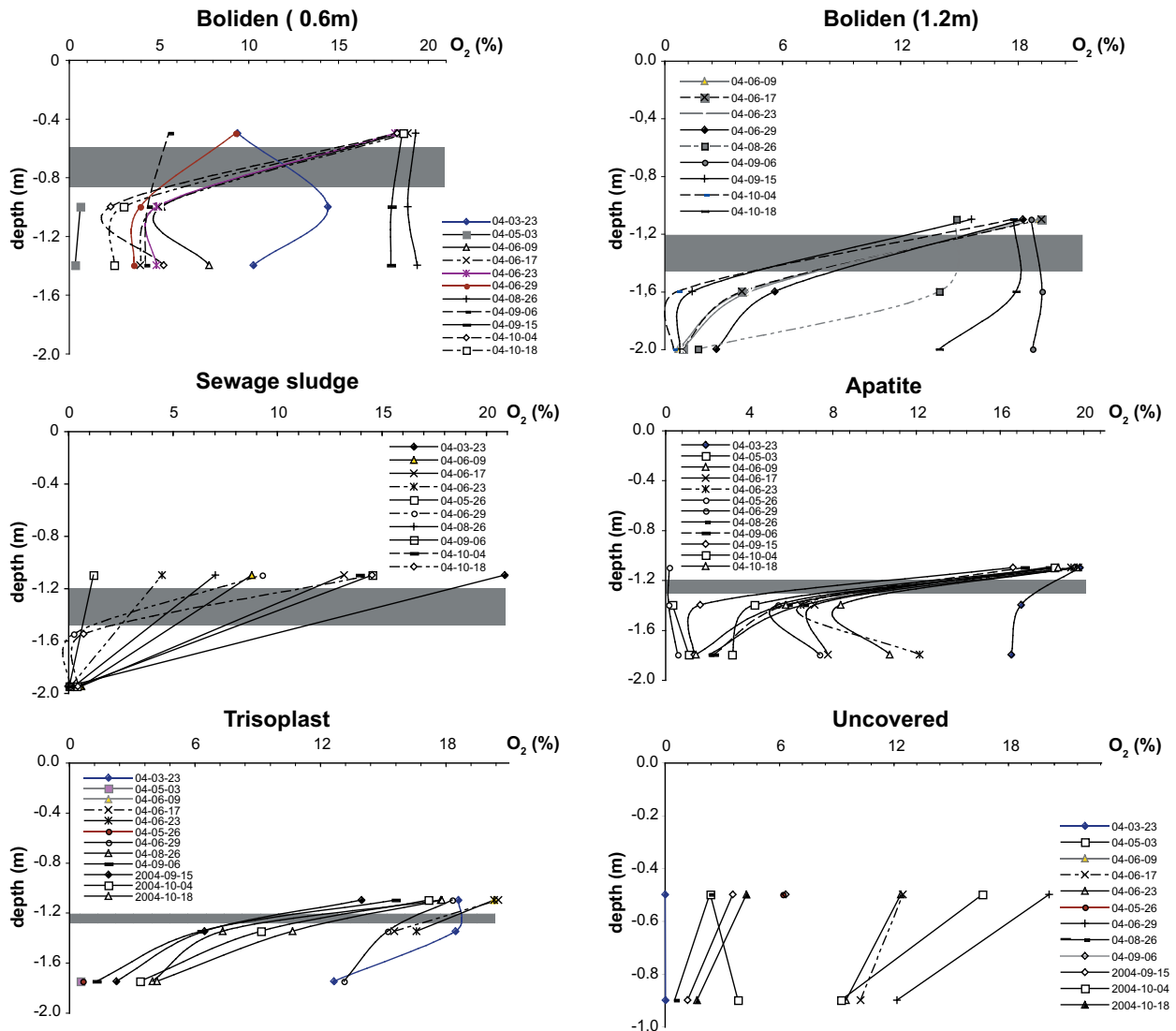


Figure 3: Oxygen concentrations beneath and above the sealing layer in all test cells.

Water chemistry

There are 5 - 6 possibilities to sample water in each cell; from the bottom drainage, from above the sealing layer, from the oxygen lysimeters, from the water lysimeters and from the suction cups. The amount of water available was a factor which limits the sampling occasions and the priority of analysis. Samples from all levels have been taken at least once, but analyses of samples from the bottom water and from the suction cups have been given priority. Average chemical composition of the water from different layers is shown in table 2. Above the sealing layer it has been possible to collect water through the drainage pipes. The chemical analyses of

this water have been few because of lack of water and to prevent drying of the sealing layer. The water collected above the sealing layer in all cells has percolated through the till cover only. This water shows similar chemical composition in all cells and therefore an average from all cells has been estimated (table 2).

Table 2. Average concentration of selected dissolved element in water, collected from different layers in the cell

Dissolved elements	Fe (mg/l)	S (mg/l)	Zn(mg/l)	Cu (μ g/l)	Ca (mg/l)	pH	Conduct. (mS)
<i>Infiltrating water 1</i>							
Average for all cells (5)	3.6E-03 \pm 1.6E-03	157.7 \pm 104.9	0.3 \pm 0.2	4.6 \pm 0.7	194.4 \pm 112.8	6.38 \pm 0.98	0.81 \pm 0.57
<i>Pore-water in the tailings</i>							
Cell 1 (clayey till, thin cover) (2)	9.1 \pm 1.1	533 \pm 5.7	66.1 \pm 34.8	0.5 ²	642 \pm 116	7.19 \pm 0.11	
Cell 2 (clayey till, thick cover) (3)	12.8 \pm 11.5	580 \pm 24.6	94.3 \pm 57	30.3 \pm 35.3	534.3 \pm 91	7.43 \pm 0.36	2.722
Cell 3 (sewage sludge) (3)	17.8 \pm 12.2	486.3 \pm 23.5	0.301 \pm 0.33	1.07 \pm 0.09	803.7 \pm 38.2		
Cell 4 (apatite concentrate) (5)	3.6 \pm 1.4	658 \pm 175.4	214.9 \pm 247.6	3.262	536.5 \pm 164.8	7.132	
Cell 5 (trisoplast) (2)	15.1 \pm 17.3	609.5 \pm 177.5	54.6 \pm 37.3	x ³	574 \pm 17	7.3 \pm 0.32	
Cell 6 (unremediated)	0.1 \pm 0.01	616 \pm 117..3	61.7 \pm 8.84	10.7 \pm 9	50.6 \pm 92.6		
<i>Bottom water</i>							
Cell 1 (clayey till, thin cover) (5)	2.77 \pm 2.02	508.4 \pm 137.3	16.2 \pm 3.1	3.94 \pm 5.7	528.8 \pm 122.5	6.77 \pm 0.38	2.35 \pm 0.58
Cell 2(clayey till, thick cover) (5)	12.59 \pm 11.9	595.2 \pm 128	26 \pm 12.3	1.89 \pm 3.1	565.4 \pm 51.8	6.78 \pm 0.37	2.64 \pm 0.43
Cell 3 (sewage sludge) (5)	14.2 \pm 31.3	487.5 \pm 310.7	5.2 \pm 11.5	340.1 \pm 480.7	709.2 \pm 56.9	6.86 \pm 0.31	4.34 \pm 0.67
Cell 4 (apatite concentrate) (3)	0.02 \pm 0.02	586.3 \pm 111	55.9 \pm 30.6	9.0 \pm 5.5	615 \pm 46.2	6.73 \pm 0.44	2.57 \pm 0.38
Cell 5 (trisoplast) (5)	0.4 \pm 0.4	592.6 \pm 258.8	59.8 \pm 31.5	5.9 \pm 3.3	474.2 \pm 161.4	6.57 \pm 0.16	3.15 \pm 1.08
Cell 6 (unremediated) (5)	1.9 \pm 2.5	747 \pm 125	56.5 \pm 7.2	11.39 \pm 13.9	589.8 \pm 59.6	6.57 \pm 0.42	2.82 \pm 0.50
<i>Released concentration (kg)⁴</i>							
Cell 1 (clayey till, thin cover)	0.04 \pm 0.002	4.4 \pm 1.8	2.5 \pm 7.2E-05	-	4.5 \pm 1.8		
Cell 2 (clayey till, thick cover)	0.15 \pm 0.002	4.8 \pm 1.6	3.1 \pm 0.02	-	4.0 \pm 1.6		
Cell 3 (sewage sludge)	0.19 \pm 0.002	4 \pm 1.7	0.69 \pm 0.008	4.61 \pm 1.66	6.4 \pm 1.7		
Cell 4 (apatite concentrate)	2E-04 \pm 0.002	4.4 \pm 1.5	6.33 \pm 0.04	0.06 \pm 1.58	4.3 \pm 1.5		
Cell 5 (trisoplast)	5E-03 \pm 0.002	5.6 \pm 1.7	8.47 \pm 0.04	0.02 \pm 1.68	3.3 \pm 1.7		
Cell 6 (unremediated)	0.02 \pm 0.001	4.5 \pm 1.3	4.59 \pm 0.02	0.06 \pm 1.28	2.9 \pm 1.3		

¹ above the sealing layers, percolated water only through the till

² only one value, the others below the detection limit

x³ values below the detection limit

⁴ total mass from the tailings

- Less mass of an element out than infiltrating mass

Water samples from the suction cups and bottom water, consist of water that has percolated through till covers, drainage layers, sealing layers and tailings. These waters show high average dissolved S content compared to water which percolated only through the till cover. This indicates that sulphide oxidation occurs, but the S could also origin from the process water. The dissolved Fe content was relatively low in all cells, probably due to precipitation of Fe oxy-hydroxides due to the high pH and oxygenated water. The average dissolved Cu content was low (table 2), but high

Cu concentrations occurred just after filling of the cells, which increased the average value (table 2). In cell 3 the average Cu concentration was lower than $5\mu\text{g/l}$, similar to the concentration in the water which only percolated through the till cover. Zinc was on average high in all cells except for the cell with sewage sludge, which showed the lowest concentration.

Mass balance calculations were performed for the different cells. The average concentration of an element in the bottom water during 2003-2004 was multiplied with the total amount of water collected during the same period. The mass added by the till cover was calculated in the same way and subtracted from the total mass. The resulting masses for selected elements are shown in table 2, corresponding to total element release from the sealing layers and the tailings.

Masses during 2003-2004 of elements such as Ca (table 2), Al and Si were highest in the cell with sewage sludge, probably due to the decay of organic matter. A relatively high electric conductivity was observed in cell 3, which also indicates high release of elements compared to the other cells. The Ca concentrations are high in all cells and probably originate from lime added during the processing before deposition. The high calcium concentrations correspond to high pH, near-neutral, in all cells (table 2). The average pH was lower in the till cover and increased in the tailings. The pH decreases as the water moves downwards to the bottom drainage water from the upper tailings (table 2). The relatively similar pH and masses of Fe and S between the cells indicate that the sulphide oxidation was similar in all tailings. The near-neutral pH decreases the mobility of dissolved elements, and probably decreases the sulphide oxidation rate. This suggests that the oxidation will increase as the effect of process water disappears.

Conclusions

The intrusion of oxygen by diffusion through the sealing layers consisting of apatite, clayey till (with 1.2m protective cover) and Trisoplast was relatively low (0.3 - 1.1 mole oxygen, m^{-2} , year). The sealing layer consisting of sewage sludge shows low oxygen concentration beneath the sealing layer most of the year, but oxygen intrusion could not be calculated with the method outlined in this paper. The relatively high water infiltration is due to the lack of natural run-off which could result in damage of the sealing layers. The oxygen intrusion by infiltrating water was around 10% of the total oxygen intrusion and its effect could be neglected compared to the oxygen intrusion by gas diffusion. The chemical composition of the water at different levels show near-neutral pH and low iron concentration. This indicates that the process water and lime added to the tailings during concentration processes still influence the pH and dissolved element concentrations and mobility. The relatively high sulphur concentration indicates that sulphide oxidation occurs in the tailings but is in its initial phase. So far, the cover efficiency varies between the cells, and it is possible that the sealing layers will improve in the future. Measurements of oxygen concentration and water chemistry will continue to obtain knowledge of the long-term efficiency.

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