Mine Water Hydrodynamics, Stratification and Geochemistry for Mine Closure – The Metsämonttu Zn-Cu-Pb-Au-Ag-Mine, Finland

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Abstract In the case of the Metsämonttu Zn-Cu-Pb-Au-Ag-mine in Finland, which was closed in the 1970ies, the mine water chemistry, isotopes, flow and the stratification in the mine was measured for a duration of two years. Based on the results, a still ongoing tracer test was initiated. The reason for this investigation was to understand which hydrodynamic and chemical processes are occurring in a closed underground mine and how this knowledge can be used for future mine closures or in-situ remediation options as so far no general conclusions can be reported.

It was found that the mine water shows no substantial vertical stratification but that a horizontal stratification occurs which causes the water in the two shafts to be of different chemical and isotopic signatures. While the electrical conductivity in shaft 2 was low, close to low mineralized ground water, the electrical conductivity in shaft 1 was higher, showing an interaction between the ore deposit and the water. The current results of the tracer test also show that the mine water velocity seems to be very slow as no tracer was found after 3 months of operation of the tracer test.

Key words hydrodynamics, geochemistry, Metsämonttu, abandoned mine

Introduction

In the times of economic down turn, when resources deplete or political decisions require the closure of underground mines, the question arises of how to conduct mine closure. This paper will address this question. In the past, the underground mines were simply allowed to flood by turning the mine pumps off and allowing the groundwater *alias* mine water table within the mine to rise (Wolkersdorfer 2008). Once the inflow and outflow quantity of the mine water equalised or the mine water reached the lowest point of discharge, the mine water either entered the receiving water courses or was directed into a mine water treatment plant (“pump and treat”). Yet, changing environmental standards and social awareness of potential problems relating to polluted or acid mine drainage demands a more thorough planning of the flooding and mine closure process (Stacey et al. 2010a, b). Recent and current examples, where mine flooding resulted or will result in thorough planning are the German hard Coal mines (Coldewey et al. 2014; Rosner 2011), the Witwatersrand gold mines (Coetzee 2016) or the Cape Breton Island hard coal mines (Shea 2009), and in many cases a vertical stratification in the shafts was observed (Wolkersdorfer et al. 2016).

The abandoned Finnish Metsämonttu mine with two shafts was chosen as a case to study mine water chemistry, hydrodynamics and the stratification within the mine water body. For two years, chemical water data was collected, isotope studies conducted and a tracer test initiated. This proceedings paper describes the first results of these investigations. A description of the mine water treatment experiments is given in another paper of this author in this proceedings volume.

Description of mine site

The following description of the mine site is taken from Wolkersdorfer and Qonya (2017). Metsämonttu ("forrest pit") is an abandoned underground copper-zinc-lead-silver-gold mine in Aijala, situated in the Salo municipality (formerly Kisko) of the Salo sub-region of Southwest Finland (Varsinais-Suomi). Mining in this area dates back to the 17th century, but the Metsämonttu deposit was only discovered in 1945. A first drill hole was started in 1946 and the mine was operated from 1952–1958 and 1964–1974 (figures differ). As rich ore reserves were discovered, Outokumpu Oy started mining in 1951, initially with an open pit exploration but subsequently, a 3 × 4 m shaft I was sunk to a depth of 135 m (Turunen 1953; Varma 1954) and later deepened to 235 m. Mining was conducted using shrinkage-stoping with longitudinal stopes and partly cut-and-fill stoping (Matikainen and Särkkä 1982; Varma 1954). Based on the production data, shaft II, which is located 280 m south of shaft I, was very likely sunk between 1961 and 1962 and reached a depth of 545 m (fig. 1). Both shafts are connected with each other through the +190 m level. In the vicinity of the Metsämonttu mine, three other abandoned mines are located: the Aijala, Aurums-Aijala and the Hopeamonttu mines, which operated during various times between the 17th and 20th century (Mäkelä 1989; Papunen 1986; Puustinen 2003). Though the amount of ore processed was still high, the mine was finally closed in 1974. Production numbers vary from source to source, but are around 1.1 t Au, 20 t Ag, 45 kt Zn, 7.1 kt Pb, 1.6 kt Cu and 113 kt S from a total of 1.5 Mt of ore mined (Geological Survey of Finland (GTK) 2017; Nurmi and Rasilainen 2015).

Tectonically and genetically, the mine belongs to the Orijärvi-Aijala area (Aijala subarea *sensu* Eilu) of the Uusimaa Belt and is classified as a Zn-Cu±Au volcanic massive sulphide (VMS) deposit (Eilu et al. 2012; Hanski 2015; Latvalahti 1979). It is characterised by felsic to mafic volcanics and chemical sedimentary sections. Usually, the volcanics are intensely altered with an increase of K, Fe and Mg and a decrease of Na and Ca with gneisses of varying composition and skarn, all of them highly metamorphosed (Eilu et al. 2012). According to Latvalahti (1979), this alteration results in "dolomitization, silicification, sericitization and magnesium-iron metasomatism" of the ore deposit. This nearly vertical deposit has a maximum thickness of 20 m, but mostly it is less than 10 m thick and the ore itself is located within dolomitic limestones and skarns as well as quartz and cordierite-anthophyllite wall rocks in disseminated or breccia deposits. Typical main ore minerals are pyrrhotite (18–20 %), pyrite (9–10 %), sphalerite (7 %), chalcopyrite (0.25 %) and galena (0.12 %) with a large number of secondary minerals (Turunen 1953; Warma 1975, Table 1).

On the first visit in 2015, ferrous mine water with a circum-neutral pH was discharging from shaft 1 into the cellar of the abandoned shaft housing and from there into the receiving environment. After about 50 m of surface flow, where substantial ochre deposits have been build up since the mine closure, the mine water seeped into a waste rock pile north of the shaft building. At the point of discharge from the shaft into the cellar, H2S could be smelled

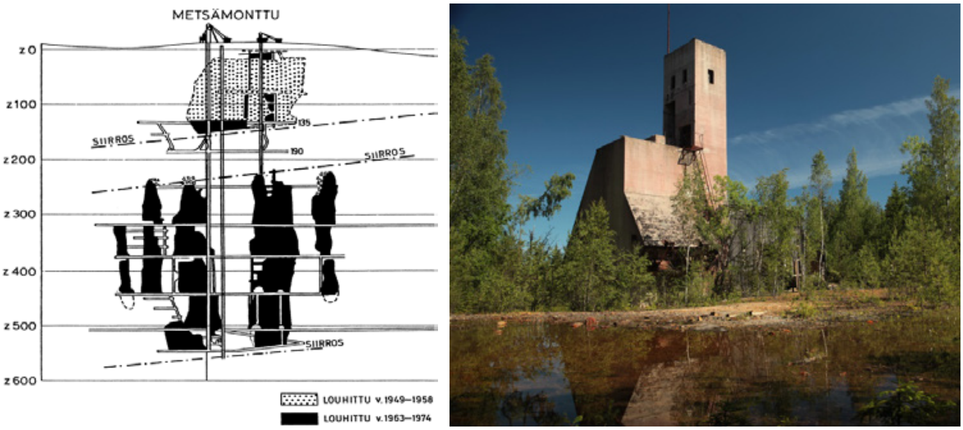

***Figure 1** Left: Cross section of the Metsämonttu mine site with shaft 1 on the right and shaft 2 on the left. Indicated are the two mining phases (from Warma 1975). Siirros: fault, louhittu: mined. Right: shaft 1 and part of the flooded open pit lake in the foreground (2015-07-02).*

and white filaments, very likely sulfur reducing bacteria, could be observed. In shaft 2, the mine water was standing 11.63 m below shaft bank and a 20 cm (1 m³) thick layer of badly smelling oil, grease and fat was encountered. This was later removed from a specialised company. In both shafts, the mine water has a distinctive aromatic smell of PAHs.

Methods and Material

Mine water samples were taken in filtered, acidified (0.2 µm) and unfiltered aliquots and analysed in the accredited Ramboll Lahti laboratory using ICP-MS and discrete analysers. k_B and k_A were analysed in the field with a Hach digital titrator and on site parameters measured with the relevant Hach electrodes connected to a Hach HQ40D. Stable isotope ratios $\delta^{18}O$ and $\delta^{2}H$ were sampled in 2 mL glass vials with septum screw caps were completely filled with water samples and analyzed at the Institute for Groundwater Management, Technical University of Dresden, Germany by a stable isotope mass spectrometer MAT 253 (Thermo Fisher Co., Bremen, Germany) after pyrolysis in a high temperature pyrolysis device at 1450 °C (HEKAtech Co, Wegberg, Germany). $\delta^{18}O$ and $\delta^{2}H$ ratios were estimated by an average of a fourfold analysis and calibrated by the IAEA-standards VSMOW2 and SLAP2. Temperature and electrical conductivity measurements in the shafts were conducted once using a Heron Conductivity Plµs 300 m dipper (the instrument failed to work properly after the first measurements). Depth dependent water samples were taken with a 1 L plastic depth sampler. While shaft one could be sampled up to its maximum depth of 210 m, shaft 2 had an obstacle in a depth of 290 m and could not be sampled to the maximum depth. Flow was measured with the bucket and stopwatch method.

Results and Discussion

Water is discharging from shaft 1 at a flow rate of 0.6 – 34.6 L/min, with an average of 9.3 L/min (n = 66). pH values are circumneutral between 6.0 and 7.9 with an average of 7.0 and electrical conductivities range from 209 to 1300 µS/cm with an average of 550 µS/

cm. No water discharges from shaft 2, as the mine water level is 13 m below surface. Based on the production data, the mine has a volume of 500 – 600,000 m^3, which would result in an average theoretical flooding time of 100 years. As this is obviously wrong, the mine water make during production and the flooding period must have been higher, but no data is known hitherto, and the first flush period can therefore not be calculated.

All chemical and isotope data show that the mine waters in the two shafts of the Metsämonttu mine are slightly, but statistically significantly different (Tab. 1 and Fig. 3). In general, the mine water in shaft 1 is higher mineralised than that of shaft 2. Isotopic analysis show that the samples in shaft 1 are heavier compared to those of shaft 2, but are not on one of the local meteoric water lines of Finland. Yet, as mine water in shaft 2 is clearly precipitation influenced, this water falls within the range of isotope signature typical for rain water in Finland, as reported by Kortelainen (2007). The difference between these two isotopic compositions could be related to winter or summer isotope signatures in the two shafts, an isotopic fractionation of mine water in shaft 1 or mixing with water showing heavier isotope ratios. Detailed studies to understand these differences are still ongoing. From the depth depended temperature and electrical conductivity measurement in shaft 1, two distinctive water bodies can be identified, whereas the upper one is characterised by lower temperatures and electrical conductivities, compared to the lower water body. As would be expected, the separation occurs at one of the main levels connected to shaft 1 (+83 m level, 80 m below ground). Interestingly, this difference is not mirrored in the chemical composition of the mine water at different depths, which can either be related to a malfunctioning of the dipper or the depth depended samples were not taken in the depth indicated. Thought the chemical analysis also show a tendency to higher mineralisation with depth, it is not as obvious as in the dipper measurements.

Some of the most distinct difference between the two shafts is the trace metal concentration. While shaft 2 is generally lower mineralised then shaft 1, there are some, hitherto unexplained differences: Al, Cd, Cu and Zn are higher in shaft 2 then in shaft 1. As the average pH in both shafts is similar, one reason might be the redox potential, which is around 105 mV in shaft 1 and 275 mV in shaft 2. Most metals are less mobile in lower redox conditions than in higher ones, which partly might explain this difference. One of the main reasons for the higher mineralisation in shaft 1 is the fact that the water flows through large parts through backfilled stopes, while the mine water in shaft 2 is predominantly rain or ground water flowing into the shaft. The higher sulfate concentrations in shaft 1 are an indication of pyrite weathering, but the protons are buffered by the prevailing carbonates in the ore body. Only in the lowest part of shaft 2 the shaft is connected with the ore body, but cannot be samples due to obstacles in the shaft.

Interesting is the relatively high As-concentration in the mine water of shaft 1, which is due to the occurrence of elemental As and As minerals in the ore body, as described by Warma (1975). This is an indication that the mine water discharging at shaft 1 either flows through the backfilled stopes or the unmined ore body, whereupon the first option is more unlikely due to the waste rock–cement mixture used for backfilling.

Table 1 *Results of the depth dependent chemical analysis in the shafts 1 and 2 between 2015-08-20 and 2016-12-21. n = 4. The relative standard deviation for most of the parameters is around 11%. Ion balance from PHREEQC (WATEQ4F database) calculation.*

	Shaft 1				**Shaft 2**			
	15 m	**65 m**	**145 m**	**210 m**	**13 m**	**95 m**	**220 m**	**290 m**
Ca, mg/L	110	107	110	113	37	37	42	46
Mg, mg/L	9.3	9.3	9.7	9.6	1.6	1.6	2.4	3.6
Na, mg/L	11.7	11.4	12.5	12.5	5.2	5.1	6.9	10.6
K, mg/L	2.2	2.2	2.2	2.3	1.4	1.3	1.3	1.4
Sr, mg/L	0.2	0.2	0.2	0.2	0.0	0.0	0.1	0.1
Li, µg/L	5.0	5.3	5.4	5.0	1.4	1.5	1.7	1.8
NH_4, mg/L	0.2	0.2	0.2	0.1	<0.006	<0.006	0.02	0.01
HCO_3, mg/L	160	160	160	160	95	95	96	96
SO_4, mg/L	198	198	208	215	28	28	53	48
Cl, mg/L	3.1	2.9	3.1	3.2	2.5	2.4	2.7	4.7
F, mg/L	1.5	1.4	1.4	1.4	0.2	0.2	0.2	0.2
Fe, mg/L	7.7	7.7	8.0	8.0	0.6	0.6	1.0	1.3
Mn, mg/L	0.7	0.6	0.7	0.7	0.0	0.0	0.1	0.1
As, µg/L	51.5	51.3	52.0	51.0	1.7	1.7	2.8	3.1
Al, µg/L	<10	<10	<10	<10	118	120	120	115
Ba, µg/L	9.9	9.8	9.9	9.9	8.3	8.1	8.2	8.3
Cd, µg/L	<0.030	<0.030	<0.030	<0.030	0.4	0.4	0.4	0.4
Cu, µg/L	1.4	<1.0	<1.0	<1.0	6.0	6.1	5.9	5.9
Pb, µg/L	1.1	0.9	1.1	2.2	2.8	3.0	3.0	2.8
Si, mg/L	7.7	7.4	7.5	7.4	4.5	4.4	4.6	4.7
U, µg/L	3.2	3.3	3.4	3.4	1.1	1.1	1.3	1.8
Zn, µg/L	8.0	9.3	9.4	12.5	210	208	208	200
Ion balance, %	1.84	0.60	0.83	0.72	1.40	1.31	-1.42	7.95

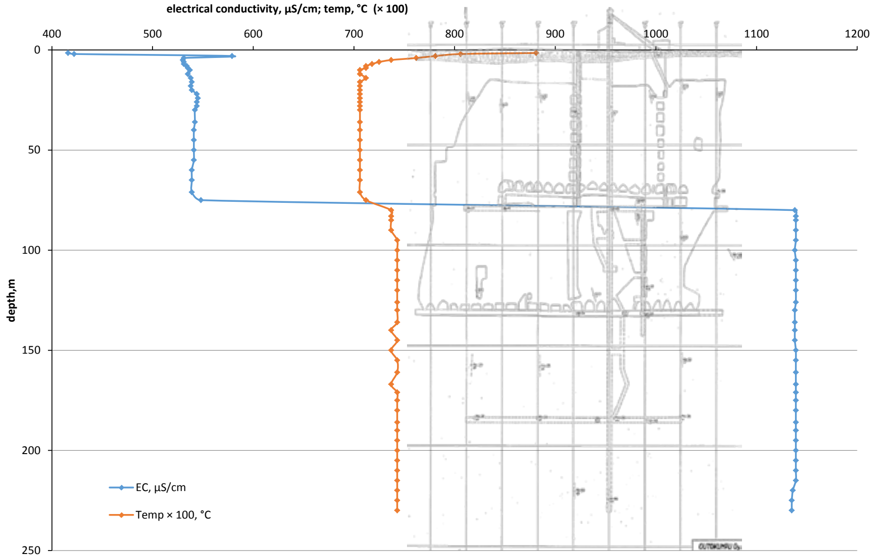

Figure 2 *Vertical electrical conductivity (EC) and temperature measurements in the Metsämonttu shaft 1 (2016-08-22). Superimposed is a cross section of shaft 1.*

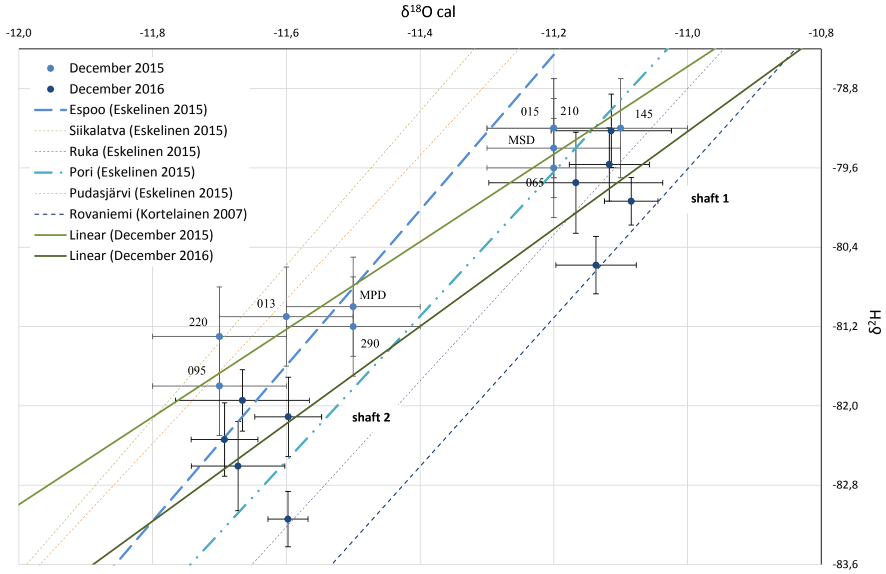

Figure 3 *Depth dependent stable isotope compositions in the Metsämonttu mine. LMWL: various local mean water lines from Finland. Left lower cluster from shaft 2, right upper cluster form shaft 1. MPD: Metsämonttu pipe discharge (shaft 1) and MSD: Metsämonttu shaft discharge (shaft 1) Local Meteoric Water lines (LMWL) from Eskelinen et al. (2015) and Kortelainen (2007). Espoo and Pori are the closest to the mine site.*

Conclusions

This investigation shows that there is a chance to flood mines such that the discharge of potential pollutants is kept to a minimum. This requires a control of the mine water hydrodynamics to ensure that the surface pollution is minimised. Yet, the results of the investigation do not allow establishing a hypothesis of what causes the stratification to occur at a given position in the shaft. As the two shafts are connected with each other at the +190 m level, it would have been expected that the separation of the two mine water bodies would occur around this depth, but it occurs at the level +83. It is also unknown so far why the stratification measured with the temperature-EC-dipper is not clearly mirrored in the chemical composition of the mine water. What can be concluded is that the mine water discharging at the Metsämonttu mine shows a relatively low mineralisation and that the only constituents of environmental concern are As and Fe, both of which are successfully removed in a passive mine water treatment scheme (Wolkersdorfer and Qonya 2017).

These investigations once again show that natural stratification can occur in abandoned, flooded underground mines. Yet, stratification, as has been shown in other investigations (Wolkersdorfer 2008; Wolkersdorfer et al. 2016), does not occur in all flooded mines. Because stratification can be considered a result of hindered hydrodynamic mixing in a flooded mine, it will be beneficial if mines are technically modified before mine closure to prevent an overall circulation of the water in the to be flooded mine.

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References

Coetzee H (2016) Management of water levels in the flooded mines of the Witwatersrand, South Africa. In: Drebenstedt C, Paul M (eds) IMWA 2016 – Mining Meets Water – Conflicts and Solutions. TU Bergakademie Freiberg, Freiberg, p 630-635

Coldewey WG, Wesche D, Rudolph T, Melchers C (2014) Methods for Evaluating the Hydraulic Barrier Effects of the Emscher Marl Following Cessation of German Hard-coal Mining. In: Sui W, Sun Y, Wang C (eds) An Interdisciplinary Response to Mine Water Challenges. International Mine Water Association, Xuzhou, p 693-698

Eilu P, Ahtola T, Äikäs O, Halkoaho T, Heikura P, Hulkki H, Iljina M, Juopperi H, Karinen T, Kärkkäinen N, Konnunaho J, Kontinen A, Kontoniemi O, Korkiakoski E, Korsakova M, Kuivasaari T, Kyläkoski M, Makkonen H, Niiranen T, Nikander J, Nykänen V, Perdahl JA, Pohjolainen E, Räsänen J, Sorjonen-Ward P, Tiainen M, Tontti M, Torppa A, Västi K (2012) Metallogenic Areas in Finland. Special paper – Geological Survey of Finland 53:207-342

Eskelinen R, Ronkanen A-K, Rossi P, Isokangas E, Marttila H, Kløve B (2015) A Review of Stable Water Isotope Studies done in Finland. In. https://www.researchgate.net/publication/277580220_A_review_of_stable_water_isotope_studies_done_in_Finland Accessed 2017-05-07

Geological Survey of Finland (GTK) (2017) Metsämonttu. In: Mineral Deposit Report. http://tupa.gtk.fi/karttasovellus/mdae/raportti/578_Mets%C3%A4monttu.pdf Accessed 2017-05-06

Hanski E (2015) Chapter 2 – Synthesis of the Geological Evolution and Metallogeny of Finland. In: Maier WD, Lahtinen R, O'Brien H (eds) Mineral Deposits of Finland. Elsevier, p 39-71

Kortelainen N (2007) Isotopic Fingerprints In Surficial Waters – Stable Isotope Methods Applied In Hydrogeological Studies. University of Helsinki

Latvalahti U (1979) Cu-Zn-Pb ores in the Aijala-Orijarvi area, southwest Finland. Econ Geol 74(5):1035-1059. doi:10.2113/gsecongeo.74.5.1035

Mäkelä U (1989) Geological and geochemical environments of Precambrian sulphide deposits in southwestern Finland. Ann Acad Sci Fenn A 3 Geol Geogr 151:1-102

Matikainen R, Särkkä P (1982) Cut-and-Fill Stoping as Practiced at Outokumpu Oy. In: Hustulid WA (ed) Underground Mining Methods Handbook. p 571-584

Nurmi PA, Rasilainen K (2015) Chapter 11 – Finland's Mineral Resources: Opportunities and challenges for future mining. In: Maier WD, Lahtinen R, O'Brien H (eds) Mineral Deposits of Finland. Elsevier, p 753-780

Papunen H (1986) Geology and ore deposits of southwestern Finland. In: Gaál G (ed) 17e Nordiska Geologmötet 1986 – Excursion guide, excursion C 3 – Metallogeny and ore deposits in South Finland. vol Guide 16. Geologian Tutkimuskeskus, Espoo, p 8-18

Puustinen K (2003) Suomen kaivosteollisuus ja mineraalisten raaka-aineiden tuotanto vuosina 1530–2001, historiallinen katsaus erityisesti tuotantolukujen valossa, Geological Survey of Finland, Report M 10.1/2003/3, Espoo, 578 p

Rosner P (2011) Der Grubenwasseranstieg im Aachener und Südlimburger Steinkohlenrevier – Eine hydrogeologisch-bergbauliche Analyse der Wirkungszusammenhänge. unveröff. Diss RWTH Aachen, Aachen

Shea J (2009) Mine Water Management of Flooded Coal Mines in the Sydney Coal Field, Nova Scotia, Canada. Document Transformation Technologies, Pretoria

Stacey J, Naude A, Hermanus M, Frankel P (2010a) The socio-economic aspects of mine closure and sustainable development – guideline for the socio-economic aspects of closure – Report 2. J S Afr Inst Min Metall 110(7):395-413

Stacey J, Naude A, Hermanus M, Frankel P (2010b) The socio-economic aspects of mine closure and sustainable development: literature overview and lessons for the socio-economic aspects of closure – Report 1. J S Afr Inst Min Metall 110(7):379-394

Turunen E (1953) Aijalan ja Metsämontun kaivokset [The Aijala and Metsämonttu mines]. Vuoriteollisuus – Bergshanteringen 11:16-28

Varma A (1954) The copper-zinc ore deposits of Aijala and Metsämonttu. Geol Tutkimuslaitos 55:20-24

Warma A (1975) Outokumpu Oy:n Aijalan ja Metsämontun kaivosten vaiheita [Outokumpu Ltd: The Ajala and Metsämonttu operations]. Vuoriteollisuus – Bergshanteringen 33:94-98

Wolkersdorfer C (2008) Water Management at Abandoned Flooded Underground Mines – Fundamentals, Tracer Tests, Modelling, Water Treatment. Springer, Heidelberg

Wolkersdorfer C, Qonya B (2017) Passive Mine Water Treatment with a full scale, containerized Vertical Flow Reactor at the abandoned Metsämonttu Mine Site, Finland. Paper presented at the 13th International Mine Water Association Congress – Mine Water and Circular Economy, Lappeenranta:this issue.

Wolkersdorfer C, Shongwe L, Schmidt C (2016) Can natural Stratification prevent Pollution by Acid Mine Drainage? Paper presented at the IMWA 2016 – Mining Meets Water – Conflicts and Solutions, Leipzig/Germany:115-121.