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Preliminary volume and concentration estimation of the Aijala tailings pond – Evaluation of geophysical methods

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1. Introduction

Raw materials are becoming more important for the EU economy. The recycling and recovery of these materials is increasingly relevant as they become scarcer and their prices rise. According to estimations presented in Hogland et al. (2011), Vossen (2005) and by the European Enhanced Landfill Mining Consortium (EURELCO), in the EU area there are between 150,000 and 500,000 highly variable landfills, and these could contain a significant potential for secondary raw materials. However, no standardised inventory is available for the secondary raw materials in these landfills, and the present reporting standards are insufficient.

The SMART GROUND project, funded by the EU's Horizon 2020 programme, aims at improving the availability and accessibility of information on secondary raw materials in the EU (Dino et al., 2016). The consortium will create a single EU database (the SmartGround database) that will integrate all the data from existing sources and new information that is obtained in the future. Such a database will enable the exchange of contacts and information among relevant stakeholders (e.g. companies) who are interested in providing or obtaining secondary raw materials. The project will produce detailed information on secondary raw materials from three pilot landfills in each partner country. The Aijala tailings pond is one of the Finnish pilots. The database will include the preliminary mineral resource estimate to raise interest within secondary raw material processers. Further development of the tailings pond as a source of secondary raw materials is dependent on the estate owner, an operator eager to generate business from waste.

To produce the mineral resource estimate of this tailings pond, where tailings from three mines have been deposited, several geophysical methods were utilised together with soil drilling and geochemical analyses. The research question was which or which combination of the geophysical methods (electrical resistivity tomography (ERT) and induced polarization tomography (IPT), together with gravity, magnetic and electromagnetic methods) provide most usable information for 3D modelling the tailings pond bottom and interfaces between the tailings from different mines? ERT has been successfully used to study the internal structure of tailings ponds by Placencia-Gómez et al. (2010), Lghoul et al. (2012) and Martín-Crespo et al. (2015). Gravity survey has been used by Balia (2018) and Vanhala (2005) in surveying thickness of tailings ponds. Magnetic and electromagnetic methods have been utilised in tailings ponds by Buselli and Lu (2001) and Brosten et al. (2011) to study seepage.

2. Material and methods

The closed Aijala Cu mine operated from 1949 until 1958. Its dressing plant operated as late as 1974, because Zb-Pb ore from the nearby Metsämonttu mine (active in 1952–1958 and 1964–1974) and Ni-Cu ore from the Telkkälä mine (active in 1970) was also processed in Aijala. Thus, the tailings pond in Aijala includes tailings from three different ore bodies (Sipilä, 1994).

Aijala and Metsämonttu ores belong to VMS type mineralization of Orijärvi area, ca. 1895–1891 Ma (Skyttä et al., 2005). They are in relation to intensively altered felsic to mafic volcanic rocks and chemical iron and chert forming sedimentary units. The volcanic rocks were altered into cordierite-mica, cordierite-antophyllite and andalusite-cordierite-muscovite, but also into tremolite ± diopside skarn, which indicates submarine VMS system (Latvalahti, 1979; Colley and Westra, 1987; Mäkelä, 1989). The main ore minerals are pyrite, pyrrhotite, sphalerite, chalcopyrite, galena, arsenopyrite and fahlore (Hänninen, 1978a, 1978b). The Telkkälä ore belongs to the Saimaa-Lahdenpohja metaturbidite-synorogenic intrusive area, ca. 1.89–1.88 Ga (Makkonen and Huhma, 2007). Host rock of Telkkälä ore is intrusive metaperidotite, norite and hornblende-kummingtonite gabbro (possibly metanorite). The Telkkälä ore contains pyrrhotite, pentlandite, chalcopyrite, and pyrite or marcasite in the oxidised parts. Pentlandite has violaritised or even bravoitised (Hänninen and Sotka, 1988).

Chemically differing tailings layers resulting from different ore types were already observed in 1982, when the mining company Outokumpu Oy took samples from 28 drill holes in the tailings (Kokkola, 1982). Fig. 1 presents the drilling locations and the results of chemical assays for copper and zinc. The total concentrations of Cu, Zn,

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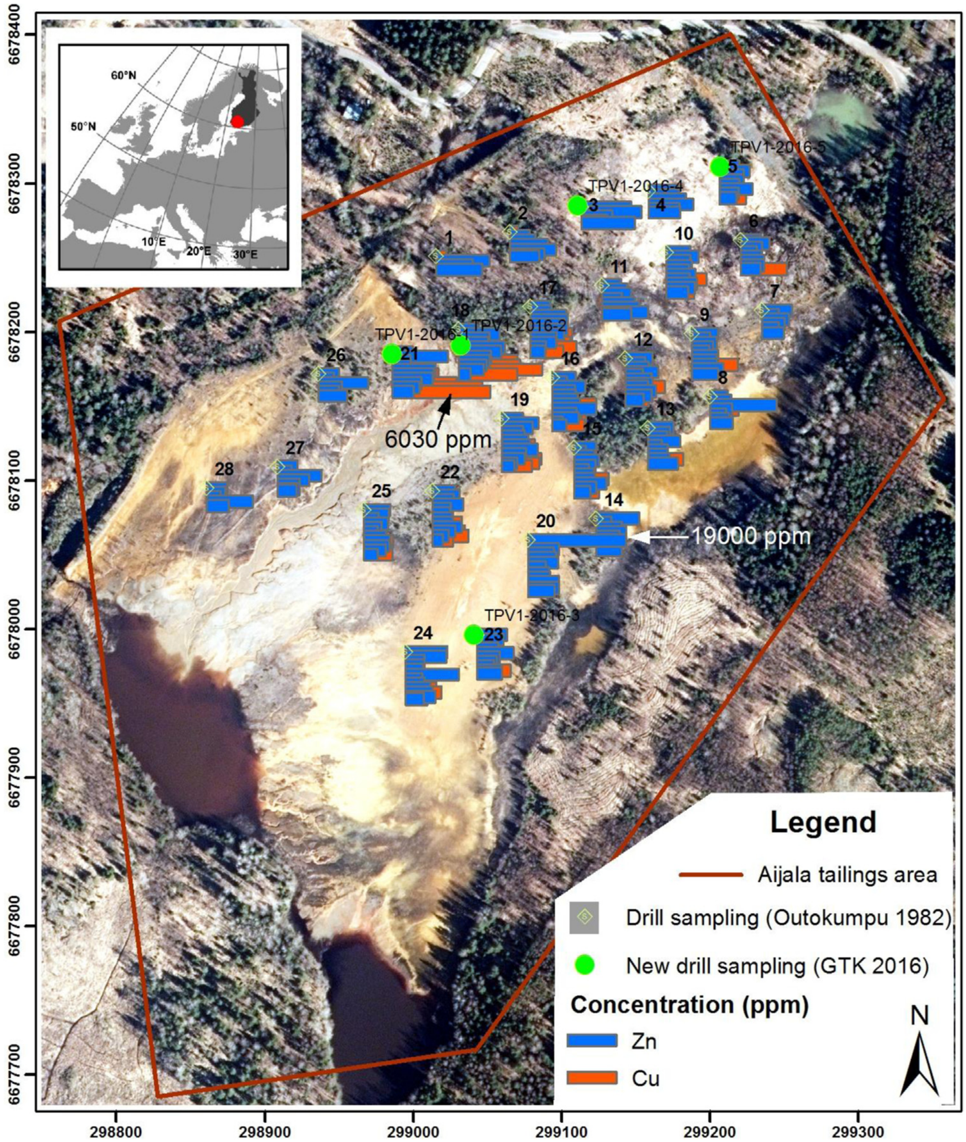

Fig. 1. Drill samples taken and analysed in 1982. Blue bars represent Zn concentrations and red bars Cu concentrations at different depths. The locations of 5 new drill samples are marked with green dots.

Ni, Co, Pb, Mn, Ag and Fe were analysed from the drill cores at 1-metre intervals by AAS. Gold was only analysed from some selected samples. The depth of the tailings varied from 4 to 11.7 m. The average depth of the tailings area was 8.7 m. The lower part of sampling profiles tends to have higher Cu concentrations derived from the Aijala ore, while the upper part has higher Pb and Zn concentrations from the Metsämonttu mine. The location of tailings from the processing of Telkkälä ore cannot be distinguished from the data.

Mineralogical alteration occurred in the oxidised zone above groundwater level. Silicates had a strong iron hydroxide pigmentation. Nearly all sulphides had been oxidised, only pyrite and few nuggets of chalcopyrite and pyrrhotite were observed. Carbonates had been leached away and gypsum crystallised. (Sipilä, 1996) Tailings material has been altered to approximately 40 cm deep (Sipilä, 1994).

During tailings operations and monitoring from 1976 to 1981 pH values were high (6.4–7.1) in the ditch draining out towards Kiskonjoki, because weathering of the carbonate minerals in the tailings buffered the drainage water. In 1992 pH had dropped to 4.9 (Sipilä, 1994) and sum of dissolved metals (Zn, Cu, Cd, Pb, Co, Ni) had risen. The reason is that in 1992 there were not enough carbonate minerals left in the upper oxidised part of the tailings to control pH. Electrical conductivity and concentrations of SO_4^{2-} and many trace metals are highest in the upper part of the ditch. However, the highest lead concentration was measured from the small pond situated inside the tailings area. (Sipilä, 1994) In 2001–2004 another sampling campaign revealed that the mean pH of 7 samples from the ditch < 500 m from the pond was 5.3 (Räisänen et al., 2005). Yet another sampling campaign in 2016 (Tornivaara et al., 2016) measured pH 4.1. Copper concentration in the drainage water has increased from 0.06 mg/l to 0.09 mg/l, then to 0.17 mg/l and finally decreased to 0.026 mg/l in 2015. Zinc performed same kind of peaking concentrations trend: 0.39 mg/l, 7.47 mg/l, 4.59 mg/l and 1.40 mg/l. Also $SO4^{2-}$ performed the same trend: 100 mg/l, 1050 mg/l, 434 mg/l to 160 mg/l.

It has been estimated that the Aijala tailings area contains 2 million tons of mining waste with the following average element concentrations (Sipilä, 1994): Cu 0.12 wt%, Zn 0.50 wt%, Pb 0.11 wt%, Ag 7.95 mg/kg and Au 0.69 mg/kg. According to Kokkola (1982), the highest Cu concentrations were observed in the northernmost part of the tailings area. The zinc concentrations did not show a clear regional distribution within the tailings area. Pb concentrations were higher in the upper parts of sample profiles. Ag concentrations displayed a weak positive correlation with Pb concentrations. The concentrations of Ni

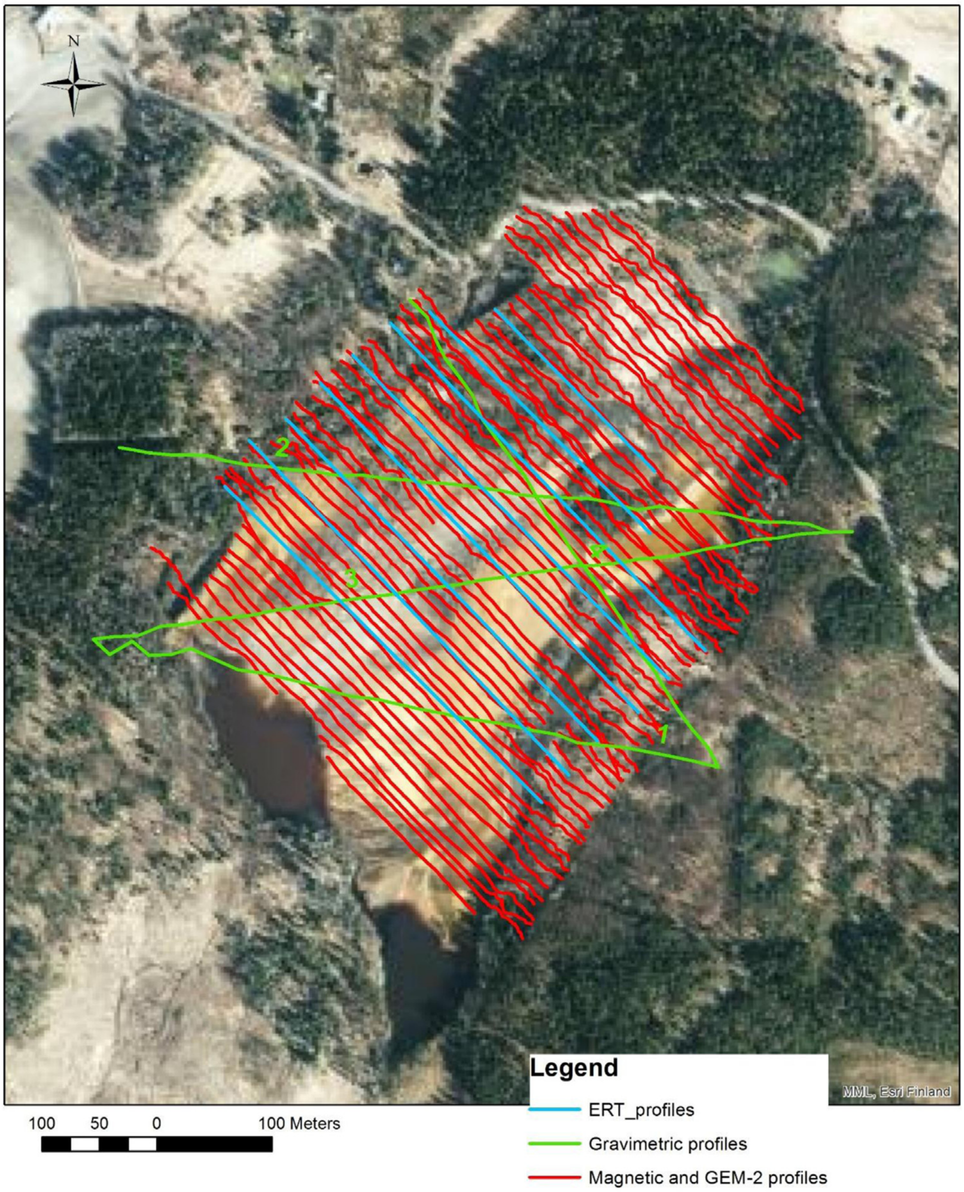

Fig. 2. Location of profiles investigated with different geophysical methods at the Aijala tailings pond.

and Co were close to the regional background concentrations.

In summer 2016, the Geological Survey of Finland (GTK) took additional samples from the Aijala tailings pond. Five additional holes were drilled and the tailings samples were analysed at 1-m intervals, resulting in 48 samples in total. The aim of this sampling campaign was to also determine the concentrations of metals that had not previously been analysed, and which have become desired by the modern world, as well as some environmentally harmful elements. Two replicate analyses were carried out in the quality assurance, and three monitoring samples were included in the analytical batch. Samples were first dried at 40 °C and the entire sample was pulverized in a hardened steel bowl (LM5). Dried and pulverized samples were then extracted by total dissolution with strong concentrated mineral acids (Tarvainen, 1995). Even though extensive geochemical analysis was carried out from these five drill cores, only copper, zinc, lead and silver were taken into account in the mineral resource estimation. This is because they were also analysed in the old drilling campaign, and a sufficient amount of data was therefore available for concentration interpolations. Two replicate analyses were carried out in the quality assurance, and three monitoring samples were included in the analytical batch. A good correlation was observed between the results of replicate analyses: Ag concentrations in the first replicate pair were 8.52 and 8.59 mg/kg and in the second pair 16.3 and 16.5 mg/kg. Cu concentrations were 2810 and 2780 mg/kg for the first replicate pair and 12,100 and 12,300 mg/kg for the second replicate pair. For lead the replicate analysis were 634 mg/kg and 607 mg/kg for the first pair and 2050 mg/kg and 2050 mg/kg for the second pair. For zinc the replicate analysis were 8650 mg/kg and 8620 mg/kg for the first pair and 5810 mg/kg and 5860 mg/kg for the second pair.

Although the tailings material had the same appearance from top to bottom, the geochemical assays of the samples taken from the drill holes revealed the interface of the tailings material from the Metsämonttu and Aijala mines. The top part, which contained tailings from the Metsämonttu mine, was rich in lead, and the bottom part, containing tailings from Aijala, was rich in copper. The soil drills were cored down to the hard soil material underneath the tailings pond, and they therefore also served as known reference points for the subsequent interpretations of several geophysical studies.

Geophysics was utilised to determine the location of the interface of tailings from Aijala and Metsämonttu, and the vertical and horizontal dimensions of the tailings pond. Gravity, magnetic and electromagnetic GEM-2 (Lerssi et al., 2016; Won et al., 1996), electrical resistivity tomography (ERT; Dahlin, 1996) and induced polarization tomography (IPT) surveys were carried out (Fig. 2). The results of the gravity survey were used to interpret the thickness of the tailings pond and depth of the bedrock surface (Valli and Mattsson, 1998). The magnetic survey provided a general picture of the iron content in different parts of the tailings pond. The GEM-2 method was utilised to map the apparent conductivity and susceptibility of the tailings ponds surface layers from a depth of 1 m down to 10 m.

Gravity measurements with 20 m point intervals were measured from outcrop to another across the tailings pond. ERT (multiple gradient array) was used to examine changes in the electrical conductivity of the tailings material. The depth penetration of the ERT measurements was about 30–60 m, depending on the minimum electrode spacing and the number of electrodes used in the profiles. Eight ERT and IPT profiles were measured with a 4-channel ABEM Terrameter SAS4000 with a Lund Imaging system. The measurement array was a multiple gradient array. The length and of the profiles were L1–L3 400 m, L4 280 m, L5 200 m and L6–L8 400 m, and minimum electrode spacing L1–L3 5 m, L4 2.5 m, L5 2 m and L6–L8 5 m respectively. Topology of the tailings pond was determined by the LiDAR DEM provided by the National Land Survey of Finland.

3. Results

3.1. Soil drilling and geochemistry

Soil drill samples were only taken from five drilling sites in 2016. Subsamples for chemical analysis were taken from drill cores at 1-metre intervals like in the drilling campaign in 1982. The drilling sites of the five new samples were not exactly in the same locations as the previous sampling points, and there was minor variation in the length of samples from the drill core. Fig. 3 illustrates the correlation between Cu concentrations in samples taken in 1982 and in 2016. The concentrations of all four elements analysed in both years (Ag, Cu, Pb and Zn) displayed significant positive correlations. Therefore, no significant change in the element concentrations of the tailings has occurred since 1982, and the analyses from the old survey could still be used in the mineral resource estimation. Mineralogical studies of the tailings material showed that all sulphides except pyrite were strongly oxidised to Fe-OH-minerals in the upper oxidised layer of the tailings pond (Sipilä, 1994). This layer is approximately 40 cm thick (Sipilä, 1996).

Samples from the five new drill holes were analysed in more detail for those metals not examined earlier that could pose a threat to the environment or could be utilised in the modern world. The correlations of these elements with Ag, Cu, Pb and Zn were studied and their concentrations were compared with the median European subsoil concentrations (Salminen, 2005). Table 1 summarizes the other elements analysed from the five drill holes in 2016 that had a significant positive correlation with Ag, Cu, Pb and Zn, which concentrations were available also for all samples taken in 1982. According to Table 1, Au concentrations have a positive correlation with Ag, Pb and Zn in the upper part of the Aijala tailings (material originating from the Metsämonttu mine), but not in the older, deeper layers of the tailings. The median and maximum values of Au are also higher in the upper part of the tailings area. Conversely, Co shows higher concentrations in the deeper layer and a good correlation with Ag and Cu only in this layer. All the elements presented in Table 1 had higher average concentrations than in European subsoils (Salminen, 2005). However, a higher median value than in natural subsoil does not indicate an economically interesting concentration.

The high correlations can be explained by the mineralogy. Mineralogical studied over the ore samples of Aijala and Metsämonttu mines by (Hänninen, 1978a, 1978b; Sotka 1983) showed that metallic silver, gold, bismuth and arsenic have been found as small inclusions in galena PbS, chalcopyrite $CuFeS_2$ and arsenopyrite FeAsS. Also sulfosalts such as boulangerite $Pb_5Sb_4S_{11}$, tetrahedrite $(Cu,Fe)_{12}Sb_4S_{13}$, geocronite $Pb_{14}(Sb,As)_6S_{23}$, andorite $PbAgSb_3S_6$, pyrargyrite Ag_3SbS_3 and ramdohrite $Ag_3Pb_6Sb_{11}S_{24}$ were present. Bismuth Bi is known to replace antimony Sb in the crystal lattice, arsenopyrite may bear cobalt Co, and sphalerite Cadmium Cd. Co concentration may also be partly explained tailing of Telkkälä Ni-Cu mine, where the ore contained pentlandite $(Fe,Ni)_9S_8$, which had 2% concentration of Co (Hänninen and Sotka, 1988).

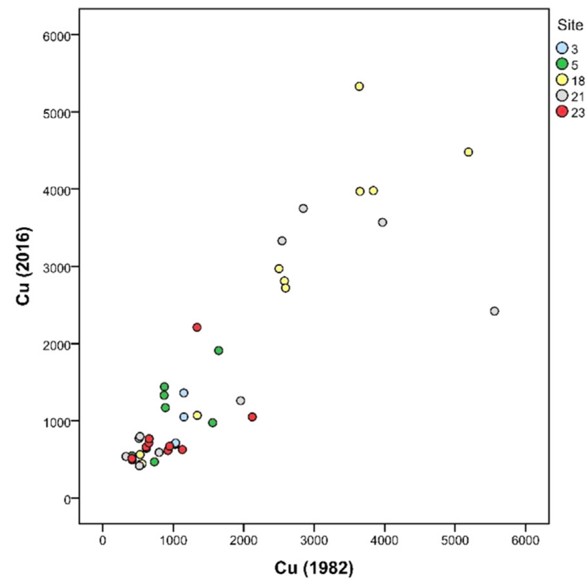

Fig. 3. Scatter diagram of the Cu concentration (ppm) in samples taken in 1982 (x-axis) and 2016 (y-axis) from the Aijala tailings area, Southwest Finland. Site = number of the drilling site in 1982 sampling.

Table 2 presents the concentrations for a selection of other potentially useful and harmful elements in the Aijala tailings and compares the results with the median concentrations in European subsoil (Salminen, 2005). Among the potentially useful elements, all except for Mg, had low median concentrations compared to European subsoil. The concentration of these potentially useful elements does not correlate with the main valuable metals of Aijala and Metsämonttu mines (Cu, Pb, Zn). The highest Ni concentrations in the upper part of the tailings (marked as the Metsämonttu layer in Table 2) could be derived from the Telkkälä Ni-Cu ore. Source for the highest chromium Cr content remained unexplained because no Cr minerals have been reported in the ores of Aijala, Metsämonttu or Telkkälä and none of the old analyses covered Cr.

Table 2 presents also the concentrations of a selection of other potentially harmful elements in the Aijala tailings and compares the results with the median concentrations from European subsoil (Salminen, 2005). The concentrations of U and V are of the same order of magnitude as typical European soil parent material. The median concentration of Tl is slightly higher than the European average. However, the highest Tl concentration in Aijala, 6.7 mg/kg, is far below the maximum value of from European baseline mapping results, 21.3 mg/kg (Salminen, 2005). Among the potentially harmful elements presented in Table 1, Ag, As, Cd and Sb, in particular, display elevated median concentrations compared to typical European soils, in addition to the ore metals Cu, Pb and Zn.

3.2. Geophysical studies

3.2.1. Gravity

The interpretations of the four gravity profiles are presented in Fig. 4. In the interpretations, the density (wet) of the tailings material

Table 1

Spearman's rho, median and maximum concentrations in mine tailings samples from Aijala for elements that displayed a significant positive correlation with Ag, Cu, Pb or Zn. Metsämonttu = upper part of the mine tailings dominated by material from the Metsämonttu mine. Aijala = lower part of mine tailings originating from the Aijala mine. European soils = median values in European subsoil according to the Geochemical Atlas of Europe (Salminen, 2005). N = 164 for Ag, Cu, Pb and Zn and N = 23 for all the other elements.

		Spearman's Rho				Concentrations (mg/kg)		European soils (mg/kg)
		Ag	Cu	Pb	Zn	Median	Maximum	
Metsämonttu	Ag†		0.333**	0.501**		8.00	23.0	0.25
Aijala			0.720**	0.202*	0.416**	6.43	14.0	
Metsämonttu	Cu	0.333**				592	2 896	13.9
Aijala		0.720**			0.260**	1 731	6 030	
Metsämonttu	Pb	0.501**			0.287**	1 430	5 890	17.2
Aijala						519	1 008	
Metsämonttu	Zn			0.287**		4 585	19,000	47
Aijala		0.416**	0.260**			5 080	9 850	
Metsämonttu	As†				0.473*	475	1 050	6.02
Aijala		0.800**	0.733**			514	1 940	
Metsämonttu	Au	0.615**		0.566**	0.520*	0.584	3.17	–
Aijala						0.353	0.88	
Metsämonttu	Bi		0.728**			0.272	1.35	< 0.5
Aijala		0.752**	0.844**			2	3.24	
Metsämonttu	Cd†				0.861**	32.5	102	0.09
Aijala		0.505**	0.400*		0.965**	33.9	61.5	
Metsämonttu	Co					15.4	46.8	8.97
Aijala		0.845**	0.825**			21.2	82.2	
Metsämonttu	Fe				0.634**	103,550	235,200	26,200
Aijala		0.552**	0.408**		0.742**	102,700	206,100	
Metsämonttu	S				0.633**	74,800	126,000	105
Aijala		0.774**	0.685**		0.524**	69,700	162,000	
Metsämonttu	Sb†	0.497*		0.622**		14.3	64.2	0.47
Aijala		0.759**	0.686**			12.8	48.6	

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

† Potentially harmful element.

was set to 1950 kg/m^3 as determined from an in-situ sample. The lower soil layer was assumed to be typical Finnish saturated till, having a density of 1900 kg/m^3. The old and new drill holes were drilled to the bottom of the tailings, the real tailings pond thicknesses at these points could be used as reference for the gravity interpretation. The bedrock topography was interpreted based on the tie points on bedrock outcrops at the line ends. Even if determining the thickness of the till layer is not exact, gravity interpretation usually provides bedrock topography rather well. Nevertheless, this study aimed at determining the volume of the tailings material, and the thickness of the tailings pond was therefore the primary aim.

The gravity interpretations of the bedrock surface, till and tailings were used in 3D modelling of the structure of the Aijala tailings material. The interpreted points along the gravity profiles together with the drill hole ends were used in generating surfaces, as shown in Fig. 5, by Laplace gridding with geology and mine planning software GEMS by Geovia. In addition, tailings layer was confined by the edges of the pond in aerial photographs and LiDAR DEM.

3.2.2. ERT and IPT

The results were computed using Res2DInv software (Loke and Barker, 1996), in which the LiDAR topography of the ground (National Land Survey of Finland) was also taken into account. The inversion of the measurement data (2D inversion) was based on the assumption of 2D geological structures (i.e. the structures that are on the measurement line continue perpendicular to the line). The 2D results were redrawn after inversion using Geosoft Oasis Montaj software. 2D-inversion results are presented in 3D in Fig. 6 together with gravity based interpretation of the bedrock, tailings and till interfaces.

The parts of the tailings with the highest conductivity could easily be detected from the resistivity results. The IPT anomalies were typically weak, and the highest values appeared in the top layer. The results of the geophysical interpretations helped in defining the inner structures of the pond, and they also provided more information on the variation in the bottom of the tailings pond and the bedrock surface. The results were converted to ASCII format, including spatial information and the computed resistivity values. These results were combined with other data in the GEMS software.

More detailed interpretation of the results was carried out after integrating the geophysical interpretations with another data sets (Fig. 7) in GEMS. The interface between the upper layer containing material from the Metsämonttu mine and the lower layer containing material from the Aijala mine was determined according to drill core samples and gravity interpretation. The interface was also clearly visible in the ERT inversion results, in which the upper layer was more conductive (resistivity < 17 Ωm) than the lower layer (resistivity 17–50 Ωm). The soil beneath the tailings material and the bedrock topography were also detectable. The ERT results did show an unexpected conductivity just outside the eastern edge of the tailings area (ERT survey line L7). This was assumed to be caused by seepage waters in a ditch. Conductive mineralization was not a potential cause, because the bedrock topography lies deeper. On the same survey line, another unexpected resistive anomaly was also detected at the surface. This was assumed to be caused by material with large particle sizes, possibly waste rock. However, no indications of such rocks were observed in the aerial photographs at this location. Another possibility is a steep cone of bedrock that causes a resistive surface in the ERT inversion, and conductive deeper parts due to the 3D effect from the surroundings.

3.2.3. GEM-2

Apparent conductivity and susceptibility were calculated from the responses at four different frequencies. The GEM-2 results provide information on conductivity variations, mainly for the first 10 m of tailings. Because of the high conductivity and the small conductivity difference between the upper Metsämonttu tailings and the lower Aijala tailings, the interface between these layers was not detectable from the

Table 2
Median and maximum concentrations in mine tailings samples from Aijala for some potentially valuable or harmful elements selected among all the analysed elements.[a] Metsämonttu = upper part of mine tailings dominated by material from the Metsämonttu mine. Aijala = lower part of mine tailings originating from the Aijala mine. European soils = median values in European subsoil according to the Geochemical Atlas of Europe (Salminen, 2005). N = 141 for the Metsämonttu layer and N = 108 for the Aijala layer.

		Concentrations (mg/kg)		European soils (mg/kg)
		Median	Maximum	
Potentially valuable elements				
Metsämonttu	Be	0.544	0.785	< 2
Aijala		0.740	1.07	
Metsämonttu	Cr	18.5	328	62
Aijala		14.7	28.9	
Metsämonttu	Li	16.8	26.8	–
Aijala		27.0	35.0	
Metsämonttu	Mg	53,600	79,400	5 909
Aijala		46,900	55,000	
Metsämonttu	Nb	2.12	3.47	9.76
Aijala		2.77	5.79	
Metsämonttu	Ni	11.5	393	21.8
Aijala		14.3	22.7	
Metsämonttu	P	191	271	418
Aijala		154	266	
Metsämonttu	REE	64.5	95.4	–
Aijala		67.8	84.2	
Potentially harmful element				
Metsämonttu	Tl	3.88	5.90	0.67
Aijala		4.97	6.70	
Metsämonttu	U	2.04	3.42	2.03
Aijala		2.78	5.06	
Metsämonttu	V	45.3	73.5	62.8
Aijala		31.8	53.7	

[a] The samples were analysed for Ag, Bi, Cd, Ce, Dy, Er, Eu, Gd, Hf, Ho, La, Lu, Nb, Nd, Pr, Sb, Sm, Sn, Ta, Tb, Th, Tl, Tm, U and Yb by ICP-MS and for Al, As, B, Ba, Be, Ca, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Rb, S, Sc, Sr, Ti, V, Y, Zn and Zr by ICP-OES.

GEM-2 results. The apparent conductivity (Fig. 8A) is quite variable in the tailings pond area. The variations roughly correlate with the metal (e.g. Cu, Zn) content of the tailings (Figs. 1 and 9). The southeastern part of the tailings pond appears to be most conductive. The main reason for the conductivity variation is the moisture content and roughness variations of the tailings. The apparent susceptibility (Fig. 8B) is quite variable in the tailings pond area. The highest apparent susceptibility values are located in the northern, northwestern and southernmost parts of the tailings pond. The variation roughly correlates with the iron content and roughness of the tailings material.

3.3. Preliminary mineral resource estimation

The Cu, Zn, Ag and Pb mineral resources in the Aijala tailings pond were estimated by interpolating the metal contents in a block model of 1 m^3 resolution using the old and new drill core samples (Valjus et al., 2016). The interpolation was carried out separately for the Metsämonttu and Aijala mine tailings layers, because they form separate geochemical units.

The blocks belonging to the tailings material were confined with the modelled bedrock surface, the tailings bottom and a surface modelled in the approximate middle of the change in geochemical content seen in the drill cores (Fig. 7). The metal contents in the block model were interpolated with anisotropic inverse distance method. The used search ellipsoid was horizontal, 200 m in length and width and 2 m in depth. This is because the metal content of the layers was assumed to be rather continuous in the horizontal direction, and the changes in metal content were more likely to occur in the vertical direction. Fig. 9 presents the interpolated copper content in the Metsämonttu mine tailings layer. The total volume of the layer is 852,399 m^3, and it contains approximately 678 t of copper. Table 3 presents copper, zinc, silver, lead, sum of rare earth elements (ΣREE) and gold concentration, masses and in-situ value of the elements. The ΣREE and Au mineral resource estimations were based on the volume and mass of the Metsämonttu and Aijala tailings layers, and the average content of the commodity within each layer.

Compared to Sipilä's (1994) estimates (Cu 0.12 wt%, Zn 0.50 wt%, Pb 0.11 wt%, Ag 7.95 mg/kg and Au 0.69 mg/kg), the new estimates Cu 10.4 wt%, Zn 0.50 wt%, Pb 0.12 wt%, Ag 7.6 mg/kg and Au 0.62 mg/kg were nearly identical. This was surprising because now only wet weight was determined for the tailing material and it causes over estimates into the mineral resource estimate. In addition, ΣREE 64.7 mg/kg was estimated now.

4. Discussion

In this case example, the most useful methods to characterize the tailings pond volume, structure and composition were drill holes, geochemical analyses and a gravity survey. The drill hole ends were used as reference points for gravity interpretations of the bottom of the tailings pond. In addition, the wet density of the tailings material and the underlying till needed to be determined. The gravity survey lines were planned to start and end on the bedrock surface to enable interpretation of the bedrock topography. The interface between the tailings material from the Metsämonttu mine and the Aijala mine could only be detected from the geochemical analysis of drill core samples taken at 1-m intervals. The dense geochemical information also enabled mineral resource estimation.

Others have also used gravity and ERT to investigate the thickness and structure of tailings ponds. De Carlo et al. (2013) carried out ERT survey at Corigliano d'Otranto in east-western Italy to study thickness of the tailings material. ERT and gravity surveys were conducted in the Hammaslahti Cu-Zn mine tailings pond by Vanhala et al. (2005). There, a gravity survey yielded good results, but the ERT results were partly too noisy, presumably due to the dry and resistive top layer above the conductive deeper parts. Pierwoła (2015) obtained good results by combining ERT and time-domain IP in Zn-Pb methods to investigate the structure of two tailings ponds in Olkusz, Poland, although the final confirmation of the anomaly-causing materials could not be achieved by sampling of the drill core materials. Balia (2018) combined gravimetric survey with reflection seismology when lacking reference points such as drill holes.

Magnetic and electromagnetic methods can be used to locate metal-bearing and conductive areas, but interpreting their depth is difficult. Although the GEM-2 method was used in Aijala to map the conductivity and susceptibility of the pond area, it is perhaps more usable when producing 2D maps of leakages from tailings ponds. The leakages can be seen as conductive anomalies in the resistive soils around the tailings pond (f.eg. Buselli and Lu, 2001).

For homogeneous tailings ponds, our recommendation for a volume and structure survey programme is to start with a few ERT survey lines with 1–2 drill cores as reference points. After 2D inversion of the ERT results and an initial 3D model, the tailings pond can be investigated in more detail with several complementary gravity survey lines. The initial use of only a few ERT lines is due to the laboriousness and the higher cost of the method compared to gravity.

After studying the volume and structure of the tailings pond, a mineral resource estimate can be considered. Several samples taken with regular depth intervals from evenly spaced drill holes are then needed for reliable interpolation of the commodity contents. The distance between drill holes should not exceed about 50 m, depending on the continuity of the structures. When the samples are sparse, a less reliable estimation can be based on the average contents of the tailings material masses.

The combination of geophysical and geochemical methods provided

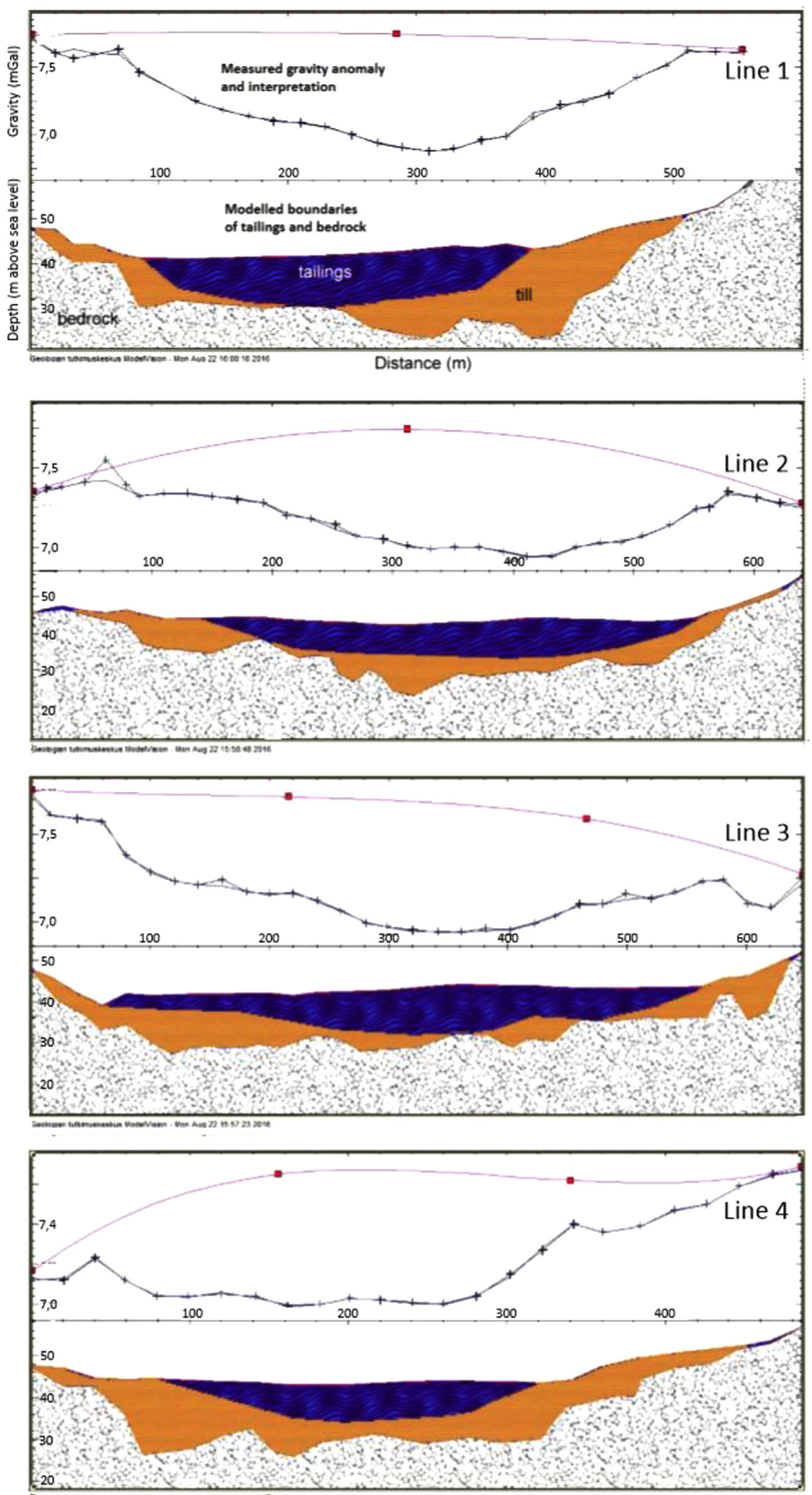

Fig. 4. Interpreted gravity lines along profiles shown in Fig. 2.

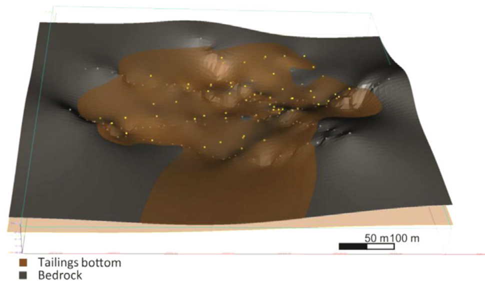

Fig. 5. Bedrock (grey) and tailings bottom (brown) layers according to the gravity interpolations of the bedrock depth (grey points) and tailings bottom (yellow points). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a good basis for in-situ estimation of the commodity masses. However, further studies on ore mineralogy, separation and enrichment techniques, as well as potential environmental contamination will be needed before any decision is made on the applicability of the secondary raw materials.

5. Conclusions

The Aijala tailings pond pilot represents an example of mining waste as a potential secondary raw material source in the EU. Information concerning the landfill will eventually be provided in a standardised EU landfill database, and it could be utilised by possible re-users of the raw materials to conduct a feasibility study and planning of the operations.

A variety of geophysical methods was tested in order to assay their usefullness as input data for 3D modelling of the tailings pond together with the information from 33 drill holes reaching the tailings bottom. The thickness of the tailings material and depth of the bedrock surface were interpreted from gravity surveys, using the drill hole ends as reference points. ERT interpretations were referred to the gravity, and both methods gave almost equal results when using drilling data as a reference for the interpretation. Magnetic and GEM-2 measurements were used to determine and locate the magnetizing material (metal objectives) and the most conductive parts of tailings material.

The interface between the tailings material from Metsämontu and Aijala mines was modelled at the sudden change in the Cu, Zn and Pb composition along the drill cores. The geochemistry of samples drilled in the 90's were compared with the 6 new control bore holes drilled

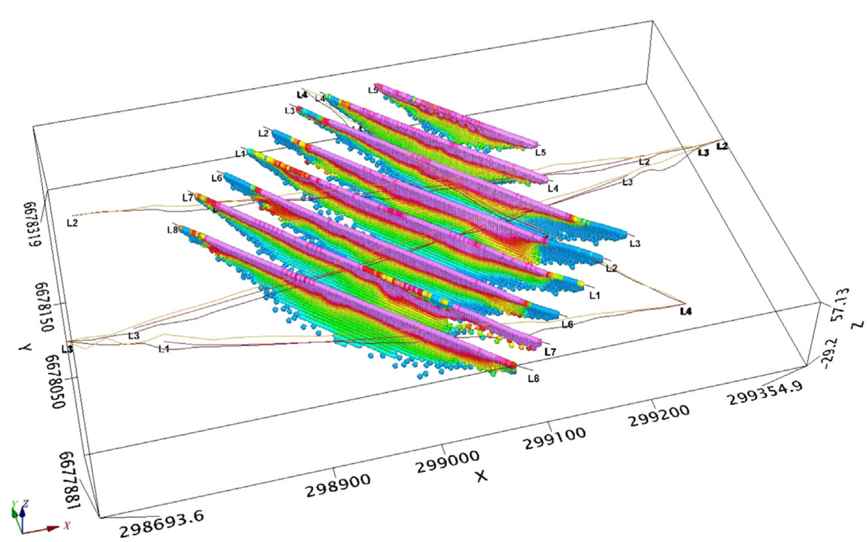

Fig. 6. Interpreted gravity lines together with ERT resistivity results. The brown line denotes the gravity interpreted bedrock surface, the red line is the bottom of tailings and the orange line is the ground surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

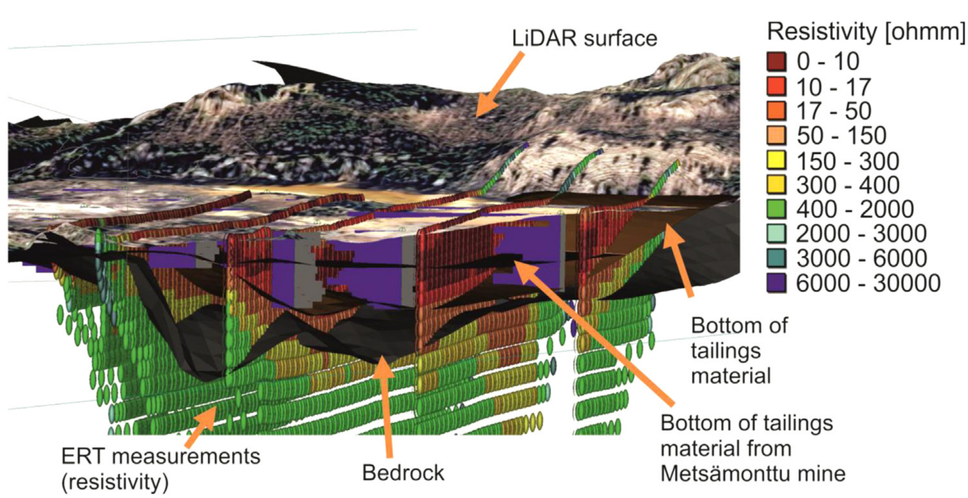

Fig. 7. ERT results integrated with surfaces modelled with gravity interpretations and analyses of soil drilling samples. View from the southwest.

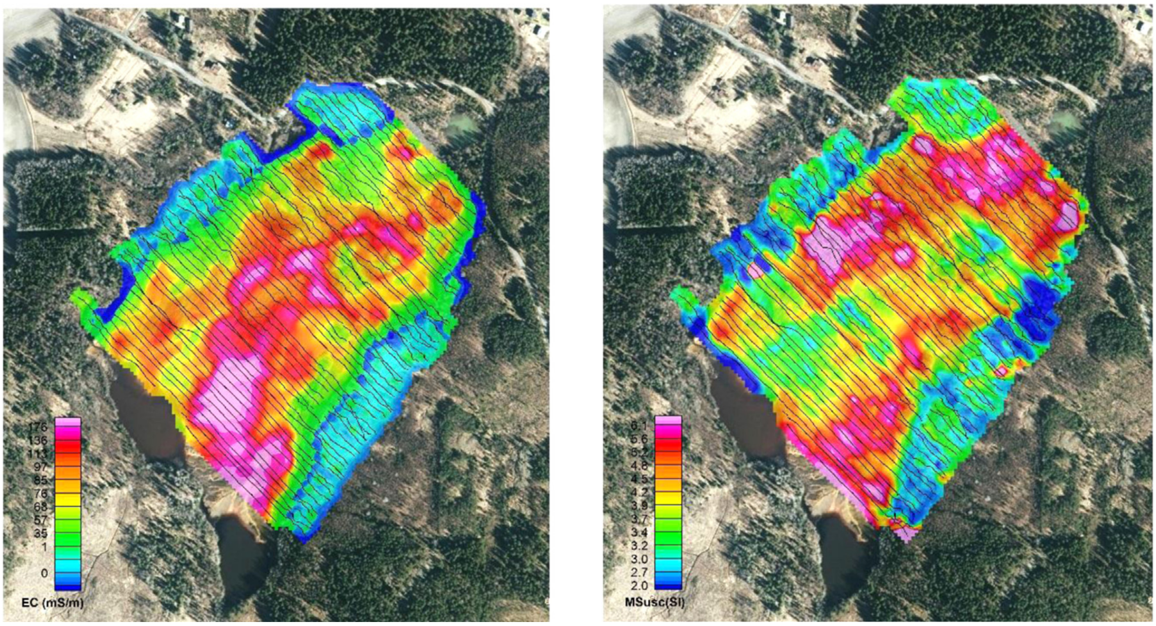

Fig. 8. A) Apparent conductivity and B) apparent susceptibility map of the Aijala mine tailings pond.

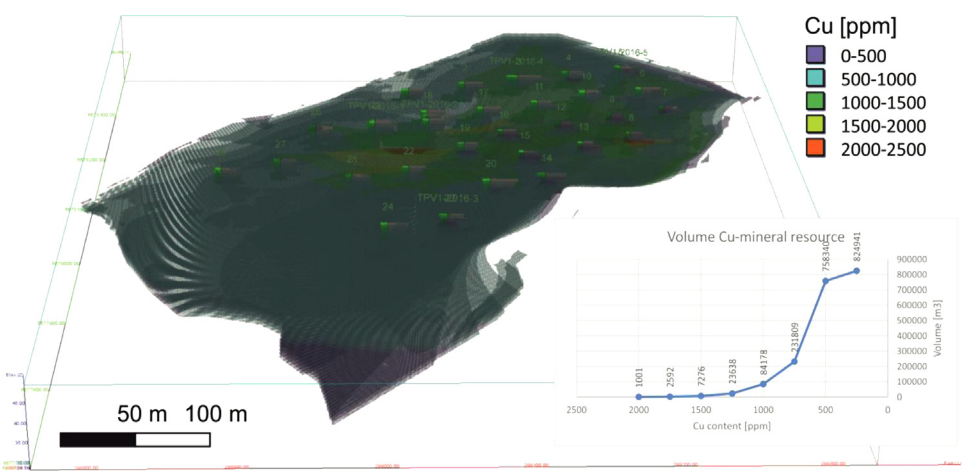

Fig. 9. Block model showing the interpolated copper content in the Metsämonttu mine tailings layer. Bar diagrams next to the drill holes indicate the copper (green) and lead (grey) contents in the analysed samples.

Table 3
The concentration and content of commodities in the Aijala tailings pond, divided into layers containing tailings from the Metsämonttu mine and the Aijala mine.

Layer	Commodity	Concentration	Commodity mass [kg]	Commodity in-situ value [€]*
Metsämonttu	Cu	0.07 wt%	1,323,073	383,437
- volume 824 941 m^3	Zn	0.50%	9,059,359	18,638,363
- mass 1 608 635 t	Ag	8.1 mg/kg	15,527	7,902,628
	Pb	0.14 wt%	2,571,163	4,617,244
	ΣREE	64.4 mg/kg	103,536	9,066,797
	Au	0.77 mg/kg	1237	1,488,456
Aijala	Cu	0.17 wt%	1,745,611	7,388,858
- volume 423,859 m^3	Zn	0.51 wt%	4,702,146	9,674,006
- mass 826,525 t	Ag	6.6 mg/kg	5,950	3,028,142
	Pb	0.06 wt%	617,444	1,108,794
	ΣREE	65.3 mg/kg	53,935	4,723,180
	Au	0.35 mg/kg	289	347,456

* Prices 18th October 2016 from www.snl.com. ΣREE and Au prices also USGS database 18th April 2017.

close to the old locations. Correlation was high indicating no geochemical changes within the tailings pond during the last 34 years.

By combining the results of old and new geochemical sampling, and geophysical studies mineral reserves for Cu, Zn, Ag, Pb, ΣREE and Au were estimated by inverse distance method into a 1 m^3 resolution block. Because the Metsämonttu and Aijala mine tailings layers were interpolated separately. The total metal content of the tailings pond, the volume and mass of the different metal contents could then be calculated from the block model. Furthermore, the commodity masses and their in-situ value according to the current stock value were calculated in fractions using their average contents. This mineral resource estimate is not JORC compliable, as the aim of the study was only to characterise the tailings pond as an input data for the SmartGround database and to assess the best compilation of survey methods for characterization.

The authors conclude that the most valuable information for characterizing the structure, dimensions and concentration of the tailings pond was produced by an adequate number of soil drillings, geochemical analyses from the drill samples, the end-depth of the soil drillings and gravity interpretations.

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