Geophysical investigations to identify groundwater pathways at a small open-pit copper mine reclaimed by backfilling and sealing

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Abstract Knowledge of groundwater pathways is decisive for the success of a reclamation plan, though difficult to access. To increase this knowledge at a small sulphidic open pit backfilled with waste rock and sealed with dry cover, ground penetrating radar and direct current resistivity were applied. Variations in electrical conductivity, visible with both methods, allowed delimiting the pit. Resistivity surveys suggested that groundwater drainage from the waste is shallow, and is a possible source of erosion of the cover. Groundwater inflows into the pit, suspected to compromise the confinement of the waste, could not firmly be identified with these two methods alone.

Key Words Ground Penetrating Radar, DC resistivity, groundwater pathways, open pit, backfilling and sealing

Introduction

After mining operations, open-pit sulphidic mines typically develop mine voids. The choice of the best closure option for the open pit is dependent on the characteristics of the site, and in particular, hydrology. The success of a post-closure reclamation plan will be greatly determined by the adequacy between the plan and knowledge of water pathways on site. At open pits, sources and sinks of water can occur both as surface water, such as water from precipitation and run-off, and groundwater, via fractures in the pit walls and/or the pit floor. Groundwater pathways can be very difficult and costly to characterise (e.g. with monitoring wells or pumping tests) and therefore indirect investigations with surface geophysical methods can be cost-effective alternatives. The most common environmental application of geophysical methods at mine sites is the localisation of contaminant plumes (Poisson *et al.* 2009). Geophysical surveys in mine environment studies have also been used to characterise mine waste repositories like tailings ponds (e.g. Yuval and Oldenburg 1996, Placencia-Gómez *et al.* 2010) and waste rock piles (e.g. Campbell and Fitterman 2000, Poisson *et al.* 2009). In the present study, the objective of the geophysical investigations was to understand the subsurface architecture of a small copper mine (Kimheden, northern Sweden), where waste rocks have been backfilled in former pits and sealed with a soil cover. This information will be used to contribute to the evaluation of the effectiveness of the reclamation. Both ground penetrating radar (GPR) and direct current (DC) resistivity were employed to identify potential groundwater pathways and characterise the conditions of the soil cover applied on backfilled waste rocks. The results presented here will, however, be exclusively concerned with relating water pathways with the evaluation of the reclamation.

Background information about the study site

The mining area (Kristineberg, northern Sweden) is dominated by felsic volcanic rocks altered to pyrite-bearing, quartz-muscovite-chlorite rocks (Årebäck *et al.* 2005). Kimheden copper mine was in operation in the 1970s. 132 kt of ore were extracted underground and in two small open pits situated on a hillside. Waste rocks were dumped on the surface close to the pits. After closure, copper and zinc-rich Acid Mine Drainage (AMD), generated from the oxidation of the sulphidic rocks, required reclamation of the site, i.e. control of the drainage water and prevention of further oxidation of the mine waste. Ditches were excavated to minimise water infiltration into the waste and to divert drainage water to a limed tailings pond downstream. Waste rocks were backfilled in both pits and sealed with a composite soil cover (0.3 m clayey till – 1.5 m unsorted till) in 1996. Backfilling and sealing of the rocks in the pits were intended to confine the contaminated material and create a barrier from oxygen and water to the sulphidic waste, thereby decreasing the sulphide oxidation. However, oxygenated water could infiltrate through fractures into the pit, which, if large enough, might compromise this confinement. During the backfill operation, a significant flow of water, occurring through a fracture, had been observed in one of the two pits (the studied pit, see Figure 1). Therefore, a sealing layer was also locally applied on the pit wall, to divert the flow of water away from the pit.

Although sealing of the waste was followed by a large decrease of Cu and Zn concentrations in the drainage from the mine, from 7 mg/L and 0.6 mg/L to 0.4 mg/L and 0.1 mg/L respectively (Villain 2010), the concentrations of elements in the drainage are still, after ten years of stabilisation, not satisfactory for discharge into the natural environment. Besides, pH values in the drainage re-

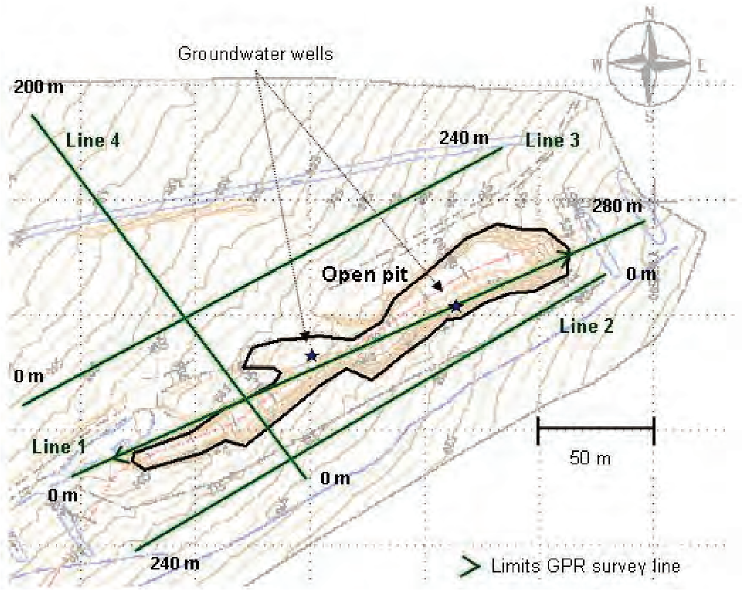

***Figure 1** Location of the studied backfilled open pit, resistivity survey lines (GPR line is a part of resistivity line 1), and groundwater wells installed in the backfill.*

main low (ranging from 3 to 3.7). A possible explanation for the limited success of the reclamation is that the confinement of the mine waste in the open pits has not been sufficient to prevent access of water and oxygen to the sulphidic rocks. Leaking could occur due to the dry cover not entirely fulfilling its role, or to fractures in the pit walls.

The geophysical investigations aim to complement geochemical information to explain the partial success of the backfilling-sealing reclamation. The results are used here to characterise the water pathways in the reclaimed pit that generates the highest loads of contaminants. A special focus was set on identifying important fractures, or flow of water into the pit.

Methods

Resistivity measurements were performed on 4 survey lines of 200 to 280 m, located in the vicinity of the studied reclaimed pit (Figure 1). The GPR results are given here for one survey line exclusively, which corresponds to a part of survey line 1. The topography along each profile was determined with a levelling instrument. Resistivity data were collected with the ABEM Lund Imaging system (Dahlin and Zhou 2006) using the multiple gradient array with an electrode distance of 2 m. This configuration with the SAS4000 terrameter permits multi-channel measurements, with 4 potential readings for each pair of current electrodes. The data were inverted using Res2Dinv with the robust inversion constrain L1-norm (Loke *et al.* 2003). The radar survey was conducted using a RAMAC GPR system from Malå Geoscience with one 50 MHz RTA antenna. Measurements were made every 5 cm along a 220 m long survey line (part of line 1 in Figure 1), and triggered using a “hip-chain”. To facilitate the interpretation of the radar data, dc-shift, band-pass filter, and altitude correction were applied.

Complementary studies were performed at two groundwater wells situated in the covered backfill (Figure 1), whereby groundwater level was measured with an electrical dip meter and electrical conductivity was measured with a WTW Multi 350i multimeter. Archive information from the company was also used to support the interpretation of the results.

Results and discussion

Delimitation of the backfilled pit

The inverted cross section from resistivity survey line 1 (Figure 2), exhibits a zone of lower resistivity, i.e. higher conductivity, from the near-surface and downward, between 80 m and 240 m. This corresponds to the position of the backfilled pit located between two zones of higher resistivity, that is, bedrock. The distribution of conductive and resistive zones is also visible on the GPR profile (Figure 3), where high conductivity in the reclaimed pit induces attenuation of the GPR signal with depth. Use of GPR at 50 MHz to map the upper limit of conductive zones by signal attenuation has also been noted by Paterson (1997). Higher conductivity in the pit can be explained by the presence of sulphidic waste rocks partially saturated with groundwater. Between 30 m and 70 m (Figure 2), the survey line is located on the bedrock but very close to the edge of the conductive reclaimed pit, which is reflected by a low resistive

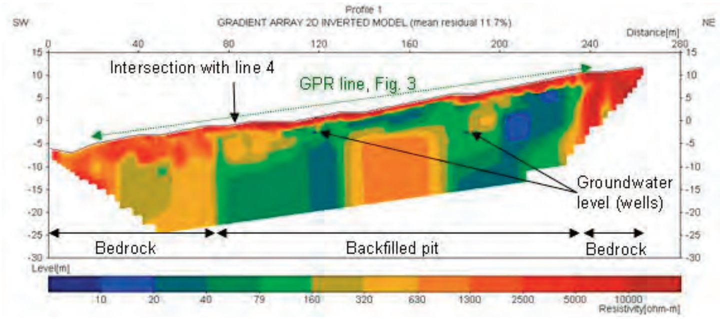

Figure 2 *Survey line 1 (along the backfilled pit): 2D inverted resistivity profile.*

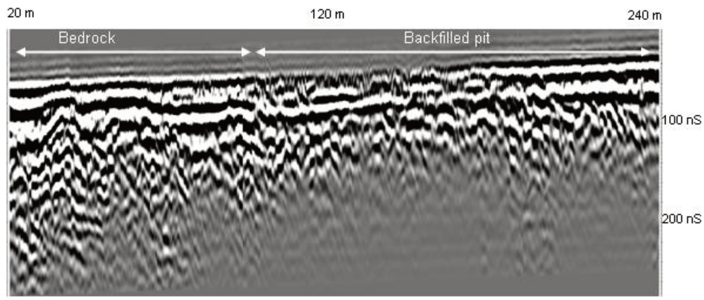

Figure 3 *Survey line 1 (along the backfilled pit): 50 MHz GPR profile.*

artefact zone situated at a depth of 5 m and downward. The dry cover is visible as a thin layer of higher resistivity on top of the pit. The groundwater level measured in the two wells situated in the backfilled pit (Figure 1) is indicated on the resistivity profile (Figure 2). Electrical conductivity measured in the groundwater during the field campaign was 0.7 mS/cm, and resistivity, obtained with DC resistivity in the same area, is 80—160 ohm-m. No clear indication of the groundwater table in the pit was obtained with resistivity, certainly due to the noise from the mineralised waste. Neither could any reflection from the water table be identified from the radar data, which is probably due to the radar signals suffering from scattering and attenuation from travel in conductive medium. No relevant explanation has yet been found to explain the higher resistivity zone in the center of the pit (130 m to 170 m on Figure 2). A potential interpretation can be that more resistive material had been dumped there (e.g. concrete). Another possibility is that the higher resistivity values are caused by a 3D effect from the more resistive bedrock surrounding the pit.

Archive information from the mining company and data from the groundwater wells indicate that the pit should not be deeper than 15 m (including the dry cover). The pit floor, expected to be revealed by a transition to higher resistivity material at depth, is not visible on the inverted resistivity cross section (Figure 2), suggesting that the real penetration depth is less than in the given model. As mentioned before, GPR signals suffer from large attenuation in the open pit, which probably explains why the pit floor could not be determined with GPR either.

Possible pathways of water

The inverted cross section from survey line 4 (Figure 4) shows the transversal section of the backfilled pit as a zone of high conductivity between 10 and 40 m. Outside of the pit, between about 50 m to the end of the profile, the surface is characterised by more conductive values than the bedrock, in particular towards the end of the profile.

This area downstream of the pit is covered with peat and is constantly humid, which may explain the lower resistivity values. Observations in the field indicate constant seepage and localised oxidation zones, which suggest that this is the seepage area from the pit. Resistivity data from lines 3 (not shown) and 4 corroborate this assumption, and delimit the seepage area to 0—110 m along line 3 and 50—200 m along line 4. A closer look at the inverted resistivity data gives further information on this seepage area. Both line 3 and line 4 tend to show that water discharge occurs close to the surface, and no indication of deep groundwater can be found in this area. The conductive layer is located at a depth of about 3 to 6 m. However, as mentioned before, the penetration depth of the signal is limited; therefore, the possibility of deeper groundwater pathways cannot be excluded. On survey line 4 (Figure 4), a conductive junction between the waste material in the pit and

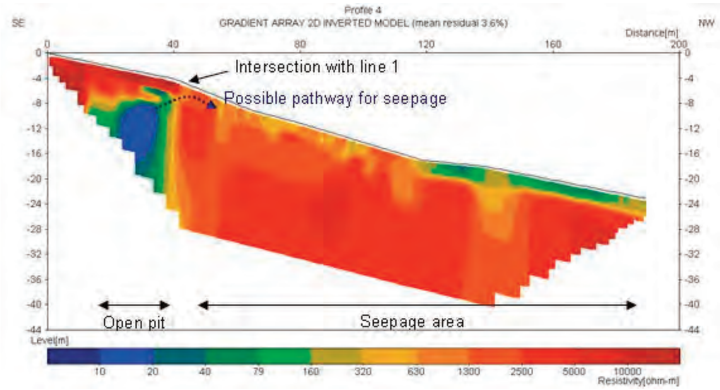

Figure 4 *Survey line 4 (crossing the backfilled pit): 2D inverted resistivity profile.*

the seepage area is observed close to the surface, within the soil cover (at about 40m). It may indicate that seepage from the pit exits through the dry cover. This interpretation is supported by the observation of localised zones of oxidation on the surface of the dry cover near the edge of the pit. A risk, in that case, is that water seepage from the pit occurs through the sealing layer and may progressively erode it.

A report from the mining company (Rosén and Wilske 1994) states that almost all inflow to the open pit occurs through fractures in the bedrock. Results of GPR and resistivity turned out, however, not to be very informative in mapping potential inflows to the pit. GPR did not show obvious reflections from probable fractures, as had been expected. Neither did the resistivity survey provide reliable data for identification of fractures. In the reclaimed pit, close to the suspected position of the main fracture which was sealed, a highly conductive area is observed on line 1, from 200 m to 230 m (Figure 2). However, there is no evidence that the higher conductivity there is related to an inflow of water into the waste. It could as well be explained by the accumulation of water-saturated fine particles in this zone, or a higher concentration of metals. A possible solution to identify if the inflow of water observed during backfilling has been redirected from sealing the pit wall, as it was supposed to, would be to perform one more resistivity investigation transverse to line 1, at the edge of the pit (240 m on line 1). It has been observed with the available data that groundwater mapping is more relevant in the bedrock than in the open pit. Therefore, an additional survey line entirely outside of the pit in this area might help for identification of the flow.

Figure 5 summarises the knowledge of groundwater pathways close to the backfilled pit, obtained from company archives and the geophysical investigations.

Suspected main water flow directions and the seepage area are indicated. Groundwater isolines outside of the pit should only be considered as a representation of the presumed groundwater movement rather than an actual result since no groundwater level was measured in the bedrock.

Conclusions

GPR and resistivity measurements at Kimheden allowed imaging the position of the studied backfilled open pit. Edges of the pit could be determined. However, the floor of the pit could not be located by either of the methods. DC resistivity

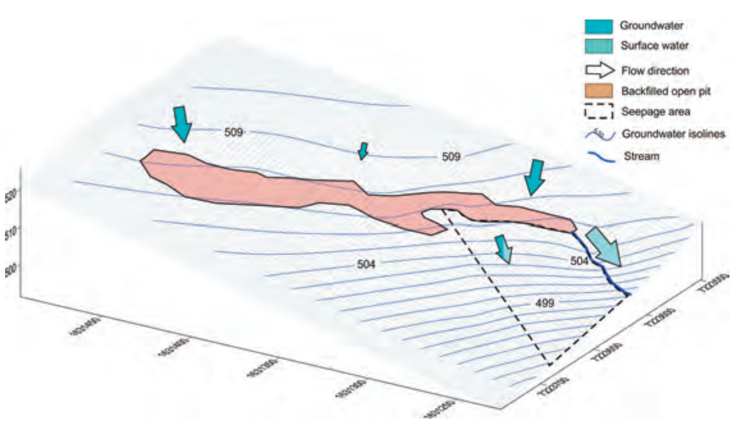

Figure 5 *Water pathways in the vicinity of the studied backfilled open pit. The size of the arrows is proportional to the importance of the inflows (outflows) to (from) the pit.*

provided useful information on water pathways outside of the pit. It contributed to the delimitation of the seepage area from the pit, gave indication that drainage occurs in the shallow subsurface, and supported the assumption that seepage through the dry cover might cause erosion of the sealing layer. It also recognised the more conductive/resistive regions in the overall conductive backfilled pit. Flows of water through the pit walls could not, however, be firmly localised with the information from this geophysical investigation alone. The results could nevertheless be used to provide background information for further investigations by e.g. tracer tests, to document the fracture system close to the pit and determine if it compromises the confinement of the backfilled waste.

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