Amendment of the Unsaturated Zone of a Sulphide Containing Cover Applied During Remediation of the Hornträsk Cu-Zn Mine, North Sweden

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ABSTRACT
The Hornträsk open pit mine was originally reclaimed in 1995-1996. However, due to continued discharge of metals to nearby Lake Hornträsk additional amendments were found necessary. In 2005-2006 mesa lime, a calcite containing residue from production of wood pulp, was applied in the saturated zone of the soils within the industry area. Additional measures in 2007-2008 focused on reducing drainage of surface water from the local catchment’s area and neutralisation of the acidity produced by sulphide oxidation. A saturated solution of mesa lime dissolved in water was infiltrated in the unsaturated zone at a 1:1 volume of solution to soil ratio. The infiltration of the mesa lime solution was terminated in September of 2007 and was continued during the snow free period in 2008. The discharge of water from the springs was reduced to about 50%. While the content of Cu, Zn and Cd in the discharge was reduced by about 85% respectively 50% in one of the springs only a minor increase in pH and varying concentrations of heavy metals was observed in another spring. The groundwater close to the lake showed a significant increase in pH and a decline of the metal concentrations.
INTRODUCTION

Lake Horntrask is located in the mining district of Kristineberg, County of Västerbotten, in northern Sweden. In the early 2000s, people living around the lake noticed that there had been a substantial decline in the fish population in the lake. In 2004 Boliden Mineral AB and GeoEnvix AB initiated an investigation of the ecological and chemical state of the lake and its surroundings (GeoEnvix 2005). The biological investigations revealed abnormal conditions and that fish, bottom fauna and zooplankton, were stressed. The chemical investigations showed elevated concentrations in copper, zinc and cadmium sufficient to disturb the ecological system in the lake.

Within the catchments of the lake, there are two Cu-Zn mines located close to the lake, as shown in figure 1. Both the Horntrask- and Rävlidmyr mines were shut down in the early 1990’s. In both mines, surface as well as underground mining were performed. After closure, the surface pits were backfill with waste rock and the industrial areas and pits were covered with till. The investigations performed in 2004 revealed that there was a substantial drainage of metal-contaminate waters from the closed mines into the lake (Table 1) (Eriksson 2004, GeoEnvix 2005). With respect to copper, the Horntrask mine was found to contribute with approximately 85% of the total load. In 2005 Boliden Mineral and GeoEnvix initiated a project aimed to reduce the discharge of metals from the Horntrask mine. The project is still ongoing, and this paper reports results obtained up to the autumn of 2008. Specifically, we evaluate the effects found by using mesa lime to reduce the discharge of metals from the industrial area into the lake. We also present some results from a laboratory study of the properties of mesa lime. Mesa lime is a waste product from the pulp industry and can be obtained at a low cost.

SITE DESCRIPTION

The Horntrask Lake

Lake Horntrask is a source lake and with only a small inflow of surface water. 80% of the inflow comprises of groundwater. The area of the lake is 6.6 km² and the catchment’s area is approximately 40 km². The lake feeds Brook Vormbäcken.

The surroundings of Lake Horntrask are strongly mineralized. The bedrock of the catchment comprises paleoproterozoic, primary orogenic volcanic and sedimentary rocks of the Fennoscandian Shield (Figure 1).
Figure 1. Geological map of the surroundings of Lake Hornträsk including former surface mines. Red line delimits the catchments area.

The bedrock of the western and eastern parts of the catchments are dominated by felsic and intermediate meta-volcanic rocks. The central part consists of clay sandstones (greywackes), metamorphosed to graphite schist, phyllite, and mica schist. Those rocks are also intruded by dikes of mafic eruptives turned to green schist and greenstone. All of these rocks are more or less mineralized by sulphide minerals such as pyrite (FeS$_2$), arsenopyrite (FeAsS), chalcopyrite (CuFeS$_2$), galena (PbS) and sphalerite (Zn(Cd)S).

The semi-quantative metal budget, based on two investigations performed in the lake in 2004, is presented in Table 1. The results indicate that the Hornträsk mine contributes approximately 85 % of Cu and 40 % of Zn discharged to the lake. With respect to zinc, there is also a substantial contribution from the soils surrounding the lake.


<table>
<thead>
<tr>
<th>Source</th>
<th>Zn kg/year</th>
<th>Cu kg/year</th>
<th>Zn kg/year¹</th>
<th>Cu kg/year¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Export to Vormbäcken brook</td>
<td>- 9 400</td>
<td>- 1 400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedimentation</td>
<td>- 700</td>
<td>- 100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hornträsk mine</td>
<td>4 200</td>
<td>1 300</td>
<td>6 000</td>
<td>1 000</td>
</tr>
<tr>
<td>Rävlidmyran mine</td>
<td>300</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaching from soil</td>
<td>5 600</td>
<td>130</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The mining activities at the Hornträsk mine were started with underground mining at a depth of 260 m. Mining at the Hornträsk open pit was commenced in 1988 and reclaimed in 1996. The reclamation was performed according the treatment plan approved by the local and regional environmental authorities. The remediation of the open pits comprised refilling the mine with mineralized waste rock material covered by 0.3-1 m of till. The industrial areas, as well as a deposit of waste rock, was also covered by till. The till used for covering was taken from the local areas and generally contained high concentrations of sulphidic minerals.

OBJECTIVES OF THE PROJECT

Since 2005, several attempts have been made to minimize the leakage and transport of metals from the industrial area of the Hornträsk mine (cf. Jacks et al., 2005; GeoEnvix 2006). In 2005 and 2006, the saturated zones of the former open pit mine area was treated by injection of mesa lime suspended in water. The treatment resulted in a significant reduction of Cu (90%) and Zn (60%) in the major spring draining the area (the Yellow spring; see figure 3). However, during summer of 2006 there were heavy and extended rains resulting in decreased pH and an increase in metal discharges to the lake. It was concluded that this change was mainly due to the leakage from the unsaturated zone, consisting of sulphidic rich cover till and waste rock. Hence, the results emphasized that there was also a need for neutralization of the unsaturated zone and to reduce the flow of water through the area, and the restoration plan was revised (GeoEnvix 2007).

The major objectives of the remediation plan (GeoEnvix 2006, 2007) were to

- Minimize input of surface water and shallow groundwater into the former industrial area by means of diversion ditching.
- Neutralize the acid produced by oxidation of sulfides in both the saturated and unsaturated zones
- Finally, to minimize the access of oxygen and water by covering the mine and industrial areas and the waste rock deposit, by applying a layer of till with low permeability.

REALIZATION AND RESULTS

The present paper presents results of the application of mesa lime in the unsaturated zone of industrial area at Hornträsk Mine. Furthermore, results from laboratory experiments performed to help design the mesa lime treatment are presented.

Laboratory tests of mesa lime

Mesa lime is a re-utilizable residue from the causticisation of sodium carbonate with burnt lime in the manufacturing of wood pulp after the sulphate process. The main component of mesa lime is calcium carbonate (Cunha et al., 2008).

The remediation project started in the spring of 2007 with laboratory characterization tests on the mesa lime and its effects on pH and its effectiveness in reducing the metals discharge from the sulphidic soil to the water. Presented are results from short terms tests of mesa lime and till samples from the Hornträsk mine. A complete presentation of the results from the laboratory tests performed is found in GeoEnvix 2007b.
The pH in a saturated solution of mesa lime was measured at approximately 12.5, corresponding to a solubility of 1.9 g CaCO$_3$/dm$^3$. The laboratory tests showed that approximately 2.5 g/dm$^3$ was dissolved to obtain a saturated solution (pH 12.5-12.6). The specific weight of mesa lime is 1.05 g/cm$^3$.

For the tests of the acid neutralizing effect of mesa lime on the till cover at the Hornträsk mine, 8 m$^3$ of soil/waste rock material was taken from 3 localities where the content of Cu, Zn and Cd was high and by far exceeding the limit values set by the Swedish National Environmental Protection Board (Naturvårdsverket, 1999). The limit values for Cu, Zn and Cd are 100, 350 and 0.4 mg/kg DS, respectively.

Short term tests were performed in 0.5 dm$^3$ plastic bottles by mixing different proportions of saturated mesa lime solution and filtered soil (0-1.2 mm). Six bottles were shaken in 8 hour intervals during the 288 hours test. At the end of the test, samples of the water/mesa lime solution were analyzed for metal content and pH. Several series of tests were performed and the results for a typical series are given in figure 2. The results revealed that at a proportion of 1:1 of saturated mesa lime solution/soil pH-value increased from 3.5 to approximately 5.5 and the concentration of copper was reduced by > 90%. To reduce Zn and Cd to the same extent, a proportion of approximately 2:1 and a pH value of 7 or higher, was required.

![Figure 2](image_url)

**Figure 2.** Relation between the proportion of saturated lime solution/soil and the concentration of copper after 288 hours in test (squares). The corresponding values of pH and a linear regression line is also shown. Results from laboratory tests in 0.5 l (or dm$^3$ - be consistent) bottles after 288 hours.

**Treatment of the unsaturated zone in the mining area**
Prior to treatment with mesa lime in 2007, the mining area was divided into 5 sub areas as presented in figure 3. Areas 1, 3, and 4 are ordinary industrial plains filled with waste material from the mining activities and covered with till. Area 2 refers to an
approximately 10 m high deposit of waste rock that is covered with till. Area 5 refers to the former open pit of the mine, which is now filled with waste rock and is covered with till. The figure also shows the location of three springs with substantial flow of contaminated water from the industrial area and where chemical and physical parameters were measured. Point 12 is located in a small brook which also has a substantial inflow of surface water from surroundings outside the industrial area. The location of wells for monitoring of chemical parameters in ground water is also indicated.

Establishment of complimentary ditches in the industrial area

The activities of remediation started in summer of 2007 by establishing new complimentary diversion ditches designed to divert surface water from the catchment area of the mine (Figure 3). The bottom and edges of the ditches were covered with a plastic liner. The new ditches were connected to older ones already present in area.

Measurements of the outflow from the springs k4, k6 and the Yellow spring, after the establishment of the new ditches, showed that the outflow from the springs was generally reduced by approximately 50%. In fact, the surface flow stopped in spring k4, located at the NE corner of a deposition of waste rock material.

Figure 3. The industrial area of the Hornträsk mine. Location of springs with substantial flow of groundwater from the area, as well as wells for chemical controls of groundwater, are shown. Point 12 is located in a small brook which also have a substantial flow of surface water from surroundings outside the industrial area. The sub areas (stippled and denoted with red numbers) treated with mesa lime are shown. The location and extension of the new ditches established, is also shown.
**Application of mesa lime**

Prior to the application of mesa lime the uppermost cover of till was ploughed in order to increase infiltration into the subsurface of the contaminated area.

The amount of saturated mesa lime solution required for each sub area was calculated from the laboratory results, the area and the thickness of the unsaturated zone. The goal was to provide at least a 1:1 relation between mesa solution and soil material. This was expected to result in a decline in the amount of copper leaching from the soil cover by 90%, and the amounts of Zn and Cd by about 60%. The accumulated amount of mesa lime solution provided to the 5 sub areas by the end of autumn 2008 is shown in figure 4.

![Diagram](image.png)

**Figure 4.** The accumulated relative amount of saturated mesa lime solution provided to the different sub areas during 2007 and 2008. The relative amounts are given as percent of the volumes required to obtain a 1:1 volume relation between mesa lime solution and the cover of soil/waste rock for each area.

Before the shut down of the mine, **area 1** was used for storage of ore. Today it is a rather flat area built on 1-2 m of waste rock overlaying peat soil and is covered with approximately 0.5 m of till. By the end of 2008, this area was treated with slightly more than the amount of mesa lime required to obtain a 1:1 ratio of mesa lime solution to the soil/waste rock cover (figure 4). There are no visible above ground springs in this area, and most of the discharge of groundwater occurs through a small mire before reaching the lake. Monitoring of metal concentrations in this area was done by sampling from the groundwater wells. One of these (no.11, see figure 3 for location), did show extremely high concentrations of all the 3 metals, Cu, Zn and Cd, before 2007. After treatment, the pH value of the groundwater in this well has significantly increased from between 3.7 to
4.2, to a level between 4.7 to 5.1, in autumn of 2008. This increase in pH was correlated to a corresponding decline of the metal concentrations of 70 to 80 % (figure 5).

Figure 5. Concentrations of copper, zinc and cadmium in groundwater sampled from groundwater well no. 11 located in the centre of area 1. See figure 3 for location.

Area 2 comprises an approximately 10 m high deposit of waste rock covered by 0.5 m of till. In this area, approximately 65 % of the required amount of mesa lime was provided by the end of 2008 (figure 4). Today there is no visible spring in this area and most outflow of groundwater is directly infiltrated to a small mire before reaching the system of ditches. Prior to the ditches established in 2007, there was a small flow of groundwater in the NW corner of the deposit (k4) containing high levels of Cu, Zn and Cd. However, the flow was very low compared to the other springs found in the industrial area. Likely, there is a need to provide more mesa lime solution to treat the large volume of waste rock in this area.

Before the closing of the mine, area 3 was a major ore storage area. Today it is a flat area composed of 3-4 m of waste rock overlaying peat soil and is covered by a 1-1.5 m layer of till. A large volume of mesa lime solution (200 %) has been used to treat this area, but so far no obvious effects of the treatment can be observed. As monitored in spring k6 and groundwater well no. 6 there has been no consistent increase in the pH values and corresponding decrease in metal concentrations. One of the reasons for this lack of effect, might be that the treatment of this area with mesa lime started late in the autumn of 2008. Therefore, it may be too early to see any clear effects of the amendments. Another reason might be the underlying layer of peat, which can be
expected to exhibit a high ability to buffer at low pH values. For that reason a higher dose of lime solution may be required for this area.

In area 4 mesa lime solution has been provided to about 50%. Most of the groundwater in this area is likely to enter area 1, which is down gradient. There are no springs or groundwater wells in this area.

Area 5 comprises the former open pit mining area. Today it is filled with waste rock and covered with till. The topography of the area has the form of a “pot”, and practically all drainage of water from this area is discharging via “the yellow spring”, and then directly to the lake about 3 m below (figure 3). Treatment of this area started in 2005-06 with injections of mesa solution through pipes into the saturated zone. These injections revealed an instant result by increasing the pH-value and decreasing the metal concentrations. However later on, heavy rainfall in 2006, tended to diminish these effects, and it was concluded that the unsaturated zone should also be treated.

In autumn 2008, about 65% of the calculated requirement of mesa solution for the unsaturated zone was charged to this area, and there has been a consistent increase in pH of 1 to 1.5 unit from the autumn of 2005. With respect to metals, the discharge of Cu has been reduced by about 70-85 % and that of Zn and Cd by about 40-50 % (Figure 6).

Figure 6. Concentrations of copper, zinc and pH values in water sampled from the “yellow spring” located in area 5. Results refer to the major spring for the flow of groundwater from the former open pit at the Hornträsk mine. See figure 3 for location.
DISCUSSION AND EVALUATION

Laboratory tests showed that a saturated solution of mesa lime has a pH-value of 12.5 and that approximately 2.5 g/l of mesa can be dissolved in water. The tests also revealed that the mesa lime is effective in increasing the pH-value of sulphidic soils and reducing leaching of metals into water. However, in order to obtain an efficient reduction in the metal leaching from the unsaturated zone at the Hornträsk mine, there is a requirement of a 1:1 volume to volume ratio, or more, of saturated mesa lime solution to till/soil. This requires large volumes of mesa solution to neutralize the volume of contaminate soil/waste rock at this site.

The general experience from remediation of the Hornträsk mine emphasises the importance of treating different types of industrial areas differently. For instance, in area 5, the former open pit mine, there was a rather clear and persistent effect of the mesa treatment, with increasing pH-value and decreasing levels of the metal concentrations as measured in the major spring. This effect appeared despite that the amount of mesa lime was far less (65 %) than the calculated need. The topographic properties of this area, with a rather deep hollow in the centre parts of the area, most likely facilitated the infiltration of the mesa solution. In fact, during treatment a pond of mesa solution appeared in the centre of the area. Contrary to area 5, area 2 (the deposit of waste rock) has the shape of a small hill, which makes it more difficult to treat. Large amounts of the mesa solution did not infiltrate into the waste rock pile, but flow off the treatment zone. Hence, in this area it may be necessary to create small embankments and ditches to keep the mesa solution on site and thereby increasing the infiltration. Areas 1 and 3 are seemingly alike and have the same general history in that both have been temporary storages for ore. However, the ground layer and the unsaturated zone is much deeper in area 3 than in area 1. Furthermore, the treatment of area 3 started in late in autumn 2008, which was considerably later than the treatment of area 1. Most likely both these factors contribute to the different results obtained in these two areas, i.e. there was a rather clear effect of the treatment in area 1, but not in area 3.

Another lesson learned is that minimization of the infiltration of precipitation and inflow of surface water from off site is very important. In this case, the outflow of contaminated water was reduced by approximately 50% by establishing lined diversion ditches. Thus, the discharge of metals contaminated water to the lake is also reduced by 50%.

Implications for the final treatment of the Hornträsk mine

During the year 2009, the previously treated unsaturated zone will be monitored and and further treated if necessary. The adjacent peat area, which is leaching metals at high concentrations, will be treated separately to:

- Reduce the outflow of metals from the point P12.
- Minimize the leakage of metals from springs to the lake Hornträsk.

The discharge from the peat area will be reduced by constructing an additional diversion ditches that will bypass the contaminated peat area. The reduction of metal leaching will be achieved by liming of the peat area contaminated by the spring K6. The dose of mesa lime needed will be estimated using laboratory tests.
The final treatment of the mine area will begin with laboratory tests to estimate the efficiency and durability of the final cover construction. The laboratory method used will be accelerated infiltration in a system of columns.

The final covering of the selective areas is estimated to begin during the second half of 2009.

The experiences from the remediation of the Hornträsk mine has indicated the complexity of each treatment area relating to the type of ore, geology and structure of the bedrock, hydro-geological conditions, mining and reclamation methods used, diversity of environmental surroundings, etc. The knowledge of all those factors have important role for successful accomplishment of the remediation treatment.

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