Suggestion for a Protocol for Detailed Investigation of Historical Mine Sites

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ABSTRACT

A protocol for detailed investigation of mine sites is suggested. Results from the investigation are important when planning mine site reclamation. Initially, the mine site is divided into several sub sites according to topography. For general appearance the following parameters were developed and estimated directly in the field for every sub site: (1) shape, (2) historical land use, (3) amount of waste rock, (4) weathering, (5) waste rock size, (6) carbonates and silicates, (7) vegetation cover, (8) low and high species, (9) moss and grass/herbs, (10) broad-leaf and coniferous, (11) spruce and pine, (12) birch and aspen, and (13) blueberries and lingonberries. Every parameter was designated a numerical value between 0 and 5.

After sampling ocular mineral/rock classification was performed on composite samples from every sub site and the following major components were determined: (14) silicate, (15) mica, (16) granite/pegmatite, (17) carbonates, (18) iron oxide ore and (19) sulphide ore. In addition the relative distribution between the different sulphide minerals was also determined: (20) chalcopyrite vs sphalerite; (21) galena vs sphalerite; (22) chalcopyrite vs galena and (23) pyrite vs pyrrhotite.

Results from a historical mine site in Kopparberg, Sweden, are used to illustrate the methodology.

Key Words: Mapping, vegetation, waste rock, mineralogy, land use

INTRODUCTION

Background

Kopparberg, in the middle of Sweden, is a typical small village founded around a mine in the beginning of the 17th century. The mine is now closed and the only legacy is the weathered remains in the middle of the village. Due to the high residual trace element concentrations and low pH in the waste rock (approximately 200 000-300 000 m^3) together with the close vicinity to permanent housing there is a growing concern that it poses a threat to public health and the environment. Ljusnarsberg mine field was discovered in 1624 (Tegengren 1924) and the latest mining period ceased in 1975. Approximately 65 large or small pitheads have been found within the central parts of the field. It is estimated that a total area of 500 m by 400 m is affected by mining, ore and waste rock dumps.

Until late 19th century mining was focused primarily on copper and secondary on iron ore.

In mid Sweden several hundreds of abandoned historical mine sites are found and there is a need for cheap and reliable methods to assess their potential health and environmental impacts.

In this paper a method combining ocular inspection in the field and mineralogical identification is presented. The aim is to suggest a uniform inventory protocol for primarily historic mine sites.

Field site geology

The bedrock in the Ljusnarsberg ore deposit is dominated by strongly metamorphosed and deformed metavolcanics with partially skarn altered carbonate beds and lenses.

The main source of the economic mineralisation has been a more or less complex mixture of chalcopyrite/sphalerite/galena/pyrrhotite/pyrite/magnetite in various types of Ca-/Mg/-Fe-skarns and silicified metavolcanics without carbonates and/or skarn minerals.

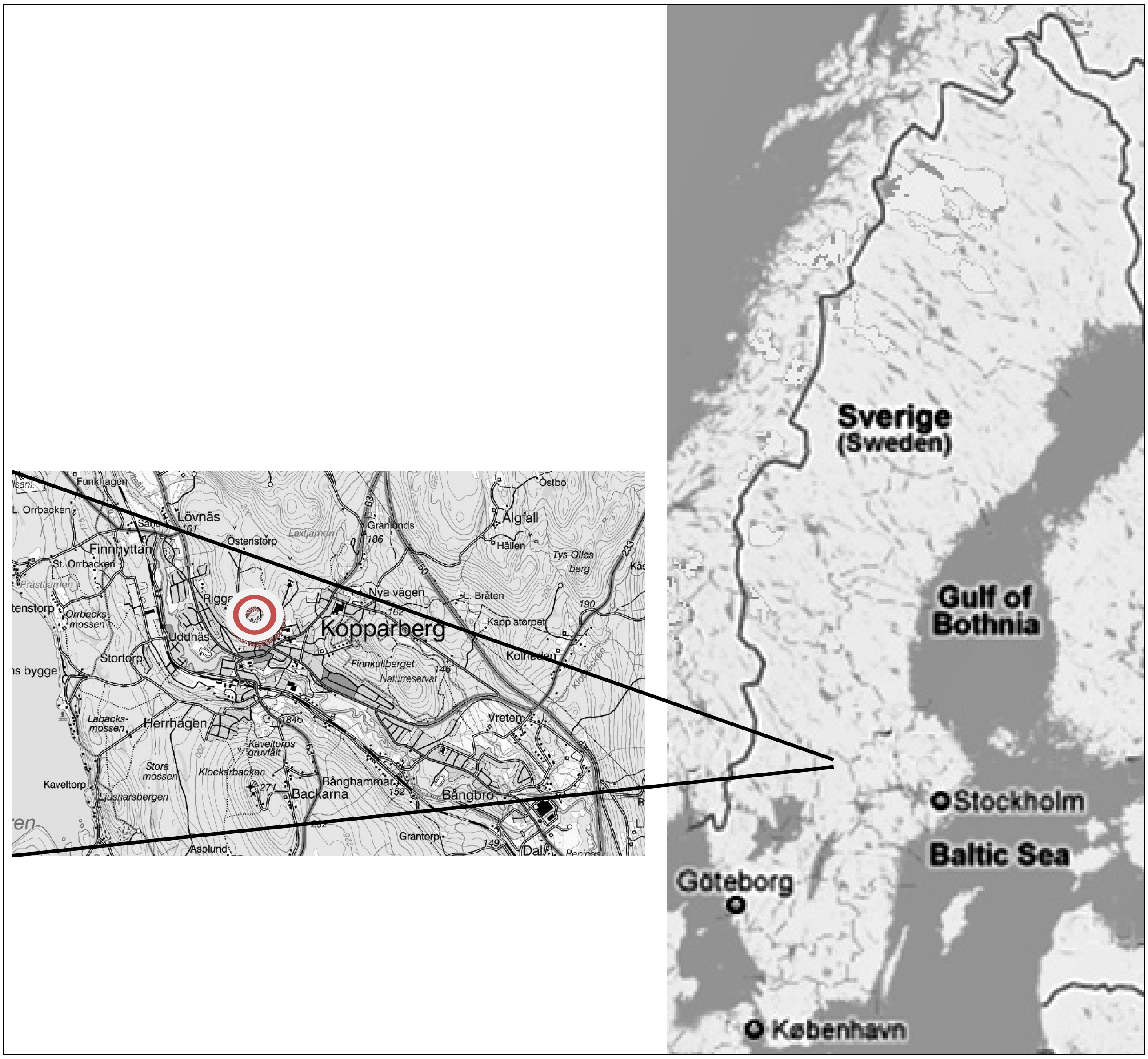

Figure 1. Location of the Ljusnarsbergsfältet historical mine site in the middle of Kopparberg, Sweden.

Sulphides are present in almost all rocktypes in the area, even outside the economic parts of the mineralisation, the only exception being the numerous younger granite-/ pegmatite dykes that intersect the mineralisation and its wallrocks.
Copper ore is dominated by chalcopyrite ($CuFeS_2$) that occurs as disseminations, small lenses and veinlets. The chalcopyrite is mixed with pyrrhotite (FeS), pyrite (FeS_2) and magnetite (Fe_3O_4) and has quartz, hornblende, actinolite, biotite, chlorite and red garnet as wallrock. From the middle of the 19th century and onwards galena (PbS) and sphalerite (ZnS) ore were also produced.

The northern part of the field have been mined for fine grained and somewhat sulphidic magnetite ores in several small mines.

MATERIALS AND METHODS

Background

The mine site is generally vegetated, but the vegetation is seriously disturbed in many parts of the site due to mining. Several areas are also recovering from the last period of mining that ceased 1975. To quantify and map the impact from mining and the degree of recovery by nature approximately 110 000 m^2 of the central parts of the mine area were mapped during the summer of 2007. A fenced industrial area used for district heating was excluded from mapping.

Table 1. Mapping parameters used for the objects in the field.

Parameter	Explanation
1	Waste piles. Shape. Continuous scale where completely natural shape (undisturbed) = 1, entirely artificial or affected = 5.
2	Waste piles. Interpreted historical land use (waste dump, farm land, forest, disturbed land, open pit).
3	Waste piles. Fraction of waste rock at the object 0 = 0-10 % waste rock, 1 = 10-20 %, 2 = 20-30 % etc
4	Waste piles. Level of waste rock weathering. 1 = Almost no weathering, 2 = weak weathering, 3 = mild weathering, 4 = strong weathering, 5 = almost complete weathering. Level of waste rock weathering is a combination of the parameters weathering (fraction) and weathering depth.
5	Waste piles. Waste rock average size. Continuous scale where 1 = mainly very coarse (boulders often 50 to >100 kg), 2 = coarse, 3 = medium coarse, 4 = mainly fine-medium, 5 = mainly fine grained waste.
6	Waste piles. Proportion between carbonates and silicates in the waste rock. Continuous scale where 1 = carbonates are dominating, 5 = silicates are dominating.
7	Vegetation cover. 1 = no vegetation, 2 = sparse vegetation, 3 = moderately vegetated, 4 = vegetated, 5 = lush vegetation.
8	Vegetation. Estimation of the numbers of ”low” species.
9	Vegetation. Dominating ”low” species. 1 = Lichens, 2 = moss, 3 = grass, 4 = herbs.
10	Vegetation. Proportion between trees. 1 = broad leaf trees are dominating, 5 = coniferous trees are dominating.
11	Vegetation. Distribution between coniferous trees. Continuous scale where 1 = pine, 5 = spruce.
12	Vegetation. Distribution between broad leaf species. Continuous scale where 1 = birch, 5 = aspen.
13	Vegetation. Proportion between lingonberries and blueberries. 1 = blueberries are dominating, 5 = lingonberries are dominating.

Mapping was performed in five steps:

1) Reconnaissance and choice of parameters;
2) Identification of objects and mapping of parameters;
3) Sampling and waste characterization;
4) Description of samples; and
5) Analytical.

Reconnaissance and choice of parameters
During the reconnaissance a large number of parameters such as surface shape, flora, waste pile geometries, colour of lichens, size distribution, weathering, mineralogy, site history etc were evaluated before the final parameters were selected (Table 1). Here it is important to note that each individual site needs their specific set of parameters. Parameters for other sites must be selected from descriptive parameters specific for that site and its surrounding environment (especially with regards to the vegetation).

Identification of objects and mapping of parameters
The mine site was divided into smaller objects and every object was selected in a way that the object could easily be described by the parameters in Table 1. The line between different objects could locally be very hard and motives for dividing into different objects vary. Mapping was also limited by natural and cultural consideration. Parameters have been based on visible waste rock and objects with established vegetation have not been disturbed during mapping.

Geographical mapping
Borders for every object were determined through a combination of hand held GPS and a map from the last mining period. All coordinates and all parameters for the objects were imported into GIS software for further processing.

Sampling and waste characterization
At the historical mine site Ljusnarsberg in Kopparberg 237 objects were identified during mapping. 111 of the 237 were determined to be mainly waste rock. Every object has been described according to the parameters in Table 1. Parameter 4 (level of weathering) and parameter 6 (proportion between carbonates and silicates), for instance, are affected by the mineralogical and petrological composition of the waste rock. In order to get a better picture over what mineralogy and chemistry that affects the environment in the area 74 out of the 111 objects were sampled for preliminary mineralogical/petrological determination and classification.

Representative sampling for each single object was probably not achieved due to varying waste rock sizes and different degrees of vegetation covers. Sampling of waste rock piles for determination of average metal concentrations is very difficult due to the "nugget effect". One of the few ways to counteract the "nugget effect" is to increase the sample volume and determine the factors behind the concentration distribution. This has not been possible within this project.
Due to the ”nugget effect” results from the waste rock sampling can only be considered indicative and a single result from an object cannot be considered statistically significant. Altogether the results are considered to give a fair picture of the mineralogical/petrological and chemical character of the waste rock piles. Sampling was performed using hammers to obtain small pieces from as many waste rock pieces as possible (only one piece from each waste rock piece) resulting in approximately 5 L from each object. Typically every composite sample consisted of approximately 35 different waste rock pieces.
Samples were sorted and classified according to the 10 parameters presented in Table 2. Mineralogical/petrological parameters were chosen based on the geology of the deposit to reflect the variation in the deposit, i.e. the typical mineralogy of the different ore zones and typical gangue compositions. This approach can easily be adapted to other mine sites with other mineralogy.

A more thorough discussion about the relationship between element content through chemical analysis and preliminary mineralogical/petrological classification can be found in Bäckström and Sädbom (2008).

Table 2. Mineralogical and petrological parameters for the solid waste samples.

Parameter	Explanation
14	Mineralogy. Fraction of the samples consisting of fine grained silicates, probably more or less converted meta volcanics (mainly fine grained quartz, feldspars, mica).
15	Mineralogy. Fraction of the sample consisting of different micas (biotite, muscovite, phlogopite).
16	Mineralogy. Fraction of the sample consisting of granite, pegmatite, aplite materials (quartz, feldspars, mica).
17	Mineralogy. Fraction of the sample consisting of carbonate minerals (calcite, dolomite).
18	Mineralogy. Fraction of the sample consisting of magnetic ”iron oxide ore” (magnetite).
19	Mineralogy. Fraction of the sample consisting of “sulphidic ore” (pyrite, pyrrhotite, chalcopyrite, sphalerite, galena).
20	Sulphides. Distribution between chalcopyrite and sphalerite. Continuous scale where 0 = only chalcopyrite (copper), 5 = only sphalerite (zinc).
21	Sulphides. Distribution between galena and sphalerite. Continuous scale where 0 = only galena (lead), 5 = only sphalerite (zinc).
22	Sulphides. Distribution between chalcopyrite and galena. Continuous scale where 0 = only chalcopyrite (copper), 5 = only galena (lead).
23	Sulphides. Distribution between iron sulphides. Continuous scale where 0 = only pyrite, 5 = only pyrrhotite.

RESULTS AND DISCUSSION

Preliminary reconnaissance and field estimation

Development of the waste dumps

Waste dumps at the historical mine site have been created through mining of a geological very heterogeneous ore body during nearly 400 years of technical development. This has resulted in a rather chaotic situation where the properties of each waste dump are determined by a combination of historical and geological factors. For instance metal prices and the period of production directly governed the mining technique, remediation method (if any), choice of mining location in the mine, and the grade cut off between ore and waste rock.

Another factor is that the period of production influences the time available for weathering, leaching, recovery and development of vegetation.

The following factors were considered the most important for the development of the waste dumps:

- Period of production → Mining method → Waste rock size
- Ore minerals left in the waste rock → Content of sulphide minerals
- Geology → Mineralogy/petrology in mined materials

Period of production → Mining method → Waste rock size

Fire setting was probably used as mining method until the late 18th century, perhaps even during the early parts of the 19th century. The method is based on large fires placed in direct contact with the rock. Obtained cracks were then worked with hammers and chisels until pieces of the rock were obtained. Fire setting created thin flakes of rock with a lot of fine cracks. Waste rock particles from fire setting are seldom more than a few centimeters thick and a few decimeters long. Waste rock generated by fire setting is therefore probably more prone to weathering and decomposition of the waste rock.

Gun powder and dynamite blasting produce a coarser waste rock. In the early days gun powder was poured into hand drilled holes, thus limiting the total volume of rock produced at every blast and the size of the waste rock particles produced. Hand loading of the rock also put a limit to the waste rock size. Dynamite blasting in machine drilled holes and increased mechanization in the mine gradually increased the size of the waste rock particles.

Ore minerals left in the waste rock → Content of sulphide minerals
Techniques used in the mine during the years have of course varied and thus also the content in the waste dumps. During the 17th century until early 20th century only hand sorting was used. This method can only handle rich solid ores with a size suitable for hand sorting.

Geology → Mineralogy/petrology in mined materials
Choice of mining area within the mine was made on a day to day basis considering potential customers and the revenue potential of the techniques in use during that period of time.
Geology, mineralogy and chemistry in both ore and waste rock produced thus vary significantly within the field site.

Reconnaissance parameters
Historical land use (Figure 2) was one of the first parameters logged and was for instance used to identify waste piles for further sampling.

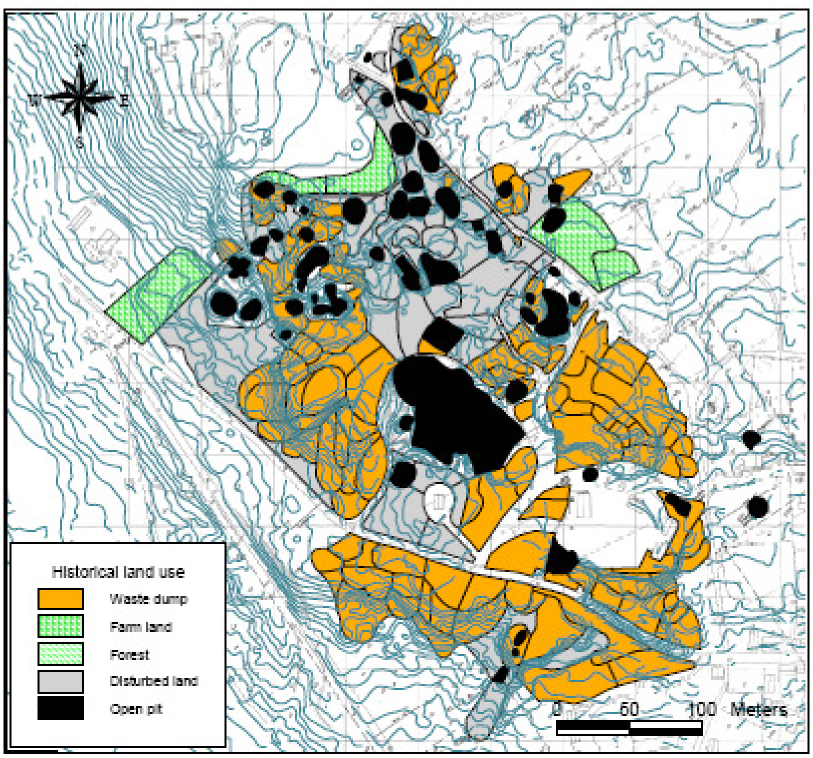

Figure 2. Initial description of all identified 237 objects at the historical mine site based on the historical land use (waste dump, farm land, forest, disturbed land and open pit). 111 out of the 237 objects were sampled for further mineralogical/petrological characterization.

In summary 237 different objects were found at the mine site based on topography and other features of the landscape. Out of the 237 objects 111 was classified as waste dumps, 60 as open pits and 52 as disturbed land. Disturbed land is a relatively broad parameter including work areas for mining (including roads, storage areas) as well as dumps of overburden.

In Figure 3 the field parameter "vegetation" is illustrated. Generally the northern part of the mine site has more normal vegetation compared to the southern part. This is partly due to the fact that in the northern part the main mineralization consists of magnetite and a lower content of sulphides. This is also one of the older parts of the mine site and has had the longest period of natural recovery. In the southern part of the mine site several objects lacking vegetation were found. These objects are connected with the last period of mining that ceased in 1975. As can be seen in Figure 4 the waste rock size in these objects is very coarse and thus unlikely to sustain vegetation. A few objects, roughly in the middle of the mining area, contain very weathered material and readily accessible metals. In these areas no vegetation exists due to high toxicity towards plants.

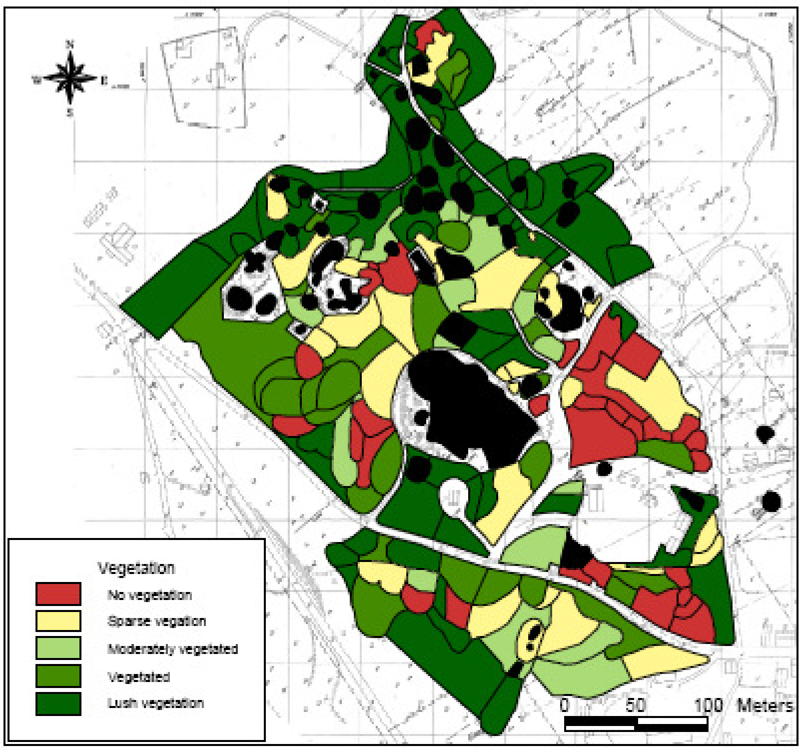

Figure 3. Description of the vegetation at the mine site (no vegetation, sparse vegetation, moderately vegetated, vegetated, lush vegetation).

In Figure 4 the field parameters "waste, particle size" and "waste weathering" can be found. Particle size gives a rough idea of the variation of waste size within the mining site. This can both be a representation of production period, as later mining methods gave larger waste rock sizes. But it can also be a rough measure of the weathering activity and metal leaching. Smaller sizes might indicate a high weathering activity as well as a higher leachability due to larger surface areas.

It is important to note that the suggested method has limitations and comparisons between different sites and even between a site at different times might not be possible. However, the main purpose of the suggested protocol is to map one site, study variations between objects within a site and find likely hot spots.

Mineralogical/petrological waste characterization

In Figure 5 some examples from the mineralogical/petrological characterization of the content in the waste dumps are illustrated. The waste rock generally is high in sulphides and low in carbonates. There are signs of carbonate minerals being present originally in the waste rock, but they have been dissolved by the acid production at the site. The dominance in acid generating potential over acid neutralizing potential at the site is also confirmed by the average composition of all waste dumps (Table 3). There is only 4 % carbonate minerals (calcite and dolomite) present in the waste dumps compared to 29 % sulphidic minerals (pyrite, pyrrhotite, chalcopyrite, sphalerite and galena identified during ocular characterization). Carbonate minerals are, of course, not evenly distributed at the mine site, but rather found at higher concentrations in certain dumps, and the most common concentrations are very low.

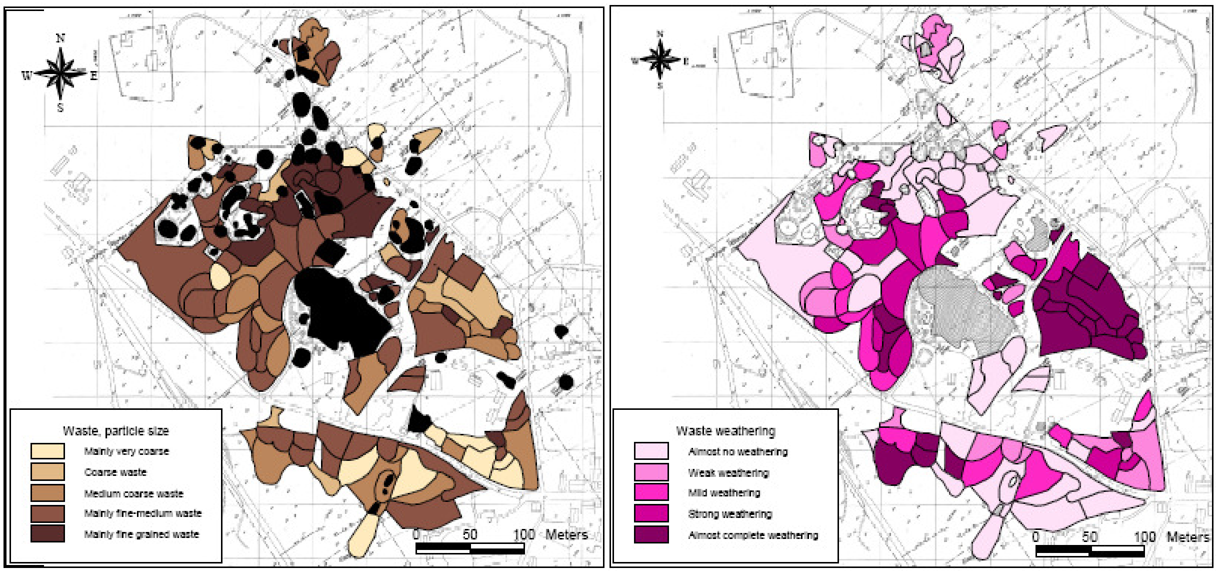

Figure 4. Description of the two field parameters "Waste, particle size" (mainly very coarse, coarse, medium coarse waste, mainly fine-medium waste, mainly fine grained waste) and "Waste weathering" (almost no weathering, weak weathering, mild weathering, strong weathering, almost complete weathering).

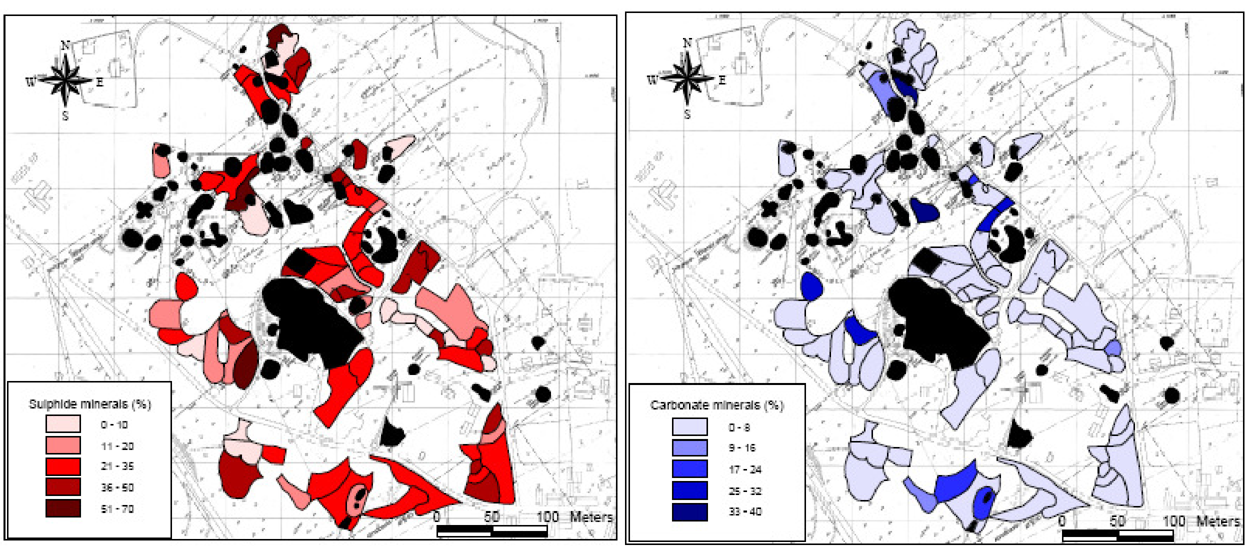

Figure 5. Description of the two mineralogical/petrological parameters "Sulphide minerals" (%) and "Carbonate minerals" (%).

Table 3. Average composition of all mineralogical/petrological characterized waste dumps at the mine site.

	Average values
Fraction of the samples consisting of fine grained silicates, probably more or less converted meta volcanics (mainly fine grained quartz, feldspars, mica).	14 %
Fraction of the sample consisting of different micas (biotite, muscovite, phlogopite).	14 %
Fraction of the sample consisting of granite, pegmatite, aplite materials (quartz, feldspars, mica).	6 %
Fraction of the sample consisting of carbonate minerals (calcite, dolomite).	4 %
Fraction of the sample consisting of skarn minerals (pyroxene, diopside, amphibols, tremolites etc)	20 %
Fraction of the sample consisting of magnetic ”iron oxide ore” (magnetite).	12 %
Fraction of the sample consisting of “sulphidic ore” (pyrite, pyrrhotite, chalcopyrite, sphalerite, galena).	29 %
Total	100 %

Another way of illustrating the lack of carbonate minerals relative to the sulphide minerals is by mapping some rough measure of net acid potential. According to the Sobek method (USEPA 1994) acid generating potential is calculated by multiplying the sulphur concentration (in weight%) by 31.25 to compare it with the concentration of carbonate minerals (assuming calcite). In our case we only have rough numbers on the presence of sulphide minerals. Sulphur content in pyrite is around 54 % and in the other minerals much lower (pyrrhotite 36 %, galena 13 %, sphalerite 33 % and chalcopyrite 35 %). Thus, in our calculations we have used the sulphide minerals content instead of sulphur and removed the requirement for a conversion factor for sulphur. Calculated net acid potential for each object is presented in Figure 6. This illustration confirms the fact that there are only a few objects within the mine site that do not have the potential to generate acid in the future.

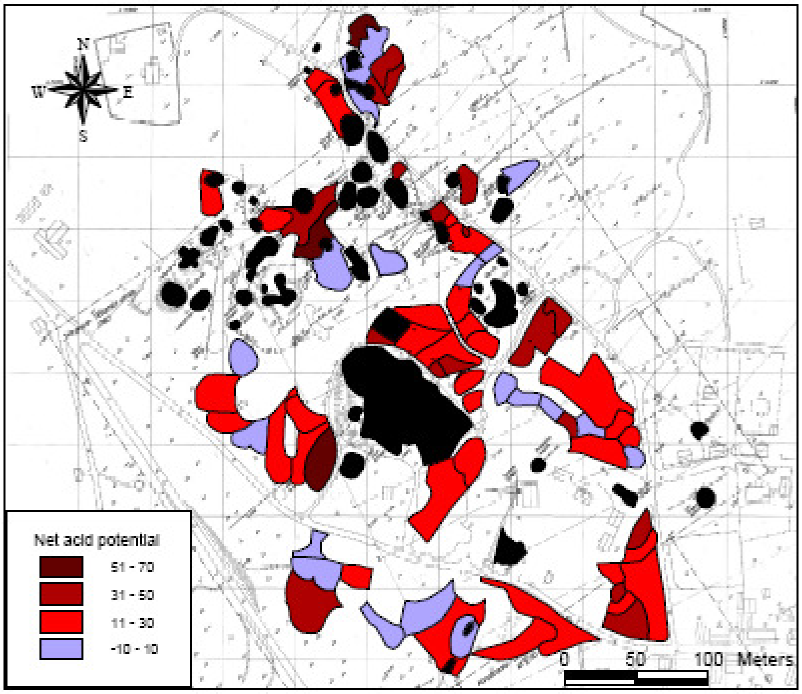

Figure 6. A rough estimate of the balance between acid producing minerals and acid consuming mineral expressed as net acid potential (positive values indicate acid producing potential). See text for further details about assumptions and calculations.

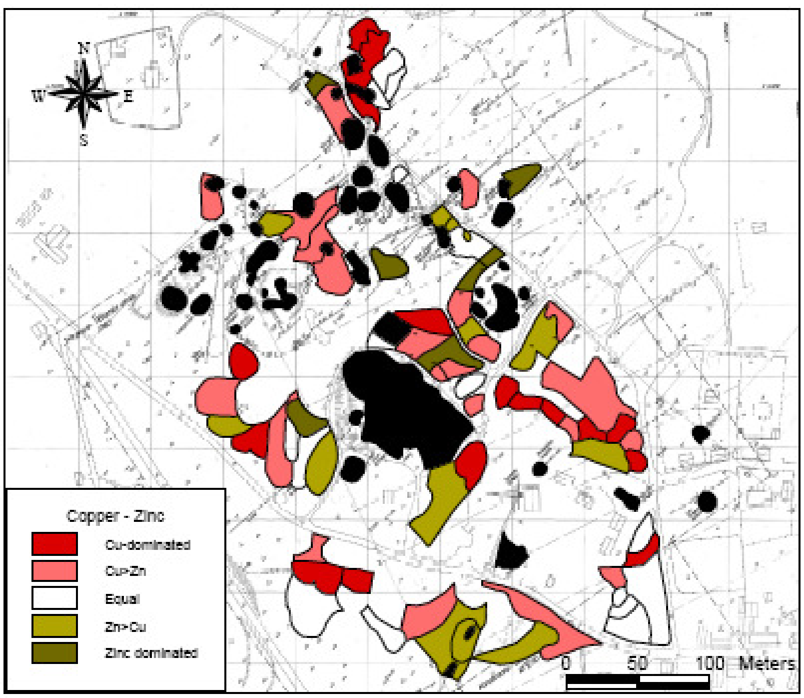

Figure 7. An illustration over the dominance by either zinc or copper (based on % minerals by weight) in the waste dumps.

Another possibility this method has is to show areas dominated by different minerals using ratios. An example with copper and zinc is illustrated in Figure 7. In general copper minerals are present at higher concentrations than zinc minerals considering the entire mine site.

CONCLUSIONS

This study has shown that much complimentary information can be gained from using a pre determined mapping system and by adding mineralogical/petrological characterization for every sample taken for chemical analysis. Several new dimensions can be brought into characterization of mine sites by using detailed mapping during sampling campaigns. This tool should not be used instead of chemical analysis, but as a complement with low extra cost. In fact an earlier paper (Bäckström and Sädbom, 2008) concerning the same mine site showed that the samples sent for chemical analysis could be reduced with almost 80 % if the mapping technique were used.

It is, however, important to note that the technique has only been used at one historical mine site in Sweden and the use should be confirmed at other sites with other types of geology. For every individual site there is probably a need for a specific set of both mapping as well as mineralogical/petrological parameters. Mapping parameters could easily be adapted to other sites by considering the vegetation at the site and in the surrounding environment. Mineralogical/petrological parameters can also easily be adapted by considering the ore zones and gangue mineralogy. All parameters presented in this paper should only be considered an inspiration for others and not an absolute truth.

ACKNOWLEDGEMENTS

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