Report

Sampling of mining waste – historical background, experiences and suggested methods

Carbonate hosted magnetite

Stefan Sädbom
Mattias Bäckström

BKBAB 18-109 Rep

2018-11-29

Summary

Sampling of mining waste might be performed for several reasons;

(1) assess environmental problems
(2) determine potential secondary resources
(3) for exploration purposes.

Sampling of mining waste is, however, anything but straightforward. Heterogeneity issues, for instance, make the use of classical statistical methods problematic. Aim of this report is to describe the creation of mining waste deposits in order to understand how to sample and suggesting an approach for surveying and sampling mining waste.

In order to collect a fair sample from a mining waste deposit it is crucial to know how the waste has been generated, why it is deposited in different areas and how the handling of the waste has influenced its homogeneity and thus the prerequisite for collecting a fair sample.

In the report the reader is given a thorough background describing some of the technologies that have been used and have affected the formation of different mining waste types through history.

How sampling in different medias can be done is described and how impossible it is to sample mining waste. The concept of using cumulative moving average (CMA) to determine when enough samples have been collected to establish saturation is described and exemplified with series of analytical results from several mining waste sampling campaigns.

It is also suggested that several seemingly peripheral, parameters regarding the mining site (shape of the deposit, vegetation cover, vegetation type etc) are recorded in order to increase knowledge about the site. Specific approaches for sampling waste rock and tailings are provided in detail. A step wise approach in analysing samples is recommended in order to obtain a valid result for larger sites. It is shown that the minimum number of samples, in order to obtain a valid result with respect to the average concentrations (±25 %) for the sample set is around 15 samples for waste rock. Smaller sample sets are often enough for tailings. It is also suggested that prior to submitting the samples for chemical analysis all pieces in a sample is characterised with respect to paragenesis and mineralogy.

It is, however, important to remember that every mining site is unique and site-specific information is important in order to be able to revise the sampling strategy.

Sampling of mining waste is impossible, but it can still be done!

Contents

Extracts from mine maps are based on scanned originals in the archives of the Mining Inspectorate of Sweden.

Historical photos have unknown photographer unless where stated.

Figures and photos by Stefan Sädbom, Bergskraft Bergslagen AB, except where otherwise stated. Aerial photos and maps are from Lantmäteriet open source data.

1. Introduction

1.1. Aim of this report

Sampling of mining waste might be performed for several reasons;

1. assess environmental problems
2. determine potential secondary resources
3. for exploration purposes.

Sampling of mining waste is, however, anything but straightforward. Heterogeneity issues, for instance, make the use of classical statistical methods problematic. This report has been commissioned by the Geological Survey of Sweden in order to lay a foundation for a general sampling method for mining waste. Aim of this report is to describe the creation of mining waste deposits in order to understand how to sample and suggesting an approach for surveying and sampling mining waste.

1.2. Background

Mineral raw materials are a fundamental prerequisite for the function and development of modern society. Current supply of materials is provided through a combination of freshly mined virgin ore and recycled materials.

Mineral raw materials have a well-developed functionality in the recycling chain, compared to other materials in the society, but with a growing global population, increasing per capita usage and a desired and increased retention time in infrastructure and products, recycling only will not provide enough supply.

To fill a part of the supply gap historical mining waste has been discussed as a potential, albeit, limited source of mineral raw materials. Extractions from mining waste would also in theory lower the pressure on active mining operations and extend their life time as well as remove some elements from historical mining sites that may pose environmental problems.

These ideas have to some extent been investigated in the historical, and in parts still active, Bergslagen Mining Region in South Central Sweden, where thousands of mines have been in operation since perhaps even before Medieval time. Mining has resulted in large amounts of mining waste in the form of waste rock, jig tailings, tailings, and slag.

Bergslagen mining waste deposits contain large amounts of minerals and elements that may be of interest for extraction, elements that may be environmentally harmful, but may also function as an exploration tool to find additional primary mineral raw materials deeper in the earth's crust.

Identification of occurrences of common industrial metals or more unusual, exotic, or critical minerals and commodities can be difficult. Comparison between different sites and objective quantification of the content and the value of the occurrence is not easy, and since a specific element may occur in different concentrations, in different minerals and in different paragenesis, the conditions for representative sampling varies strongly and is mostly not known in advance.

The purpose with this report is to describe, with the aid of several case studies/examples, how mining waste is created and how variations in a number of primary geological parameters in combination with a number of historical/technological parameters affect the possibility to collect a representative sample from mining waste.

1.3. Assumptions and limitations

Methods and experiences described in this report are essentially limited to sampling by hand with the aid of manual tools. Heavy equipment such as mechanised drill rigs would of course enable larger samples and samples from deeper parts of the mining waste deposits, but on the other hand, would not be practical or accepted in remote areas with historical mining waste or areas of natural conservation or heritage status.

Another limitation is that all sampling described in this report is based on sampling at the surface (no digging). A thin cover of grass or moss may be lifted to enable a sample to be collected but in the suggested sampling procedure excavations are no included to reach the sample.

Although vegetation at a first glance is nothing but an obstacle to proper sampling, vegetation may also give some clues to what is hidden beneath. In performed work in Bergslagen documentation of some non-geological parameters describing the vegetation and distribution of a selection of individual plants were also included in the study. It is clear that a certain geology/mineralogy/chemistry favour some species while other plants avoid certain areas. Experiences from the work in the Bergslagen Mining Region may not be possible to extrapolate outside the northern part of Europe (or even outside Bergslagen), but we recommend that the vegetation is considered and studied in relation to the mining waste in your local area.

Figure 1: Vegetated iron mining waste pile at Slotterbergsgruvan, Hällefors with a thick, healthy cover of Wood Anemone (*Anemone Nemorosa*) with Pine (*Picea Abies*) and Mountain Ash (*Sorbus Aucuparia*).

Sample preparation is not included in this report. It has been assumed that the sample, once it arrives in a modern, accredited laboratory is treated according to standard procedures and that all measures are taken to ensure that there is no contamination between samples and that standard quality assurance and quality control is implemented.

2. Mining waste – definitions

Waste from mining can have several shapes depending on a series of factors largely related to the geology, when in time and where in the value/waste chain the waste was generated.

Mining waste is normally deposited close to the origin in order to reduce haulage costs, but it may be deposited further from the source due to practical reasons, because of limited space, other infrastructural or planning reasons.

2.1. Waste rock

Waste rock can be defined as barren, sub marginal rock that was not valuable enough to process at the time of mining/processing.

Waste rock was removed from the flow of materials before it could enter the post mining processing chain of activities aiming at increasing the grade of the:

- **E**lement,
- or the **M**ineral **O**f **I**nterest

In the continued text referred to as **"EMOI"**.

Figure 2: Mining waste deposited in a lake. Note several lobes of mining waste in the background. Svartbergsgruvan, Ställdalen, Sweden.

2.2. Waste rock dump

A waste dump is an area where mining waste was deposited. It can have the shape of a pile or a fill in a previously low area in the terrain. Sometimes the mining waste is deposited in a depression and then naturally, the surface topography may not fulfil the definition to be called a pile. Waste (rock) dump is neutral to shape but can be combined into waste (rock) pile to include the shape parameter (ex: Figure 1).

If the mine is in a hilly environment, it is fairly common that the waste has been deposited on the hillside down slope, to form something that has the characteristics of a talus slope, a waste talus. Similarly, open pits and shafts have often been used for deposition and can then be characterised as waste backfill (Figure 3).

Figure 3: Old open pit with mining rock waste deposited over the edge as backfill. Note size variation down "talus slope" to the left and erosional channels on opposite side. Ljusnarsberg copper mine, Sweden.

2.3. Tailings

Technologies of separating EMOI from waste has changed through history and particularly since the beginning of the 19th century. Water, however, has always been an essential component in crushing, milling and separation of EMOI:s be it by gravitational, hydro-chemical or chemical processes.

When the EMOI has been separated, the remaining material, often in the form of sand or very fine-grained material, slime, has been deposited. Such a deposit is referred to as a tailings dump or if deposited within the walls of a dam construction a tailings dam.

Figure 4: Old tailings from the Kaveltorp mine in Kopparberg. Photo: Mattias Bäckström.

2.3. Stockpiles

Crude ore (classified as ore in the mine or after sorting) is often stockpiled outside the mine, the sorting building or close to loading docks, railways or roads for transport.

Valuable material separated by various enrichment processes may be added to the same stockpiles or be stockpiled in separate piles. If the enrichment process included milling the product is called a concentrate which is stored in a concentrate stock pile.

3. Origin of mining waste

Origin of mining waste and how the primary geological/mineralogical factors are combined with different historical/technical contexts such as the local economy, time span, topography, technological matureness and duration of the operation, all affect the shape, design and content distribution of particles in the mining waste and thus eventually the prerequisites for successful collection of a representative sample.

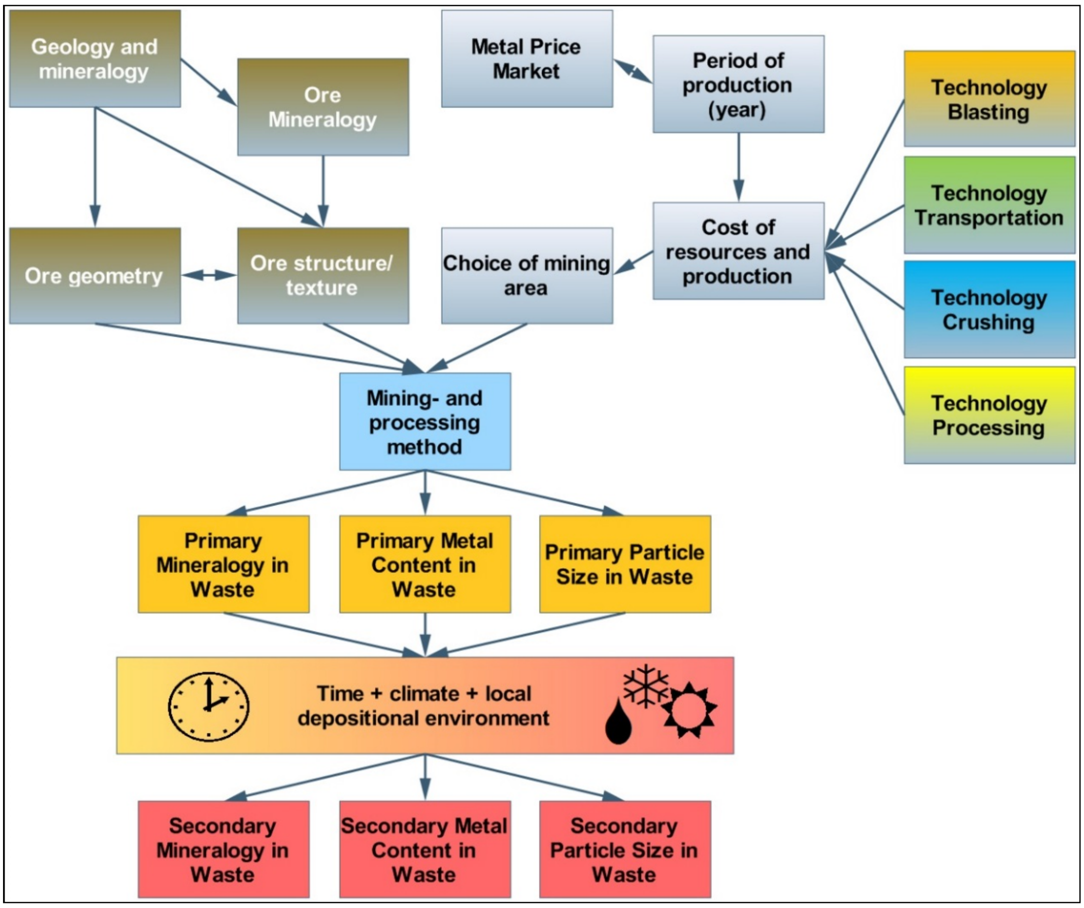

Figure 5: Chains of cause and effect. Relation between primary and secondary parameters that influence the composition and conditions for collecting a representative mining waste sample.

3.1. The complex history of mining waste rock.

Complexity of waste rock is dependent on the primary degree of heterogeneity in the mineral deposit itself multiplied by the complexity added when the rock was extracted, i.e. the time parameter. Many mining operations have a long life, some more than 1 000 years, and naturally, technology has shifted and developed through time, creating an almost chaotic overlap between geological and historical factors.

As an example, the metal/mineral price and the mining costs (including labour, powder, dynamite, fuel etc.) has directly governed the mine planning, selection of mining area, minimum grade for classification as ore and waste, the decision to sort, pre-process and/or crush, mill, and process the ore. Similarly, the decisions on where and how waste rock should be deposited shifted with time, depending on current technology, haulage cost and access to land etc.

Time, together with local environment and climate control length of exposure to weathering, leaching, redistribution of elements through chemical processes, erosion and introduction of vegetation and biological processes.

Finally, and on top of, the natural post mining processes, secondary anthropogenic activities may affect the mining waste. For example, waste rock has often been used as building materials or has been the subject of environmental rehabilitation (with or without additional materials brought to the site to regulate pH or hydraulic conductivity) to minimize harmful effects on the environment.

Some parameters and events in the chains of cause and effect in the creation of mining waste are illustrated in Figure 5 and will be studied in more detail in the following three subchapters.

3.1.1. Historical period → EMOIs

Rocks as a raw material has been used since the beginning of time. What has been considered useful and valuable has shifted and today's use of elements in modern technology has shifted our opinion regarding what elements are critical from flint to cobalt and REEs.

Similar shifts have occurred through the history of mining and many of the elements we value highly today was totally ignored, or not even known by the early miners. Some favourites (like mercury) have lost their glory and are more seen as an annoyance, an environmental problem or an element of penalty today.

Knowing the detailed history of a mining operation is equal to have the key to why, how and where a specific material was deposited and history can provide the clues to how to collect representative samples.

Figure 6: Shards from fire setting. Note common aspect ratio 10:10:<1. Finngruvan Coppermine, Ljusnarsberg, Sweden.

3.1.2. Period→ Mining method → Size of waste material

Evolution of mining is fostered by local conditions and influences from other mining districts. Therefore, the usage of the same mining method may have occurred at different periods of time in different parts of the world. In the following sections some examples of technologies used in hard rock mining in open pit and underground mining in Scandinavia will be described to give an insight into how these methods have affected the formation of mining waste.

Fire setting was a common method in hard rock mining before the introduction of black powder and dynamite.

In short, the method is based on setting big fires directly towards the rock face, floor or roof of a mine. The heat, sometimes followed by addition of cold water, creates small, but extensive cracks in the rock. When the remnants of the fire have been removed, chisels, hammers and sledges are used to break the rock. The method creates many relatively small discs/flakes of rock, normally not more than a few cm thick and with disk like shape up to a maximum of some tens of cm across.

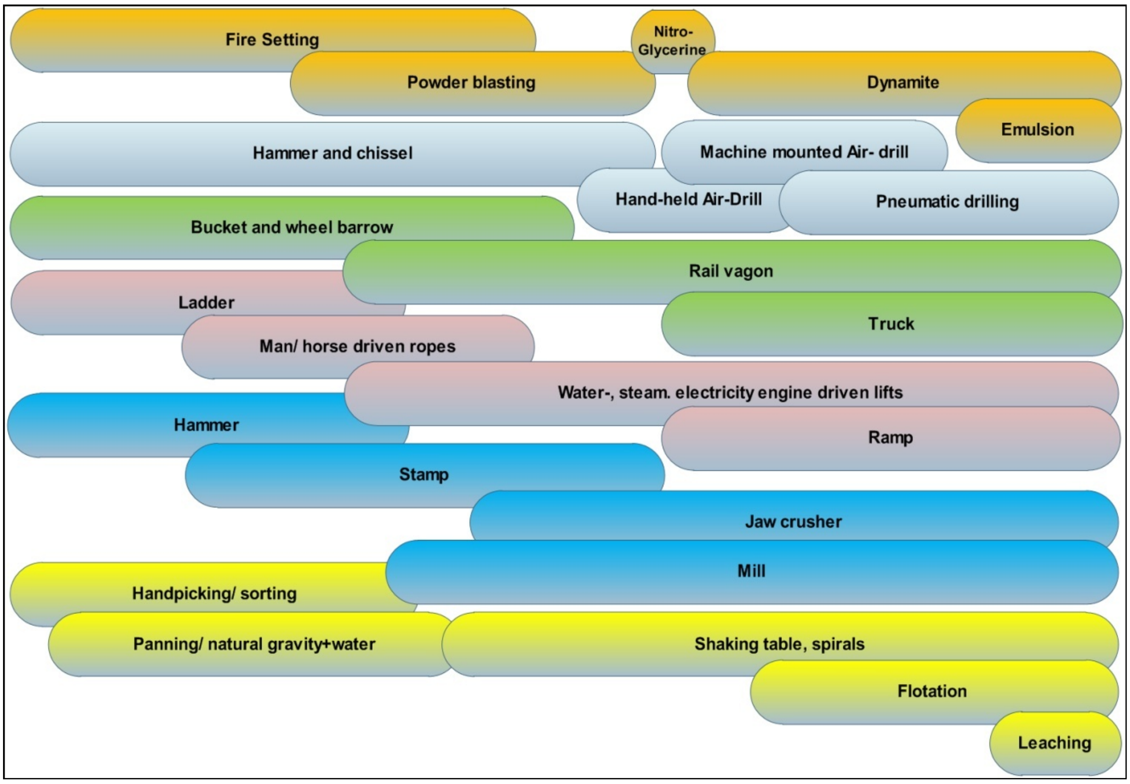

Figure 7: Thematic subdivision of technologies influencing mining waste parameters. Gradually more advanced methods to the right.

Pieces brought to the surface were often small since most material was brought to the surface by hand using ropes and bucket, wheel barrows and backpacks.

Important to note is that the material often has a large volume to surface ratio which enables easy handpicking of EMOIs but does also create a waste material that is very susceptible to surface weathering once exposed to air and water on a waste dump.

Fire setting was slow, normally a rock face would only progress 1-10 cm per fire setting and the wood to rock ratio is said to have been more than 6:1, i.e. more than 6 m^3 of wood to 1 m^3 of rock extracted.

Powder blasting was introduced while fire setting was still in use but did not always replace the old method since powder was relatively expensive compared to the wood and the people used for fire setting. Powder was introduced and ignited in cracks and in hand drilled short holes and created rock fragments that were larger and more angular than those from fire setting.

Figure 8: Drill hole for explosives drilled by hand. Svinnersta iron mine, ca 1870. Askersund, Sweden.

Cracks from explosives don't always follow the natural structure in the bedrock and the pieces thus often contain more than one paragenesis/rock type.

Sizes of individual blasts gradually increased and created pieces with a rough surface and an angular blocky shape. Sizes of rock pieces brought to the surface were limited by manual loading on simple wooden wheel barrows and the material and power available to haul buckets to the surface with the aid of horse, water or man driven winches.

Later, wagons driven by man or horses increased the sizes of rock pieces that could be brought to the surface but loading on to the wagons was still performed by hand.

Nitro glycerine and later dynamite blasting introduced more powerful fragmentation and when machine drilling of blast holes was introduced the overall productivity increased dramatically.

Parallel with the development of blasting technology, the industrial revolution brought a rapid flow of inventions to the mines. Rail was introduced in many mines; first rail wagons were driven by manual labour and later by small engines. Horse or man driven hoisting was gradually replaced by water wheels, steam engines and electricity.

Today variations of emulsion blasting technology have been introduced in many mines although variations of dynamite are still frequently used.

Figure 9: Sorting of iron ore by hand. Ca 1930. Stripa, Örebro, Sweden.

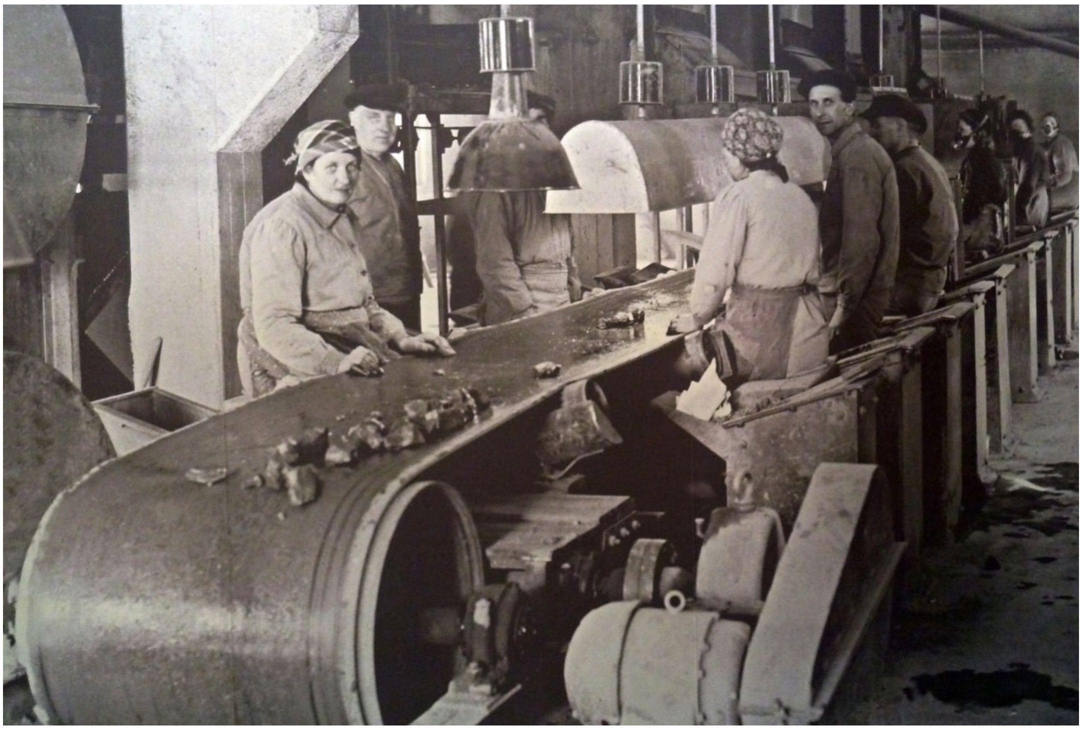

Figure 10: Sorting of iron ore by hand. Ca 1950. Stripa, Örebro, Sweden. Note size of pieces on conveyor belt.

To summarise, the technological developments in fragmentation, loading and hoisting of rock to the surface has led to stepwise changes in the aspect ratio and the size of the rock fragments brought to the surface.

Shape has shifted from small, flaky pieces generated by fire setting to gradually larger blocky pieces generated by the use of black powder, nitro glycerine and dynamite. Later more advanced sequential blasting of dynamite and emulsion explosives have increased fragmentation so that today again, smaller, more even sized, but blocky pieces are produced.

3.1.3. Amount of sulfides in the waste material

Minerals that contain sulfides are and have been important since they in many parts of the world carry important industrial elements such as copper, zinc, and lead with secondary valuable elements such as silver and gold. Sulfide minerals in combination with water and oxygen is a problem since the formation of acid rock drainage poses a threat to the environment and over time has the potential to entirely change the mineral- and elemental distribution in the mining waste and the surroundings.

Figure 11: Jönsbergs gruva. Godegård, Sweden. Shaft with bridges and pocket for loading of crude ore to wagon. Waste rock dump to the right.

When mining waste rock piles rich in sulfides weather, the size of the pieces can be dramatically reduced to gravel or sand grain sizes. When fine grained, intensively weathered material is found, it is quite logical to interpret the material as tailings, but before the classification has been fixed, consider if the place, from an industrial perspective is a logical place. Consider the possibility that particle size is a result of reduction due to weathering of sulfide rich material. See for instance Figures A2 and A18 in Appendix A.

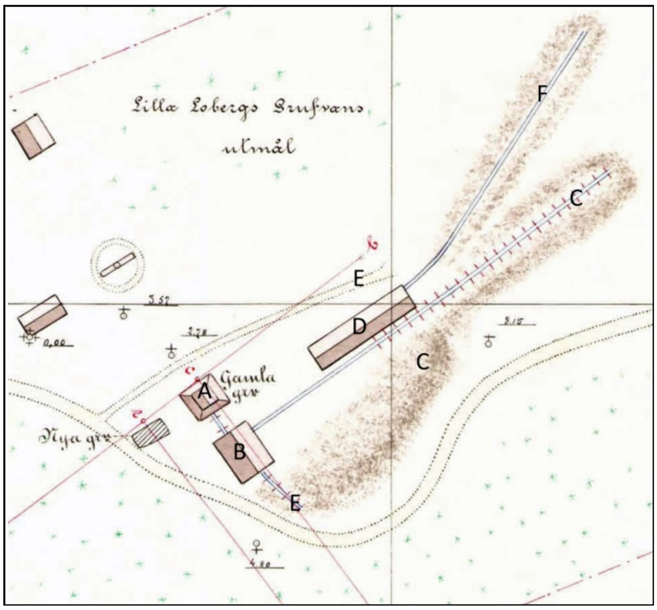

Figure 12: Lilla Lobergsgruvan, zinc-mine, Säter, Sweden. Shaft (A), switch (B), mining waste rock (C, F), sorting (D) and loading (E).

Technologies used for extraction of EMOI from waste always have a strong influence on the mining waste properties, but is particularly strong when it comes to deposits that also contain sulfide minerals where the different technical methods used for separation of ore from waste will interact with secondary natural processes (such as weathering and erosion) that have significant impact on the post processing long term status of the mining waste.

When technology was at the hammer and chisel stage and hand picking was the main method of separation of ore from waste, only pieces of ore that where easily visible and possible to hold by hand where recovered.

Disseminated ore was difficult to treat by hand and impregnations could often not be recovered at all. Disseminated sulfides, to large extent, ended up on the waste piles. Introduction of stamps in combination with panning and washing tables enabled gravimetrical separation also of smaller mineral fragments. Spirals and cyclones made the processing even more efficient and when hydrometallurgical processes such as flotation were introduced it was more the energy consumption and the ability to liberate the individual grains of minerals that would limit the recovery.

In some areas, the introduction of new technologies inspired re-processing of mining waste, in some cases more than once, due to gradual introduction of new technologies.

A successful gravitational process can collect a reasonable portion of the sulfide minerals to the concentrate product whereas it was not until hydro-chemical processes such as flotation was introduced that fine and extreme fines could be effectively treated. Refractory minerals are still difficult and may require chemical leaching processes.

Waste rock produced during the modern mining era is often as carefully as possible separated while ore grade material is subject to complex and advanced processes that often result in a concentrate product and tailings.

In summary, early mining of sulfide minerals focused on very high-grade deposits and could only recover pieces that were possible to see and handle by hand. Low grade or disseminated material often ended up on the waste dumps. Later, processing has become gradually more efficient, but early tailings deposits can have surprisingly high contents of EMOIs.

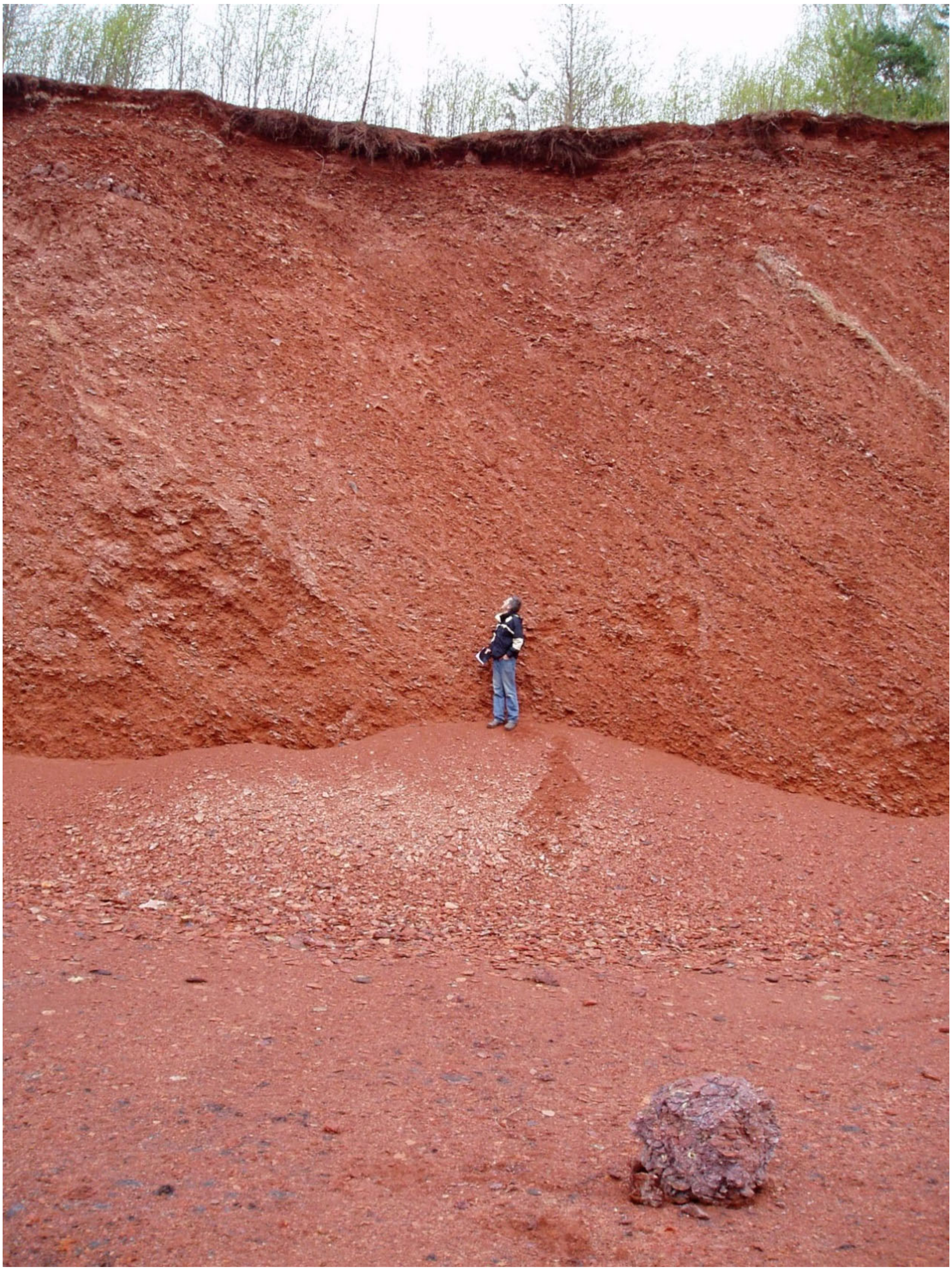

Figure 13: Section through an alum shale ash pile at Latorp, Örebro, Sweden. Note stratification and size segregation in scree/debris. Photo: Inger Johansson.

3.2. History and properties of a waste rock deposit

Although the geology and mineralogy of a mineral deposit is unique in detail, there will always be some fundamental similarities with other deposits. Similarly, technical solutions occur in a limited number of combinations and are often possible to identify, estimate and/or recognise.

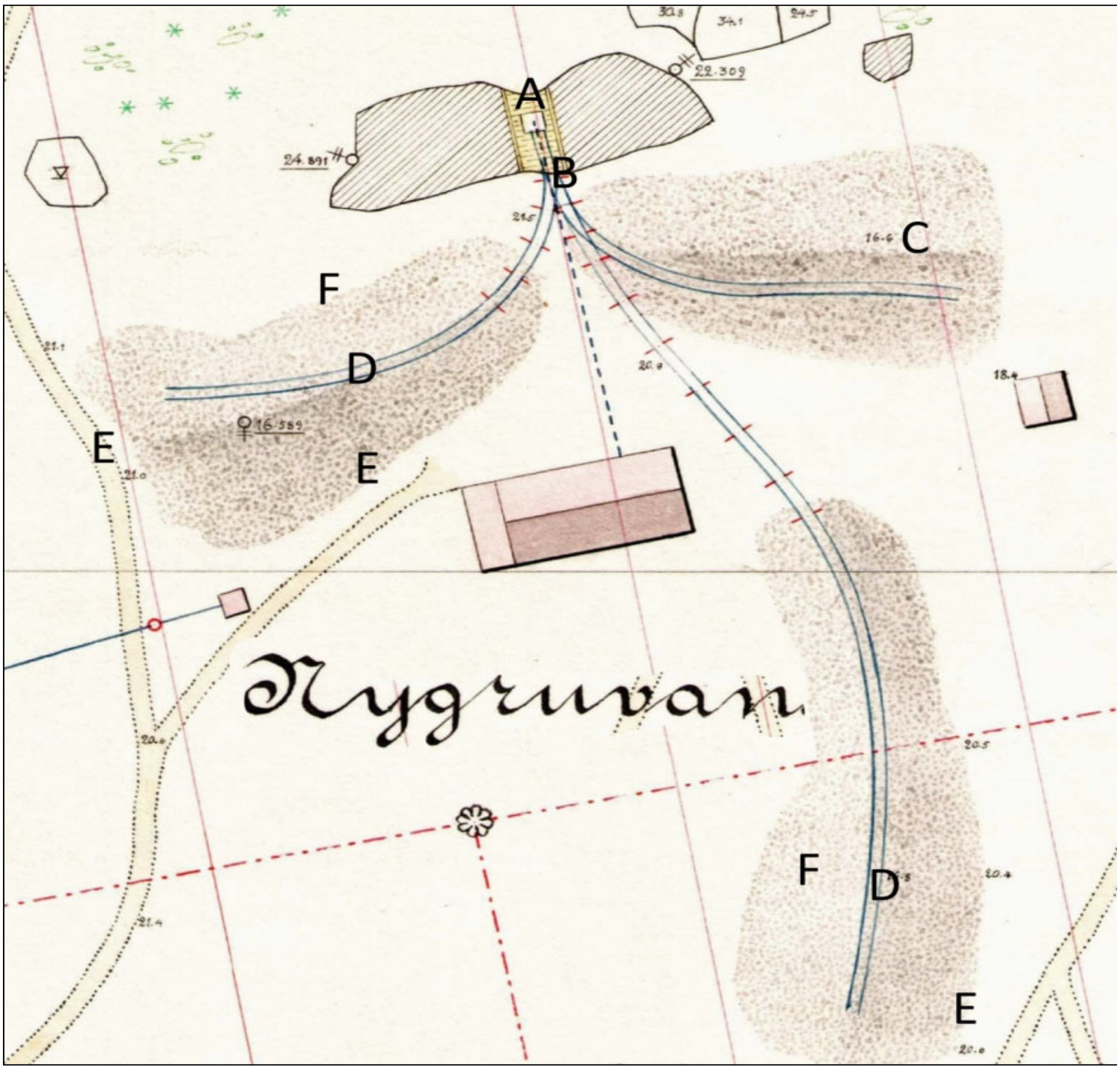

Figure 14: Nygruvan, Mariebergsfältet, Nyköping, Sweden. Shaft (A), switch (B), mining waste dumps (C, F), outdoor sorting (D) and stockpile/loading (E).

It is a lot easier to collect a representative sample, if it is possible to understand the flow of material at the mining site.

In the following, maps, photos and text will give some examples of how the material flow at different mines in the Bergslagen area was organised.

In all types of hard rock mining, it begins with the separation of pieces of rock from the solid bedrock in the mine.

As an example, follow a piece of rock along one of the many possible pathways from the wall of an underground mine to the waste rock pile, during the early semi-mechanized period between 1875 and 1940.

A blast that separates the piece from the wall of the mine will be the first disturbance to the natural relation between individual particles.

Figure 15: Långgruvan, Norberg, Sweden. Headframes with bridges, switch and sorting stations. Note dumping by hand at waste pile in the right back.

The blast will carry the particles out from the wall and they will collide and tumble while in the air and then settle on the floor in the drift.

Due to gravity, density and shape the pieces are separated and sorted; large dense boulders close to the blast, finer and denser particles will fall between larger particles while lighter finer particles will form dust and settle on top of the blast and further away.

Varieties of this natural sorting process will occur time after time during the flow of material from the rock face until each piece of rock has settled on the waste rock pile. Man and technology will intervene and disturb the natural sorting at various stages in the flow.

Degree of material mixing and segregation can vary significantly between different blasts and the daily workflow. Having said that, it is often surprisingly obvious that pieces on a specific part of the waste rock dump still have a relationship to each other and it is sometimes even possible to relate a specific part of a waste rock dump to a specific mining room. Reason for this is how the ore and the waste rock were handled in batches, wagons or lots.

Once at the surface, a quick inspection of the pieces on the top of the wagon decide the future faith; waste, sorting or crude ore. At mines with an enrichment plant, disseminated ore and pieces with half-grains go to crushing and further processing.

Crude ore is stockpiled or directly loaded for transport. Pure waste rock goes to the waste rock pile using wheel barrows or wagons where the waste rock is discarded by tipping from high bridges or footbridges.

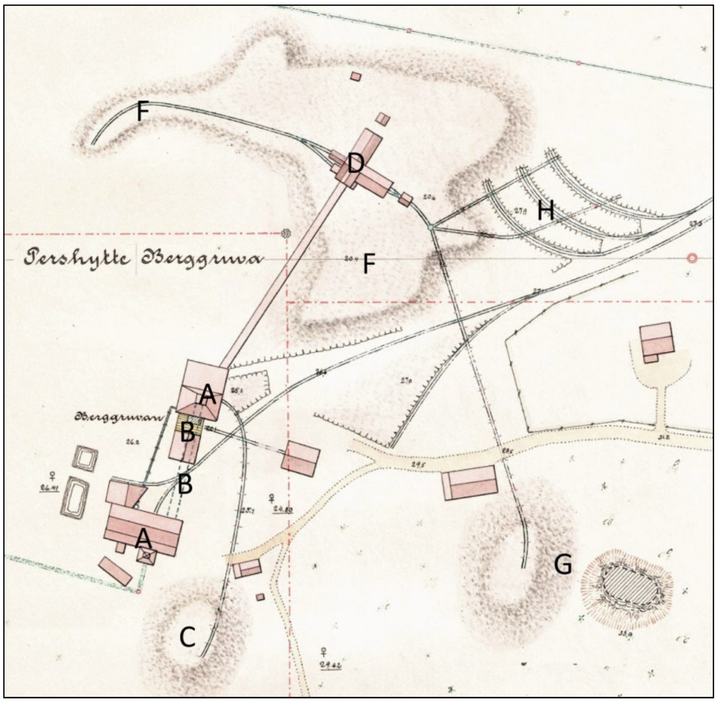

Figure 16: Pershytte Berggruva. Shafts (A), switches (B), waste rock piles (C, F), sorting (D), backfill (G) and loading docks (H).

As has already been mentioned, each mine and its precise layout is different, but have similar technologies and solutions.

Compare the images in figures in the surrounding pages. Points to notice are: shaft (A), switch where wagons are diverted in different directions (B); mining waste (C), sorting (D), stockpiles/direct loading (E) and waste rock dump (F), mining waste backfill (G) and loading docks (H).

On each of these points/cross roads, the relation between the individual particles may change. The unloading of the wagon induces a very strong segregation of the different fractions and densities of the individual rock pieces as the load tumbles down the slope.

A good example is seen in the lower right corner of Figure 15 where larger pieces tend to gather at the base of the pile while finer particles fall in between larger particles and dominate the fractions closer to the top of the waste rock pile.

Figure 17: Stripa gruva. Lindesberg, Sweden. Very steep mining waste rock pile generated by conveyor belt.

During the 1950s transport of waste rock to the pile via conveyor belts was introduced. A conveyor belt can be tilted at high angles and create very steep and high mining waste piles where pieces are effectively sorted to size, shape and density while the material tumbles to the base of the pile (Figure 17).

In a modern mine the rock can also be transported to surface by truck via a ramp. Transportation time and the potentially bumpy road to surface enable extensive sorting/segregation of the material during transport.

Dumping by truck from the top of the waste pile is like dumping from a wheel barrow or wagon, except for a more flexible localisation and sizing of each load. Dumping by truck on a flat surface creates a humpy morphology (Figure 19) where individual loads in the first series of dumps do not mix and transportation segregation is essentially maintained.

Figure 18: Lovisagruvan, Lindesberg, Sweden. Low ore grade stockpile. Individual truckloads are visible.

Figure 19: Lovisagruvan, Lindesberg, Sweden. Mining waste rock piles on a flat surface. Individual truck loads are visible.

Some degree of segregation of fractions will always occur and regardless of means of transportation or the size of the lot that is dumped, once the rocks are falling on the top or on the slopes of the waste rock pile, pieces with different density, size and shape will end up in different parts of the waste pile. Larger pieces will end up at the base of the pile while finer and/or denser particles will stay closer to the centre of the pile.

3.3. History and properties of tailings

Tailings are waste deposits of sand or finer fractions, i.e. material that is dominated by material with a diameter less than about 2-3 mm.

Tailings from the period before the introduction of flotation (about 1905-1910), are mostly residues from gravity extraction of EMOI:s by varieties of panning, shaking tables and spirals etc.

The EMOI bearing material was crushed by hammers or in stamps and then more or less milled. Milling in ancient times was by hand or horse driven flat mills (not very different from flour mills). Later the EMOI was separated from the mill flour by use of jigs or sluices where water separated the low-density particles from the heavier particles. Later, and in parallel use, more advanced/efficient methods were introduced that more precisely utilised the differences in density/particle size. A variety of shaking tables, spirals and sluices were developed.

The most widely used method for separation of EMOI:s from waste are variations of froth flotation. Enormous volumes of tailings have been produced with this method and it has mostly been used for separation of sulfide minerals although the method has other applications as well. The method originates from a series of patents from about 1860 and late 1880s but came into wider industrial use during the period 1900-1910.

Figure 20: Dylta Bruk, Örebro, Sweden. Medium – fine grained dry tailings pile after hand washing/extraction of pyrite (ca -1880).

Figure 21: Water saturated very fine-grained tailings (slime) in a depression west of Dylta Bruk, Örebro, Sweden.

Figure 22: Partly revegetated tailings from gravity separation and re-processing using flotation. Tailings have been deposited in a lake without proper walls. Yxsjöberg tungsten mine, Kopparberg, Sweden.

In a froth flotation operation, the mill feed material is reduced in grain size by crushing in stamps and/or milling in rotary mills with steel balls, steel rods or in modern operations, through autogenous milling. The purpose of the milling is to separate the EMOI minerals from the waste minerals. It is a fine balance to mill no more than necessary (to avoid unnecessary energy consumption), to find the ideal liberation-size before the material enters the hydro-metallurgical process where the skill of the operator and the chemical recipe determines the degree of recovery and what is left in the waste tailings.

When the waste material leaves the plant there will be variations in grain-size and composition that reflect the daily combination of primary mill feed properties and the performance of the enrichment process.

Figure 23: Large dry tailing within walls of waste rock. Stråssa magnetite-hematite mine, Lindesberg, Sweden. Note the recycling of material for production of aggregates in the northern part of the tailing facility.

Tailings as such can be dewatered and deposited as a dry tailing, as a paste or a wet tailing and the tailing can be transported to the site of deposition by wagon, in a mobile tank or pumped as a slurry in pipes, chutes or open ditches etc. Deposition can be on land, in lakes and in the sea. Deposition on land is often over the edge of a nearby escarpment, in a natural low, an abandoned mine or in a constructed dam.

Fine grained materials such as tailings can be subject to significant erosion during and after deposition and is subject to ordinary sedimentary geological processes just like any fine-grained material.

Figure 24: Tailings deposited as a slurry in a walled tailings dam. Note mineral segregation of material from south to north. Stripa iron mine, Lindesberg, Sweden.

Therefore, tailings transported or deposited in water, can easily segregate in different fractions and will react to erosion as any natural material with the same fractionation.

Coarser and/or relatively dense particles are thus found close to the deposition point while smaller and lighter particles travel longer distances before they settle. When tailings are exposed in a beach-like situation, black sands with heavy minerals will be enriched through washing. If allowed to dry, and if vegetation is sparse, winds will move, particularly lighter or flaky, mineral particles and sort the surface materials. In addition to mechanical sorting, oxidation, leaching, decomposition of primary minerals, transportation and re-deposition of particles and elements and formation of secondary minerals will occur as the water table and the state of oxidation varies.

Overall, the homogeneity, or rather, the lack of homogeneity, in a tailings deposit will be, at any point in time, the current sum of primary depositional conditions overprinted by secondary sedimentary processes and/or chemical redistribution of the minerals and the elements in question.

Figure 25: Depositional stratification in tailings in contact with the partly demolished tailings dam-wall at the Stråssa abandoned iron mine, Sweden.

However, tailings have one advantage (when it comes to prerequisites for sampling) compared to waste rock in that tailings have a relatively uniform grain size distribution. On the other hand, tailings deposits can be very large, deep and have a complex 3D-historical/industrial sedimentary layering which is difficult to map and sample without heavy equipment. Another advantage is that the tailings consists of depleted ore. No concentration process has a hundred percent recovery which means that there will always be relatively representative element indications of the ore preserved in the tailings. This is not necessarily the case for waste rock.

Figure 26: Vegetated inner walled tailings dam and outer, non-walled, flotation and magnetic/gravity separation tailings. Variations in colour most likely due to different oxidation states and mineral segregation. Bäckegruvan, Riddarhyttan, Sweden.

Figure 27: Small excavation in a gravitational Zn-Pb-tailings from ca 1877-1881. Mårsätter, Zinkgruvan, Askersund, Sweden. Details in Figure 28. Photo: Inger Johansson.

Figure 28: Detail of gravitational Zn-Pb-tailings from ca 1877-1881. Note primary stratification and extensive oxidation. Mårsätter, Zinkgruvan, Askersund, Sweden. Photo: Mattias Bäckström.

4. Prerequisites for sampling

4.1. Sampling for quantitative analysis.

In order to collect samples that determine the numerical value of X in a **T**arget **P**opulation (TP) through quantitative analysis (QNA), the TP must be defined.

4.1.1. Target population

TP is often described from the objectives of the study based on a question or a problem. Once the objectives are known, and in an ideal world, the target population (TP = a part of or the entire volume of waste rock or tailings) must be firmly defined by its physical boundaries and the set of units, elements or parameters a representative physical sample is intended to draw conclusions about.

Ex: What is the average content of X (ppm/%) in the mining waste pile Y?

The scale/size of the TP must be considered and if the problem/question contains any kind of relativeness, the dimensions must be set large enough to enable the identification of background. In order to define the TP, one must also have some basic understanding of the material in order to determine the media to sample and to be able to formulate a sampling strategy (which will be further discussed in chapter 5).

In order to make a specific sample representative for the TP, the entire TP must be available for fair sampling, i.e. every portion of the TP/material shall have an equal chance of being sampled.

It should be possible to collect samples without a systematic bias and it should be possible to use procedures and sampling equipment that minimize sample variation and prevent segregation.

Once the TP fulfils all the above, the sampling-chain itself must be planned to make sure there are set requirements/descriptions for field sampling methods and equipment, fixed procedures for sample preparation, sample characterization, laboratory sub-sampling and analytical procedure including instructions and definitions of sample size/mass, fractions, sample containers, labelling, documentation and logistics.

In an ideal world, if all (or as many as possible) of the above has been considered, the prerequisites for a fair sampling can be studied.

4.1.2. Sampling of waste rock for quantitative analysis (QNA) – a reality check

Anyone that have visited an area with waste rock or tailings realize how difficult, not to say impossible it is to properly sample an area with mining waste for the purpose of quantitatively determine and report the numerical value of X for the mining waste.

Some of the most common sources of sampling error are any, or a combination of, or all of:

- Mineral and elemental distribution in the volume is not random, nor is the uneven distribution known well enough beforehand, to plan sampling so that for instance stratification and segregation can be considered when samples are taken.
- Elemental distribution between fractions is not known or cannot be easily predicted.
- Vegetation might be un-even and thus hinder fair sampling. Vegetation may vary due to a combination of: age of mining waste, waste is eco toxic or has bio-favourable mineralogy or there might be variations in the influx of leaf and humus particles which influence the access to micro nutrients and the access to water etc.
- Particle size may vary vertically and laterally; up and down scree slopes, distance from the primary source, or because of different age/technology or degree of weathering, erosion etc.
- Huge variations in particle surface to volume ratio.

A common conclusion after attempting to sample mining waste for quantitative analysis is that it is more or less impossible since the sample seldom represent a single distribution or population and since all samples have been affected by different primary and secondary processes which all have influenced the distribution of the element of interest.

Based on experience from mining waste sampling campaigns it has been concluded that sampling will always be affected by large and unknown variabilities in the sampling media and that will affect the sampling method and may hinder the chances to collect a fair sample. Bearing that in mind, it is now possible to move on to study the prerequisites for fair sampling of tailings.

4.1.2. Sampling of <u>tailings</u> for quantitative analysis (QNA) – a reality check

Even though tailings have a more restricted and uniform size fraction and possibly also chemical composition compared to waste rock, segregation, changes in primary ore feed, changes in enrichment process, oxidation of primary sulfides and so on, make the tailings suffer from the same sampling problems as the waste rock. It is, however, likely that a sample from a tailings deposit due to mixing during the process will be more representative for a larger surrounding volume compared to the waste rock, even though the actual volume the sample is representative for is unknown at the time of sampling.

4.2. Sampling theory for qualitative to semi quantitative analysis (QLASQAN) - a practical approach to solve an "impossible" task

Since it was concluded that sampling for quantitative analysis is more or less impossible, the potential sampling for qualitative analysis must now be discussed.

4.2.1. Background

Semi because it is likely that the numbers from QNA sampling and analysis, despite all the parameters that make it impossible to sample still mean something more than just being a positive indication of presence of something.

There are many protocols/suggestions/attempts to collect representative samples of waste rock and tailings. Most methods have been developed for the purpose of determining the potential for Acid Rock Drainage (ARD) (Lapakko, 2002; MEND Project, 1991; Smith mfl, 2000; Smith, 2006). They all present approaches that require extensive fieldwork and often focus on analysing a fixed fraction after mechanically having screened/sieved the material. The described methods may very well work for the intended purpose but will not be practical when it comes to sampling highly variable waste rock dumps or dumps that in part are covered with vegetation or don't have the desired grain size distribution.

So far a sampling method that is universally applicable has not been found and it is also certain that there is none and maybe, it will never be possible to formulate a generally applicable rule that specifies: what specific number of samples per mass of material are to be sampled, how many samples per hectare, per m^2 or m^3, or any other given dimension.

Bearing this in mind, the approach is based on the observation and idea that there is no rule of thumb because of high variability due to history, influence from primary and secondary processes, mineralogy, geology, the physical properties of the sites and not the least, the objectives of the sampling campaign.

Sampling must be individually tailored to fit the knowledge about the site and the objectives of the sampling campaign.

We must be content with the fact that the resulting numbers will be merely indicative compared to statistical measures like, for instance, the true average or the true median.

To summarise, the sampling is impossible, but what if we still want to, or must sample, how can we do what is not possible? How many samples, pieces, mass of sample etc are enough to get an understanding?

This is difficult to answer because of all reasons listed previously, but there might still be ways to estimate when enough samples have been collected.

In qualitative analysis it is not uncommon that a sampling continues until new samples do not change the general conclusion. This is an approach that has been adopted when it is impossible to reach a quantitatively satisfactory answer.

Qualitative sampling is often used in behavioural science, psychology and anthropogenical surveys. Typical objectives are to determine what political party has the highest support or get an indication on how the opinion is leaning in an upcoming referendum. Note that as we all, know, in these situations you can not get an exact answer, but it is often possible to reach a relatively strong indication.

Mining, chemistry and exploration are normally not satisfied with this level of uncertainty, but in the choice between using <u>extensive</u> resources and to spend a <u>lot of time</u> sampling for quantitatively acceptable results that can be evaluated with classical statistics (the result will still not be the true statistical average), the option to start with a qualitative investigation and get an indication early with small resources (at least compared with the quantitative approach), it might still be an acceptable choice.

Based on the limited, but empirical experience, it is concluded that in most cases, the qualitative approach has better chances to deliver a reliable answer than the quantitative approach which will never become satisfactory from a classical statistics point of view.

5. Preparing your sampling strategy

This chapter formulates and describes important parameters for the preparation of a sampling strategy with an ambition level suitable for regional or local detail (i.e. a sampling campaign that includes several mines in a mine-field/a mining district or several mine waste deposits originating from a single mine).

Regardless of the purpose of the sampling campaign, the general and rough work order is:

Define purpose of the sampling campaign → Planning → Sampling → Site characterisation/documentation → Sample characterisation/documentation → Prepare samples for analysis → Chemical analysis → Data compilation → Data interpretation → Evaluation

The key to avoid a garbage out-situation is careful preparations and once the campaign has, started, don't change any parameters or procedures half way through. If changes are needed, it is in most cases better to re-start the campaign from the beginning.

5.1. Strategy for sampling of waste rock

Formulation of the sampling strategy is dependent on the purpose of the sampling campaign.

In the following it is briefly discussed two examples that in different ways illustrate how different purposes may induce different considerations and influence the sampling strategy. Sampling aiming to

1) locate environmentally hazardous hot-spots or pathfinders/trace amounts for exploration purposes
2) economically viable concentrations of EMOI in waste

In both cases, the need for a set confidence interval (± x % accepted) will heavily affect the sampling density and the resolution of the results.

5.1.1. Sampling campaign aiming to locate environmentally hazardous hot-spots or locate pathfinders/trace amounts for exploration purposes

Hot spot identification has two angles, one is the desire to know the total concentration of an EMOI in the area in general, and in individual parts of the area, i.e. individual mining waste objects. The second and an almost as important parameter are the speciation and distribution of the host-mineral species in relation to other elements and minerals. In the environmental application, the motivation is identification of combinations that can improve or aggravate environmental risks and in the exploration application, the paragenesis can give important clues to ore-forming processes.

Example: A mining waste area that contains iron sulfides with dispersed chalcopyrite, sphalerite and carbonate minerals. There is in theory enough carbonates to entirely buffer the system, but since the carbonates only occur in 75 % of the waste piles, 25 % of the piles are acid producing and are thus potentially an environmental hazardous hot spot.

Sampling of the area need to separate individual piles and determine not only the chemistry but also the species and proportions between mineral species that may act as sources for formation of acidity or contain buffering minerals.

Element of interest and the critical levels for determining the environmental risk in combination with the detection limit of the available analysis method, may of course also affect the sample size and the sampling density.

But if the question is somewhat more detailed asking for EMOI in a set range or abundance of an EMOI that occur in significantly lower grades or is known to have a "nuggety" appearance, the "Enough samples" becomes more difficult to answer.

5.1.2. Sampling campaign aiming at locating economically viable concentrations of high-grade content of EMOI in waste

If the campaign is designed to locate and estimate the content of an EMOI in the mining waste the value of the EMOI determines whether viable mean grades measured in ppm, % or tens of % in order to be viable.

If the element needs to be in the tens of percent range to be at all interesting, the element will most likely be very abundant and even a coarse sampling grid/small samples will easily confirm the occurrence. However easy it will be to confirm occurrence, the task to deliver an answer that define tonnages and an average grade within a set confidence interval is a totally different thing.

Example: Iron ore prices vary with time and analysts predict a dramatic increase in the price for magnetite ore low in sulfur. The exploration company "FerroWaste" claim a huge area with millions of tons of iron-ore mining waste. Is it economically viable to extract the iron left in the waste?

Sampling has two objectives 1) Locate large tonnages and Fe-content and 2) locate areas with sulfur contamination and grade.

The first objective may be achieved with a relatively low number of samples, but the second objective is similar to the objectives in example one, i.e. the need to locate and identify hot spots that in the iron ore case might spoil the project, even if it shows to contain even so large volumes and high grades of iron. Objective 2 will determine the sample density and objective 1 regarding grade will be overestimated whilst facts for determining the tonnage will rest on a robust and detailed investigation.

5.2. Strategy for sampling of tailings

As will be described in more detail in chapter 7, sampling of waste rock can often be based on individual piles in the mining area and the boundaries are often practically determined to coincide with piles or parts of piles, such as pile-slopes or areas with obviously different material.

When it comes to tailings, one is often dealing with a large, to the naked eye, essentially homogenous area that does not have practical/easily distinguishable different properties.

This means that, such an area requires a reversal from "object distributed" to "grid-based distribution" of the sampling points and the critical question is what spacing should the samples be collected at in a grid-based sampling of a tailings deposit? The number is not precise and will be further discussed in the next chapter, but whatever number is chosen, the grid-sample distance in an object is roughly equal to the square root of the area divided by no of samples, i.e. 15.

This gives, for an area of ex. 30 000 m^2, an area of 30 000/15 = 2 000 m^2 per sample and a sample distance of about square root $\sqrt{(Area/15)}$ which is about 45 meters between each sample.

5.3. Suggested method based on cumulative moving average (CMA) value and saturation.

Our answer above was 15. This number is, although it may seem unscientific enough, a compromise between the costs for sampling and, based on empirical evidence from earlier investigations, an estimated absolute confidence error of about 25-50 % from the true average. 25 % is commonly used as a requirement for pre-feasibility studies.

Of course, anyone can use the number 30 rather than 15 to lower the confidence interval and based on unique knowledge about their area and the sample media, but it has been found that a number between 15 and 30, in most situations gives a satisfactory and cost-effective answer to most of the questions.

Different elements behave differently and have different distribution patterns, some elements are more "nuggety" than others (i.e. compare your expectation for distribution of gold versus a rock-forming element like silica).

The suggestion is that, in principle, the number of samples (be it waste rock or tailings) should be optimised to reach saturation, i.e. the point when adding new results from additional new samples does not change the general conclusion about the average.

To find the point of saturation, a study of the cumulative moving average (CMA) value of the EMOI through a series of samples from the same object (same population) will indicate when saturation has been satisfactorily reached.

In practical work, the method can be applied in such a way that samples are selected a few at a time, and then they are dispatched to the lab a few samples at a time and the cumulative moving average is studied. If saturation or a desired confidence interval has not been reached, more samples are collected and added to the dataset.

Let us demonstrate why 15 samples is a good compromise:

Three examples below show grade in individual samples (orange circles) and cumulative moving average (CMA; blue circles). The waste rock samples studied in the examples are all from the Bergslagen area and exemplify quite different and complex geological environments. Bastnäs and Håkansboda mining areas are illustrated in Figures 29 and 30 while Ljusnarsbergsfältet is illustrated in Figure 31. An example from a large tailings management facility is presented in Figure 32.

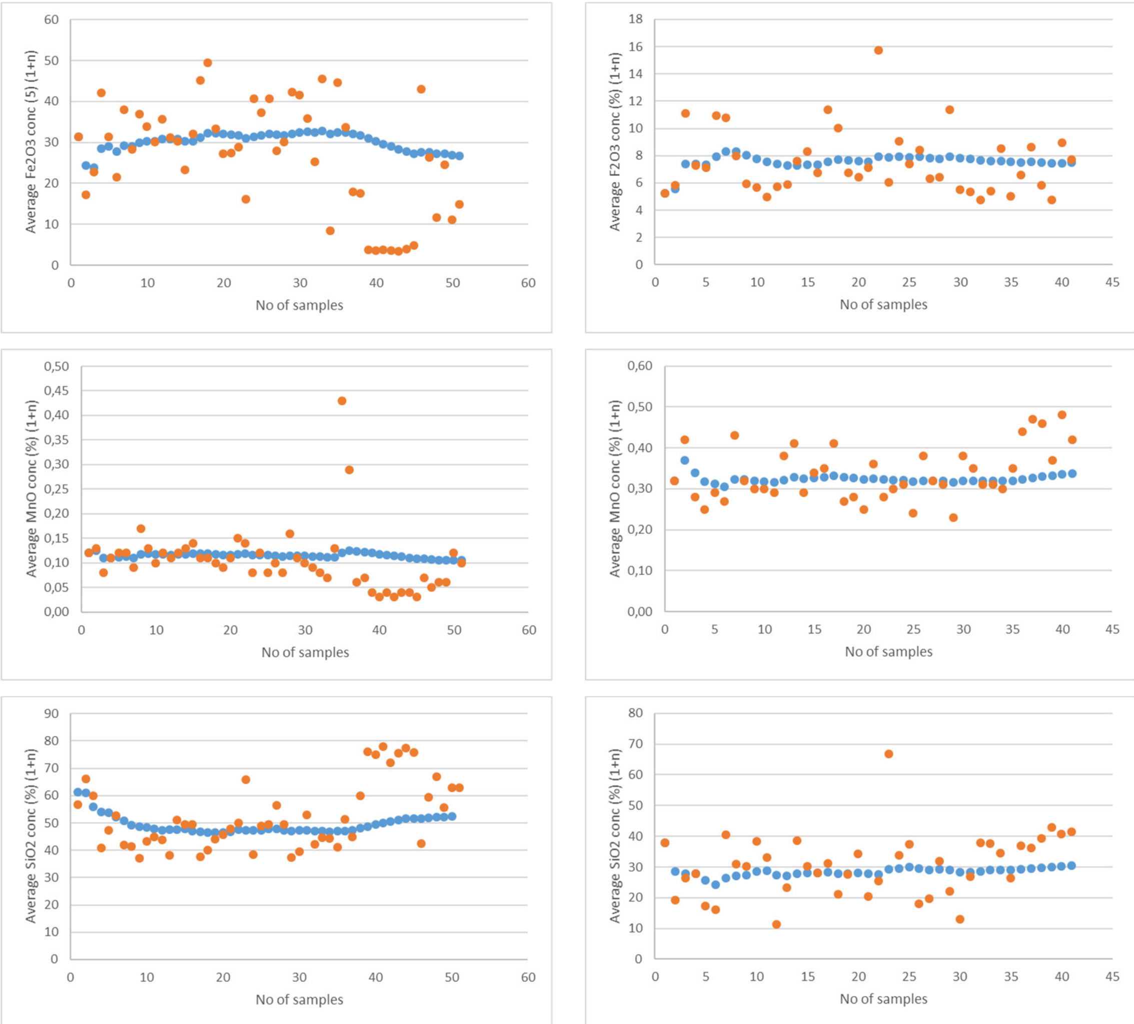

Figure 29: Cumulative moving average (CMA) concentrations (%) for Fe_2O_3, MnO and SiO_2. Average concentrations are calculated using increasing number of samples (from 1+n until all samples have been included). First column presents data from Bastnäs mining area (n 51) and the second column presents data from the Håkansboda mining site (n 41). CMA in blue and individual samples in orange.

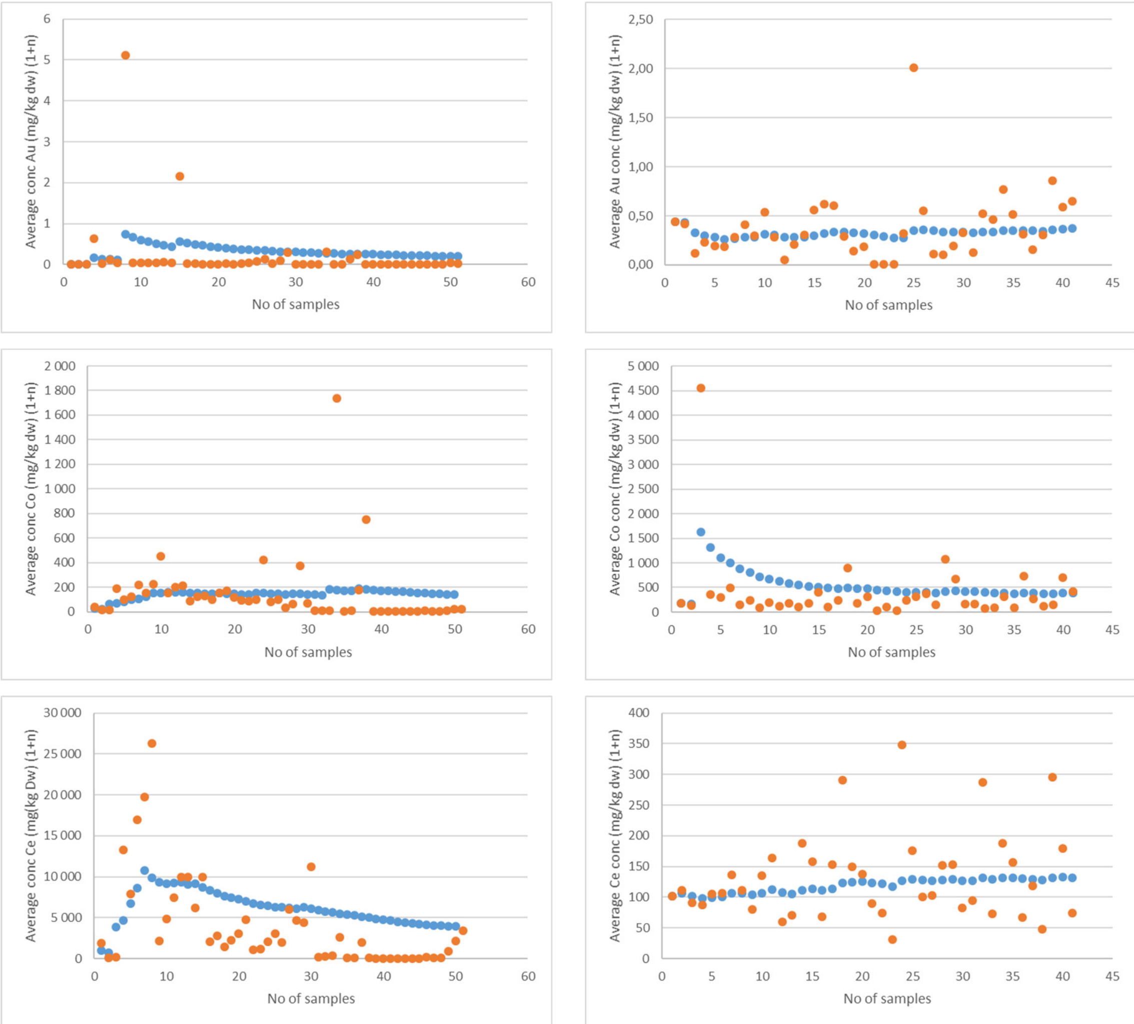

Figure 30: Cumulative moving average concentrations (mg/kg dw) for gold, cobalt and cerium. Average concentrations are calculated using increasing number of samples (from 1+n until all samples have been included). First column presents data from Bastnäs mining area (n 51) and the second column presents data from the Håkansboda mining site (n 41). CMA in blue and individual samples in orange.

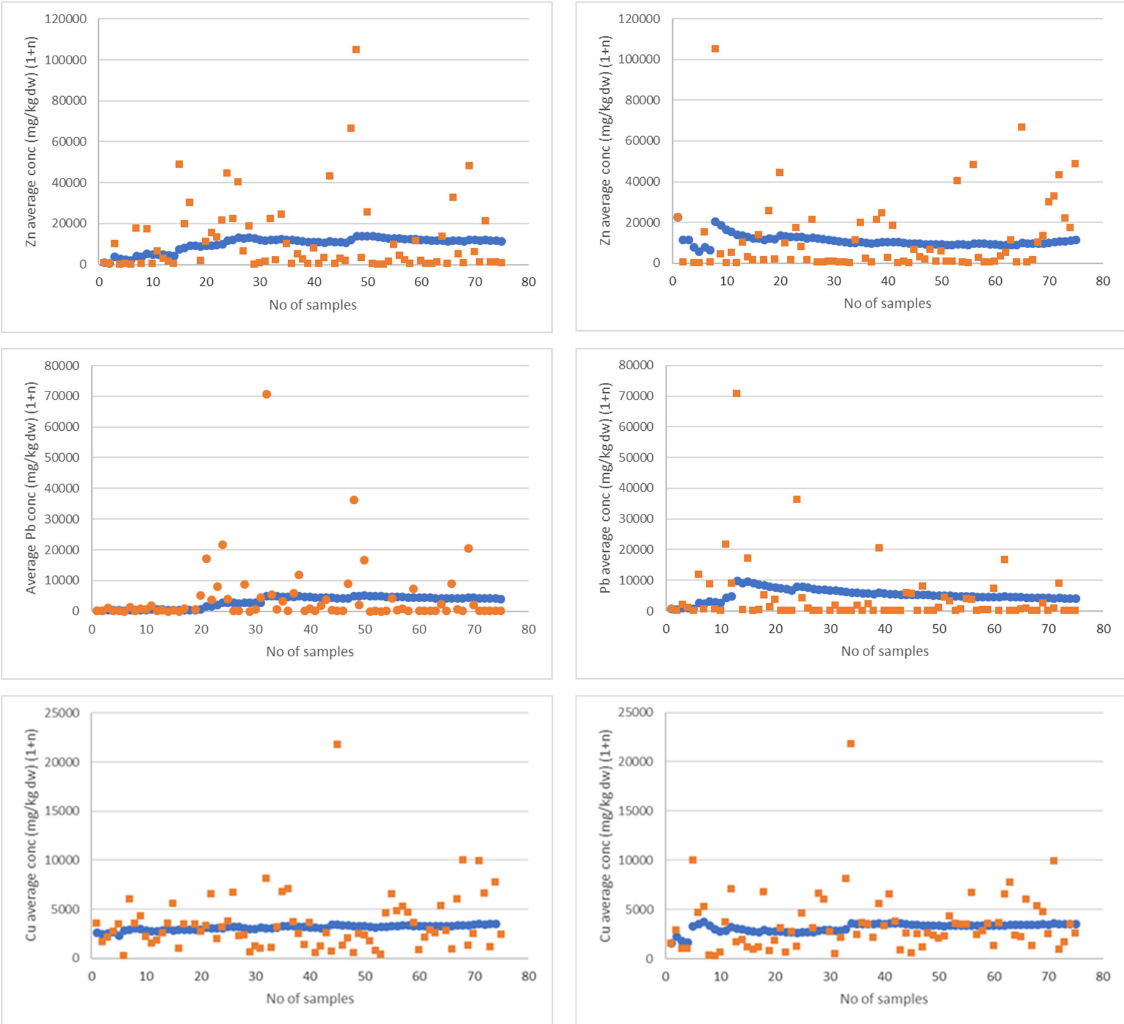

Figure 31: Cumulative moving average concentrations (mg/kg dw) for zinc, lead and copper at Ljusnarsbergsfältet, Kopparberg, Sweden. Average concentrations are calculated using increasing number of samples (from 1+n until all samples have been included). First column is based on the order the samples were collected while the second column is based on a randomised sample set. Calculated average (n 74) concentrations for zinc, lead and copper are 11 400, 4 050 and 3 500 mg/kg dw, respectively. CMA in blue and individual samples in orange.

As can be seen, the cumulative moving average often produces saturation with a lot less than 15 samples.

The same principle can be applied to the pieces of rock that make up a composite sample and we propose (described in more detail in chapter 6) that a composite sample should consist of as many pieces of rock as is practically possible and that, if the objectives require high confidence in the result, take more samples whilst in the field and send in to the laboratory after hand as results are evaluated.

If the objective is to identify regions, mining areas or individual mining waste rock piles within mining areas the sampling program and the strategy must be adopted for the larger area and the number of samples scaled up accordingly.

>15 pieces of rock in each composite >15 composites in each object >15 deposits in each mining area >15 mining areas in each region etc.

For tailings it is clear that in order to get a handle on the average concentrations fewer samples are required compared to sampling waste rock (Figure 32). Assuming a deviation of 25 % from the true average concentrations only 7-10 samples for zinc and 3-4 samples for lead are needed. Accepting a deviation of 50 % requires even lower number of samples (3 for zinc and 2 for lead).

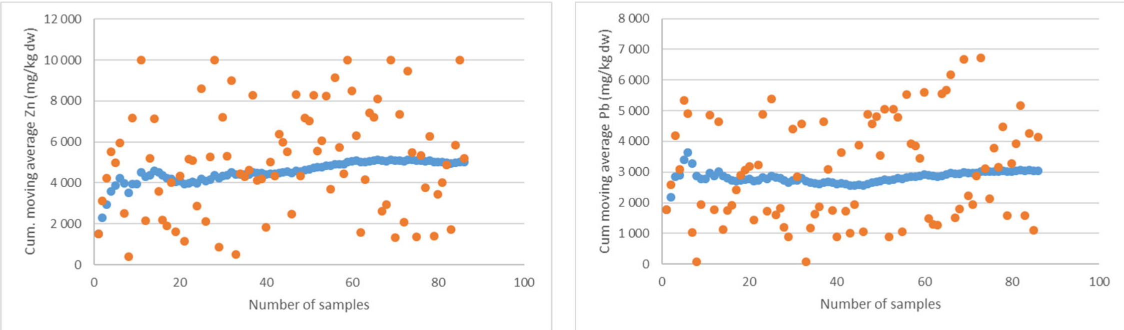

Figure 32: Cumulative moving average concentrations (mg/kg dw) for zinc and lead from a large tailings management facility (TMF) in Sweden. Average concentrations are calculated using increasing number of samples (from 1+n until all samples have been included). Calculated average (n 86) concentrations for zinc and lead 5 030 and 3 040 mg/kg dw, respectively. CMA in blue and individual samples in orange.

It must, however, be noted that every site is unique and adaptation to the sample strategy may be necessary as site specific information is obtained.

6. How to sample – <u>waste rock</u>

6.1. Documentation and sampling for QSQ <u>waste rock</u>

It is recommended that observations are made using either a field note book, or a field computer or a smartphone. By using a cloud solution already in the field, there is a big advantage since all observations are securely stored even if the notebook is dropped etc. But at the same time, functionality is dependent on cell phone coverage and enough battery capacity.

Coordinates can be recorded using GPS-apps on the smartphone and/or handheld GPS. It is recommended to use handheld GPS and crosscheck with the smartphone when entering the data. In addition, always carry note books and make additional notes on printed map sheets over the area.

At the end of the day crosscheck the digital database and transfer the data to GIS software.

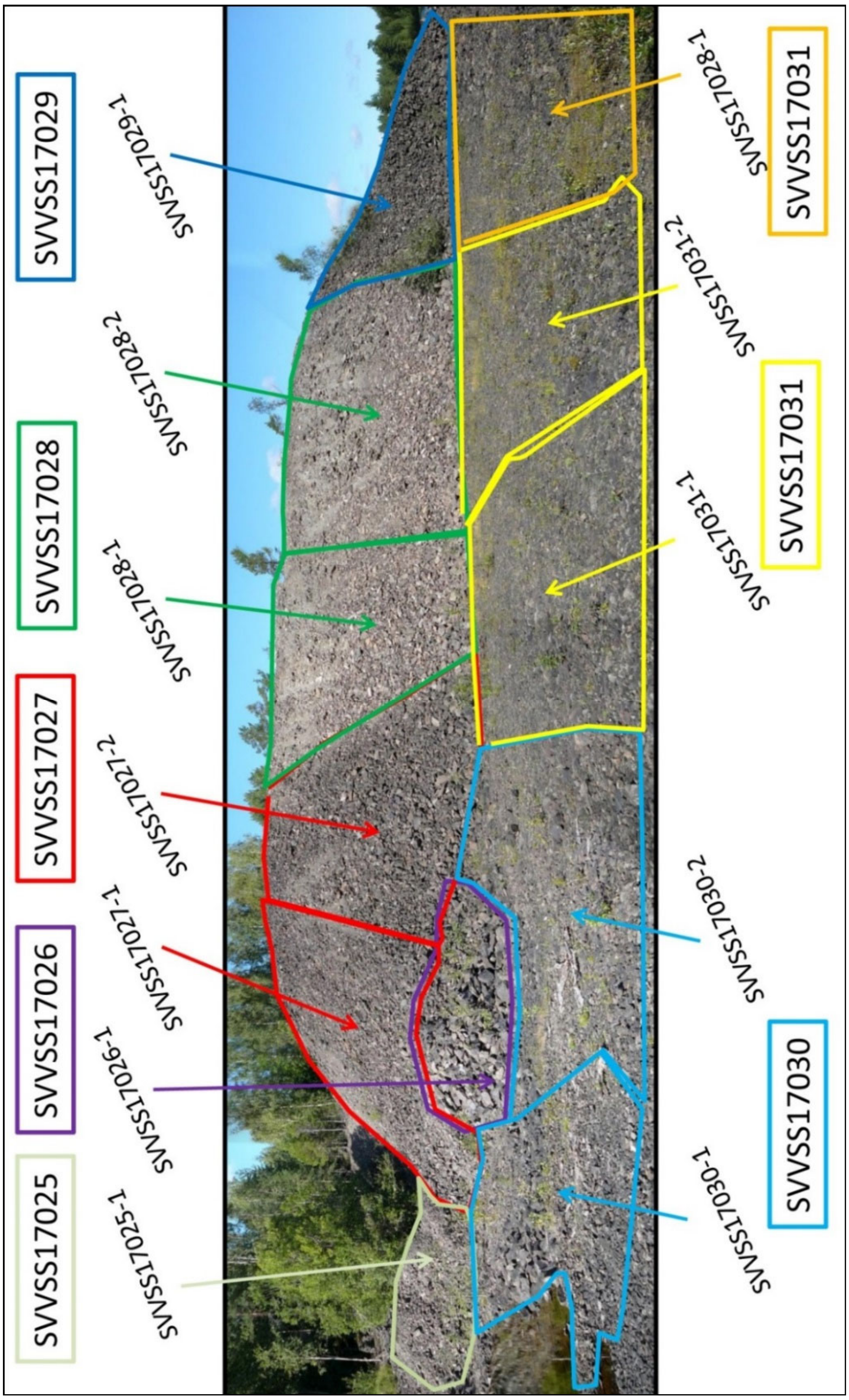

Figure 33: Example; detailed sampling campaign. Splitting of a large waste dump into objects for sampling (SVVSS17025, SVVSS17031 etc.) and samples (SVVSS17026-1,-2 etc).

6.2. Procedure

Sampling is always combined with mapping/registration of the surface features of the object regardless of the type of object (waste rock, tailings, stockpiles or slags).

6.2.1. Preparations

Plan the sampling in the office. Print maps of the area in question and note preliminary location of any possible objects of interest.

Standard safety and field practice should be followed according to your organisations field-work manuals. It is suggested that you work in pairs and that you leave a note and a map in the office with your planned working area and that someone is instructed to keep track of your movements and your safe return to home.

Figure 34: Chipping on partially vegetated waste rock pile.

Make sure mobile phones are charged and always bring extra battery power packs for recharging in the field.

Always remember that old mining areas are dangerous and that there are many hazards to avoid, use common sense and don't overestimate your own capability, beware of stability issues around old shafts, mine openings and the risk of landslides on steep mining waste slopes.

6.2.2. On arrival to the object of interest

Compare reality with the map, spend some time to reconnoitre the area, and try to grasp the industrial logic of the place. What is the general layout of the area, how was the material flow from the mine to waste and to product? Make a rough plan of where your objects are in relation to each other, note their size and create a mental plan of how you are going to divide large objects.

6.2.3. Sampling

Start by making your mental map of the boundaries for your sample (see example in Figure 33).

Figure 35: Maximum one piece per primary rock and size should be kept under 75 mm diameter to enable as many pieces as possible per object in the sample bag.

Figure 36: Collection of samples in object ID-marked bag.

Once you have decided the boundaries of the sample object, bring out sample bags and mark them with sample ID.

Put on personal safety equipment and chip pieces from the rocks in the pile. Collect only one chip per primary piece into the sample bag. Try to be as objective as possible when selecting where to chip and what to put in the sample bag, avoid favouring by size, colour, accessibility, shiny or dull minerals whilst at the same time don't omit shiny pieces.

Remember that dense material generally will stay close to the point of disposal and that large pieces will tumble down to the base of the slope. Samples should be collected evenly to include the various segregations that may have occurred as a result of disposal.

If the pile is vegetated, carefully lift the vegetation, and sample what is possible to sample without doing an excavation.

When it is obvious that there has been mineral hunting/fossicking, beware that the distribution has been biased and compensate if possible.

Normally the chips will be around 20-75 mm in size and a minimum of 25-50 pieces per sample is recommended and a total weight of about 2-5 kg. If you notice that your sample bag is getting full before you have covered the intended area, split the area and create one more object or make a larger composite of your two sample bags.

Another option is to bring a sturdy bucket into the field and rapidly collect as many pieces as you can until the bucket is full. Make sure to cover your entire sub object using one or more buckets. After sampling chose a suitable spot where you can chip smaller pieces from each piece and collect in your sample bag. This technique will remove some of the sampling bias as less time will be spent looking for interesting pieces.

Take photos, label photos the same as the object ID. Mark the object on the map and make notes about every sampling point and every sample, don't expect to remember. Make the notes in a notebook before it is entered into the digital documentation. Laziness will sooner or later force you to return to that far away located object, -just like when you had to return for that waste rock sample, it will rain this time too.

6.2.4. Digital documentation in the field

Once the object has been defined and the sample has been collected it is time to record the properties of the object and the sample. One part is done directly in the field standing at the object and one part of the documentation is done indoors with access to good light and reference literature etc. The purpose of the field documentation is to collect information about the material at the object and the properties of the object that influence the representativeness of the sample, i.e. the basis for an estimation of how fair the sample is to the volume it is supposed to represent. Field documentation includes parameters such as; object size, shape, form, variations in particle size, the degree of exposure and vegetation etc.

A digital data form should be designed according to the objectives of the sampling campaign. The example in Table 1 shows a data form from a sampling campaign in Bergslagen where the purpose was to identify occurrences of previously undetected (not analysed for) elements that could either serve as pathfinders or in themselves be of economic interest or be potentially hazardous. Because of this wide scope, additional information was also collected about the vegetation on the mining waste with the secondary purpose to investigate if distribution and degree of vegetation reflect age and/or chemistry in the waste piles. When designing the sampling project, adopt the form to the needs, local conditions and the chosen objectives.

6.2.4.1. About the database

In Table 1 an example form and questions for digital recording in the field is listed. This form is the first of two "Google forms" that are being used to digitally record observations. The form in Table 1 is used for the field documentation and in the next chapter the form for indoor documentation of mineralogy and petrology to be done simultaneously with the sample preparation and dispatching of samples to the laboratory is described.

In order to ensure uniform reporting several parameters are recorded as numerical results that are easy to export and evaluate together with chemical results in a GIS software.

Table 1. In the field mapped/recorded parameters in the "Objects database"

V1	ID No Combine: 1) abbreviated area code 2) Initials of the observer 3) Year+Number *In the example: LOSS17001; LO=Lovisa area, SS= Stefan Sädbom, 17001 is the first sample 2017*
V2	Date *2017-01-31*
V3	GPS Time Hour, minute, second: Ex: *13:45:58* *Helps to synchronise photographs with locations*
V4	Observer Name chosen from drop down list
V5	Place *The objects recognised name and numbers. If no name, a relative map reference point is used. Ex: Storgruvan 1 or North East of Hedtorpet 1*
V6	GPS Northing
V7	GPS Easting
V8	SubObservation? *Sometimes objects are too big to be recorded in one post. A* ***Yes*** *in this field indicates that the object is part of a larger object and that this recording is representative for a "subarea".* *Ex: Y/N*
V9	What is observed? Chosen from drop down list. *Examples:* *Mining waste rock dump* *Stockpile*

	Tailings *Mixed soil and waste rock* *Other*
V10	Comment on V9 Important information. *Ex: "Waste rock used in dam wall for tailings impoundment" or "Probably ore-stockpile"*
V11	Dimensions (m) Length/width/depth (height). *Ex: 14*8*5 (m^3)*
V12	Proportion of this object that is made of rocks? Answer in a 0-10 scale representing 0 % rocks to 100 % rocks *Mixture of mining waste with natural materials (soil, earth etc) is common.*
V13	Average "Grain size". Tick boxes labelled: sand, gravel, stones (5-10 cm), stones (10-20 cm), stones (20-30 cm), stones (30-60 cm), boulders (50-100 cm).
V14	Comments on grain size *Describe if there is fractionation of sizes and the degree of variation (max/min size)*
V15	Amount of the rocks that show surface weathering on the visible surface. Chose along a scale from 0 to 10 0 = No visible weathering to 10 = 100 % of all rocks show surface weathering. *An estimation of the percentage of the exposed surface that is easily, visibly surface weathered. Normally a sulfide deposit would have a high percentage while a silicate/oxide deposit of magnetite would normally have low percentage.*
V16	Distinction of "rusty" weathering. Choose from a scale: 0 to 10 where 0 = None to 10 = 100% all rocks display a rusty surface. *Of the weathered rocks. Estimate what proportion is the result of sulfide weathering with yellow/reddish secondary Fe-minerals?*
V17	Distinction of manganese weathering. Choose from a scale 0 to 10 where 0 = None to 10 = 100 % all rocks display a black sooty surface from secondary manganese minerals. *Of the weathered rocks. Estimate what proportion is the result of manganese weathering with black, sooty secondary Mn-minerals?*
V18	Distinction of copper weathering. Choose from a scale 0 to 10 where 0 = None to 10 = 100 % all rocks display surface from secondary copper minerals. *Of the weathered rocks. Estimate what proportion is the result of copper weathering with blue/green secondary Cu-minerals?*

V19	Distinction of zinc/lead weathering. Choose from a scale 0 to 10 where 0 = None to 10 = 100 % all rocks display a white surface from secondary Zn or Pb minerals. *Of the weathered rocks. Estimate what proportion is the result of Zn/Pb weathering with powdery secondary Zn and/or Pb minerals?*
V20	Presence of carbonate rocks? Choose from a scale 0 to 10 where 0 = No carbonates observed to 10 = 100 % all pieces of rocks contain carbonates.
	VEGETATION *Expand/replace the following questions with what is relevant to your sampling campaign.*
V21	Vegetative cover? Choose from a scale 0 to 10 where 0 = Object is 100 % exposed and 10 = 100 % the entire object is covered by vegetation. *Vegetation = grass, moss etc. Lichen on surface of rock pieces is not recorded as vegetation.*
V22	Is vegetation damaged by ARD or high metal content in water etc? Choose from a scale 0 to 10 where *0 = Vegetation seems "fresh" with no obvious damages, no discoloration, no unusual small or thin threes.* *10 = 100 % No vegetation on the object due to damages from ARD or high metal content as judged from surrounding vegetation which show gradual recovery changes away from object.*
V23	Estimated number of low (<30 cm) plants. *Count the number of different species below 30 cm height on the object. Moss is included, but lichen on rocks are excluded.*
V24	Estimate the percentage of the <30 cm plants that are: Mosses, grass, berries, herbs etc.
V25	Berries are dominated by: Choose from a scale 0 to 10 where 0 = Lingonberries are dominating and 10 = Blueberries are dominating *Choose plants that have different pH preferences.*
V26	Trees and bushes are dominated by: Choose from a scale 0 to 10 where 0 = Broad leaf dominate and 10 = Conifers dominate *Choose plants that have different pH preferences.*
V27	Conifers are dominated by: Choose from a scale 0 to 10 where

	0 = Picea Abies dominate and 10 = Pinus Sylvestris dominate *Choose plants that have different pH preferences.*
V28	Broad Leaf is dominated by:
	Choose from a scale 0 to 10 where 0 = Non pendula/pubescens species dominate and 10 = Betula pendula/pubescens species dominate *Choose plants that have different pH preferences.*
V29	Particular plants? *Some indicator plants/herbs/grasses/orchids may indicate chemistry or high levels of specific metals. Ex: Some orchids prefer limestone and Viscaria Alpina indicate high levels of copper in Northern Europe Alpine Region (Figure 36).*
V30	Other notable observations regarding vegetation?
V31	List of photos and notes.

Figure 37: Plants of *Viscaria Alpina* on waste rock pile at Stollberg, Ludvika, Sweden. The plant is indicative of copper enrichment in soil.

6.2.5. Digital documentation indoors and dispatching of samples.

At the end of the day, all samples are brought to the field office. Collected samples are checked against maps, field notes and digital field records to identify errors while memory is still fresh. Photos of all objects are downloaded to a secure server, external hard drive and a laptop computer. Make regular back-ups of your photos and digital records!

In the field office, clear a large flat surface, spread out the entire sample from each bag and work through one sample at a time, make notes and record observations digitally.

In Table 2 below the parameters recorded are listed. As for the in the field digital record of parameters, adopt the form according to the objectives and make sure the relevant parameters for the campaign are recorded.

Documentation is typically best performed indoors with good light, hand lens, mineral determination kit, reference books etc.

Start the work by grouping the pieces according to paragenesis/type, i.e. group pieces with similar properties. Normally there will be a maximum of 3-7 groups from a normal sized sample.

Depending on the objectives, the type/group could be on content of EMOI-minerals, rock types, degree of weathering, or another parameter that is relevant for the project. In the example below, particular interest are base metal and iron sulfides and alloys as well as some marker horizons with marble and skarn. Every object is also classified according to the historical subdivision of the mineral deposits in the area.

Table 2: Example of parameters per sample to digitally record.

P	Petrology classification
P1	ID No Combine: 1) abbreviated area code 2) Initials of the observer 3) Year+Number 4) Sample no per this object As an example: LOSS17005-1; LO=*Lovisa area, SS= Stefan Sädbom* *17005 is the fifth object 2017 and 1 is the first sample bag from this object.*
P2	Area *Minefield name or area*
P3	Is this sample representative for the entire object or is it a subsample? Choose: Representative or subsample.
P4	This is a subsample, it is representative for: xxxx *Answer what part it is representative for. Ex: This sample is from northern ½ of object. Preferably, also draw a*

	simple sketch in the notebook.
P5	Other subsamples from this object are: Answer ex: *LOSS17005-2 and 3*
P6	Is the sample still in separate bags? *Note to help in the "housekeeping". When deciding if, and to, create a composite, we recommend samples are kept separated as long as possible to enable identification of differences.*
	THE SAMPLE
P7	Weight in grams
P8	Number of pieces in the bag *Number of individual pieces collected should be in the range 30-50 pieces.*
P9	General additional information about the sample
	THE CONTENT *The content is described according to three principles,* *1) A count (n) of relevant types of rock in the sample. Later recalculated to be expressed as a percentage per rocktype and should thus summarizes to 100 % of all collected pieces in the sample. Classification example below is from the Bergslagen area.* *2) Classical mineralogical/petrological description* *3) Mandatory classification into predefined "ore types"/ "styles of mineralisation" or petrology. Example from Bergslagen area.*
P10a	No of pieces that are dominated by rock of presumed extrusive volcanic origin (i.e. meta-; volcanoclastic, lava, tuff etc.)
P10b	No of pieces that are dominated by rock of hydrothermally altered rock of unknown origin.
P10c	No of pieces that are dominated by rock of presumed sedimentary origin (i.e. meta-argillite, meta-sandstone etc.)
P10d	No of pieces that are dominated by rock of acid intrusive origin (i.e. granite, pegmatite, aplite etc.)
P10e	No of pieces that are dominated by mafic rocks (diabase, dolerite, amphibolite, etc.)
P10f	No of pieces that are dominated by carbonate rocks (marble, calcitic marble, dolomitic marble, limestone etc.)
P10g	No of pieces that are dominated by skarn.
P10h	No of pieces that are dominated by iron ore (i.e. >50 % iron minerals)
P10i	No of pieces that are dominated by sulfide ore (i.e. >50 % sulfide)
P10j	No of pieces that are dominated by other rock.
P10k	Comments and what is "other" in S10j
P10l	Control question – sum of S10a-j, compare to answer on P8
M	Mineralogy in mineralised pieces. If relevant and if it is desired to plot relative mineralogical

	speciation; sub-questions can record number of pieces that are magnetite/hematite, pyrrhotite/pyrite, chalcopyrite, sphalerite, galena etc.
M1	Ex. Of pieces dominated by iron minerals, how many are dominated by magnetite?
M2	Ex. Of pieces dominated by iron minerals, how many are dominated by hematite?
M3	Alternative Ex. Of all iron-oxide minerals. Choose from a scale where 0 = 0 % Magnetite, 100 % Hematite – 10 = 0 % Hematite, 100 % Magnetite.
CM	Classical Mineralogical/petrological description, free text.
CM1	Classical mineralogical/petrological description with focus on EMOI-mineralisation. *EX: Banded iron oxide mineralization where the magnetite component dominates completely. In the quartz-banded parts, there are also subordinate hematite in the form of leafy crystals and single grains. Dense to fine-grained, light grey metasomatically converted vulcanite contains mm-large sparse red garnet crystals (almandine). The micaceous parts carry abundant hematite. The skarn consists of actinolite / hornblende in layers about one centimetre thick in contact with quartzite hematitic rock and biotitic layers. The skarn breaks along hornblende surfaces and gives a dark green impression. The entire rock package is intensively foliated sub-parallel to original banding. S (O) // S (1). The magnetite ore consists of 1) semi-compact fine grain ore and 2) quartz-banded ore. The quartz is grey (probably coloured of iron oxide inclusions). The quartz-banded type is somewhat coarser in grain size than the semi-compact type. Compare* LOP17001 *to* LOP17004.
CM2	Classification of mineralisation to pre-set types
CM2	Choose max three types that best describes the mineralisation in the sample: Ex: • Magnetite-quartz-banded iron mineralisation (BIF) • Hematite quartz stripe banded (BIF) • Quartz iron mineralisation (not banded) • Iron mineralisation, semi-massive to massive • Skarn- iron mineralisation, banded • Carbonate hosted iron mineralisation • Carbonate hosted, manganese-oxide-iron oxide mineralisation • Manganese rich (i.e. <2 % MnO) skarn iron mineralisation • Carbonate hosted, sulfide mineralisation • Disseminated sulfide in officalcite • Sulfide ore in skarn-carbonate matrix • Skarn hosted, sulfide mineralisation • Quartz hosted, sulfide mineralisation • Carbonates- dolomitic composition dominates • Carbonates- calcitic composition dominates • Carbonates- composition unknown • Quartz-pegmatite • Disseminated sulfide in iron oxide mineralisation • Disseminated magnetite in sulfide mineralisation Etc.
CM3	Comments

7. How to sample tailings

Tailings are normally different compared to waste rock in that the tailings have a more even grain size and occur in most cases within a defined/confined geographical area.

It is recommended that each sample should be a minimum of 5 kg and that the sample can be collected, depending on the scope of the campaign, by digging, or using a hand auger to a depth below surface erosion and visible oxidation.

7.1. Documentation and sampling for QSQ tailings

It is recommended that observations are made either by hand in a field note book, or on a field computer or a smartphone. By using a cloud solution already in the field, there is a big advantage since all observations are securely stored even if notebook is dropped etc.

Coordinates can be recorded via GPS-apps on the smartphone or handheld GPS. Recommended is handheld GPS and crosscheck the locations using the smartphone when entering the data. In addition, always carry note books and make additional notes on printed map sheets over the area. At the end of the day, the digital database is crosschecked, and the data is transferred to GIS software.

7.2. Procedure

Sampling is always combined with mapping/registration of the surface features of the object regardless of the type of object (waste rock, tailings, stockpiles or slags).

7.2.1. Preparations

Plan the sampling in the office. Print maps of the area in question and note preliminary location of any possible objects of interest.

Standard safety and field practice should be followed according to your organisations field-work manuals. It is suggested that you work in pairs and that you leave a note and a map in the office with your planned working area and that someone is instructed to keep track of your movements and your safe return to home.

Make sure mobile phones are charged and always bring extra battery power packs for recharging in the field.

Always remember that old mining areas are dangerous and that there are many hazards to avoid, use common sense and don't overestimate your own capability, beware of stability issues around old shafts, mine openings and the risk of landslides on steep mining waste slopes and old dam walls.

7.2.2. On arrival to the object of interest.

Compare reality with the map, spend some time to reconnoitre the area, and try to grasp the industrial logic of the place. What is the general layout of the area, how was the material flow from the mine to waste and to product? Make a rough plan of where your objects are in relation to each other, note their size and create a mental plan of how you are going to divide large objects.

7.2.3. Sampling

Start by making your mental map of the boundaries for your sample (see example in Figure 33).

Once the boundaries of the sample object have been decided, bring out sample bags and mark them with sample ID.

Tailings are by its nature more homogenous than waste rock since tailings are a result of crushing, milling and enrichment of a larger ore volume. Standard deviation in a sample set of tailing samples are thus lower compared to a sample set of waste rock. Segregation do, however, create some differences, since coarser particles are usually found close to the outlet of the tailings. Changes with depth in the pond or the TMF is also possible due to changes in the enrichment process or processing of different ore bodies during the time of operation. Depending on the sample equipment at hand different depths can be sampled. Samples should be collected evenly to include the various segregations that may have occurred as a result of disposal of the tailings. Divide the pond/TMF in equally sized sectors in order to sample the entire area. If only surface samples are being sampled sample several sub samples in each sector and compile them into one sample for each sector. Using hand augers it is possible to also sample deeper samples. Depending on the water level and the grain size distribution depth of around 5 m can be sampled. It is preferable to sample below the oxidised part of the horizon.

If the pond/TMF is vegetated, carefully lift the vegetation, and sample what is possible to sample.

A minimum of 5 subsamples per sector and a total weight of about 2-5 kg is recommended.

Take photos, label photos the same as your object ID. Mark the object on the map and make notes about every sampling point and every sample, don't expect to remember later. Make the notes in the notebook before entering it into the digital documentation. Laziness will sooner or later force you to return to that far away located object, -on a rainy day.

7.2.4. Digital documentation in the field

Once the object has been defined and the sample has been collected it is time to record the properties of the object and the sample. One part is done directly in the field standing at the object and one part of the documentation is done indoors with access to good light and reference literature etc. The purpose of the field documentation is to collect information about the material at the object and the properties of the object that influence the representativeness of your sample, i.e. the basis for an estimation of how fair your sample is to the volume it represents. Field documentation includes parameters such as; object size, shape, form, variations in particle size, degree of weathering, the degree of exposure and vegetation etc.

The digital data form should be designed according to the objectives of the sampling campaign. The example in Table 3 below shows a data form from a sampling campaign in Bergslagen where the purpose was to identify occurrences of previously undetected (not analysed for) elements that could either serve as pathfinders or in themselves be of economic interest or be potentially hazardous. Because of this wide scope, a lot of information about the vegetation on the mining waste was also collected with the secondary purpose to investigate if distribution and degree of vegetation reflect age and/or chemistry in the tailings. When the sampling project is designed, adopt the form to the project at hand, local conditions and your objectives.

7.2.4.1. About the database

In Table 1 an example form and questions for digital recording when sampling waste rock is listed. This form can with minor changes also be used for tailings. This form is the first of two "Google forms" that is being used to digitally record the observations, this form is used for the field documentation and in the next subchapter the form for indoors documentation of mineralogy and petrology to be done simultaneously with the sample preparation and dispatching of samples to the laboratory is described.

In order to ensure uniform reporting several parameters are recorded as numerical results that are easy to export and evaluate together with chemical results in a GIS package.

7.2.5. Digital documentation indoors and dispatching of samples.

At the end of the day, all samples are brought to the field office. The series of samples are checked against map, notebook and digital field records to identify errors while memory is still fresh. Photos of all objects are uploaded to a secure server, external hard drive and a laptop computer. Make regular back-ups of your photos and digital records!

In the field office spread out the entire sample from the bag on a large flat surface and work through one sample at a time, make notes and record the observations digitally.

In Table 2 the parameters recorded are listed. As for the field digital record of parameters, adopt the form to the specific project objectives and make sure the relevant parameters for the campaign are recorded.

The documentation typically is best performed indoors with good light, hand lens, mineral determination kit, reference books etc.

Note differences in colour, grain size distribution and type of visible oxidation (red-orange for iron and brown-black for manganese) between samples.

8. Summary and conclusions

In order to collect a fair sample from a mining waste deposit it is crucial to know how the waste has been generated, why it is deposited in different areas and how the handling of the waste has influenced its homogeneity and thus the prerequisite for collecting a fair sample.

In the report the reader is given a thorough background describing some of the technologies that have been used and have affected the formation of different mining waste types through history.

How sampling in different medias can be done is described and how impossible it is to sample mining waste. The concept of using cumulative moving average (CMA) to determine when enough samples have been collected to establish saturation is described and exemplified with series of analytical results from several mining waste sampling campaigns.

It is also suggested that several seemingly peripheral, parameters regarding the mining site (shape of the deposit, vegetation cover, vegetation type etc) are recorded in order to increase knowledge about the site. Specific approaches for sampling waste rock and tailings has been provided in detail. A step wise approach in analysing samples is recommended in order to obtain a valid result for larger sites. It has been shown that the minimum number of samples, in order to obtain a valid result with respect to the average for the sample set is around 15 samples for waste rock. Smaller sample sets (5-10 samples) are often enough for tailings. It is also suggested that prior to submitting the samples for chemical analysis all pieces in a sample is characterised with respect to paragenesis and mineralogy.

It is, however, important to remember that every mining site is unique and site-specific information is important in order to be able to revise the sampling strategy.

Sampling of mining waste is impossible, but it can still be done!

9. Acknowledgement

This work has been commissioned by the Swedish Geological Survey (SGU). Anders Hallberg and Helge Reginiussen at SGU are acknowledged for their patience and interesting discussions. Funding for several of the performed sampling campaigns have been provided by the MinPro foundation and the Knutsberg foundation and is gratefully acknowledged.

10. References

Bäckström, M. and Sädbom, S. (2008) Risk assessment of historical mine waste using chemical analysis and ocular mineral/rock classification. In: 9th International Congress for Applied Mineralogy, Australasian Institute of Mining and Metallurgy, Publication Series 8/2008: 85-90

Ekholm, D., Bäckström, M., Evenhamre, P., Holm, T. och Dahlström, H. (2008) Huvudstudie Ljusnarsbergsfältet – Huvudstudie avseende gruvavfall inom Ljusnarsbergsfältet, Ljusnarsbergs kommun. Undersökningar, riskbedömning, bedömning av saneringsbehov samt översiktlig åtgärdsutredning. Rapport 1553328 000, SWECO Environment AB, Örebro (127 sid + bilagor) (in Swedish)

Lapakko (2002). Metal Mine Rock and Waste Characterization Tools: An Overview. K. Lapakko, Minnesota Department of Natural Resources, US. April 2002 No. 67

MEND Project (1991) Sampling Strategy for the Rapid Screening of Mine-Waste Dumps on Abandoned Mine Lands.

Smith, K.S., Ramsey, C.A. and Hageman, P.L. (2000) Sampling Strategy for the Rapid Screening of Mine-Waste Dumps on Abandoned Mine Lands. Open-File Report 00-016, US Department of the Interior & US Geological Survey

Smith, K.S, Hageman, P.L., Ramsey, C.A., Wildeman, T.R. and RanSille, J.F. (2006) Reconnaissance sampling and characterization of mine-waste material. U.S. EPA Hard Rock Mining 2006 Conference, Tucson, Arizona, November 14-16, 2006

Appendix A

Waste rock mapping Ljusnarsbergsfältet, Kopparberg, Sweden

The mining area is generally vegetated, but the vegetation is in many sub areas disturbed by the mining or is recovering from the last period of mining that ceased in 1975.

In order to map the impact of mining and how well the environment had healed around 110 ha of the mining area was mapped during the summer 2007.

Mapping was performed in five steps:

1) Reconnaissance and choice of parameters.
2) Identification of objects and mapping of parameters.
3) Sampling of waste rock piles.
4) Sample description.
5) Chemical analysis.

Reconnaissance and choice of parameters

During the reconnaissance several parameters were studied (for instance surface shapes, flora, waste rock geometry, colour of lichens, size distribution, weathering, mineralogy, history etc) before the final choice of parameters were decided. In Table A.1 the parameters noted during mapping are presented. Examples of parameter properties are shown in Figures 3.1-3.18.

Tabell A.1. Mapping parameters and object descriptive parameters.

	Object ID
1	Surface shape. From 1 (natural shape) to 9 (entirely artificial).
2	Interpreted historical land use
3	Fraction waste rock at the object. 0 (0-10 % waste rock), 1 (10-20 % waste rock) etc
4	Waste rock weathering. From 0 (no weathering) to 9 (entirely weathered)
5	Fraction weathered waste rock. 0 (0-10 %), 1 (10-20 %) etc
6	Weathering type. 1 = primarily iron sulfide weathering (dominated by secondary iron and manganese minerals), 9 = secondary light primarily Zn and Pb carbonated, oxides and hydroxides
7	Waste rock average size. From 1 (coarse, boulders above 50 kg) to 9 (gravel, sand with minor gravel)
8	Proportion between carbonates and silicates in the waste rock. From 1 (only carbonates) to 9 (only silicates)
9	Vegetation. From 0 (bare, dead surface, only lichens) to 9 (ample lush vegetation). High or low species. Ground covered with vegetation.
10	Estimated number of low species
11	Dominating low species. 1 = lichens, 3 = moss, 6 = gras, 9 = herbs

	Object ID
12	Proportion between trees. From 1 (only deciduous forest) to 9 (only coniferous forest)
13	Proportion between coniferous trees. From 1 (only fir) to 9 (only spruce)
14	Proportion between deciduous trees. From 1 (only birch) to 9 (only aspen)
15	Proportion between lingonberry and blueberry. From 1 (only blueberries) to 9 (only lingonberries)

Object identification and mapping

The investigated area was divided into sub areas in the field based on observed parameters. Any sub area was defined when it had reasonable size and relatively uniform selected parameters (Table A.1). Sub division of areas can locally be very difficult, and decisions are sometimes based on one parameter only and sometimes on several parameters. The possibility to investigate has also partially been limited by natural and cultural considerations. Objects with vegetation cover have not been disturbed and the classification has in such cases been based on visible waste rock only.

Sampling and analysis of waste rock

Aim

The primary aim with sampling and chemical analysis of solid material (waste rock, other mining waste and soil) is to gain information about total concentrations of elements. Mineralogy was also determined by ocular inspection.

Surficial waste rock sampling

Out of the 237 identified objects from the reconnaissance 111 were determined to be waste rock objects suitable for sampling. Each waste rock object has been described using selected parameters where parameters 4 (degree of weathering), 5 (fraction of weathered waste rock), 6 (weathering type) and 8 (proportion carbonate/silicate) are affected by the mineralogical and petrological composition of the waste rock. 74 out of the 111 waste rock objects were sampled for mineralogical/petrological classification and chemical analysis.

Sampling was performed in order to be as representative as possible for all objects. However, it should be noted that sampling of waste rock piles with varying grain sizes and vegetation cover is extremely difficult.

Experiences from the mining industry are that calculated averages often correspond poorly with the concentrations obtained during actual recovery of the waste rock pile. One reason for the poor results is the “nugget effect”. One of the few ways to counteract the “nugget effect” are increased sample volume and mapping of the parameters governing the concentration distribution in the waste rock. It has not been possible to fully cover this in this project and the results are thus only indicative.

However, the results will still provide a reasonable picture about the mineralogical/petrological and chemical character of the different part of the Ljusnarsberg mine field.

Samples were taken from each object using a hammer. Rock chips were sampled from many different waste rock pieces (only one piece from each waste rock piece) until a total volume of approximately 5 liters was reached.

Collected samples were sorted and classified according to 11 parameters according to Table A.2.

Table A.2 Mineralogical/ petrological parameters.

17	Percentage of samples consisting of fine-grinding silicate rock, (more or less transformed metavolcanics (mainly fine-grained quartz, feldspar, mica)
18	Proportion of samples consisting of "micas" (biotite, muskovite, flogopite)
19	Percentage of samples consisting of granite, pegmatite, aplit material (quartz, feldspar, mica)
20	Percentage of samples consisting of carbonate minerals (calcite, dolomite).
21	Percentage of samples consisting of skarnminerals (pyroxen, diopside, hedenbergite, amphibols, tremolite, actinolite, garnet, vesuvian)
22	Proportion of samples consisting of magnetic "iron oxide ore" (magnetite)
23	Percentage of samples consisting of "sulfide ore" (pyrite, pyrrhotite, chalcopyrite, sphalerite, galena)
24	Percentage of sulfide that is copper-dominated = 0, zinc-dominated = 9
26	Percentage of sulfide that is lead-dominated = 0, lead-dominated = 9
27	Percentage of sulfide that is copper-dominated = 0, lead-dominated = 9
28	The proportion between iron sulfide s. 0 = pyrite dominates and 9 = pyrrhotite dominate.

Analysis

Sample preparation prior to analysis was performed by ALS Chemex. Waste rock samples were crushed until 70 % was finer than 2 mm and grinded until 85 % was finer than 75 µm. Chemical analysis was performed by ALS Scandinavia using their method M-2 (nitric acid dissolution).

Number of samples

In total 74 surficial waste rock samples were analysed.

Results

Waste rock mapping

In total 237 objects were identified within the mining site. Different objects and the different parameters are illustrated in Figures A.1-A.18.

	
Objects 7616, 7504, 7563, 7564	Objects 7612, 7613
Mining waste rock, no soil/gravel (9). Weathering varying between superficial – to semi penetrative (5), almost all surfaces show weathering (8), iron oxide weathering dominates (1), coarse particle size (2), no carbonates (9), vegetation (0), single leaf plants	7613: Waste rock pile. (9). Almost penetrative weathering (7). All surfaces weathered (9), iron oxide (9), medium-fine particle size (7), no carbonates (9), only lichens and a few pine plants. (2)

Figure A.1 and **A.2.** Example of grain size and weathering grade.

	
Object 7705	Object 7691
7705: Strong weathering (8), almost all surfaces weathered (8), iron oxide (1), Coarse particles (2)	7691: Strong weathering (7). Almost all surfaces weathered (8), iron oxide secondary zinc hydroxide (4).

Figure A.3 and A.4. Example of weathering grade.

	
Object 7691	Object 7570
7691: Weathering; medium (4), Most surfaces affected by weathering (8), iron oxide and zinc hydroxide (4), medium-sized particles(5), few low species (4), lichens and mosses (4), carbonate relatively common (4)).	7570: Weathering is deep (8). All material weathered (9), iron oxides and zinc hydroxide (3), particle size: average-fine (4), no vegetation and few lichens (1). Weathering so fast that some fresh material is exposed. Black crystals are spahlerite.

Figure A.5 and A.6. Example. Waste rock with and without carbonates.

	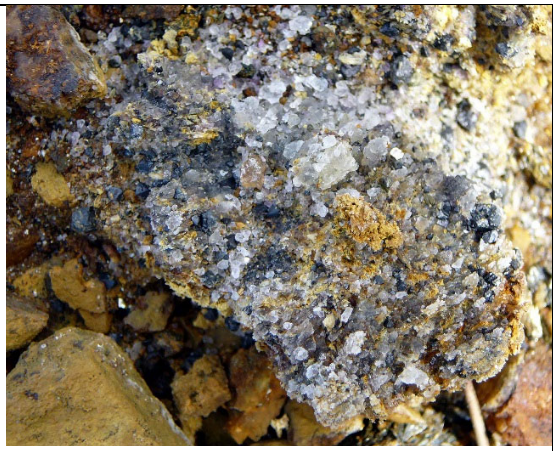
Object 7515	Object 7570
7515: Weathering totally penetrative (9), All surfaces are weathered (7), iron oxide and some zinc hydroxide (2), medium-grained particle size (3), low species (0), lichens and mosses (0), some pines, carbonate relatively commonly (4). Crystals of pyrite in iron oxide.	7570: Weathering almost entirely penetrative. (8). All surfaces are weathered (9), iron oxide and zinc hydroxide (3), Particle size average-fine (4), no vegetation except some lichens (1). Weathering so fast that some slow weathered minerals are exposed as “fresh”. Black crystals in image are sphalerite in fluorite matrix (CaF_2).

Figure A.7 and **A.8.** Waste rock with pyrite and fluorite.

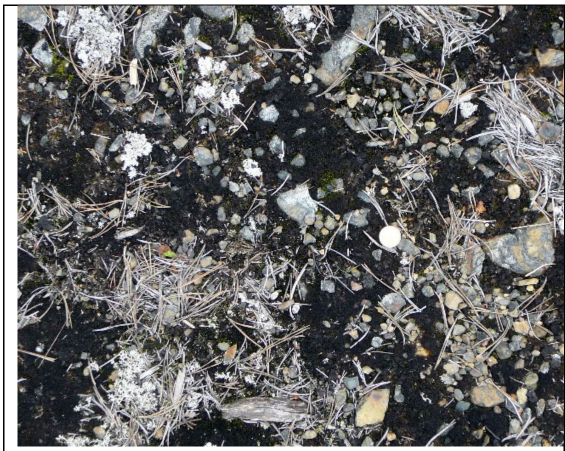	
Object 7703	Objects 7697, 7698
7703: Mining waste rock mixed with moraine (3), Weathering is mainly superficial (3), Almost all surfaces show signs of weathering (8), Iron oxides dominate (1), Medium coarse particles. (6), Low planst (3), Lichen and moss (3), Carbonate minerals are common. (1).	7698: Very little mining waste (1), Outcroping orezone with superficial weathering(1). Iron oxides dominate (1), mining waste particles are finegrained (8), some vegetation; lichens, moss, grass, some trees (4). Both leaves and conifers (5), pine dominate (8), birch (1). Barbecue place at 7697.

Figure A.9 and A.10. Example of vegetation.

	
Object 7691	Object 7651
7691: Semi penetrative weathering (4), almost all surfaces are weathered (8), iron oxides and zinc hydroxide (4), medium-sized mining waste rocks(5), Some low species (3), lichens, moss and grass (4), both leaves and coniferous trees , pine (9) and birch (1).	7651: Most mining waste, penetrative weathering. (7). Nearly all surfaces weathered (7), iron oxide dominate (1), particle size is medium-fine (4), fairly abundant vegetation (7), but only two low species (2), lichens and mosses (2) no grass. Mixed forest is dominated by pines (7) with birch (1), no lingonberries or blueberries (0).

Figure A.11 and A.12. Example of vegetation.

	
Object: between 7691 and 7700	Object: between 7691 and 7700
7691: Moraine with natural occurrence of "mineralized rock". (4), conifers (8), pine (9) and birch (1), low species (3), lichens, moss and grass (4).	7691: Detailed image of moraine with probably natural occurrence of "mineralized rock". (4), conifers (8), tall (9) and birch (1), low species (3), lichens, moss and grass (4).

Figure A.13 and **A.14.** Till mixed waste rock or till with natural presence of ore rock.

	
Object 7539	Object 7650
7539: Unknown material around old shaft, mining waste or moraine (na). Degree of weathering etc. unknown. Vegetation is lush (9), six low species (6), lichens, moss and grass (4). Mixed forest is dominated by pine (6), pine (6) but relatively abundant with leaves, birch (1) lingon- and blueberries (4).	7650: Almost completely overgrown mining waste rockpile (9). Particles are coarse – medium sized (3). Degree of weathering partially unknown, visible stones are superficially weathered (2) only part of the mining waste exposed, but weathered on the surface (2), iron oxide dominates visible material (1). Vegetation is lush (8), two low species (2), lichens, moss and some grass (3). Mixed forest is dominated by pine (6), pine and fir (5) and the leaf is dominated by birch (1). Blueberries (1).

Figure A.15 and **A.16.** Example of vegetation.

	
Object 7651	Object 7612
7561: Partially unknown material in piles. Visible parts mainly mining waste rock (9). Degree of weathering is partly unknown, visible parts above iron oxide (1) mainly superficial weathering (1) Vegetation is sparse (4) with two low species (2), lichens and mosses (2) fir dominate (7) coniferous forest with single birch trees (1), no berries (0).	7612: Mining waste rock (8) of fire setting origin with some mixing with moraine in the upper part. Large proportion of the rocks are weathered (9) relatively deeply (6) iron oxide (1). Particle size is medium-fine (6), no carbonates (9), Very sparse vegetation (1) lichens and mosses (1), no grass (1) only one pine tree (9), no berries (0).

Figure A.17 and **A.18.** Vegetation types.

The parameter "historical land use" resulted in five classes according to Table A.3.

Table A.3. The number of objects within the parameter historical land use.

Number	**Description**
5	Field or meadow. Today vegetated with young forest
9	Forest, few "islands" within the mining site, otherwise primarily at the border areas
52	Industrial use. Broad classification that include areas for mining and the industrial uses, roads, areas for storage and overburden waste piles.
60	Open pits. Visible open pits, partly water filled, completely water filled and covered (present in the historical maps) open pits.

Number	Description
111	Mining waste piles. In some cases, it is clear that waste rock piles have been relocated during overburden removal causing mixing of waste rock from several pits and overburden material.

If the results from all of the sampled objects are compiled the ”average” waste rock has the composition found in Table A.4.

Table A.4. Composition of the average waste rock at the Ljusnarsberg mining field.

		Average (%)
17	Percentage of samples consisting of fine-grained silicate rock, probably more or less altered metavolcanics (mainly fine-grained quartz, feldspar, mica)	14
18	Proportion of samples consisting of micas(biotite, muskovite, flogopit)	14
19	Percentage of samples consisting of granite, pegmatite and aplite (quartz, field patch, mica).	6
20	Percentage of samples consisting of carbonate minerals (calcite, dolomite)	4
21	Percentage of samples consisting of skarnminerals (pyroxene, diopside, hedenbergite, amphibol, tremolite, actinolite, garnet, vesuvian)	20
22	Proportion of samples consisting of magnetic "iron oxide ore" (magnetite).	12
23	Proportion of samples consisting of "sulfide ore" (pyrite, pyrrhotite, chalcopyrite, sphalerite, galena)	29
	SUM	100

The average waste rock pile (even though it only exists in theory) at the Ljusnarsberg mining field has the following properties:

Waste rock from the Ljusnarsberg mining field is medium coarse, shallow weathered rock with a surface weathering dominated by secondary iron oxyhydroxides. Rock types in the waste rock are dominated by different silicates and calcium magnesium silicates (primarily skarn) with low carbonate content. Approximately 60 % of the waste rock piles are covered by spruce and birch dominated mixed forest. The lower vegetation is sparse with only 2-3 low species, lichens-mosses-grass and often also blueberries.”

Analysis of waste rock

Total concentrations

In Table A.5 the statistical data for element concentrations in the waste rock is presented.

Table A.5. Statistical presentation of element concentrations in waste rock samples (n 74) (mg/kg dw).

	Min	Median	Average	Max
As	0.13	0.49	0.53	1.29
Cd	0.02	5.84	25.9	251
Co	1.10	10.2	23.2	481
Cr	0.98	3.11	3.76	28.1
Cu	245	2 640	3 500	21 800
Hg	0.04	0.13	0.18	0.83
Ni	0.29	0.86	1.23	12.0
Pb	6.92	479	4 050	70 800
V	0.62	2.13	2.82	18.3
Zn	41.3	2 850	11 400	105 000