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First geomorphic site in Scandinavia—current status

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Abstract

LKAB's mine site at Svappavaara, located circa 100 km north of the arctic circle, is currently producing iron ore from the Leveäniemi open pit mine. Extraction from the Leveäniemi open pit began in 2015 and the expected mine life is until 2035. The production volumes vary between 7-9 Mtons of ore and 6-9 Mtons of waste rock and dry screen waste per year. The total amount of waste rock and dry waste from the open pit and the screening plant to be deposited is circa 160 Mton for the life of mine. The current permitted waste rock storage area covers approximately 280 hectares and is surrounded by protected nature areas and reindeer migration routes.

In 2021 a conceptual geomorphic design was delivered at the Svappavaara. The phase 1 landform design outcome demonstrated it was possible to construct a fluvial, geomorphic-based landform within the permit boundary and at on maximum elevation that could integrate the existing deposit and accommodate the volume from the previous and the current mining operations at the Leveäniemi open pit. The design output was based on GeoFluv method which uses geomorphic principles to provide a long-term stable landform that would allow LKAB to meet their closure goals for the site.

The construction of the first geomorphic test site containing approximately 1.4 Mton of waste rock and a 4.3 hectares area was started in October 2021. The construction included moving the waste material from the operations with mine trucks and forming the designed landscape using bulldozers. The cover layer consisting of till, topsoil, seeds, and other organic materials were purposely excluded at this phase. In June 2022 the forming of the landscape was completed, and the site was left to settle for a year before applying the final cover layer.

In 2023 an adjacent reference site designed with a conventional bench and berm method according to LKAB´s current permit conditions will be constructed. This will include the cover layer, which will also be according to the permit. The establishment of the test site and reference site will enable for relevant comparison of the long-term performance between geomorphic landscape and conventional waste rock storage. Monitoring equipment will be installed, and respective performances will be evaluated in terms of erosion (sediment yield), run-off water quality and re-establishment of vegetation. The monitoring and evaluation will be undertaken as part of the Waste2Place project, which is funded by Sweden's Innovation Agency and supported by Swedish Mining Innovation.

This paper discusses mining at the Svappavaara site including current closure plans, the geomorphic investigations undertaken at the site including the construction of the test site and monitoring plans for the sites discussed above. The authors also discuss waste management in reference to mine closure and importantly as a pre-requisite for continued and future mining operations at Svappavaara.

Keywords: *waste management, landscape monitoring, geomorphic landscape, LKAB, Svappavaara*

1 Introduction

1.1 Geomorphic reclamation

Geomorphic reclamation transforms sterile mining landscapes into more natural landforms that can rehabilitated and returned for human activities and nature. Geomorphic reclamation is recognised as a Best Available Technique (BAT) for the management of waste from extractive industries in accordance with the European Directive 2006/21/EC (Garbarino et al. 2018).

In geomorphic reclamation the function of the landscape comes before the form. The technique used to recreate the shapes of the natural landscapes are based on observations and measurements in the field. These transform into design criteria which are used in specific modelling software as landscape inputs parameters. When designed and implemented correctly geomorphic reclamation technique results in a long-term stable landform. The slopes of the waste rock facility are regraded to simulate natural landscapes and a network of drainage channels is created. This provides the foundation for ecological recovery and increasing biodiversity. The natural looking a landscape also reduces visual impacts compared with traditional waste rock facilities.

Next chapters broaden the context in which geomorphic reclamation is discussed at LKAB in Svappavaara.

1.2 LKAB

Luossavaara Kiirunavaara AB (LKAB) is an international high-technology mining and minerals company and one of the leading producers of iron ore pellets in the world. The main underground mines and processing facilities are situated near the townships of Kiruna and Malmberget in Northern Sweden, see Figure 1. The open pit operations are situated in Svappavaara. Ore from these operations is both processed on site and railed to the processing facilities in Kiruna and Malmberget. In total, some 28 Mton of iron ore pellets are produced yearly with three rotary kilns (KK2, KK3 and KK4) in Kiruna, one rotary kiln at Svappavaara (SK1), and two straight-grate kilns (BUV, MK3) at Malmberget.

The mining method used at Kiruna and Malmberget underground mines is called Sublevel Caving. This mining method is associated with moderate to high waste rock dilution and significant ground deformations (Hustrulid 2001). Both factors have a significant influence on the amount of land needed for the mining operations.

(a) (b)

Figure 1 (a) LKAB group operations globally. The red square is enlarged in (b) depicting the operations in northern Scandinavia

1.2.1 LKAB, Svappavaara

Svappavaara is a small town located circa 50 km south of Kiruna with a population of approximately 400 inhabitants. The small town has limited services, including an elementary school and a small supermarket. LKAB is the main employer in the town; other minor businesses work in mining, the service industry, and reindeer husbandry. The mining history at the Svappavaara site dates back to around 1650 (Svappavaara hembygdsförening 2004).

Svappavaara contains of three iron ore deposits (Leveäniemi, Gruvberget and Mertainen) of which only Leveäniemi is currently mined as an open pit operation. Modern mining at Leveäniemi started originally around 1965 but the mine was closed in 1983 due to the recession and the pit was gradually filled with water.

A few decades later, mining restarted with the Gruvberget open pit mine in 2010. The Leveäniemi open pit was brought back into production in 2015 along with a new crushing and screening plant being constructed. The construction of the Mertainen open pit and processing facilities was also completed in 2015.

The Gruvberget open pit was depleted in 2018, while Mertainen open pit has been in production for a few shorter campaigns during the years 2015 and 2022 and is currently under care and maintenance. The expected Life-of-Mine (LOM) for Leveäniemi open pit is currently until 2035.

1.3 Future mining at Svappavaara

At Svappavaara the mineral reserves are only declared for the Leveäniemi deposit where current mining is taking place. The mineral reserves total approximately 97 Mton of magnetite of proven and probable categories with an average ROM grade of 45,4 %Fe.

The mineral resource at Leveäniemi exclusive of the reserves is circa 137 Mt of magnetite at measured, indicated, and inferred categories averaging circa 43.4 %Fe. The Gruvberget mineral resource contains circa 402 Mt of magnetite, hematite, and mixture of both, with ed and must take materials average grade of circa 51.4 %Fe. The effective date for the mineral resources and reserves is 2022-12-31 (LKAB 2022).

Mineral reserves and resources are stated according to the PERC standard. PERC stands for the Pan European Reserves and Resources Reporting Committee and is the Pan-European Standard for the Public Reporting of Exploration Results, Mineral Resources and Mineral Reserves (www.percstandard.org).

> *"Mineral Resources, which are not Mineral Reserves, have no demonstrated economic viability but are considered to have reasonable prospects for eventual economic extraction."*

The abundant mineral resources at Svappavaara are and have been the subject for ongoing mining studies. Nensén (2021) compiled a preliminary scoping study of the underground mining of magnetite-resources at Gruvberget and Leveäniemi. Later, Sormunen and Saiang (2022) studied caving and stoping mining methods at LKAB Svappavaara and identified specific constraints for the Leveäniemi and Gruvberget deposits. The constraints are land use and the permitting process, which affect both the mining method selection and the possible extent of future mining operations. The Mertainen-deposit, which is located circa 10 kilometres to the North of Svappavaara, is considered as a separate industrial area with regard to these constraints and is not included in this paper. The land use constraint and the permitting process are discussed in the sections below. These constraints are the driving factors for the geomorphic design and prepared the way for construction of the geomorphic test site.

1.3.1 The land use constraint

Svappavaara industrial area is geographically constrained in all directions. The European main road E10, running from South-West to North-East and the industrial railway form a natural limit to the mine site towards east. The mine site is on the west of the E10 and the Svappavaara township is located on the east of the E10. Smaller streams, lakes, and ponds included in the Natura 2000 network of nature protection areas (contributing to Torne and Kalix River systems) surround the industrial site. These are proximal to the tailings dam area, the Gruvberget open pit, and the waste rock facilities with minor outflow from the Leveäniemi open pit. The European Commission has stated the following (European Commission 2008):

> *"Natura 2000 is a network of core breeding and resting sites for rare and threatened species, and some rare natural habitat types which are protected in their own right. It stretches across all 27 EU countries, both on land and at sea. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive."*

The closest reindeer migrating routes are located to the south of the Leveäniemi open pit and to west of the waste rock facilities. More areas with high conservation values, cultural landscapes, designated reindeer herding areas, migrating routes and landscapes which are found within and outside the boundary of the mining site. The mentioned constraints and areas are depicted in Figure 2.

For Svappavaara, the most visible and substantial impacts on the landscape are the open pit excavations themselves, the waste rock storages, and the tailings dams. Eventual future underground mining could also result in significant ground deformations. Moreover, new processing facilities could be required to process lower-grade material or new ore types. Such influence results in increased need for industrial area and an expansion of the mine site.

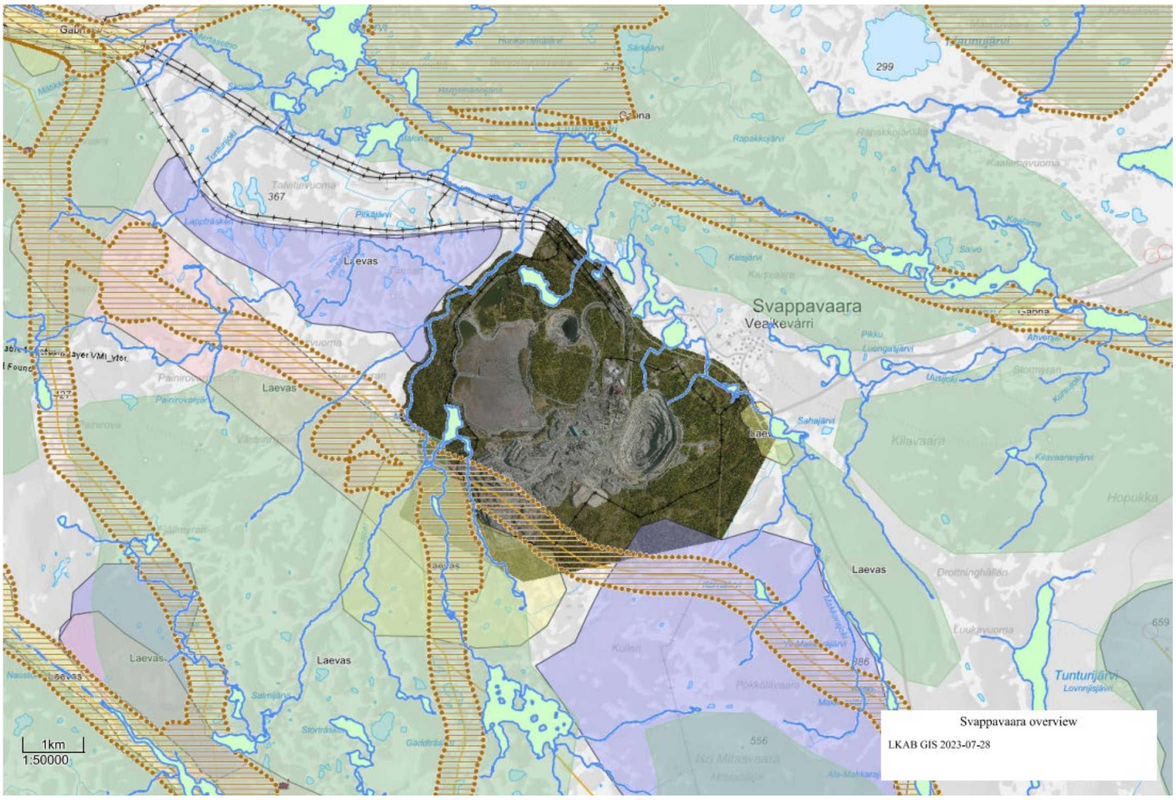

Figure 2 Overview of the Svappavaara industrial area. The orthophoto depicts the current mine site. The site is essentially surrounded by areas of interest to reindeer herding. Orange dashed areas mark reindeer migrating routes. Light green, blue and yellow areas (partly overlapping) mark grazing grounds and other areas used by the reindeer husbandry. Smaller streams and lakes contributing to Natura 2000 are depicted in blue

1.3.2 Future dry waste

Eventual future mining operations at Svappavaara will result in large amounts of waste rock mainly, from open pit operations; some waste rock could come from the potential future underground development. The pre-processing step (crushing, screening, dry magnetic separation) will result in dry waste, while the downstream concentrating processes (grinding, wet-magnetic separation) results in tailings. The Gruvberget and Leveäniemi open pit resource shells shown in Figure 3 contain circa 477 Mton and 292 Mton of waste rock, respectively. The waste rock from the underground development is likely to be less than 10 Mton. Figure 3 also shows the Gruvberget underground resource based on stope optimizer results.

Typical mass recoveries for pre-processing at Svappavaara have varied between 60-70% depending on the ore grade.

The authors note that currently no hematite or mixed magnetite-hematite material is processed at Svappavaara. The recoveries are valid for magnetite, and it is expected that processing hematite would result in somewhat lower recoveries. Processing of the current reported mineral reserves and resources at Gruvberget (402 Mton) and Leveäniemi (97 Mton + 137 Mton) would result in circa 223 Mton of dry waste assuming a mass recovery of 65% on average.

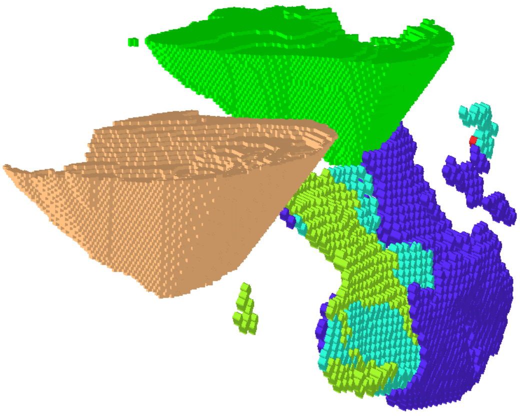

Figure 3 Open pit resource shells for Leveäniemi (front in brown) and Gruvberget (back in green). For Gruvberget, underground resources are also shown (dark blue magnetite, light blue mixed and light green hematite)

1.3.3 Permitting process

It is likely that new additional land areas are required to enable future mining at Svappavaara. Local mining projects have spurred considerable debate between the mining industry and businesses related to reindeer herding and other outdoor activities, such as hunting and tourism. Consequently, the environmental consciousness within the Swedish mining industry is increasing, and mining companies are putting more effort to gain the social license and environmental permits for mining. Sormunen and Saiang (2022) made the following statement.

> *"One way of increasing the chances of approval for a mining project is to choose mining methods that minimise negative effects on the environment and local stakeholders."*

LKAB does compensate for the land areas and interests impacted by its mining operations. An example of compensating for environmental impacts is the Mertainen-compensation (Eriksson S, 2014) that followed the BBOP (https://www.forest-trends.org/bbop/) principles (avoid, minimize, restore, offset) prior to start of the operations). Several other actions have taken place to increase biodiversity, restore cultural landscapes and relocate houses and the whole of Kiruna and Malmberget towns. Still, only a limited number of smaller industrial areas have been fully restored, for example Hopukka-site, and returned for human activities and nature (Esberg 2019).

Implementing a continuous, full-scale restoration and rehabilitation of industrial areas during ongoing mining operations, could further improve the chances of approval for extended or new mining projects.

1.3.4 Sustainability within LKAB

LKAB's mission is to produce climate-efficient quality products in an innovative and competitive way, and sustainability has a central role in the business strategy. The goal is to be a long-term, sustainable business, in which diversity is an asset (LKAB 2022).

To achieve its mission LKAB takes a holistic approach to the sustainability field – environmental, climate-related, social, and financial sustainability. It serves as a roadmap showing the way forward for LKAB to raise its ambitions in every area of sustainability.

For each part of the roadmap, there are priority action areas. For example, there is an action area for Climate sustainability: Fossil freedom and reduced carbon emissions (HYBRIT). The priority action areas for Environmental sustainability are increased biodiversity, sustainable management of water and waste, secure energy supply, efficient energy use, and circularity and resource efficiency. (LKAB 2023)

SveMin stands for Swedish Mining Industry branch association. SveMin states the following in the Mining with Nature (2020). This document is the industry's roadmap for increased biodiversity:

> *"The Swedish mining and minerals industry´s target is by 2030 to contribute to a biodiversity net gain in all regions where mining and minerals operations and prospecting is taking place. This means that the industry will be investing further in developing innovative solutions for achieving sustainable land use in harmony with nature."*

LKAB's strategy aligns with the SveMin roadmap. This is also a central part of the permitting process (LKAB 2023).

> *"Our internal guidelines also describe ecological remediation efforts which aim to speed up the increase in the land's biodiversity as well as its values for reindeer husbandry."*

LKAB is committed in sustainable mining and mining methods. This includes pursuing for best practises in remedying the environmental impacts mining has on land and on the environment.

1.3.5 Increased biodiversity

The loss of biodiversity is just as great of a threat to our welfare as climate change and the two threats reinforce each other. As a mining and mineral company, LKAB uses land for its operations and needs to take up new land to continue developing.

This means LKAB has an impact on the natural environment and biodiversity in the surroundings. Thus, the company has a responsibility and an interest in working proactively to increase biodiversity. LKAB's primary strategy is to avoid or minimise any impact on biodiversity.

Current focus areas for the remediation are the creation of natural and ecological landscapes that foster reindeer herding, biodiversity, and other ecosystem services.

2 Waste dump rehabilitation practises at LKAB

LKAB:s rehabilitation plans (Esberg 2017) align with current regulations and conditions stated by the authorities. Often, the rehabilitation is proposed to take place after mining operations have ceased using conventional rehabilitation methods and are a central part of the current mine closure procedures.

2.1 Conventional waste dump design and rehabilitation

A typical waste dump design and rehabilitation scheme and a cross section are shown in Figure 4a. At Svappavaara, conventional waste dumps are designed in terrasses using 20-meter lifts and 10-meter berms, with slopes regraded to an angle of 1:2.5. The maximum height of the dump is not to exceed the surrounding landscape and is currently set to 465m asl. Uniform layer of 30 cm till and 10 cm of growth media is required before applying industrial seed mix for revegetation (Esberg 2017) (Figure 4b).

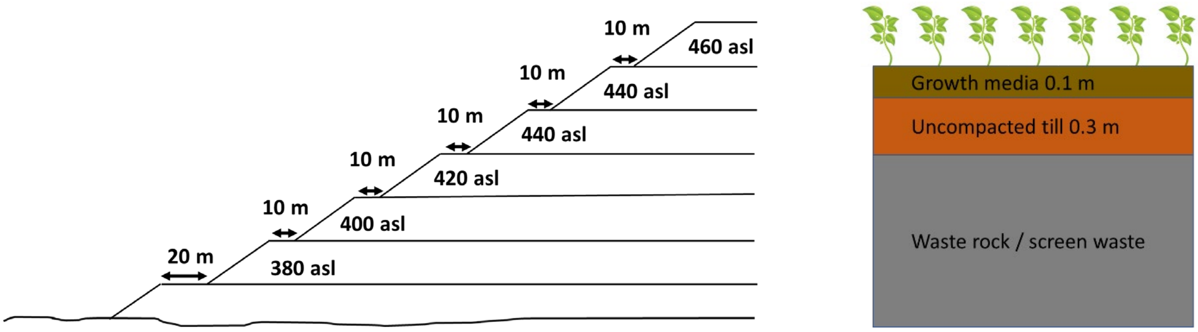

Figure 4 (a) Cross section of the conventional waste dump design; (b) Schematics for rehabilitation. Note this design is suitable for non-acid-generating waste rock and other aspects should be taken into account if the method is to be used for potentially acid-generating waste rock

The current footprint with a conventional design is shown in Figure 5a and has an approximate volume of 90 Mm^3 translating to circa 162 Mt. A loose density of 1.8 t/m^3 is assumed for the waste rock.

2.1.1 Additional waste dump capacity

Additional conventional waste dump designs are shown in Figure 5b, c, and d. The authors note that these waste dumps are not included in the current operations or permits. The designs are shown here to illustrate possible waste dump capacities within the current land lease without restriction to the maximum height.

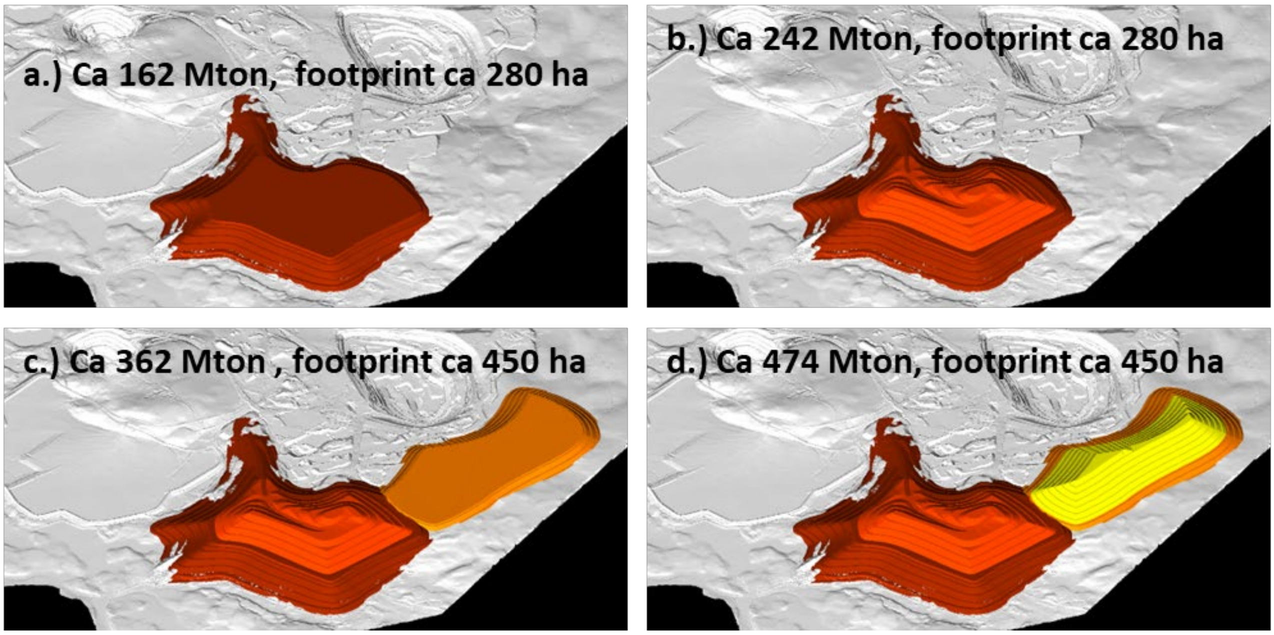

Figure 5 Conventional waste dump designs: (a) Current design with maximum height of 465-meter asl and capacity of circa 162 Mton; (b) Current design build to maximum height at 560 asl adds circa 80 Mton to the waste dump capacity; (c) New design limited by maximum height of 465-meter with circa 120 Mton capacity; (d) New design build to maximum height at 600 asl adding circa 112 Mton to the capacity.

The deficit between the expected amount of waste rock and dry waste (477 Mton + 292 Mton + 10 Mton + 223 Mton= 1002 Mton) and conventional waste dump designs (474 Mton) in Figure 5d is 528 Mton.

Vast land areas within and around the Svappavaara mine-site will be required to enable dry waste rock storage. For reference and for scale, Aitik – the largest open pit operation in Europe – is estimated to produce circa 750 Mton of waste and the waste rock dumps occupy an area of circa 4 square kilometres (Lindvall M and Eriksson N, 2003) (Lindvall M, 2005).

2.1.2 Geofluv phase 1 design for the Svappavaara site

In 2021, VAST Landscape Architecture was engaged to provide a conceptual geomorphic design covering the Svappavaara site. The work included site-specific field data collection, desktop studies, and run-off tracking to understand the site and to define the first design criteria (volume, footprint, height) for the geomorphic design. This was followed by intermediate landform designs. The final Geofluv Phase 1 design report resulted in 22 separate sub-watersheds with acceptable run-off and slope analysis with 3D-models and CAD-design files aligning with the design criteria and site-specific criteria set. The Phase I geomorphic design is shown in Figure 6a, and has a designed capacity of circa 106 Mton (VAST 2021). Figure 6b depicts the 22 sub-watersheds.

At the time, Svappavaara was not ready to adopt geomorphic design as a site-wide method for rehabilitation because method was still unpreceded in Sweden. The main practical concerns were related to construction during winter months as well as managing of the coarse fraction, large sized boulders, and the connection to existing surface runoff water management systems. Management concerns included operating costs and potentially losing waste dump volume compared to conventional design, thus risking possible future pushbacks on the Leveäniemi pit. In this case, the volumetric loss was calculated to 35% (106 Mton / 162 Mton) between conventional and geomorphic waste dump designs. Therefore, a construction of so-called geomorphic test site was proposed in order to validate or eliminate these concerns.

The test site is referred to as subwater-shed 0 (SW0). The overlap of the SW0 and the Phase I design is shown in Figure 6a.

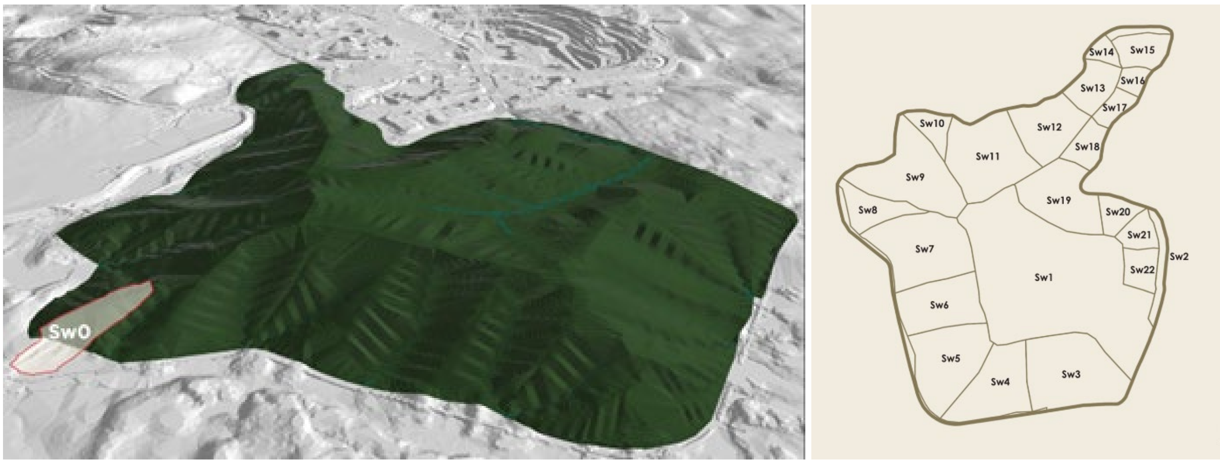

Figure 2 **(a) Geomorphic phase I design within current footprint, the test site SW0 shown on the left, (b) Phase I divided into 22 sub-watersheds,**

2.2 The geomorphic test site

The test site SW0 has an area of circa 4,4 hectares and peaks at 405 meters asl, the peak of the design is called Daniels Peak. The main channel is 364 meters long and starts at 398 meters asl resulting in drainage density of 85,84 m/Ha. The head elevation is 359 meters asl and connects to the existing drainage channel at the perimeter of the waste rock facility that was also considered to be the local base level. The design consists of the main channel, 19 ridges, 18 swales and a floodplain area. A shorter meandering channel goes through the floodplain area and is included in the channel length. The till and topsoil layer thicknesses will vary between 0-30 centimetres across the site. The test site design was based on the landscape input parameters collected during the Geofluv-phase 1 design.

2.2.1 SW0 construction

Building a test site provided a way to understand how the geomorphic landform can be built and constructed. The test site location was determined by accessibility and minimizing rehandling of the existing material. It was also decided that the test site should connect to the existing drainage channel, which would be the discharge point for SW0. SW0 does not align with the conceptual Phase 1 design shown in Figure 6b but is located across both SW 8 and SW9 The test site design and built outcome is shown in Figure 7a and b.

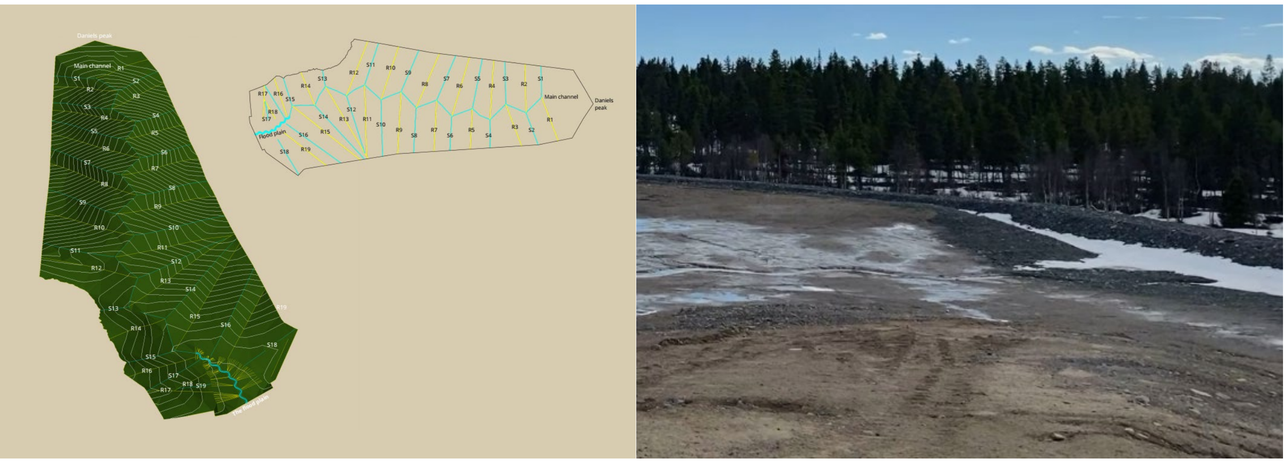

Figure 3 **(a) Design of the SW0; (b) Floodplain and the meandering channel at SW0, the drainage channel represents the local base level (discharge point) for the SW0**

In early 2021 Svappavaara applied for a change to its permit conditions for its waste management. An application was sent to and approved by the Swedish County Administration Board (CAB) for the test site. A geomorphic approach requires a different construction and closure method from what is stated in the permit currently. The differences include a change in terrace heights, slope gradients of the final landform and thicknesses of the cover materials. The application was approved in October 2021 and construction started immediately after.

The construction relied on machine control and a 3D-model was delivered for the operators. Figure 8a shows the operators with the model downloaded to a stick, the same model would be available on the bulldozers to aid with the construction. Figure 8b shows the start of the intermediate ramp that was cut from level 380 down to level 360, which is also the base level of the waste dump. Later this ramp was used to transport material between the levels 360 and 380. The top part of the design was filled from existing waste dump bench at level 400. Circa 1400 kton of material was used in the test site and the construction was completed in June 2022. Construction took place during wintertime in snowy conditions and was undertaken intermittently as the required waste material was not prioritised from production for the project. Of the construction of the landform's ridges and swales were constructed using bulldozers as shown in Figure 8c.

Figure 8 **(a) Operators Håkan Jonsson (left) and Andre Stenman (right) planning the work ahead; (b) First ramp cut down to 360 on the existing waste dump; (c) Ongoing contouring and shaping of the test site using bulldozer**

The construction project lasted for 6 months, however, the actual construction time based on machine hours and timesheets was circa six weeks. The total amount of waste rock moved corresponded to roughly one month's mine production volume. The cover layers, which include moraine till, and topsoil were not applied immediately but the decisions was to leave the landform to settle until the Spring 2023. This was based on assessing the landform's function during the snowmelt period in spring 2023.

The construction-process was followed visually, and occasionally scanning the topography with Drones. Two time-lapse cameras were installed on the site. The first timelapse camera was installed 2021-12-15 to the south of the test site having limited line-of-sight towards the test site. The second camera was delayed until 2022-11-28.

2.2.1.1 Observations during and after the construction

The test site provided answers to some of concerns related construction of geomorphic landscapes during the winter months in arctic to subarctic conditions. The test site also provided insights on the actual construction and other practicalities that are briefly discussed here.

Concerns related to managing large boulder and the coarse fraction size including were not realised. In fact, the operators were able to hide all the big rocks and succeeded in creating a smoothly contoured landscape. While some benefit could arise from having large rocks and boulders on the surface to provide a more natural-looking landscape, these features could pose a safety concern (for example, boulders located underneath bulldozer tracks can cause a slip situation).

It was also shown that the geomorphic landscape can connect onto existing engineered drainage systems as shown in Figure 7b, though these special conditions could require some tweaks and adjustments aligning the discharge points with the channel.

Naturally, rehandling of material when working on existing waste dumps adds to overall costs. This applies both when working on and rehabilitating existing waste rock facilities but also when working with new designs. In this case "a minor change" from the designer measured in millimetres in the computer screen resulted having to dig and move tons of material from the main channel.

When working with inexperienced crew (first geomorphic site in Scandinavia), it could be easier to start the construction from the scratch. Also, if a test site is to be built, it needs to align with the overall Phase I design and subwater-sheds. The test site in Svappavaara was a stand-alone and interferes with the subwater-sheds 7, 8 and 9, implying that the parts of the Phase I design work need to be revised later. The authors note that this risk was known and accepted before the start of the construction.

The subarctic conditions and periods of heavy snowfall led into snow being packed and blended in the waste rock materials. This was deemed not to have caused any issues when handling waste rock material but would be detrimental for placing of till and other cover materials due to material freezing.

The landscape should be left undisturbed for at least one year to settling before applying the cover material. Settling contributes to a more natural-looking surface through frost-heave breaking of the engineered smooth slopes and surfaces.

2.2.2 Current status on the test site

By summer 2023, the test site has seen its first fall, winter, and spring season. Based on visual observations, the geomorphic design was successful; the depth of the snow has varied across the site and the landform provides varying shelter from the wind. During the spring flood, water was observed in the main and meandering channels in the floodplain. The connection between the meandering channel and the drainage system is functional as shown in Figure 7b. No significant erosion has been observed although there were some minor potholes or subsidence on the test site surface (Figure 11b). These are likely results of the local ground frost or pockets of snow and ice thawing and are considered minor deviations from the planned design.

Despite the rehabilitation not being complete, the site has already gained interest in Sweden. The site showcases how both LKAB and the mining industry in Sweden are actively working towards increased biodiversity and sustainable waste management. The interest has manifested itself in a joint research project, Waste 2 Place, which is described in the next chapter.

3 Waste 2 Place project

The Waste 2 Place is a three-year project carried out within the strategic innovation program for Swedish Mining Innovation, a joint venture by Vinnova, Formas, and the Swedish Energy Agency. The project participants come from the mining industry, academia, and specialized consulting companies. The project applies a geomorphic approach to waste rock management in mining to create functional post-mining landscapes with the goal to provide an alternative for conventional waste rock storage.

Experiences, knowledge, and other observations are shared during the project and different work phases from design process to construction and rehabilitation. The interrelationship with the different work packages and the project hierarchy is shown in Figure 9.

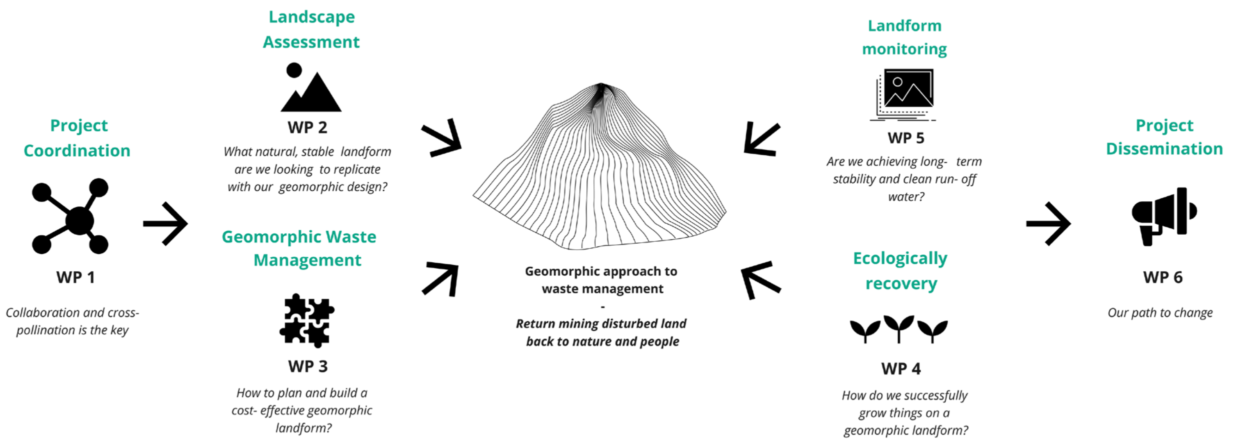

Figure 9 Description of the W2P project and the different Work Packages or the interrelationship between the different WPs and how they collectively achieved the project's overall aim

Expected results include tools (methods, databases, design criteria, geospatial reference data, landscape, and ecological data) for geomorphic restoration in Sweden. The landscape and the environmental performances, for example biodiversity, are made quantifiable and comparable through different measurements. The work packages and the setup for comparison and reference sites are discussed below.

3.1 Comparison and reference sites

A conventional waste dump design is compared side-by-side with a geomorphic design shown in Figure 10a.

In 2023, an adjacent comparison site with a conventional bench and berm design is to be constructed and cover layers will be applied. Two 20-meter-high benches with 10-meter-wide berms are located at levels 360 asl aligning with the drainage channel on the foot of the dump and at level 380 asl. The top of the design is a flat surface at 400-meter asl. Cover material thickness for the comparison site is uniform comprising of 30 centimetres of till and 10 centimetres growth media as shown in Figure 4. Both the top surface and the berms are slightly inclined to guide the runoff towards measuring station before entering the drainage channel.

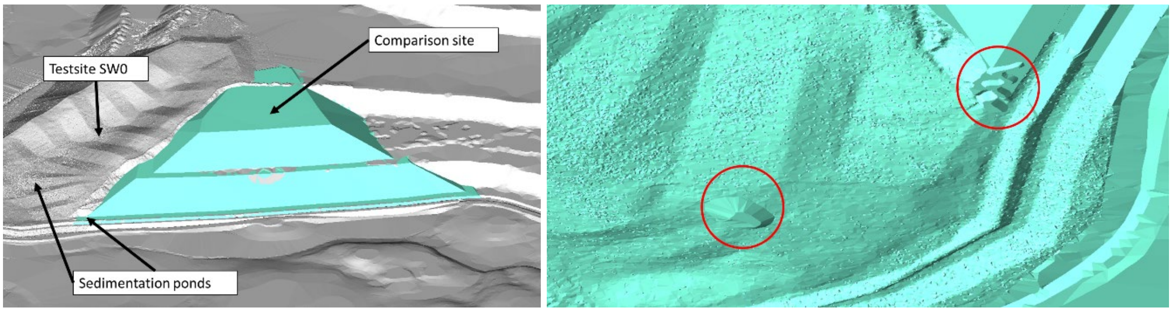

Figure 10 (a) Test site SW0 and the side-by-side comparison site to be constructed; (b) Approximate locations for the sedimentation pools and measurement stations are marked with red circles

The setup will allow for a side-by-side comparison between geomorphic landscape and a conventional waste rock storage. The work is also ongoing finding an unaltered landscape that can be used as reference site.

3.2 W2P work packages

The project consists of six different work packages of which two (WP1 and WP6) are related to project coordination and administration. Work packages 2-5 are discussed briefly below. It is noted that three-year time span of the project will not assess the long-term performance on WP4 Ecological recovery and WP5 Landform monitoring.

3.2.1 WP2 landscape assessment

The fieldwork is important both for observations and for the collection of the landscape parameters. It is also valuable for understanding the landscape as it is for confirming the work done on the desktop.

The current geomorphic designs criteria at Svappavaara and in Northern Sweden are based on a limited number of field observations due to relatively inaccessible landscapes in the area. This is also a relatively costly and ineffective method when needing to analyse large areas. Therefore, this work package will also utilize high-resolution satellite images and topographical maps for identification and locating reference sites for collecting the landscape parameters and fluvial processes.

The results will be used initially for reviewing current geomorphic landscape parameters in Northern Sweden. This will also contribute towards the landscape parameter collection methodology and the Swedish landscape parameter database.

3.2.2 WP3 geomorphic waste management

The test site (SW0) construction took circa eight months to complete despite the material moved corresponding to circa one month´s worth of production from the mine. The relatively slow pace in construction is partly explained by the lack of experience of both the construction crew and the project being of lower priority for the mine production department. For example, extra resources were required to rehandle some material and to build new access roads at the existing waste dump. This is fine when working with specific areas and independent projects that are uncoupled from the production. However, such approach does not allow for continuous large-scale rehabilitation of geomorphic landscapes to be integrated in the mine production and is likely to increase the overall costs.

Work package three will investigate how a progressive, geomorphic approach could be integrated in available mine planning and scheduling software. This includes modelling a conceptual geomorphic design and scheduling plans including haulage and dozer push modelling. The generated plans and scenarios are then used as input for cost calculations and evaluation of different waste management scenarios. The chosen scenario is then developed into a finalised working document (so called Phase 2b design) and will be delivered to both mine planning and production department for construction.

3.2.3 WP4 ecological recovery

On the test site (SW0), a varying thickness of covering layers will be applied whereas the comparison site will have uniform thickness of material applied on the berms, slopes and on the top. The varying thickness of the cover layer on the test site is believed to have a positive effect on the biodiversity. Less of a thickness will also help householding the limited topsoil resource in the area. The materials used for the reclamation originate from previous mining operations and have been stored separately on the site. Both the till and the topsoil materials naturally contain some seeds and roots that will help to propagate the revegetation.

Specific areas are tested by planting of birch and pine trees and sowing a selected seed mix both on the geomorphic test site and the adjacent comparison site. Figure 11a show the proposed seeding, planting, and control areas on the test site. A similar setup will be developed for the comparison site. The outside areas are both control areas and rely on the natural transportation of the flora.

The specific goal for this work package is to develop a revegetation strategy for geomorphic landforms in northern Sweden that focuses on the ecological recovery of the key northern Sweden biotopes. The landscape as shown in Figure 12a (August 2022) forms the base for the revegetation and a vision of a fully rehabilitated site is shown in Figure 12b.

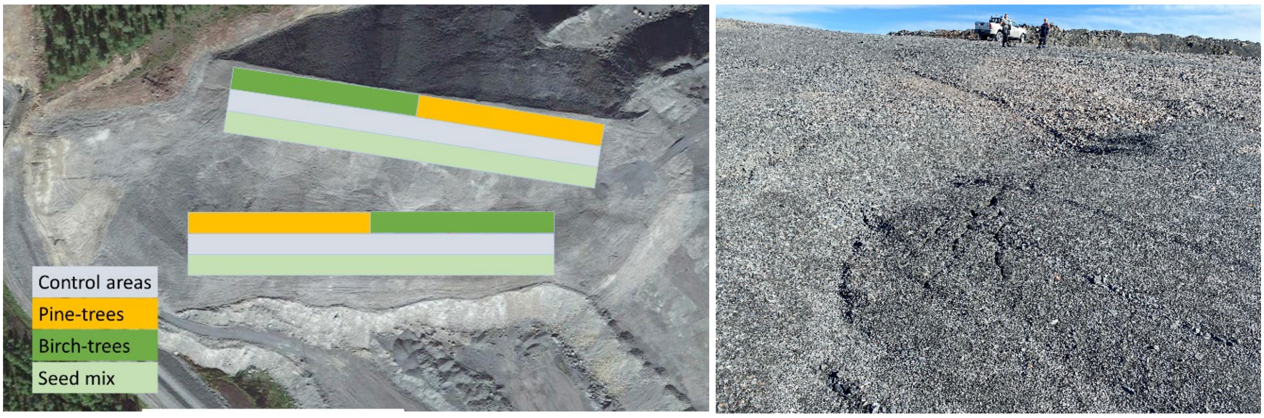

Figure 11 (a) Proposed revegetation plan for SW0 test site; (b) Observed subsidence due to local ground frost thawing

Figure 12 (a) Geomorphic test site at LKAB, photo taken 2022 August showing the as-built geomorphic surface before applying till and topsoil layers; (b) Vision of the fully rehabilitated and restored geomorphic landscape

3.2.4 WP5 landform monitoring

Geomorphic landscape design is used to recreate the functionality of the natural landscapes while reducing visual impacts compared to conventional waste dump design. However, visual impression or subjective observations do not allow for quantitative measurement of function and performance of the landscape. Work package five provides several quantifiable measurements allowing for objective comparison between the test site (SW0) and the conventional comparison site. Results from both sites will be compared with a natural surface. Three methods listed below will be used providing continuous measurements for water discharge (m^3/s), sediment (g/l and g/sm) and the total sediment yield (t/ha*y). Approximate locations and layouts for the sedimentation pools is shown in Figure 10b.

1.) Hydrological and sedimentary stations including flumes and sampling instruments
2.) Ponds at the outlets and downstream of the hydrological station
3.) A multi-temporal topographic comparison with data surveyed by photogrammetric procedures combined with drone images and a LiDAR sensor

Other measurements include satellite-derived surface movement analysis (interferometry), timelapse cameras and vegetation monitoring which is included in the work package four.

4 Discussion/Conclusion

The authors believe that access to land and environmental permits are the most significant constraints for any planned future mining at the Svappavaara site. The geomorphic design provides tools to mitigate some of the effects associated with waste management but also requires larger footprints to fit equal amounts of waste rock.

The ongoing research project provides a unique side-by-side comparison between geomorphic and conventional waste dump designs and the results will form the basis for the future waste rock management. For the geomorphic approach to be viable, a few key considerations and conditions need to be met:

- The geomorphic landscape must perform and function better within the measured parameters included ecological parameters (biodiversity) when compared to conventional design.
  - The construction of a geomorphic landscape implies added cost due to regrading and sloping of the waste rock surface. It is imperative that the extra cost results in a functioning landscape that adds value to the operation.
- The material handling and logistics of the geomorphic rehabilitation must adapt for full-scale production.
  - Current practises in waste rock management focus on the operational costs and efficiency resulting in engineered and conventional waste dump and haul road designs. To enable similar optimization (fleet utilization) on geomorphic landscapes, the landscape design and construction must be integrated onto mine plans and production schedules. Stand-alone projects are not sustainable and require rehandling of material increasing costs.
- Landscape rehabilitation and return rate must be greater than the areas required for active waste rock management to decrease the net impact of waste rock facilities.
  - While conventional waste dump designs do maximise the volume, they do not provide for natural-looking and ecologically sustainable landscapes. This will also affect possible post-mining land-uses and can manifest in permitting issues and social acceptance. One way to mitigate this is by successfully and continuously rehabilitating and returning waste rock and tailings storages for the stakeholders.
- Geomorphic design and construction need to be implemented from the beginning.

- Applying geomorphic design from the beginning will eliminate need for rehandling of material. It also allows for full integration with the mine production at full production and enables for continuous rehabilitation.

This three-year project and its success are essential for the future mining and mine waste management at Svappavaara, in Sweden, and in Scandinavia. Being able to successfully rehabilitate and return mining landscapes for the future generations should allow for continued mining and new sustainable mines for our generation.

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