EMPOWERING UNDERGROUND LABORATORIES NETWORK USAGE

Activity Report of WP3.3 **12|2021**

SITE DESCRIPTION AND DATA OF THE CALLIO LAB

Site services, Characteristics and Data

J.Joutsenvaara[1,2], M.Holma[1,2], J. Puputti[1,2], K.Szkliniarz[3], Jan Kisiel[3]

15th December 2021

[1]Callio Lab

[2]Kerttu Saalasti Institute, University of Oulu, Finland

[3]University of Sielsia, Poland

Interreg Baltic Sea Region
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Table of Contents

1 Aim and Introduction

1.1 Aim

This report provides an overview of the Callio – Mine for Business(1) and Callio Lab(2) research infrastructure for external users and site managers.

The aim is to support marketing, project planning/execution, business, and innovation development. General site information, including current use and access to the site, is followed by information on research, innovation and cooperation possibilities, and the onsite support, including the database. The bedrock geology, hydrogeology, and hydrochemistry data and properties are described in detail.

1.2 Introduction

Pyhäsalmi mine is located in Finland, and it is one of the deepest base metal mines in Europe. The development of the research possibilities and actual infrastructures started already in the late 1990s at the margin of then known ore resources. With the discovery of the new ore deposit below the old one, the life span of the mine has been gradually extended to 2022. The foreseen end of the underground mining will enable more extensive reuse activities at the mine site for science, research and business. The University of Oulu, Kerttu Saalasti Institute coordinates research and science

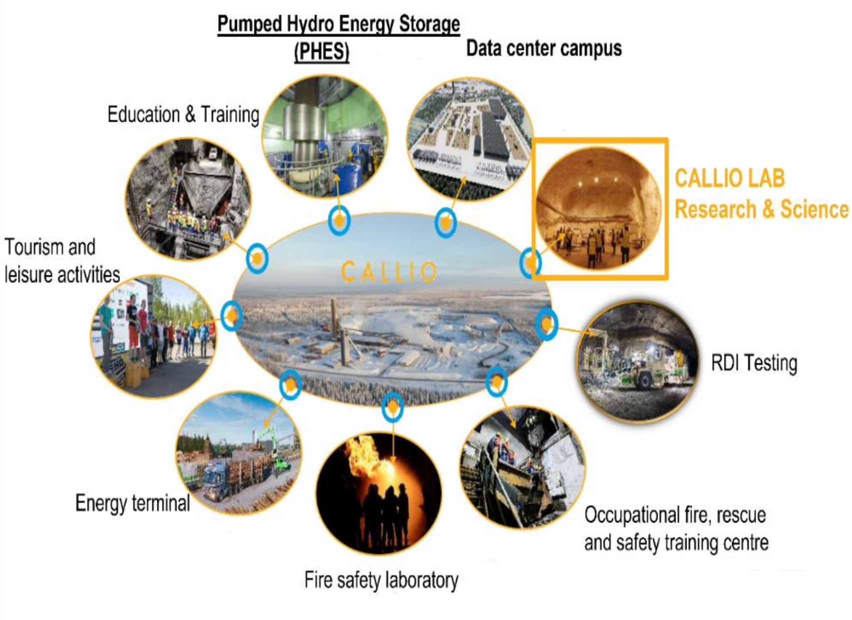


Figure 1. Callio Lab is one of the cornerstones of Callio - Mine for business. The Callio Lab is both an underground research infrastructure and a network of underground researchers . The research is an overlapping activity offering cooperative projects for science, research, and innovation. Research activities are coordinated by the University of Oulu, Kerttu Saalasti Institute, Finland. The coordinator for the business activities and the facilities and facility services provider is the Callio – Mine for business, and it is owned by the Town of Pyhäjärvi.

activities under the Callio Lab ((3,4), and Callio – Mine for Business (1), as the name stated, coordinates the business activities. Callio – Mine for Business is owned by the Town of Pyhäjärvi, and they also provide the facilities and facility services for the users of the mine infrastructure.

Contacts:

Callio Lab c/o Kerttu Saalasti Institute Pajatie 5 85500 Nivala Finland Email: contact@calliolab.com www.calliolab.com	Callio – Mine for Business Mr Sakari Nokela Ollintie 26 86800 Pyhäsalmi Finland Sakari.Nokela@pyhajarvi.fi www.callio.info

2 Overall description of the Callio Lab

2.1 Location

2.1.1 Geographical settings

Callio Lab is one of the northernmost underground research infrastructures in Europe. It is located within the Pyhäsalmi mine, in the Town of Pyhäjärvi in the Northern Ostrobothnia region. The Callio Lab is located within approx. 150 km from the regional airports and regional centres (Oulu, Kokkola, Jyväskylä, Kajaani, Kuopio), and only approx. 400 km north from the Helsinki/Vantaa airport. The coordinates for the site are N 63,6593, E 26,0419 WGS 84, locating it in the vicinity of the geographical centre of Finland.

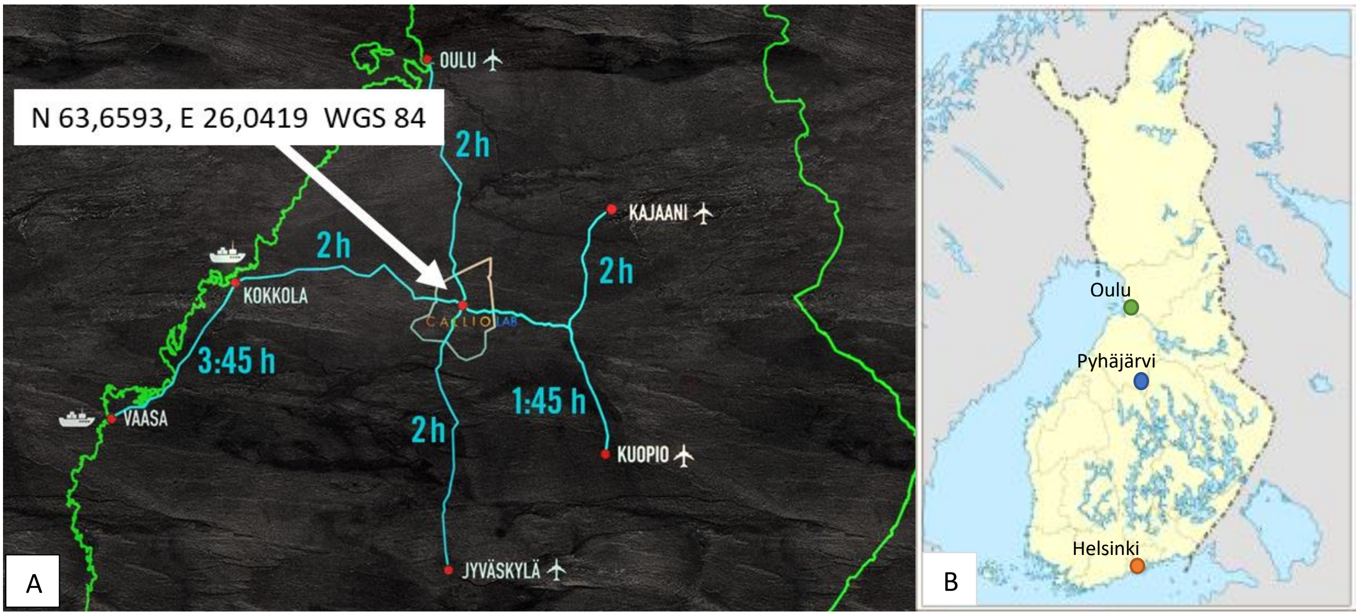


Figure 2. A) Callio Lab is located right at the centre of regional airports and centres. B) Callio Lab is located at the vicinity of the geographical centre of Finland.

2.2 Use and Access

2.2.1 The original purpose and current use

Pyhäsalmi mine and the mine environment as first-adaptor and a test site

Figure 3. Pyhäsalmi mine area with the old open pit seen in the right. Picture by J. Puputti.

The 1.4 km deep Pyhäsalmi mine is located in the town of Pyhäjärvi, Finland, Finland. The mining started in 1962 as open-pit mining. In the 1970s, the extraction was taken fully underground, leading to the development of one of the deepest base metal mines in Europe and globally one of the most efficient ones. The mine has been a first-adaptor of advanced technologies and a test site for emerging technologies throughout the mine life span. The underground mining is expected to end in 2022.

With the historical record of advancing the frontiers of engineering and science within the mining industry, the Pyhäsalmi mine is a globally well-known mine and a wanted environment for testing future technological solutions.

MINE FOR BUSINESS
CALLIO
PYHÄJÄRVI, FINLAND

Callio – Mine for Business is now the mine reuse partner of Pyhäsalmi Mine Ltd. Callio offers facilities, facility services and even turn-key solutions for the developers, manufactures and test operators. Callio – Mine for Business is owned by the Town of Pyhäjärvi through its subsidiary Kvanttikiinteistö Oy.

Pyhäsalmi mine and the scientific activities

The open-mindedness and willingness to act as test sites for new and emerging technologies have allowed scientists to get their foothold at the Pyhäsalmi mine. At the foreseen closure of the old mine at the end of the 1990s, the local stakeholders started looking for possibilities how to utilise then the kilometre deep underground mine infrastructure. The idea to use it for underground physics was initiated. The Centre for Underground Physics in Pyhäsalmi, CUPP (5), was initiated in 1997 in cooperation with the Universities of Oulu, Jyväskylä and Turku. Since the beginning, the University of Oulu has been coordinating scientific activities through various ERDF, Academy of Finland, University of Oulu, and foundation-based projects.

CALLIO LAB
Underground Center for Science and R & D

The onsite research activities started with underground physics demonstrations and experiments (MUG, MUD, EMMA) to show that underground research can be done at the Pyhäsalmi mine and in Finland (6–8). Early on, CUPP was soon recognised as one of the European underground laboratories and joined the Deep Underground Laboratory Integrating Activity, DULIA.

The international networks established in the early stage of the Centre for Underground Physics in Pyhäsalmi has laid the groundwork for Pyhäsalmi mine as one of the candidate sites studied in European Commission funded Large Apparatus for Grand Unification and Neutrino Astronomy, LAGUNA, & LAGUNA-LBNO Design Studies (9–11). With the LAGUNA DS, ERDF funded Site Investigations and the existing data from the mining company made the in-depth analysis of Pyhäsalmi's capabilities to host large volume scientific instruments (or any large scale apparatuses) globally known. At the Pyhäsalmi bedrock, it is technically possible to excavate large tens of meters or even hundred meter-scale caverns even at the depths of more than 1 400 m (12).

The current use

The Pyhäsalmi mine is at its margin of known ore resources. The underground mining is expected to end in 2022, but the re-beneficiation of minerals from the tailing ponds is expected to carry on for additional five to six years. The eventual end of underground extraction will give more room both in physical facilities and in terms of extended or even 24/7 access times. Most importantly, the future of the Pyhäsalmi mine infrastructure looks bright for both business operations and scientific activities. The pre-investment for an underground pumped-hydro storage facility to be built at the area utilising the existing tunnel network for construction has been made. This investment ensures the existing and future utilisation of the underground and surface facilities.

Callio Lab

The scientific activities of Callio Lab are coordinated by the University of Oulu, Finland. Depending on the research proposal and its maturity, Callio Lab can act as a gateway and networker between research and industry, helping the researchers find industrial partners and industries to find research partners for their projects. Callio Lab can provide full coordination, cooperation, or facilitation for research initiatives based on the project's needs. With long-term activities, the possibility of using local onsite staff and 1+ Gb/s secure and remote accessible internet connection compared to full-time own staff is a major cost-benefit. Throughout the years the various scientific activities and research initiatives have been started at the Callio Lab. The scientific activities that utilise the Callio Lab research infrastructure range from mining and mining-related training to geothermal concept and technology testing, underground food production, working environment research, and particle physics.

2.2.2 Available infrastructure

Finland and Sauna

The Pyhäsalmi mine is located in Finland, and it has the world´s deepest located sauna at the mine´s main level at a depth of 1410 m. The main level hosts also a diner, office spaces, two 70 m long mobile equipment maintenance lanes, a large underground storage facility, a rescue chamber for the whole shift, 3G mobile network together with wide coverage wireless internet connection.

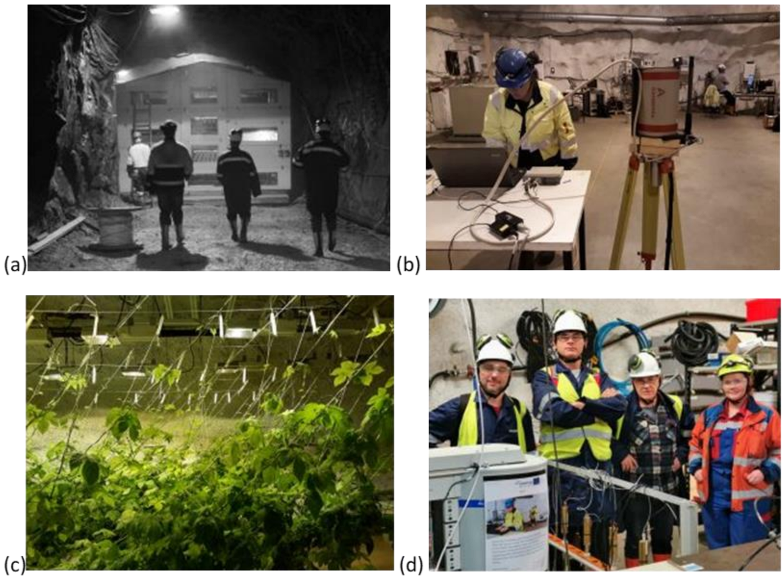


Figure 4. (a) Lab1 – site of the EMMA experiment, b) Lab2 - place used for experiments in the field of physics, c) Lab4 - site used for plant and fungal breeding research, (d) Lab5 – site of the C14 experiment.

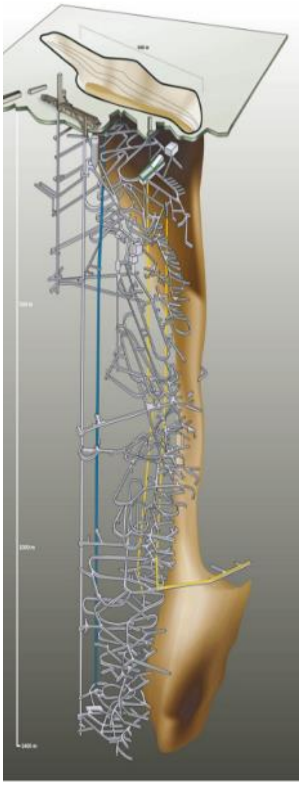


Figure 5. Axinometric profile of the Pyhäsalmi mine. The 1.4 km deep mine, with hundreds kilometres of tunnels amke an excellent facility of underground business, R&D and research.

The Labs and reuse sites

The activities are project-based, so research conducted or the general use at the different facilities can change over time. For example, Lab 2 at a depth of 1 436 m was designed as a multipurpose, low muon background underground facility. The first user was underground physics, and later it was followed by developers of underground food production.

Lab 1 at a depth of 75 m is the first underground level that was transformed into more permanent scientific reuse. The experiments carried out are cosmic ray experiments Muons UnderGround (MUG) and later Experiment with MultiMuon Array (EMMA). Now the Lab 1 is used for the NEMESIS experiment (New EMma Experiment Searching for Indirect Signals), which incorporates infrastructure from the EMMA experiment. Lab 3 at a depth of 990 m was originally used for testing mushroom farming, then for radon barrier testing, all happening in a single room. Now the whole level is for testing of next-generation mining equipment by Normet Ltd. Lab 4 is located at a depth of 660 m, where the former maintenance and diner area was transformed into two underground hydroponic greenhouses. The greenhouses have been used to test the growth and chemical compositions of high-value-added plants. The steady and safe growing environment has provided up to five steady quality harvests per year.

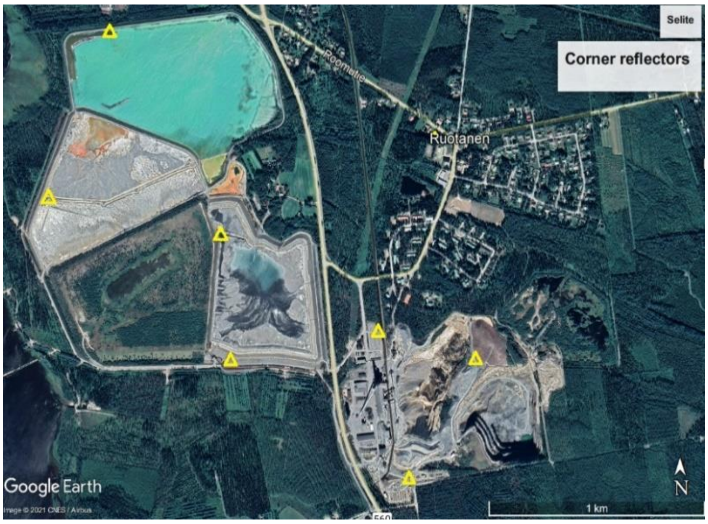


Figure 6. Pyhäsalmi mine area taken from Google Earth. Yellow triangles indicate the positions of corner reflectors designed for Copernicus earth observation satellites. The Callio Lab research activities utilise both the surface and the underground facilities.

Lab 5 at a depth of 1410 m, built inside a mine's main storage facility with walking distance from the elevator, has been used for physics experiments and providing gamma spectrum analyses using the electrically cooled low background HPGe detector from Baltic Scientific Instruments. The facility provides sample analysis services for the EUL project laboratories (13), but other scientific institutions benefit from the facility too. Lab 6 consists of a former main level at a depth of 400 m. The activities there concentrate on underground occupational safety, fire and rescue training and related research.

Additional activities have taken advantage of the underground access and existing facilities, still used by the mining-related activities. E.g., drill holes reaching 2.5 km are used for deep geothermal energy research, the ancient deep, saline water pockets offer possibilities for the astrobiologist. The usage has not limited to the underground mine but also the surface infrastructure is used. The infrastructures, together with historical ground truth data sets, offer possibilities also for a wide range of multi- and transdisciplinary research activities.

Besides the underground infrastructures, the surface area of the mine site expands to several hundred hectares, with tailing ponds alone reaching 250 hectares. The surface facilities include workshops, office areas, old open pit and backfill open pit, transit areas, ore storage areas and a railway connection reaching the site. The versatile mining site offers Earth Observation (EO) data verification and validation possibilities, whether utilising satellite or aerial data. Additionally, the site can be used for launching vertical take of equipment such as helicopters and drones.

With its surface and underground infrastructures, the mine environment enables the testing of autonomous mobile equipment, whether a drone or large mining machinery. The safe tunnel network makes it possible to test equipment in a real mine environment without intervening with the mining operations. The high-speed optical internet connection with secure remote access possibilities allow the operators to work on their machinery in real-time, even while working remotely.

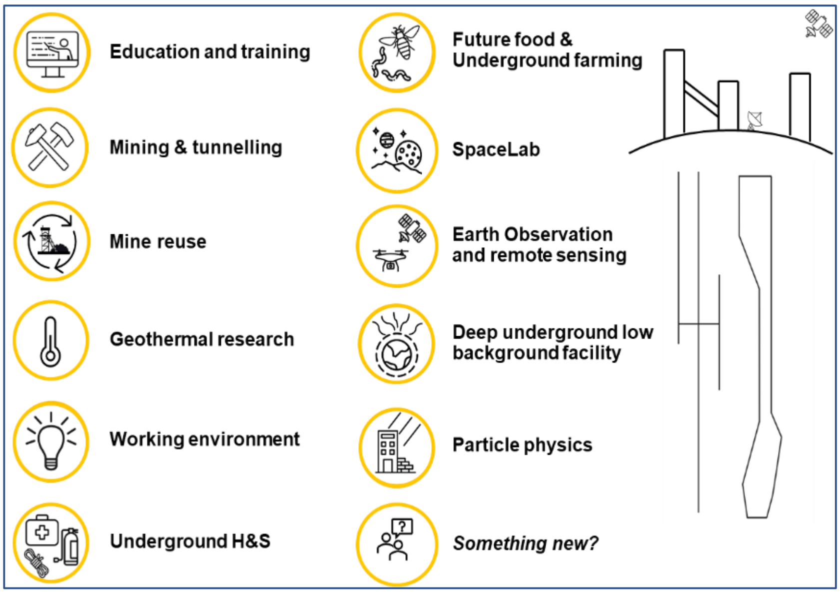


Figure 7. Callio Lab´s research fields have expanded from single field to multi- and transdisciplinary resaerch centre.

Safety and safety infrastructure

Safety is the top priority. The Pyhäsalmi mine, as a mining company and the current mining permit holder, is responsible for the safety of the infrastructures, facilities and activities onsite. Callio – Mine for Business and Callio Lab as operators are subject to the rules and regulations additional to their institutional or company regulations related to occupational safety.

Figure 8. Visitors at a refuge chamber at 990 level in the Pyhäsalmi mine.

The mine provides a quality system for visitors and a safe working environment for employees at all mine levels. All the new activities undergo a risk analysis to see how the planned activities would fit the current operations and permits.

All the operators and users need to undergo site-specific training and have valid occupational safety and first aid certificates. Additional certifications would be required if work contains heat sources or working in high altitudes or enclosed spaces, e.g., tanks. The H&S department of the mine must accept this additional certificate requiring tasks.

Pre-planning, identifying the possible risk and thorough risk analysis to find measures or alternative practices for mitigating the risk is mandatory for all operations. The risk analysis covers various what-if scenarios and measures what to do if something happens. Use of protective gear is mandatory at the site when working underground or working at the surface facilities. These include helmet, safety goggles, safety boots, flash or headlight and, for specific purposes, antistatic, fire-resistant etc., clothing or protective gear.

Safety infrastructure at the Pyhäsalmi site includes fire extinguishers in all mobile equipment, intermediate levels, main level, workshops, and social areas. First aid kits are also available at mobile equipment and working spaces. Air quality and various gases are monitored through infrastructural and carry-on sensors. Data from the infrastructural sensors are available through the local database.

The electronic login system is used to monitor where people are working, and a two-way radio is used for internal and safety communications both on the surface and in the underground. The underground mine is monitored for mining-induced seismic events using a mine-wide micro-seismic network. The emergency communication is in Finnish, and thus all non-Finnish speakers need to be accompanied by Finnish-speaking staff.

In an emergency requiring evacuation, the underground mine is equipped with a main level survival station and intermediate level refuge shelters. These provide fresh air supply from compressed airlines and air bottles and shelter from smoke and other gases.

Pre-planning, risk analysis and mitigation, and well-trained personnel are the keys to successful and safe operations.

2.2.3 Current ownership and organisation

Table 1. The organisational structure of Callio and Callio Lab at the Pyhäsalmi Mine Ltd. premises.

	Pyhäsalmi Mine	**Callio – Mine for Business**	**Callio Lab – centre for underground R&D&I**
Legal entities	Pyhäsalmi Mine Oy	Kvanttikiinteistöt Oy, a subsidiary of town of Pyhäjärvi	Brand, coordinated by the University of Oulu, Finland
Rights to the infrastructure	Site owner	Contract with the Pyhäsalmi mine: exclusive right to reuse, rent and lease mine facilities.	Client of Callio
Permitting	Holder of mining, environmental, chemical permits	Operates within the permits of the site owner	Operates within the permits of the site owner

Types of Contracts		Business agreements
		• Project-based
		   • Coordination
		   • Cooperation
		   • Facilitation
		• Facility rent
		• Service agreements
			Research & education agreements
			• Coordination
			• Cooperation
			• Facilitation
			• Scientific instrument rental

Approval of operations	Final say	Business and development project proposal evaluation	Research & education project proposal evaluation
Relevant Authorities	TUKES – is a bundling authority. All other authorities are contacted via the mining authority. Valid as long as the site owner has a mining permit.		
Relevant law jurisdiction			
Responsible organising permitting	Site owner		
Language	Finnish, English Site´s emergency communications in Finnish	Finnish, English	Finnish, English
Contacts		Sakari Nokela (CDO) Chief Development Officer MINE FOR BUSINESS CALLIO – PYHÄJÄRVI, Town of Pyhäjärvi +358 40 180 9511 Sakari.Nokela@Pyhajarvi.fi	Jari Joutsenvaara Callio Lab research coordinator, Kerttu Saalasti Institute, University of Oulu +358 40 5569396 contact@calliolab.com

2.2.4 Underground access

There are two access routes to the underground mine infrastructure. The mine can be accessed via an 11-kilometre long and 1.4 km in depth incline tunnel. The incline can be accessed with all sizes of mining equipment and supply trucks. Most of the machinery is kept at the main level of the mine. The main level is accessible also via a Timonkuilu elevator. The elevator has two functions; it is used to transport ore from the bottom of the mine to the surface facilities (21.5-ton capacity, 15m/s) and provide access to the personnel. In personnel transport, its maximum speed is 12 m/s, which means 3 minutes is enough to get to the bottom of the mine. The elevator can accommodate a maximum of 20 people.

Figure 9. Timo Shaft is the 2001 opened hoist to the current main level of the Pyhäsalmi mine.

Various materials, devices, and other items can be transported to the interior of the mine by elevator or trucks. Via incline up to a 20-foot container can be transported (no weight limit in the incline).

Figure 10. The main level at a depth of 1 410 is spacious for large equipment. Photo W.H. Trzaska.

The journey by truck takes approx. 40 minutes. Smaller items can be transported through the elevator shaft (the elevator entrance measures 70 x 200cm) in less than 3 minutes.

2.2.5 Commuting

The Pyhäsalmi mine is locaten at the intersection of interstates E4/E75 and VT27, in Pyhäjärvi, Finland. The site is located within approx. 150 km from the regional airports and regional centres (Oulu, Kokkola, Jyväskylä, Kajaani, Kuopio), and only approx. 400 km north from the Helsinki/Vantaa airport. The journey from Helsinki-Vantaa airport to Callio Lab is approximately 5 hours by car or 6.5 hours by public transport (train and/or bus).

The nearest bus stop (Kaivos P) is 800 m away (10 min on foot) from the site, while the nearest train station is approx 5 km (6 min by car).

2.3 Research, innovation and cooperation possibilities

2.3.1 Innovation and research

For innovation and research, we provide access to a unique data and operational underground facility with typical Scandinavian bedrock conditions. The conditions are very well documented in reports, scientific articles and doctoral theses.

Callio Lab is a multidisciplinary R&D environment aiming to utilise better the unique infrastructure and facilities of the Pyhäsalmi Mine. At Callio Lab, various types of research are carried out in physics, biology, earth sciences, chemistry, mining technology, and underground construction and architecture. Callio Lab is a coordinator of the research community utilising the underground facilities of Callio for scientific research.

2.3.2 National and international cooperation

Callio Lab is a member of the European network of deep underground laboratories DULIA, and it is also a founding member of the European Underground Laboratories association (14). In 2020 Callio lab has been proposed as a candidate thematic core service for the European Plate Observation System (EPOS), which is an ESFRI status research infrastructure network (15). Callio Lab is also a member of Nordic and Finnish EPOS research infrastructures. It is also a strategic research infrastructure of the University of Oulu.

2.4 Support at the site and available database

2.4.1 Project handling, competencies and quality control

See table 1.

2.4.2 Database

See chapter 3.

3 Site description data and data properties

3.1 Geological bedrock data and properties

3.1.1 Deposit model

The Pyhäsalmi Zn-Cu ore deposit belongs to one of the best-understood ore deposit types, the volcanogenic massive sulphide (VMS) class of deposits (16). Deposits of this type typically constitute one or more lenses or sheets of polymetallic massive sulphide, typically comprising at least 60% sulphides (hence the name). The VMS deposits formed originally at or near the seabed in spatial, temporal and, in many cases, genetic association with deep-sea submarine volcanism (17–20) (Fig. 11). The tectonic setting is mostly an oceanic or continental arc or rifted arc (Fig. 12). Some deposits are formed in shallower basins related to back-arc settings.

The unifying factor between VMS deposits formed in different tectonic environments is that an extensional setting is required (e.g., (21). The immediate host rocks of VMS deposits can be volcanic or sedimentary, or both (Fig. 13). In Pyhäsalmi, the dense sulphide ore is constituted of a single flat, elongated, subvertical ore body surrounded by a sequence of volcanic rocks with minor sedimentary rock intercalations. However, before an event of mountain building and associated deformation, the Pyhäsalmi ore sequence formed a horizontal sequence (Figure 14).

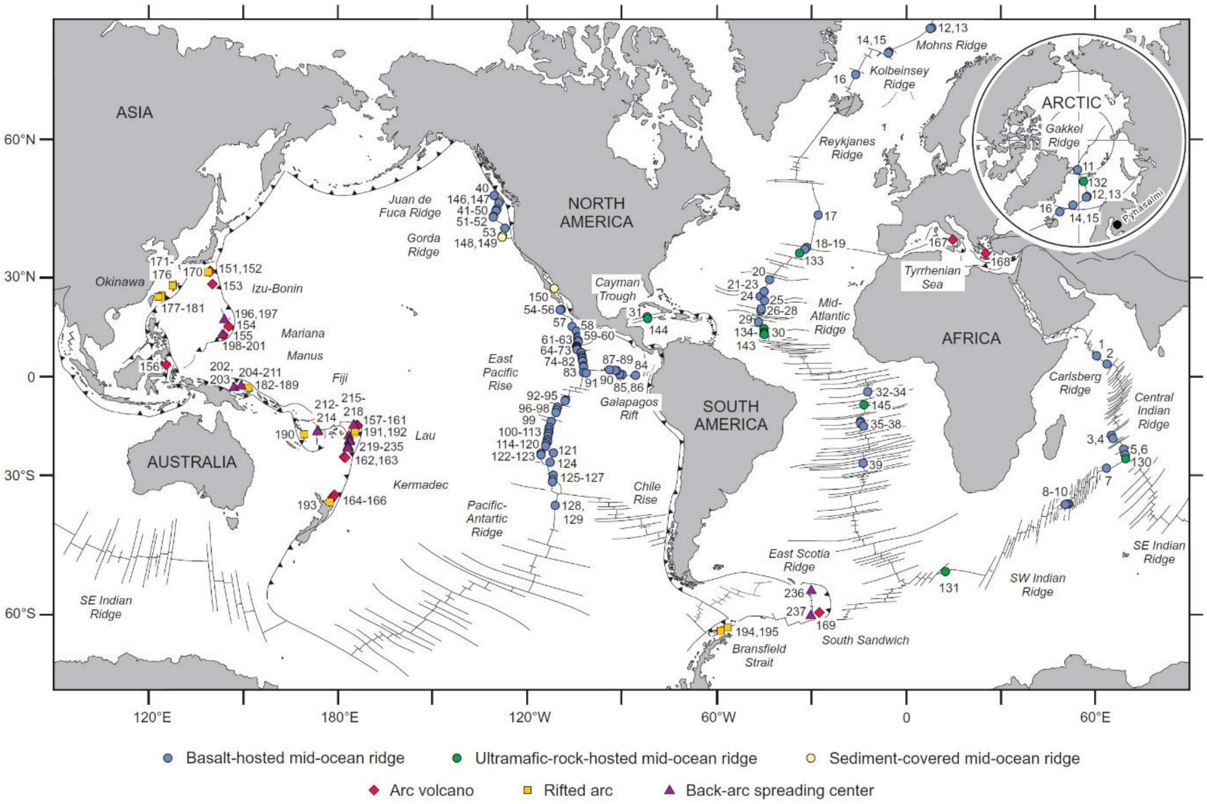


Figure 11. Locations of modern seafloor volcanic massive sulphide (VMS) deposits in the world's oceans. The distribution partly reflects the amount of seafloor exploration done in any region. Ancient VMS deposits have been destroyed by subduction underneath the continents or, much more rarely, thrust atop or on the margin of the continents. Many, if not

most, of the VMS deposits that escaped the subduction process of the seafloor and became part of the rock record associated with continents have subsequently been destroyed by erosion. The location of the ancient Pyhäsalmi VMS deposit is marked in the circular inset. Modified from (22).

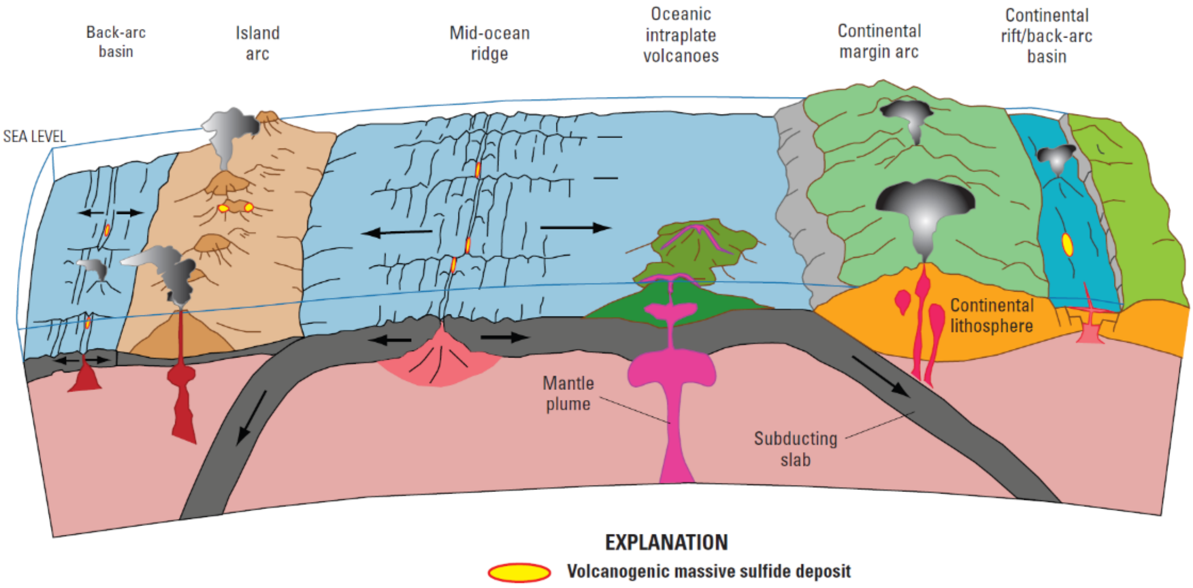


Figure 12. Schematic diagram showing volcanogenic massive sulphide deposits in divergent (mid-ocean ridge and back-arc basin) and convergent (subduction-related island arc and continental margin arc) plate tectonic settings. From (18).

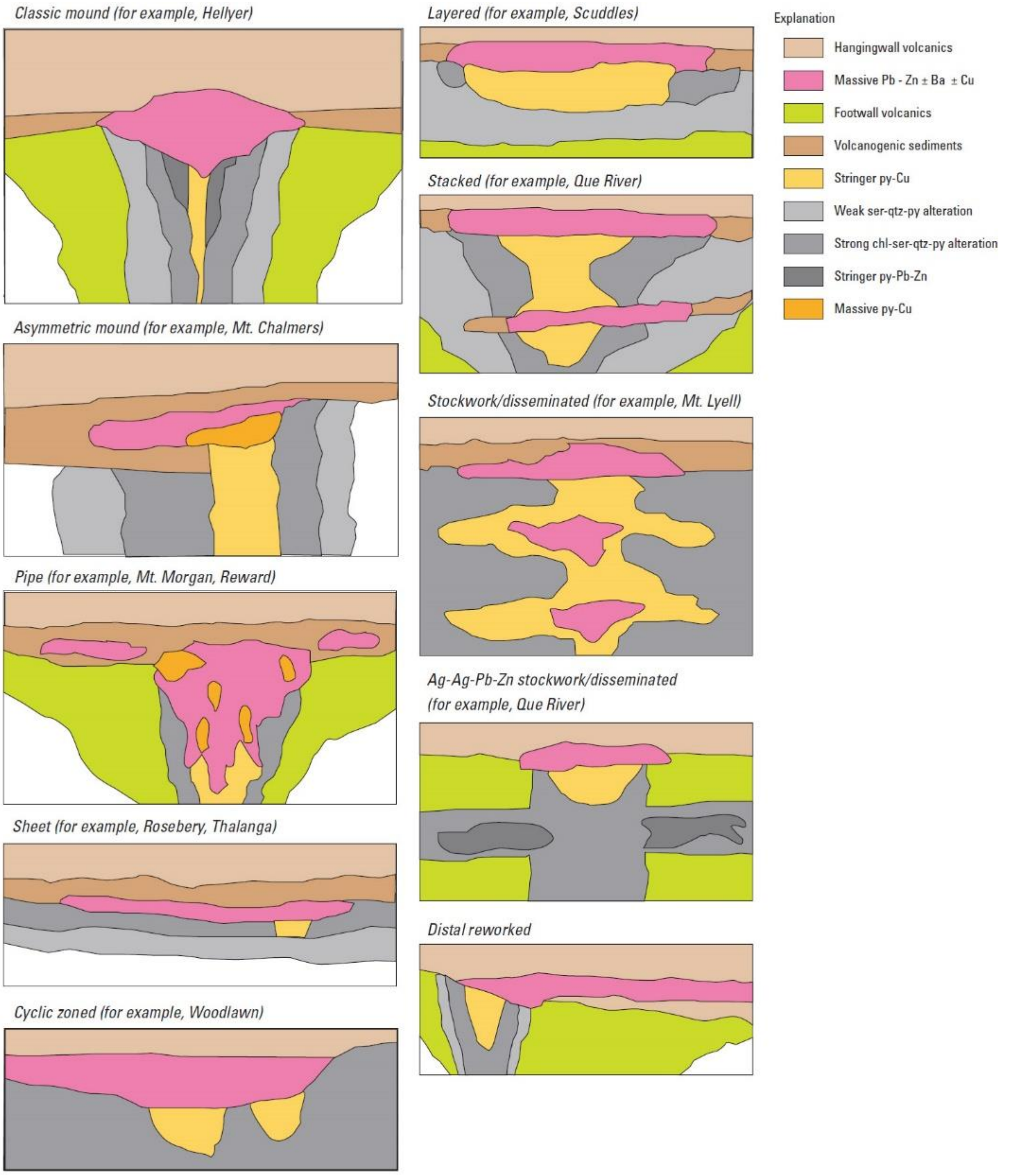


Figure 13. Schematic *presentation of different forms and styles of volcanogenic massive sulphide deposits before superimposed deformation, which may occur if the deposit survives long enough. However, most primary deposits become eventually subducted (see the previous figure). Nevertheless, some deposits have a chance to get thrust over continental lithosphere (particularly those formed in continent rifts/back-arc basins). Ag, silver; Ba, barium; Cu, copper; Pb, lead; Zn, zinc; chl, chlorite; py, pyrite; qtz, quartz; ser, sericite. From* (18).

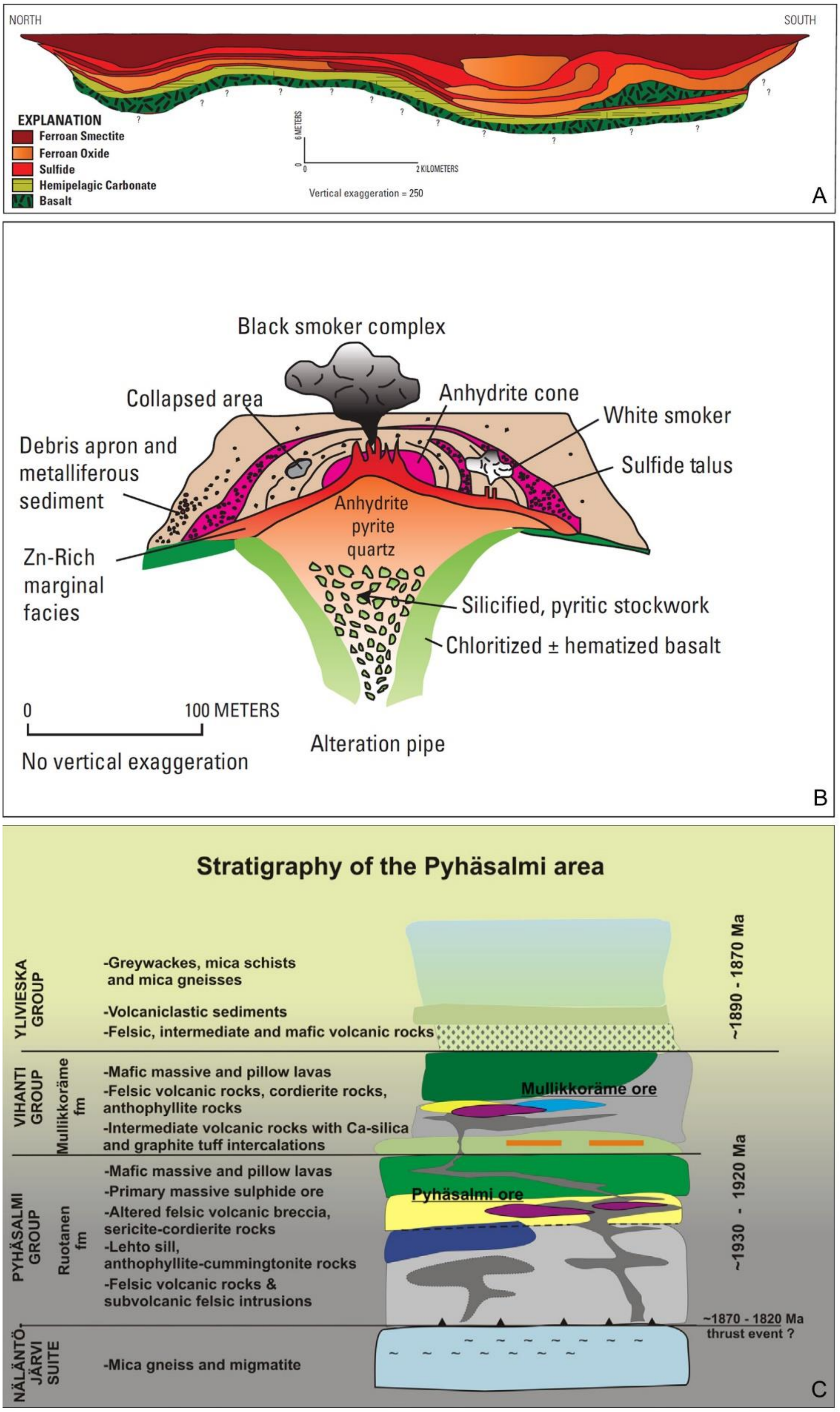


Figure 14. A) A representative example of a large modern seafloor massive sulphide deposit, metalliferous mud facies, Atlantis II Deep, Red Sea. From Shanks & Thurston (2012). B) Another representative example of a large modern seafloor massive sulphide deposit, Trans-Atlantic Geothermal (TAG) sulphate-sulphide mound, Mid-Atlantic Ridge. From Shanks & Thurston (2012). C) Stratigraphy of the Pyhäsalmi area. This is a reconstruction of the Pyhäsalmi stratigraphy before a mountain-building event and associated deformation. From (23).

At its present form, the Pyhäsalmi deposit begins from the ground surface and continuous to the depth of c. 1.5 km. However, the original deposit at or slightly below the seabed, some 1.93–1.92 billion years ago (23), was a roughly horizontal body of accumulated metal sulphides gathered around a series of active vent sites discharging high-temperature hydrothermal fluids to the cold seawater. Modern seafloor hydrothermal and black smoker systems at various types of spreading ridges (Fig. 15) are the closest equivalent of the processes and sites of how and where the different types of ancient VMS deposits once formed (24–28). The modern systems are located at fast-, intermediate-and slow-spreading mid-ocean ridges, on axial and off-axis volcanoes and seamounts, in sedimented rifts adjacent to continental margins and subduction-related back-arc environments (29).

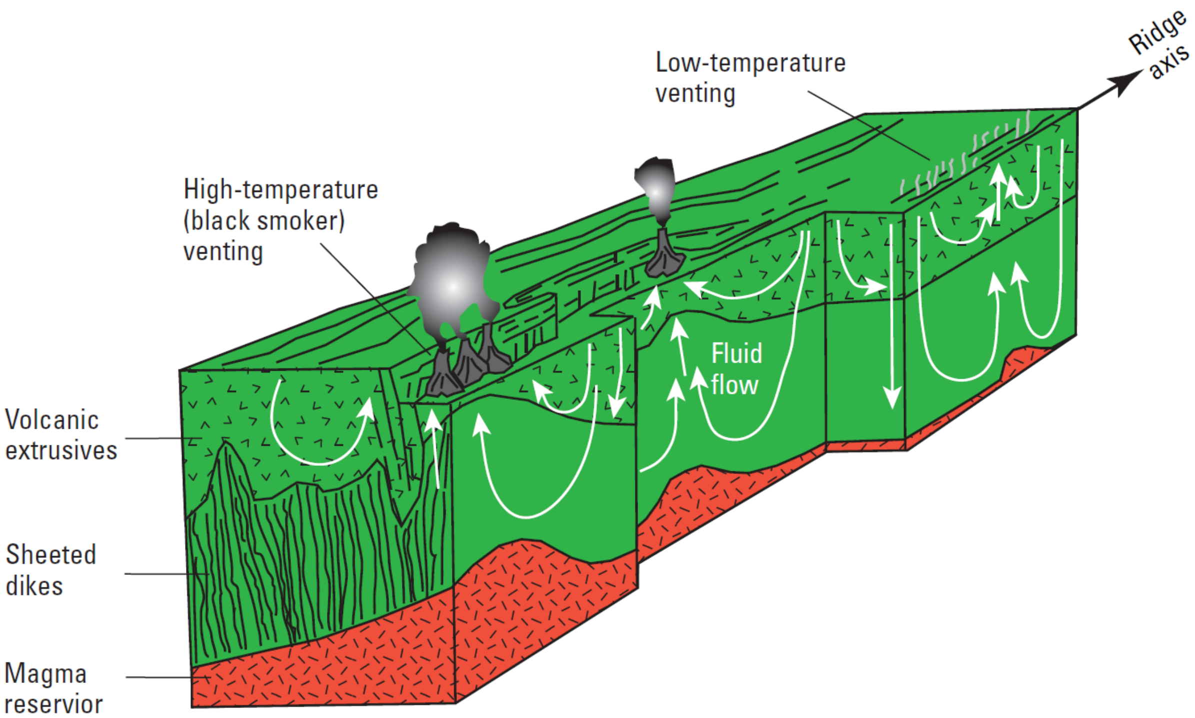


Figure 15. A schematic diagram shows hydrothermal fluid flow at a fast-spreading ridge (for example, East Pacific Rise). Note that high-temperature (black smoker) vents occur above shallower segments of the axial magma reservoir. This illustration is not a direct analogy for how the Pyhäsalmi VMS deposit formed, but it gives a realistic sense of how fluids circulate in the extensional seafloor. From (18).

The currently favoured genetic model of the Pyhäsalmi deposit involves many steps typical to the above-described VMS genesis. Without going into details, these can be summarised to those relating to the original formation of the deposit in a submarine island arc setting (e.g., primary sulphide accumulation and sub-seafloor hydrothermal alteration; for examples, see (30), and (23)) and subsequent closure of the host ocean basin due to tectonic plate movements (e.g., emplacement of the deposit to its present subvertical position; (23)). As a consequence of the ocean closure and an event of mountain building (the so-called Svecofennian orogeny), the rocks at Pyhäsalmi (including the ore) witnessed metamorphic recrystallisation, continental uplift, several periods of faulting and shearing, minor mafic and felsic magmatism, and a prolonged period of erosion (23,31,32). From the viewpoint of radionuclides, several of these stages bear potential importance in supplying and, in some cases, redistributing elements of natural radioactive decay series in Pyhäsalmi as the deposit and its host rocks were reshaped to its present form (Fig. 16 & 17). In the following, we will describe in more detail only those processes that fall into this category.

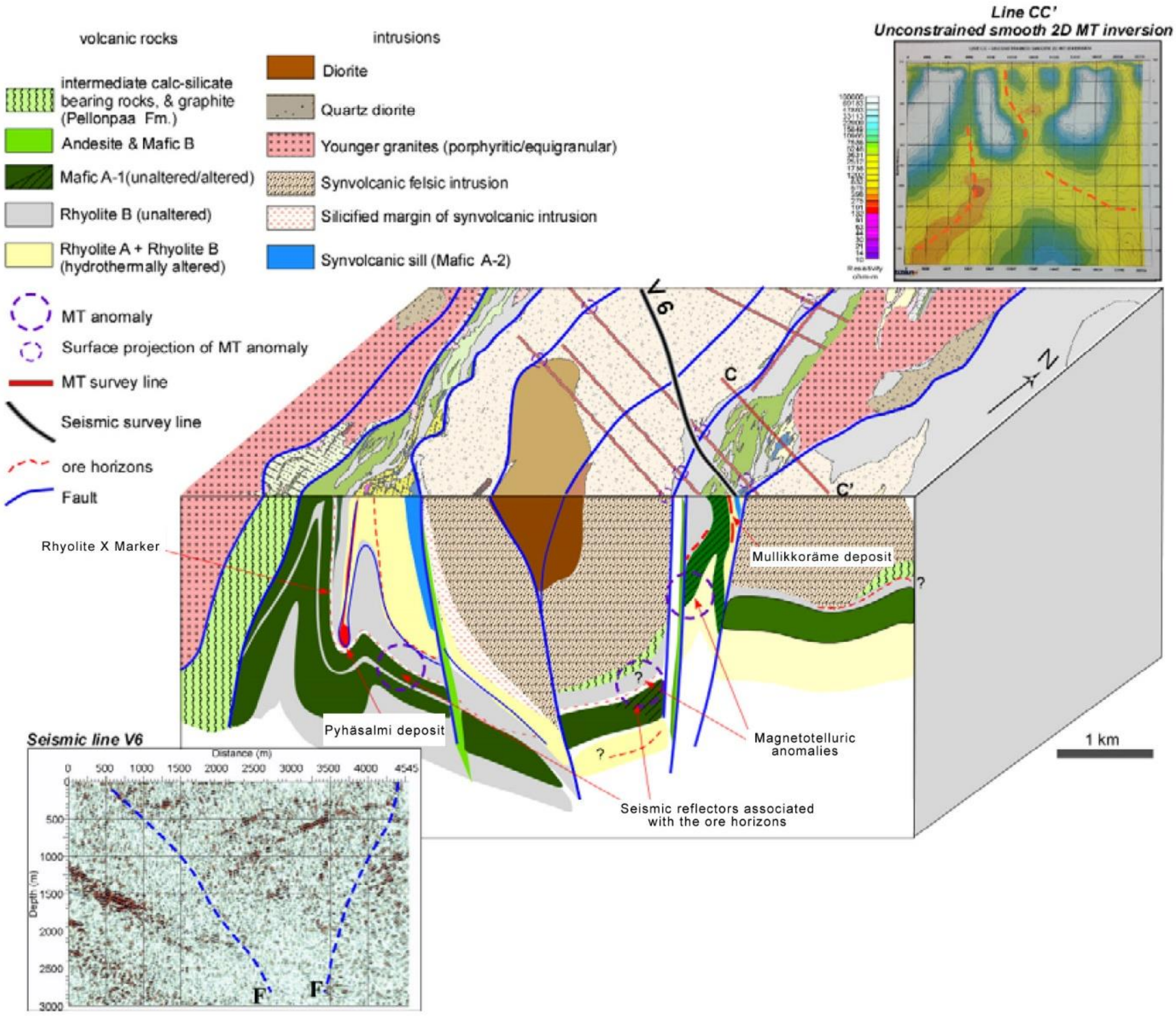


Figure 16. A 3D geological interpretation is representing the VMS exploration potential in the Pyhäsalmi district. From (33).

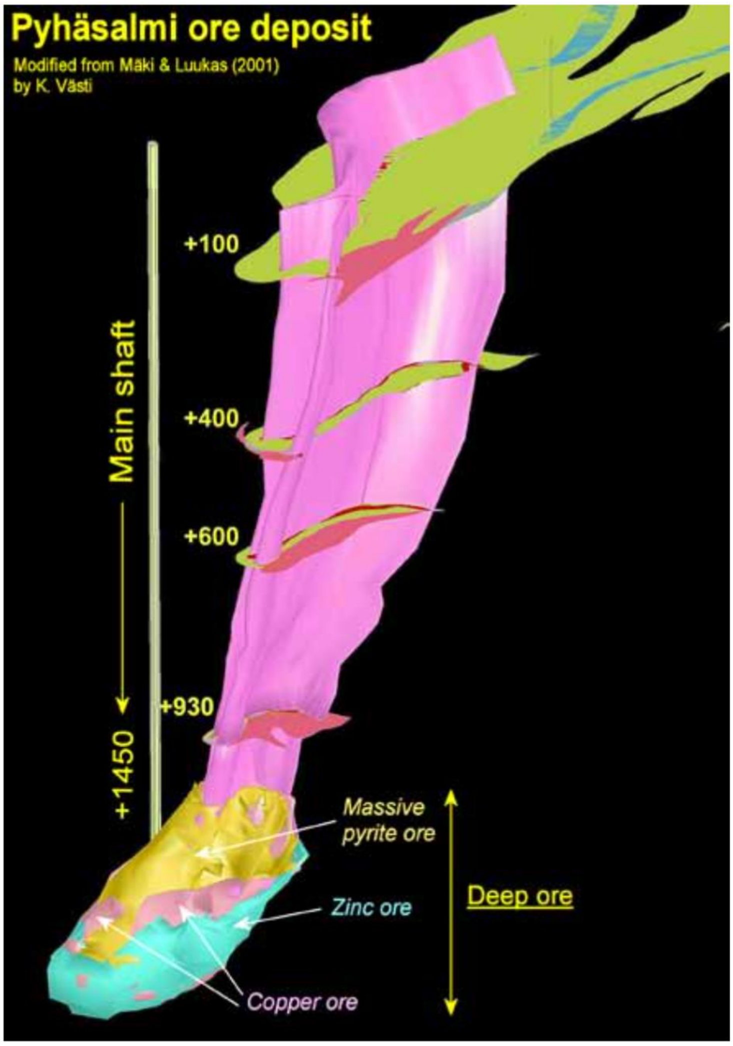


Figure 17. A 3D model of the Pyhäsalmi Zn-Cu deposit viewed from the southeast. From (34).

3.1.2 Geological location

The Pyhäsalmi mine is located in the Vihanti-Pyhäsalmi belt that is a moderate-size (~100 Mt) base metal mining camp (23,35). The upper part of the deposit has been eroded, exposing one flank of the original deposit to the surface. Currently, this surface is covered by a few meters thick section of Quaternary sediments, mainly clay and till. The Vihanti-Pyhäsalmi belt contains two large volcanogenic massive sulphide (VMS) deposits, namely the 75.7 Mt Pyhäsalmi and 28 Mt Vihanti deposits, and several smaller deposits and occurrences. Structurally the area belongs to the Raahe-Ladoga structural domain that represents a Paleoproterozoic collisional border between the Archaean continent in the east and Palaeoproterozoic island arc-type volcanic rocks in the west. The Pyhäsalmi VMS deposit is hosted by a bimodal suite of 1.93–1.92 Ga rhyolitic and basaltic volcanic rocks metamorphosed in a lower amphibolite to upper amphibolite facies conditions.

The Pyhäsalmi VMS deposit forms an elongated accumulation of base metal sulphides stretching from the current erosional level to 1400 m depth. The deposit has a flat, subvertical shape. It can be subdivided into two ore bodies separated by a shear zone: the upper ore body is 1000 m long, 150–650 m wide, and 10-60 thick and extends from the surface to about 1000 m depth, whereas the deep ore forms a 300–400 m wide and 200–300 m thick "potato"-shaped sulphide body between about 1000 m and 1400 m depths. The mined ore contains on average 0.92% Cu, 2.45% Zn, 37.4% S, 0.4 g/t Au and 14 g/t Ag (23).

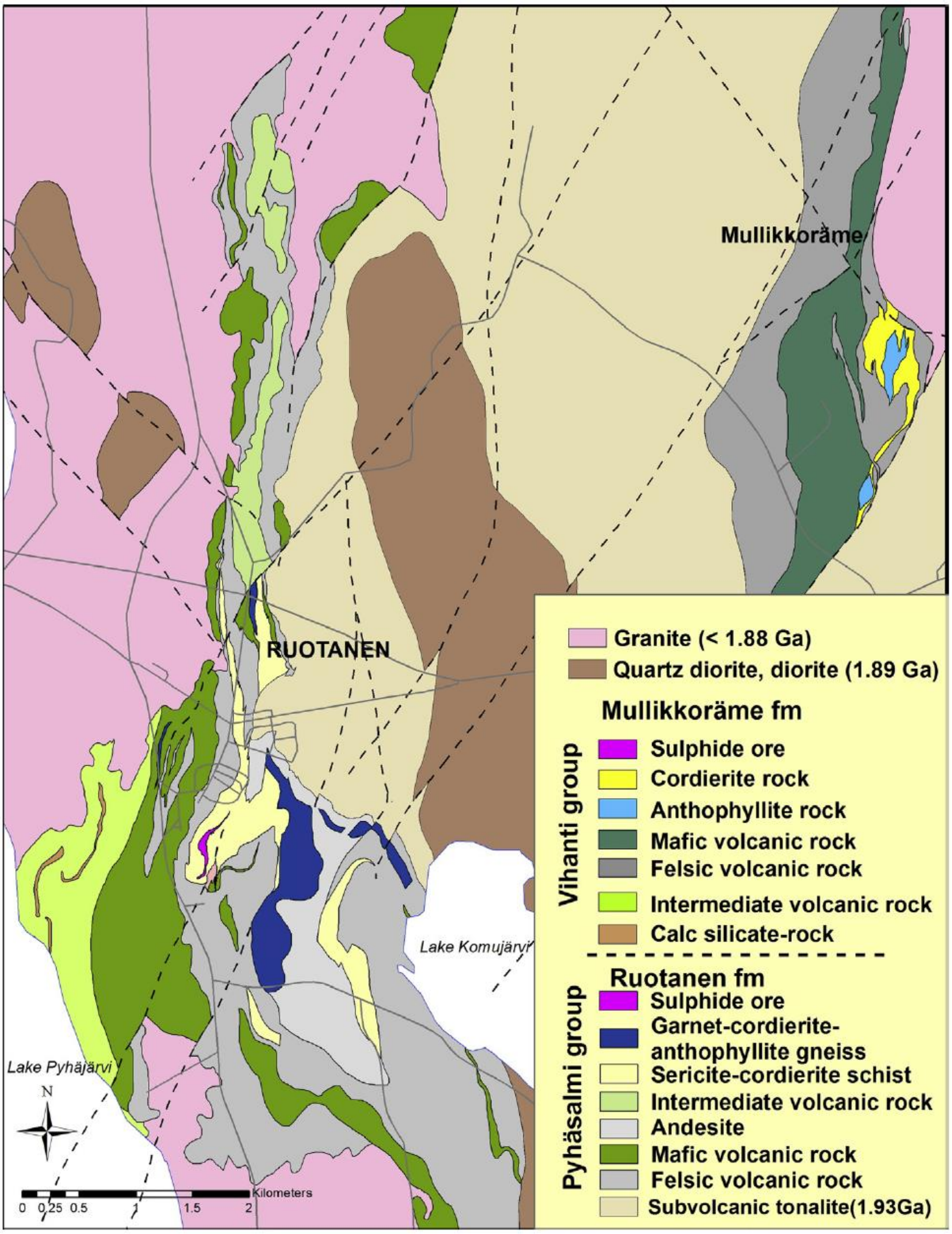


Figure 18. Geology of the Pyhäsalmi-Mullikkoräme area. The Mullikkoräme is another Pyhäsalmi-like VMS deposit. From (23).

3.1.3 Major rock types and their properties

3.1.3.1 Mineralogical properties and geological conditions

Mineralogically speaking, the ore is characterised by massive pyrite and subordinate amounts of sphalerite, chalcopyrite, pyrrhotite, dolomite, calcite and baryte. There also occur minor amounts of arsenopyrite, bournonite, electrum, galena, gold, hessite, jordanite, magnetite, marcasite, molybdenite, seligmannite and tetrahedrite.

A significant proportion of sulphide mineralisation occurs within the domain of hydrothermally altered Rhyolite B unit (Fig. 19). This pervasively altered unit extends to more than 1 km depth and represents strong alkali (Ca and Na) depletion and significant enrichment in Fe, K, Mg, Si and Ba with local Cu and Zn (31). Altered rock types are mainly in the form of sericite schist and cordierite-anthophyllite rock. Alteration patterns regarding the deep ore are presented in Fig. 20. The present metamorphic mineral assemblages are dominated by muscovite, cordierite, quartz, biotite and baryte. Other wall rocks include mica schist, felsic tuff, tholeiitic basalt and dolomitic marble. The trace element geochemistry of the volcanic rocks indicates a mature island arc setting during submarine volcanism.

The host sequence is cut by several late unaltered mafic dykes enriched in Au and As. In addition, there occur voluminous pegmatite dykes relating to D_4 faulting near the eastern tectonised contact of the deposit, especially alongside the deep ore. Drill hole data from greater than 1400 m indicate that mafic volcanic rocks dominate the bedrock underneath the deep ore. These comprise interlayers of felsic volcanic rocks, pegmatite, tonalite and skarn (23). Table 2 summarises the mineralogical compositions and typical density ranges of the main rock types in the Pyhäsalmi mine.

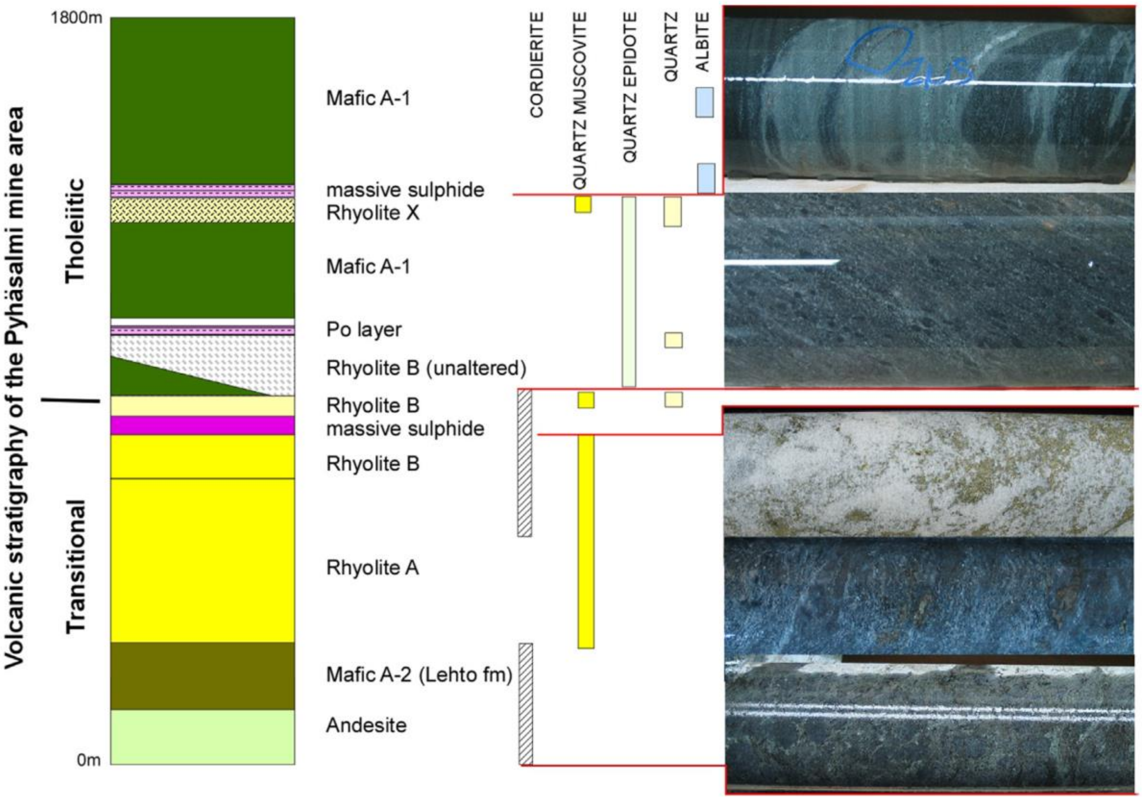


Figure 19. Chemostratigraphy and alteration of the Pyhäsalmi mine area. A significant proportion of sulphide mineralisation occurs within hydrothermally altered Rhyolite B rocks. From (23).

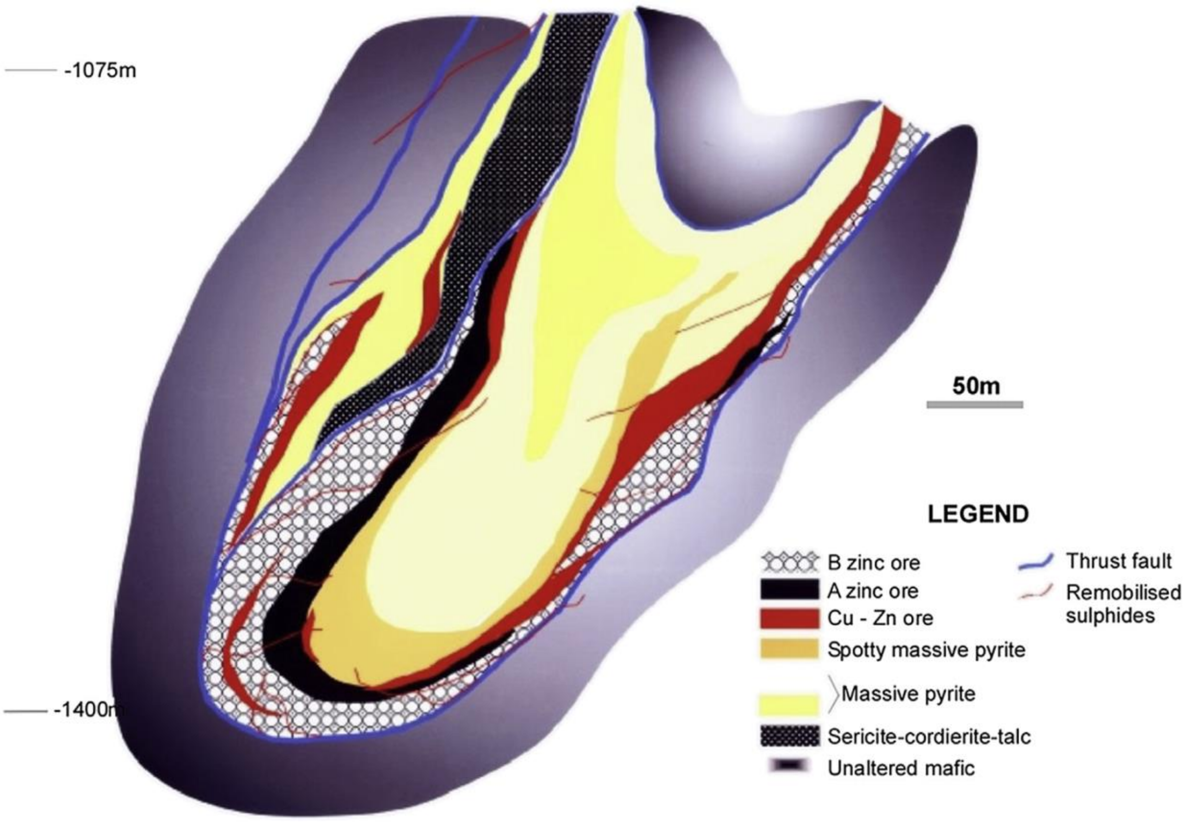


Figure 20. Hydrothermal alteration and ore zonation in the deep ore body. From (23).

Table 2. Overview of the mineral components in the Pyhäsalmi VMS deposit. Only the most important accessory minerals are included. Most densities are from (23).

Rock/formation	**Main mineral content**	**Formula**
Felsic volcanic rocks (rhyolites) ~2.72 g/cm³ (all), ~2.71 g/cm³ (unaltered), ~2.76 g/cm³ (altered, no sulphides), ~2.84 g/cm³ (altered, with sulphides), ~2.92 g/cm³ (altered sericite-quartz schist)	Quartz	SiO_2
	Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$
	Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$
	Feldspar (albite plagioclase)	$Na(AlSi_3O_8)$
	Cordierite	$(Mg,Fe)_2Al_4Si_5O_{18}$
	Sillimanite	Al_2SiO_5
	Hornblende (in unaltered varieties)	$(Ca,Na)_{2-3}(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH,F)_2$
	+ occasionally some sulphides	
Mafic volcanic rocks (basalts) ~2.92 g/cm³ (all), ~2.94 g/cm³ (unaltered), ~2.85 g/cm³ (altered, no sulphides), ~3.14 g/cm³ (altered, with sulphides)	Orthoamphibole (anthophyllite)	$(Mg,Fe)_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
	Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$
	Cordierite	$(Mg,Fe)_2Al_4Si_5O_{18}$
	Garnet	$X_3Z_2(SiO_4)_3$, wherein X = Mg, Ca, Fe(II), Mn(II), etc., and Z = Al, Fe(III), Cr(III), V(III), etc.
	Sillimanite	Al_2SiO_5
	Plagioclase	$Ca(Al_2Si_2O_8)$
	Quartz	SiO_2
	+ occasionally some sulphides	
Pegmatite ~2.68 g/cm³	Potassium feldspar	$KAlSi_3O_8$
	Quartz	SiO_2
Sulphide ore (VMS) ~3.49 to 4.55 g/cm³	Pyrite (most voluminous main mineral)	FeS_2
	Sphalerite (main mineral)	ZnS
	Chalcopyrite (main mineral)	$CuFeS_2$
	Pyrrhotite (main mineral)	$Fe_{1-x}S$, wherein x = 0 to 0.17
	Dolomite (main mineral)	$CaMg(CO_3)_2$
	Calcite (main mineral)	$CaCO_3$
	Sericite	$KAl_2(AlSi_3O_{10})(OH)_2$

	Baryte (main mineral)	$BaSO_4$
	Arsenopyrite (accessory mineral)	FeAsS
	Bournonite (accessory mineral)	$PbCuSbS_3$
	Galena (accessory mineral)	PbS
	Magnetite (accessory mineral)	Fe_3O_4
	Molybdenite (accessory mineral)	MoS_2

3.1.3.2 Stress field conditions

The three main rock types of Pyhäsalmi mine are mafic volcanic rock ('volcanite'[1]), felsic volcanic rock and pegmatite. Due to the deepness of the Pyhäsalmi mine (its maximum depth is nearly 1.5 km), the deep parts of the mine are surrounded by rocks with high in-situ stress. Such high-stress rocks are vulnerable to breaking into "discs" when they are drilled. Rock core discing is common when drilling through a rock mass with high in-situ stress (e.g., (37)). Figure 21 summarises how the discing develops and illustrates how it is witnessed in Pyhäsalmi.

[1] In Finnish, the term 'volcanite' is widely used, but in English it is an obsolete term and not to be recommend. A 'volcanite' simply means 'volcanic rock'.

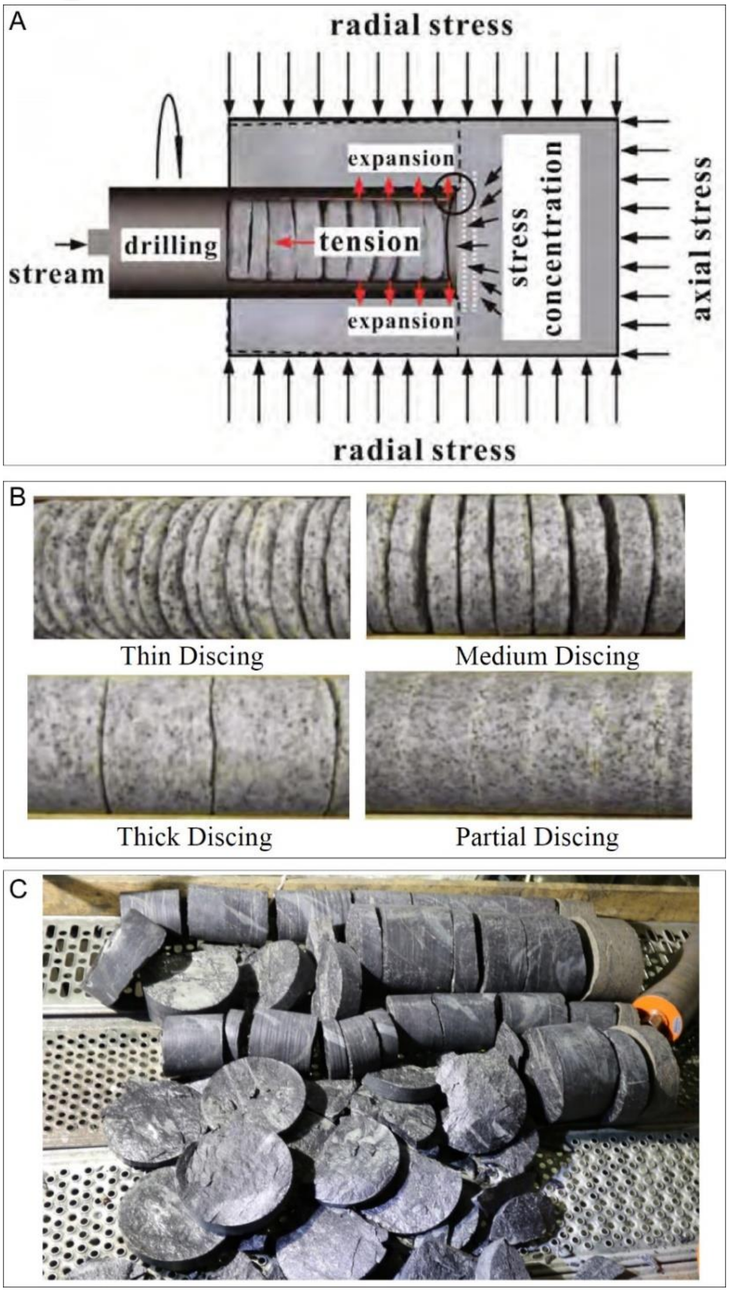


Figure 21. A) The formation process of core discing (37). B) Manifestation of core discing ((37). C) Partial, thick and medium (if not thin) discing in the Pyhäsalmi drill cores from PH3 and PH4 holes. From Rockplan (38).

Rockplan report describes in-situ stress measurements conducted with LVDT-cell in Pyhäsalmi Mine for the LAGUNA project (38). The measurements were carried out in very high-stress conditions to obtain a realistic understanding of the maximum stress field in the mine. For the unconstrained solution, the interpreted mean maximum in-situ stress component σ1 is 65 MPa. This component has an almost horizontal plunge of 7° and a trend of 124° clockwise from North. The intermediate principal stress σ2 is 53 MPa, while the minor principal stress σ3 is 31 MPa. Intermediate and minor principal stresses are rotated 55°/35°around the maximum principal stress. According to Rockplan, this may result from geometrical constraints resulting from limited coverage of measurement holes around the tunnel perimeter. The vertical component is 7% higher than the weight of overburden (38).

3.1.3.3 Strength and deformation properties of the rock

When excavating open space within a rock mass, it is vital to understand the strength and deformation properties of the said rock. This is essential not only from the excavation point of view but also from that of reinforcement. Many parameters falling to this category have been reported in a report by Rockplan (38). The various tests and measurements performed on 44 core samples from holes PH102, PH103, PH104, and PH106 were uniaxial compressive strength, tensile strength, Young's modulus, Poisson's ratio, density, thermal expansion coefficient, thermal conductivity and specific heat capacity. Average values of the first five parameters are given in Table 3. Results of the other parameters are given in the next section.

For construction and engineering, volcanic rocks are the most favourable in Pyhäsalmi (39). They are strong and form large, identifiable domains around the mine. Pegmatite is considerably weaker, and its presence is somewhat random within the rock mass. Although pegmatite does not have similarly built-in weakness planes than volcanic rocks, such as foliation planes, it has a higher variation in grain size. Thus, when considering only the rock matrix, pegmatite is the weakest of the principal rock types. However, the mica rich foliation planes of the volcanic rocks have even lower uniaxial compressive strength values. Other rock types are rare in the mined area and are usually concentrated close to graphite formations.

Felsic volcanic rocks in Pyhäsalmi have more variation in the mineral structure than their mafic counterparts. They also are more strongly foliated. All in all, foliation planes are potential zones of weakness. Especially graphite and/or micas along foliation planes strongly weaken compressive strength. Hence, constructing wherever they are known to appear is to be avoided. In addition, when planning new caverns, it is recommended to consider the foliation orientation as a distinct weakness plane of the rock.

Table 3. Average values of strength and deformation properties of the rock types at Pyhäsalmi mine. Standard deviation is given in brackets. N = number of samples. Note that the term 'volcanite' means 'volcanic rock' from Rockplan (38).

Rock type (number of samples)	Unit weight (kg/m3)	Young's Modulus (GPa)	Poisson's Ratio	Compressive Strength (MPa)	Tensile strength (MPa)
Mafic Volcanite (N=9)	2857 (132,3)	94,10 (22,1)	0,24 (0,02)	225 (98,1)	13 (4,04) N=18
Mafic volcanite with graphite (N=1)	2770 (-)	55,90 (-)	0,15 (-)	104 (-)	7 (2,6) N=2
Altered mafic volcanite (N=1)	2810 (-)	79,60 (-)	0,22 (-)	147 (-)	12 (2,7) N=2
Mixed volcanite (N=1)	2690 (-)	75,00 (-)	0,24 (-)	227 (-)	16 (0,4) N=2
Red granite (N=3)	2430 (72,1)	29,40 (25,3)	0,18 (0,09)	80 (67,5)	4,46 (3,01) N=6
Felsic volcanite (N=15)	2769 (190,1)	71,60 (16,5)	0,18 (0,06)	158 (79,4)	13 (3,7) N=30
Banded felsic volcanite (N=2)	3110 (28,3)	115,60 (4,4)	0,25 (0,03)	289 (149,8)	17 (2,4) N=4
Pegmatite (N=7)	2619 (32,4)	69,00 (10,4)	0,21 (0,03)	144 (36,8)	9 (2,0) N=14
Sericite quartzite (N=1)	2690 (-)	41,30 (-)	0,1 (-)	135 (-)	12 (0,8) N=2

3.1.3.4 Thermal properties and conditions

The thermo-mechanic properties of the rock are studied by analysing thermal expansion factor (1/K), specific heat coefficient (kJ/kg*K), heat conductivity (W/m*K) and thermal diffusivity (m²/s). The Rockplan report contains results from thermo-mechanic property analyses on selected representative rock type samples from drilled cores (Ø50.6 mm) from the Pyhäsalmi mine (39). A list of the studied core samples is presented in Table 4.

Table 4. List of samples that have been studied by thermal analysis. Note that the term 'volcanite' means 'volcanic rock' from (39).

Hole/ID	Depth (m)	Rock Type	Description of sample
#107/301	48.22-48.73	Pegmatite	Light coloured, coarse-grained. Contains some biotite.
#102/302	132.22-132.65	Mafic volcanite	Very fine-grained, dark, massive. Dominant of dark minerals is amphibole.
#104/303	252.85-253.36	Felsic volcanite	Quite fine-grained, light coloured, massive. Poor in micas.
#105/304	115.43-115.87	Mafic volcanite	Mafic/intermediate, banded. Rich in mica.
#102/305	305.60-306.10	Felsic volcanite	Felsic/intermediate, banded. Average amount of mica.
#102/306	201.20-201.66	Pegmatite	Light coloured, coarse-grained. Contains some biotite.
#104/307	378.54-378.92	Pegmatite	Light coloured, coarse-grained. Contains some biotite. Mineral-filled/weathered micro fractures.
#104/308	226.72-227.10	Pegmatite	Light coloured, coarse-grained. Contains some biotite.
#107/309	115.33-115.64	Pegmatite	Light coloured, medium-grained. Contains some biotite.
#102/310	230.26-230.78	Mafic volcanite	Fine-grained, dark, M1, rich in micas.
#107/311	76.23-76.49	Mafic volcanite	Fine-grained, banded. Mica gneiss with strong schistosity. Mica alteration.
#103/312	539.53-540.00	Felsic volcanite	Fine-grained, light coloured, massive. Poor in mica.
#103/313	305.07-305.46	Felsic volcanite	Fine-grained, grey, oriented L2. Rich in micas.
#105/314	169.49-169.77	Banded felsic volcanite	Fine- to medium-grained, mixed, banded. HVULK and EVULK alternates.
#103/315	393.98-394.38	Mica gneiss	Medium-grained, mixed and banded with thick mica layers and sections.

Thermal expansion (1/K) is the tendency of a material to change in volume in response to a change in temperature through heat transfer. Table 5 shows the results from the thermal expansion tests. The coefficient is the highest in pegmatites and the lowest in mafic volcanic rock. The complete thermal expansion results are in Appendix D4-II of Rockplan (39).

Table 5. Summary of the results from the thermal expansion tests. Note that the term 'volcanite' means 'volcanic rock' from Rockplan (39).

Hole/ID	Rock type	Thermal expansion [1/K]
107/301	Pegmatite	8.60E-06
102/302	Mafic volcanite	7.80E-06
104/303	Felsic volcanite	8.30E-06
105/304	Mafic volcanite	8.10E-06
102/305	Felsic volcanite	1.00E-05
102/306	Pegmatite	1.00E-05
104/307	Pegmatite	9.80E-06
104/308	Pegmatite	1.10E-05
107/309	Pegmatite	7.90E-06
102/310	Mafic volcanite	9.20E-06
107/311	Mafic volcanite	7.00E-06
103/312	Felsic volcanite	8.40E-06
103/313	Felsic volcanite	8.50E-06
105/314	Felsic volcanite	8.20E-06
103/315	Mafic volcanite	8.40E-06

Thermal conductivity (λm, [Wm-1K-1]) is the quantity of heat transmitted through a unit thickness in a direction normal to a surface of the unit area due to a unit temperature gradient under steady-state conditions. A selection of Pyhäsalmi samples has been studied for this parameter, which has been compiled in the Rockplan study (39). Inaccuracies in thermal conductivity values are considered to be smaller than ±5 %. The results of the thermal conductivity tests are shown in Table 6. The highest value is found in pegmatite. It appears that the thermal conductivity of volcanic rocks decreases with the increasing content of dark (mafic) minerals in the rock.

Table 6. Results of the thermal conductivity tests. From Rockplan (39).

Hole/ID	**Thermal conductivity (λ_m)** [W m^{-1} K^{-1}]
107/301	2.87
102/302	1.95
104/303	2.77
105/304	1.74
102/305	2.52

Specific heat capacity (cp, [Jkg-1K-1]) is the amount of heat energy required to raise the temperature of a body per unit of mass. The sample is heated in boiling water to a known temperature and placed into a calorimeter containing a weighted amount of water. The final equilibrium temperature of the calorimeter-water-sample system is then measured. Specific heat capacity is calculated from the initial and final temperatures of the sample and calorimeter (final temperature about 60°C), the heat capacity of the calorimeter, and the masses of water and sample. The method used by Rockplan has an inaccuracy of less than ca. 5 % or smaller (39). Repeatability is ca. 3-5 %. The specific heat capacity test results of Rockplan's report are shown in Table 7 (39). The highest value is found in a sample of pegmatite, the lowest in a felsic volcanic rock. However, there seems to be no correlation between specific heat capacity and rock type.

Table 7. Results of the specific heat capacity tests. From Rockplan (39).

Hole/ID	**Specific heat capacity (c_p)** [J kg^{-1} K^{-1}]
107/301	758
102/302	731
104/303	725
105/304	738
102/305	757

Thermal diffusivity (a, m²/s) measures the ability of a substance to transmit a temperature difference. It is the thermal conductivity divided by density and specific heat capacity at constant pressure. This parameter is determined indirectly by using measured thermal conductivity, specific heat capacity and density values. The method has an error of about ±10 %. Thermal diffusivity values for a selected collection of rock samples from Pyhäsalmi are shown in Table 8. As the mafic rock types are denser than felsic ones, their thermal diffusivity values are lower than those calculated for felsic rocks.

Table 8. The density and diffusivity of the selected rock samples from Pyhäsalmi. From Rockplan (39).

Hole/ID	Density **D** [kg m^{-3}]	Diffusivity **a** [$m^2 s^{-1}$]
107/301	2642	1,43E-06
102/302	2970	8,96E-07
104/303	2640	1,45E-06
105/304	2954	7,99E-07
102/305	2696	1,23E-06

3.1.3.5 Radionuclide data

Radionuclides are of importance for both occupational safety and for users looking for low natural background radiation environments. The radioactivity of the rock is evaluated by measuring the natural gamma radiation from rock samples. Only those radionuclides and their decay products that have half-lives close to the age of the Earth can still be found in the rock today. Rockplan reports radiogenic measurements from 20 drill core samples (Ø50.6mm), each approximately 10 cm long. Table 9 describes the studied samples. Figure 22 shows a photograph of the analysed samples. (39).

Table 9. Description of the samples of radiogenic measurements from Pyhäsalmi (39).

Hole/ID	Depth (m)	Rock type	Description of sample
#102/201	255.84-255-95	Pegmatite	Light coloured granitic pegmatite
#107/202	114.93-115.02	Granite	Light coloured granite of medium grain size
#104/203	235.24-235.33	Pegmatite	Light coloured granitic pegmatite
#105/204	194.03-194.12	Pegmatite	Light coloured granitic pegmatite with low abundance of biotite
#102/205	92.75-92.88	Mafic volcanite	Very fine grained, dark colour, slightly foliated. Mainly amphiboles
#102/206	230.26-230.38	Mafic volcanite	Very fine grained, dark colour, slightly foliated, biotite-rich
#106/207	49.06-94.14	Mafic volcanite	Very fine grained, migmatized. Mainly amphiboles in the dark material
#102/208	331.90-332.00	Felsic volcanite	Medium grain size, grey coloured, strongly sericitified quartz porphyry. Slightly foliated and migmatized
#102/209	198.40-198.60	Banded felsic volcanite	Medium grain size, grey coloured volcanite with banded structure. Slightly foliated
#104/210	243.31-243.41	Mafic volcanite	Medium grain size, grey coloured hornblende porphyrite. Slightly foliated.
#103/211	539.90-540.00	Felsic volcanite	Fine grained, light coloured, massive. Low abundance of mica
#103/212	601.77-601.89	Felsic volcanite	Fine grained, light coloured, massive. Low abundance of mica
#102/213	295.10-295.21	Felsic volcanite	Medium sized grains, banded structure with leucosomes. Lots of sulphides
#102/214	185.28-185.40	Banded felsic volcanite	Banded mica gneiss. Medium grain size, migmatized. Biotite-rich.
#104/215	178.77-178.86	Banded felsic volcanite	Fine grained, grey coloured, banded structure and migmatized. Contains amphiboles and stripes of micas and some sulphides.
#102/216	52.59-52.69	Mafic volcanite	Medium grain size, grey coloured, some bandening. Intermediate composition with rather massive texture. Contains micas.
#104/217	152.82-153.00	Mafic volcanite	Very fine grained. Dark colour, mostly amphiboles. Includes some bands with felsic composition and sulphides. Rather massive texture with a weak foliation
#104/218	371.77-371.85	Felsic volcanite	Medium grain size, grey colour, banded and migmatized structure. Some biotite and sericite.
#105/219	233.77-233.85	Mafic volcanite	Fine grain size, grey colour, banded and foliated. Includes bands of micas.
#104/220	436.77-436.86	Felsic volcanite	Medium grain size, grey color, massive texture and some migmatization. Contains somewhat micas

According to the report of Rockplan (2014b), the 200 Bq/kg limit for ^{238}U and ^{232}Th is only exceeded in samples 202 (granite) and 203 (pegmatite). Legal radiation index (L1) higher than 1.0 is found from samples 202 and 214. Moderate L1 values (0.2…1.0) are observed in all the selected rock types. However, it appears like the mafic volcanite has a better tendency to hold low (≤0.2) L1 values. Results of the gamma-ray spectra analyses are shown in Table 10.

Figure 22. A photograph of the analysed radiogenic samples. From Rockplan (39).

Table 10. Results from the gamma-ray spectra analyses. 232Th and 238U values greater than 200 Bq/kg and L1 values greater than 1 are marked with red colour. L1 values less than 0.2 are marked with green colour, from Rockplan (39).

Hole/ ID	Rock type	^{40}K		^{214}Bi		^{226}Ra		^{232}Th		^{238}U		L1
		Bq/kg	*Err.*	*Bq/kg*	*Err.*	*Bq/kg*	*Err.*	*Bq/kg*	*Err.*	*Bq/kg*	*Err.*	
102/201	P	1391	2	65	2	73	1.4	17	6	ND	-	0.79
107/202	G	166	5	531	1	588	1	60	4	902	3	2.31
104/203	P	1355	2	110	0.8	121	1.2	17	3	198	8	0.94
105/204	P	1857	1.4	14	2	15	2	4	14	ND	-	0.69
102/205	M	167	3	17	4	19	3	3	25	ND	-	0.13
102/206	M	651	2	15	2	17	3	19	3	ND	-	0.37
106/207	M	163	3	2	16	3	11	1.1	39	ND	-	0.07
102/208	F	391	3	39	2	43	3	38	9	57	26	0.46
102/209	B	665	2	20	4	22	3	21	6	ND	-	0.40
104/210	M	384	2	32	2	35	2	24	3	32	19	0.37
103/211	F	430	3	15	4	15	4	12	8	ND	-	0.25
103/212	F	780	2	20	3	24	2	15	6	ND	-	0.42
102/213	F	61	5	64	1.3	72	1.2	14	5	86	23	0.33
102/214	B	605	2	159	1.2	178	1.1	44	4	107	49	1.01
105/215	B	98	5	20	3	21	10	1.1	20	32	21	0.11
102/216	M	632	2	23	4	25	3	26	6	ND	-	0.42
105/217	M	99	4	47	2	50	2	ND	-	ND	-	<0.21
105/218	F	330	2	19	3	23	2	21	4	ND	-	0.30
105/219	M	148	4	1.5	23	1.5	24	0.9	25	ND	-	0.06
104/220	F	439	3	30	4	35	4	51	5	85	19	0.52

ND = Not Detected (below the detection limit)

Err. = Uncertainty (%) of one (1) standard deviation precision

Rock type: P=Pegmatite, G=Granite, M=Mafic volcanite, F=Felsic volcanite, B=Banded felsic volcanite

L1 = 226Ra/300 + 232Th/200 + 40K/3000

3.1.4 Data sources

3.1.4.1 General information

Many surface data regarding regional geology, the Pyhäsalmi VMS deposit and the mine proper are digitally and without charge from the Geological Survey of Finland (GTK). Most of the datasets can be either downloaded for desktop usage (https://hakku.gtk.fi/en) or used with the online platforms of GTK (such as the Mineral Deposits and Exploration, Fennoscandian Mineral Deposits application, ore deposits database and metallogenic map, and Bedrock of Finland online map services). All these three online data sources are described below. Datasets include, for example, bedrock maps, geochemical point data and various types of airborne and ground geophysics. At the time of writing, there are various online services available on this page: https://www.gtk.fi/en/services/data-sets-and-online-services-geo-fi/map-services/. The following data types are available from Hakku:

- **GTK Publications, reports, maps and posters** at https://hakku.gtk.fi/en/reports
  - Information about all archive reports drawn up by GTK and handed over to it, and maps and research publications were published by GTK. The approximate number of full texts in PDF format is 13,500
  - This search service includes metadata of all publications produced by GTK, archive reports drawn up by or handed over to GTK, and maps and map sheet legends
  - Almost all products can be downloaded through the service for free
- **Spatial data products** at https://hakku.gtk.fi/en/locations/search
  - The most recent land and bedrock map data. There are numerous data types available and downloadable free of charge for anyone who wants to study the Pyhäsalmi deposit or its related regional geology in an own desktop software (e.g., ArcMap, MapInfo and QGIS)
  - Includes coordinate-bound, digitally distributed material. Different types of units, occurrence information and map files, prepared from observation and measurement material, are distributed as geographic information products. New products are being developed continuously
- Photos at https://hakku.gtk.fi/en/pictures
  - Geology in different forms in artefacts, buildings, landscapes and rock samples
  - Includes more than 12,000 image files, starting from the year 1870
- Map drawings at https://hakku.gtk.fi/en/maps
  - Information about GTK's old geological maps, drawn by hand, in 1850–1970. There are more than 3,100 maps, and they are all downloadable in high-resolution pictures

3.1.4.2 Surface data

Seismic reflection profiles (HIRE DATA) can be downloaded from here: https://hakku.gtk.fi/en/locations/search?location_id=216. Available free data include HIRE data from the Pyhäsalmi area. Hire data can be described as follows:

- GTK carried out a significant reflection seismic project called HIRE (High-Resolution Reflection Seismics for Ore Exploration) between 2007 and 2010
- In the project, seismic reflection soundings were conducted in cooperation with companies at 16 different sites around Finland. The Pyhäsalmi and Mullikkoräme deposits are included.
- At each site, several intersecting profiles were measured, which enabled 3D interpretation of the reflectors. Information was obtained from the study areas on bedrock structures to a depth of more than 5 km. The measurements included a total of 402 active channels at intervals of 12.5 meters. The source points were located at intervals of 25 or 50 meters. Vibroseis trucks and explosions were employed as sources depending on the local circumstances.
- Additional metadata can be found from here: https://tupa.gtk.fi/paikkatieto/meta/seismic_reflection_profiles_hire.html

One of the most useful online services of GTK is the **Mineral Deposits and Exploration (MDaE)** page. MDaE is an online map service covering Finland and showing the locations of known ore and industrial mineral deposits. Its address is http://gtkdata.gtk.fi/MDaE/index.html. The MdaE website is available in Finnish, Swedish and English. All the copyrights of the content published on the website are held by GTK unless otherwise stated. The website's content can be used and linked elsewhere, as long as the source is also specified. Any commercial use of the content must always be separately agreed with the Geological Survey of Finland. More detailed terms of use of GTK's service contents and products can be found here: https://www.gtk.fi/en/site-information/.

The MDaE online map service offers, for example, the following tools:

- Search
    - Search by Address
    - Search by Place Name
    - Search By Zip Code, County, etc.
- Measure
    - The measure tool provides the capabilities to draw a point, line, or polygon on the map and specify the unit of measurement.

- Print
    - The map can be exported to various formats and layouts.

The MDaE online map service offers many surface data layers that are relevant from the viewpoint of the Pyhäsalmi mine. These include, for example, the following data layers:

- "Mineral Deposits" and "Mines" layers
    - These layers are extracted from the GTK's Mineral Deposit database. The database contains all mineral deposits, occurrences and prospects in Finland
    - The structure of the database is based on global geostandards (GeoSciML and EarthResourceML) and classifications related to them
    - The database contains an extensive amount of information about mineral occurrence feature along with its associated commodities, exploration activities, mineral resource and reserve estimates, mining activity, production and geology. The database will be updated whenever new data (e.g., resource estimate) is available or a new deposit is found
    - "Mineral Deposits" layers contain the following types of information:
        - Simplified information of the deposits, such as name and alternative names, coordinates, commodities, occurrence type, mine status, discovery year, total amounts of commodities, latest resource/reserve estimate, current holder of the deposit, metallogenic province and district, genetic type of the deposits, host and wall rocks, the shape of the deposit, orientation and dimensions
        - The total commodities in each deposit are calculated from the latest resource/reserve estimate and total production (if mined). The total amount of each commodity defines the size of the deposit
        - A deposit can contain many commodities; thus, one deposit can occur in several layers. However, there is only one primary commodity per deposit. These are shown in the All Deposits –layer. Deposits are also classified into separate map layers by the end-use potential of the main commodities. These layers contain all the main commodities which occur in the deposit
    - "Mines" layers contain the following types of information:
        - All the mineral deposits with past or present mining activity
        - Information includes mine name and alternative names, coordinates, mine status, current holder of the mine, start and end year of mining, total years mined, main product, size of the deposit, total production, total ore and

waste rock mined, and all commodities of the deposit and latest resource/reserve estimate

- Exploration layers
    - Bedrock observations layer
        - Contains location data for over 650 000 outcrops in Finland, some of which are located in the Pyhäsalmi area
        - Observation data has been produced by GTK and Outokumpu Oy bedrock mapping and exploration activities since the beginning of the 2000 century
    - Bedrock drillings layers
        - “Bedrock drillings” layer
            - Contains location data for over 26 000 drill holes, some of which are located in the Pyhäsalmi area
            - Drilling data has been produced by GTK and Outokumpu Oy bedrock exploration activities since 1920
        - “National drill core archive” layer
            - Contains location data for over 32 000 drill holes that are stored to Loppi national drill core archive. More information on the Loppi drill core archive in here:

              https://www.gtk.fi/en/research-infrastructure/national-drill-core-archive/
    - Ore boulders and showings
        - “Layman samples” layer
            - Layman samples contain mainly boulder but also bedrock observation data for over 24 000 layman samples sent to GTK and Outokumpu Oy
            - The dataset also contains analysis data in case the samples have been analysed
        - “Boulder observations” layer
            - Contains boulder observations gathered by GTK and Outokumpu Oy. It also contains boulder ore showings gathered by GTK. The total amount of boulders is approximately 23 000, some of which are located in the Pyhäsalmi area
    - Geological maps
        - “Bedrock of Finland 200k” layers

- The Bedrock of Finland 1:200 000 is a unified whole-of-Finland database compiled by generalising the not-to-scale data. The data consists of lithological unit layers (Rock class and Rock name) and structural line layer
- Lithological unit layers (Rock class/Rock name) include unit codes, age information and lithological codes as attributes in accordance with the Finnish Register of Geological Bedrock Units (Finstrati)
- The structure –layer includes structure types

▪ "Superficial deposits of Finland 200k" layers

- Superficial deposits of Finland 1:200 000 is a unified whole-of-Finland database, which has been compiled by generalising 1:20 000, 1:50 000 and 1:100 000 Quaternary base maps
- The surface sediment –layer shows the blanketing peat overburden
- Base sediment –layer contains soil types

▪ "Bedrock map of Finland 1M" layer

- The Bedrock map of Finland 1: 1 000 000 shows the basement lithologies by age group, as tectonic units and divided into separate domains

▪ "Superficial deposits of Finland 1M" layers

- Superficial deposits of Finland 1:1000 000 present the sediments which are classified according to their mode of geological development
- The deposit classes are pre-Quaternary bedrock exposures, various Quaternary deposits and landforms

o Metallogenic areas in Finland 2M

▪ The metallogenic map shows the extent of presently known metallogenic areas in Finland, defined by the presence of metal mines, deposits, favourable bedrock geology, and indications from geophysical and geochemical surveys. Information naturally covers also the Pyhäsalmi area

▪ More information: Eilu, P., 2012 (ed.) Mineral deposits and metallogeny of Fennoscandia. Geological Survey of Finland (2012). Special Paper 53. https://tupa.gtk.fi/julkaisu/specialpaper/sp_053.pdf

o Radiometric ages

    - Radiometric ages contain published isotope results from Finland, which comprise predominantly U-Pb zircon data produced at GTK
    - The information in the "Published age determinations" section consists of location data, rock type, minerals analysed, method, age data, references and comments. The "Published Sm-Nd isotope results" gives data in a standard format, predominantly produced at GTK
    - More information: Isotope Results of Finnish Bedrock at https://tupa.gtk.fi/metaviite/isotope_results_of_finnish_bedrock_explanations.pdf
  - Geochemistry
    - Regional till geochemistry
      - Regional till geochemistry describes the distribution of 25 elements in basal till. The sampled material was chemically unchanged C-horizon till preferably under the water table. The average sampling depth was approximately 1.5-2 m. Sampling was done during the years 1983-1991. The sampling density was one sample per 4 km^2
      - The whole country was covered by the till sampling, and the total amount of samples is 82062, from which some samples are from the Pyhäsalmi area. The samples were collected as a composite of 3-5 subsamples. The coordinates of each sample are calculated based on the coordinates of these 3-5 subsamples. More information: Geochemical Data, Regional Geochemical Mapping in Finland in 1982-1994 at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_130.pdf
    - Targeting till geochemistry
      - Targeting till geochemistry contains information on soil sampling and geochemical analyses. Sampling was done by GTK during 1971-1983, and it contains approximately 385 000 samples. Sampling was done discretionarily by 1:100 000 map sheets in lines. The sample material is mainly glacial till but also weathered bedrock, graded sediments and their mixed variants are included
      - More information: Report on geochemical mapping methods at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_039.pdf
    - Rock geochemical data

- The Rock Geochemical Data contains the total and partial concentrations of 57 elements in the bedrock of Finland analysed using several different methods. The data cover the whole of Finland and consist of 6544 samples taken by a mini-drill with the sampling density between one sample per 30 km^2 and one sample per 120 km^2
- In addition to the chemical concentrations, the data include information on the quality of the chemical analyses, geographic location and several geological attributes for each sample. More information: The Rock Geochemical Database of Finland at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_164.pdf

- Detailed till geochemistry
  - GTK's detailed till geochemistry contains location and information of soil sampling done by GTK. Sampling started in 1970, and it still continues
  - Detailed till geochemistry obtained from Outokumpu Oy contains location and information of soil sampling done by Rautaruukki Oy, Lapin Malmi Oy, and Outokumpu Oy. Sampling was done approximately in years 1970-1998
- Regional stream sediment geochemistry
  - Regional stream sediment geochemistry contains information on organic and mineral samples and geochemical analyses. Sampling was done by GTK during 1971-1985, and it contains approximately 156 000 samples. Regarding Pyhäsalmi, the closes samples are from a few kilometres north of the mine
  - Analysed samples are in separate layers classified by sample type (organic/mineral) and analysis method. More information (in Finnish): Report on geochemical mapping methods at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_039.pdf

- Mining Registry
  - Mining Act 1.7.2011
    - Mining registry according to the new mining act (621/2011) after 1-Jul-2011. More information: https://tukes.fi/en/mining © Finnish Safety and Chemicals Agency (Tukes)
  - Previous Mining Act

            - Mining registry according to the previous mining act (503/1965) before 1-Jul-2011
        - Expired claims
            - Expired claims contain historical information about expired mineral exploration claims and permits granted by the Finnish mining law. The dataset contains an expired claim or exploration permit area as polygon, the attributes related to this specific area and the hyperlink to the mineral exploration report if such a report has been relinquished. The dataset contains material from 1948 forward

- Nature conservations areas
    - Groundwater areas
        - The dataset includes those groundwater areas that are investigated and classified for water supply purposes. Groundwater areas are classified based on their usability and protection requirements into three classes: Class I = Groundwater area important for water supply, Class II = Groundwater area suitable for water supply, Class III = Other groundwater area. More information and © by SYKE & ELY-Centres
    - Natura 2000
        - The dataset contains nature conservation areas belonging to the Natura 2000 network. More information and © by SYKE
    - Nature conservation areas
        - The dataset contains nationally designated protected areas established on state-owned land in accordance with the Nature Conservation Act or Nature Conservation decree and areas established on private lands with a decision from the local Centres for Economic Development, Transport and the Environment (ELY-Centres). More information and © by SYKE
- Geophysical maps
    - Ground geophysical surveys
        - A ground geophysical survey contains surveyed areas as polygons and metadata relating to the survey. Geophysical surveys are done by GTK and Outokumpu Oy
    - Detailed aeromagnetic surveys
        - GTK has carried out detailed aerogeophysical low-altitude surveys during 2001-2008. The flight altitude has been 30-40 m and the flight line spacing 50

- 100 m. The sample distance along the survey line has been 6-50 m depending on the registration rate. The flight direction was selected perpendicular to the main geological structures

  - Bouguer anomaly map of Finland 2.5 km x 2.5 km
    - The Bouguer anomaly map of Finland contains the Finnish section of the Bouguer anomaly map of the Fennoscandian Shield, 1: 2 000 000 (resolution 2.5 km x 2.5 km). The origin of the Finnish section of the map is the regional gravity data of the Finnish Geodetic Institute and GTK
  - Aerogeophysical low altitude surveys
    - Low altitude aerogeophysical maps cover whole of Finland. Aerogeophysical surveys were carried out during 1973-2007. The nominal flight altitude was 40 meters, and flight line spacing was 200 meters. The sample distance along the survey line has been 6-50 m depending on the registration rate. The choice of standard flight direction (North-South and East-West) was made to suit the main geological trends. More information: Aerogeophysics in Finland 1972–2 004 Methods, System Characteristics and Applications at https://tupa.gtk.fi/julkaisu/specialpaper/sp_039.pdf

It is worth noting that Pyhäsalmi related general level information and surface data can also be found from the "**Fennoscandian Mineral Deposits application, ore deposits database and metallogenic map**" online service.

- This online service provides, for example, the following datasets:
  - Mineral deposits, mines, metallogenic maps as well as geological and geophysical maps from the Fennoscandian Peninsula
  - Links to downloadable map files, a database and summaries of information about critical minerals

Bedrock geology of the Pyhäsalmi region can also be examined with the "**Bedrock of Finland**" online search service.

- This online service provides an online map of the bedrock of Finland on a 1:200,000 scale

It also provides geological units (Finstrati), as well as related electronic publications

The MDaE online map (see section "Surface data" for description) service offers the following borehole data layers:

- Exploration layers
  - Bedrock drillings layers
    - "Bedrock drillings" layer
      - Contains location data for over 26 000 drill holes, some of which are located in the Pyhäsalmi area
      - Drilling data has been produced by GTK and Outokumpu Oy bedrock exploration activities since 1920
    - "National drill core archive" layer
      - Contains location data for over 32 000 drill holes that are stored to Loppi national drill core archive. More information on the Loppi drill core archive can be found from here:

https://www.gtk.fi/en/research-infrastructure/national-drill-core-archive/

3.1.4.3 Underground data

The MDaE online map (see section "Surface data" for description) service contains many geophysical datasets that are useful when interpreting the underground properties of the Pyhäsalmi rocks.

3.1.4.4 Petrography, geochemistry, rock mechanics, petrophysics and thermal properties

The MDaE online map (see section "Surface data" for description) service offers the following data layers:

- Geochemistry
  - Regional till geochemistry
    - Regional till geochemistry describes the distribution of 25 elements in basal till. The sampled material was chemically unchanged C-horizon till preferably under the water table. The average sampling depth was approximately 1.5-2 m. Sampling was done during the years 1983-1991. The sampling density was one sample per 4 km^2
    - The whole country was covered by the till sampling, and the total amount of samples is 82062, from which some samples are from the Pyhäsalmi area. The samples were collected as a composite of 3-5 subsamples. The coordinates of each sample are calculated based on the coordinates of these 3-5 subsamples. More information: Geochemical Data, Regional Geochemical Mapping in Finland in 1982-1994 at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_130.pdf

- Targeting till geochemistry
  - Targeting till geochemistry contains information on soil sampling and geochemical analyses. Sampling was done by GTK during 1971-1983, and it contains approximately 385 000 samples. Sampling was done discretionarily by 1:100 000 map sheets in lines. The sample material is mainly glacial till but also weathered bedrock, graded sediments and their mixed variants are included
  - More information: Report on geochemical mapping methods at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_039.pdf
- Rock geochemical data
  - The Rock Geochemical Data contains the total and partial concentrations of 57 elements in the bedrock of Finland analysed using several different methods. The data cover the whole of Finland and consist of 6544 samples taken by a mini-drill with the sampling density between one sample per 30 km^2 and one sample per 120 km^2
  - In addition to the chemical concentrations, the data include information on the quality of the chemical analyses, geographic location and several geological attributes for each sample. More information: The Rock Geochemical Database of Finland at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_164.pdf
- Detailed till geochemistry
  - GTK's detailed till geochemistry contains location and information of soil sampling done by GTK. Sampling started in 1970, and it continues
  - Detailed till geochemistry obtained from Outokumpu Oy contains location and information of soil sampling done by Rautaruukki Oy, Lapin Malmi Oy and Outokumpu Oy. Sampling was done approximately in years 1970-1998
- Regional stream sediment geochemistry
  - Regional stream sediment geochemistry contains information on organic and mineral samples and geochemical analyses. Sampling was done by GTK during 1971-1985, and it contains approximately 156 000 samples. However, the closest sample points are a few kilometres north of the Pyhäsalmi mine

Analysed samples are in separate layers classified by sample type (organic/mineral) and analysis method. More information (in Finnish): Report on geochemical mapping methods at https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_039.pdf

3.1.4.5 Natural background radiation data

In-situ measurements of natural radioactivity in the Callio Lab underground laboratory were carried out as part of the BSUIN project by a group from the University of Silesia in Katowice (Poland), the National Center for Nuclear Research (Poland), and Baltic Scientific Instruments (Latvia) at Lab 2 and Lab 5. For analysis, samples of rocks, building materials, and water were also collected from the examined locations. Additionally, as part of the EUL project, rock and water samples were collected from Lab 3 and Lab 4.

The neutron flux was measured with proportional ^{3}He counters in Lab 2 and with liquid organic scintillators in Lab 5. The thermal neutron flux in Lab 2 at +1430m level was measured for 45 hours, and the results showed flux of $1.73 \cdot 10^{-5}$ cm^{-2} s^{-1}. For the energy range of 0-1.5 MeV, the flux of fast neutrons in Lab 5 at +1410m level was $37.5 \cdot 10^{-7}$ cm^{-2} s^{-1}, and at Lab 4 at +660m level, the flux was $20.8 \cdot 10^{-7}$ cm^{-2} s^{-1}. The flux of neutrons with energy above 25 MeV was under $0.6 \cdot 10^{-7}$ cm^{-2} s^{-1} for both Labs 5 and 4. (40,41).

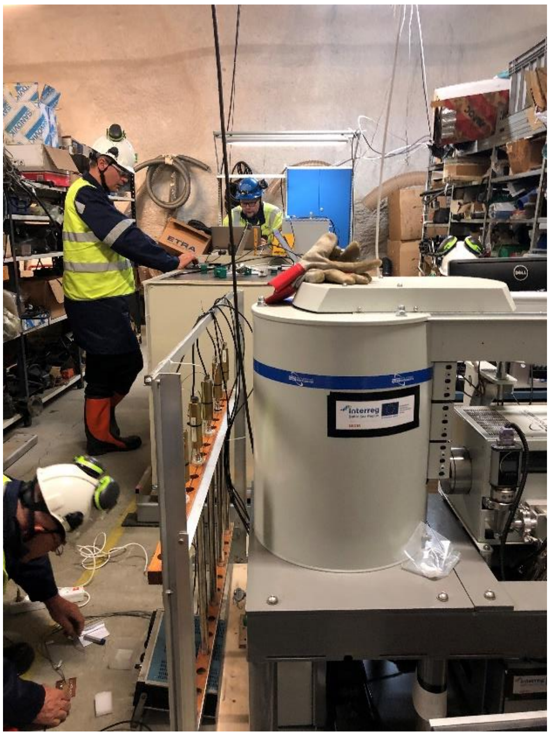


Figure 23. Lab 5 at the main level +1410 meters below surface. Neutron flux measurements with liquid organic scintillators being prepared. BSI low background HPGe gamma spectrometer also pictured.

The gamma-ray background (GRB) was first measured with portable CZT semiconductor, HPGe and scintillation spectrometers, and then with a dedicated low-background HPGe spectrometer measurement setup. The portable MultiSPEC-6000 CZT semiconductor detector showed count rates between 59-64 s^{-1} in Lab 2 and count rates of 29 s^{-1} in Lab 5. (42,43)

Evaporated liquid nitrogen flushing was used to mitigate the radon effects in the low background HPGe measurements, and in Lab 2, purging at a natural evaporation rate showed decreases in radon/thoron induced counts by up to 7%. In GRB measurements at Lab 5, the purging rate was increased, and the integrated count rate decreased from 0.028 $s^{-1} \cdot kg^{-1}$ to 0.021 $s^{-1} \cdot kg^{-1}$. In Lab 2, the gamma-radiation dose rate was 0.158 ± 0.029 µSv/h, and total integrated counts for the main peaks were 0.095 s^{-1} kg^{-1}. The GRB in Lab 5 was observed to be significantly lower than in Lab 2, with counting rates showing 1.5-7 times less. (40,43,44)

The in-air radon concentration was measured with a Rad7 electronic radon detector with 1 h sampling time and measurements between 24-48 hours. Time-dependent variations were not observed, and the levels for Lab 2 were found to be around 213 Bq/m3, and for Lab 5, measurements showed 22 Bq/m3. Lab 5 showed much lower radon levels because it is situated on the main level and is part of a much more efficient air ventilation system blowing radon-free air from the surface to the mine. (40,44)

These results and in-depth results on sample radioisotope concentrations $^{234,238}U$, $^{226,228}Ra$, ^{232}Th, ^{40}K in water, rock, and building materials are available in the BSUIN project reports on A2.2 activity (Scheme of Callio Lab devoted to natural background radiation (NBR) characterisation) in the EUL project report on A3.3 activity, and publications and conference presentations including references (40,43).

Muon flux measurement at Callio Lab was done in 2004-2005 using a trailer-built plastic scintillator setup called Movable Underground Detector, MUD. See ref. (7) for more details. Thermal and fast neutron data was measured in 2005 by Abdurashitova, J.N., and now during the BSUIN project by the Polish Institute of Nuclear Research team. See ref. (45) for more details.

3.2 Hydrological data and properties

3.2.1 Hydrogeological data and properties

3.2.1.1 Description of data

Data described in this section is based on the LAGUNA-LBNO-project’s report of Rockplan (46). The data is not representing the whole mine, but samples have been collected from drillholes PH101, PH102, PH104, R2229, R2238, R2245 and R2247. Three water samples were collected from each hole. The drill hole information is summarised in Table 11. The only physical property analysed was electrical conductivity (mS/m).

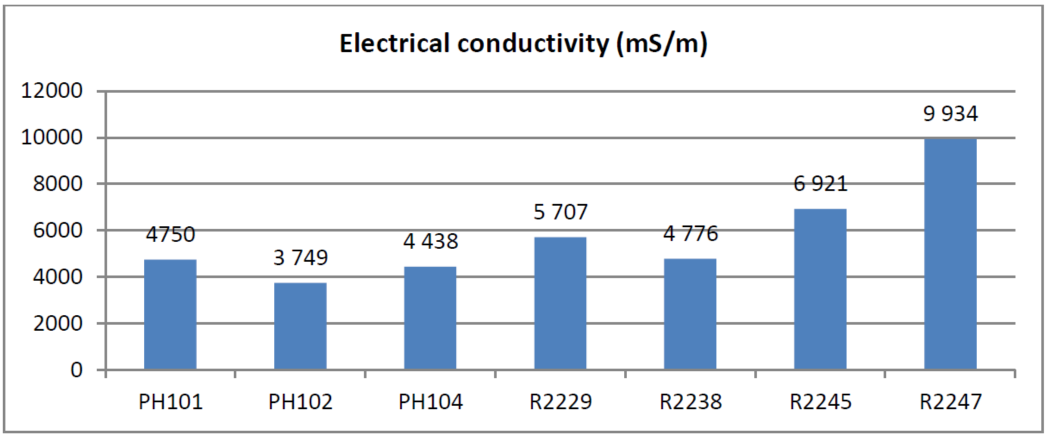
Table 11. Summary of drill hole information for water sample testing carried out in the LAGUNA-LBNO-project. From Rockplan (46).

Hole ID	Location			Planned		Length (m)	Comments
	x (m)	y (m)	z (m)	Dip (°)	Dip dir. (°)		
PH 101	8104.00	2244.00	1083.00	45.0	268.0	748.87	Samples from intervals 0-604, 0-717 and 0-748.87 meter. Water flow ~ 0.1 – 1.0 L/min.
PH 102	7999.50	2397.00	-1437.50	5.00	262.00	427.00	Very low flow - dry hole, strongly stained walls, iron oxide
PH 104	8098.00	2410.00	-1438.00	-2.00	284.60	610.00	Low flow
R 2229	2397.70	8101.26	-1440.08	70.00	183.50	547.00	High water flow
R 2238	2247.71	8104.63	-1084.82	27.00	301.00	614.00	High water flow
R 2245	2416.70	8102.73	-1430.00	46.00	340.00	948.00	Sample scooped from hole
R 2247	2415.81	8103.06	-1430.00	80.00	195.00	1002.00	High water flow

3.2.1.2 Description of properties

Electrical conductivity measurements of the studies carried out in the LAGUNA-LBNO project are shown in Table 12.

Table 12. Electrical conductivity measurements (mS/m) of drill hole-hosted groundwater in the Pyhäsalmi mine. Based on water sample testing carried out in the LAGUNA-LBNO-project. From Rockplan (46).



3.2.2 Hydrogeochemical data and properties

3.2.2.1 Description of data

Data described in this section is based on the report of Rockplan (46). In that project, the groundwater samples were collected from drill holes for conducting chemical analyses to evaluate the chemical strain level for the structures and rock reinforcements. Groundwater samples were collected PH101, PH102, PH104, R2229, R2238, R2245 and R2247. For details, see Section "Hydrogeological data and properties" or the report of Rockplan (46). The following hydrogeochemical parameters were analysed:

- Total dissolved solids (mg/l)
- pH
- Carbon dioxide (CO_2 mg/l)
- Contents of:
  - Chloride (Cl)
  - Sulphate (SO_4)
  - Calcium (Ca)
  - Sodium (Na)
  - Copper (Cu)
  - Manganese (Mn)
  - Magnesium (Mg)
  - Iron (Fe)
  - Zinc (Zn)

3.2.2.2 Description of properties

Based on the results of the LAGUNA-LBNO project, the most anomalous concentration of analysed chemical parameters in the groundwater is chloride Rockplan (46). The chloride concentration is about the level of marine waters, which gives an assumption of ancient (relict) seawater. This also increases the electric conductivity and calcium concentration. This fact leads to a high potential risk of corrosion. The amount of total dissolved solids (TDS) is distinctly higher than ordinary freshwater. The hydrogeochemical analyses of TDS, pH and CO_2 values and the contents of chloride, sulphate, calcium, sodium, copper manganese, magnesium, iron and zinc are summarised in Table 13.

.

Table 13. Summary of analysis results of hydrogeochemical studies of drill hole-hosted groundwater in the Pyhäsalmi mine. Based on water sample testing carried out in the LAGUNA-LBNO-project. From Rockplan (46)

Analysis	Method	PH101 0-604.00	PH101 0-717.00	PH101 0-748,87	PH102 6979-1	PH104 6979-2	R2229 6979-3	R2238 6979-4	R2245 6979-5	R2247 6979-6	Unit
Total Dissolved Solids, TDS	Int.method. DA				22 493	26 630	34 240	28 654	41 528	59 604	mg/l
pH	SFS 3021:1979	5,3	6,0	6,5	7,4	7,9	8,3	7,7	8,4	8,4	
Electrical conductivity	SFS-EN 27888:1994	332	4750	19	3 749	4 438	5 707	4 776	6 921	9 934	mS/m
Carbon dioxide	KV 100-98 St.				1,0	< 0,5	< 0,5	0,8	< 0,5	< 0,5	CO2 mg/l
Chloride, Cl	Int.method. DA	1100		42	20 000	20 000	22 000	20 000	29 000	44 000	mg/l
Sulfate, SO4	Int.method. DA	25	35	4	39	37	81	56	56	150	mg/l
Calcium, Ca	ISO 17294-2	450	8050	18	640	7 400	9 800	8 400	13 000	21 000	mg/l
Sodium, Na	SFS-EN ISO 11885:2009			12	2 700	3 100	4 300	3 000	5 300	7 600	mg/l
Magnesium, Mg	SFS-EN ISO 11885:2009				11,4	14,1	4,0	31,0	2,4	43	mg/l
Copper, Cu	ISO 17294-2	10	100	<10		2,2	1	< 0,2	17	3	µg/l
Copper, Cu	SFS-EN ISO 11885:2009				210						µg/l
Manganese, Mn	SFS-EN ISO 11885:2009	770	1200	250	110	47	38	44	40	59	µg/l
Iron, Fe	SFS-EN ISO 11885:2009	7200	29000	5700	2 900	69	100	21	2 200	310	µg/l
Zinc, Zn	SFS-EN ISO 11885:2009	30	17000	320	440	39	26	< 5	17	12	µg/l

Sulphate concentrations are about the same level as groundwater in coastal cities in Finland. Copper, magnesium, manganese and zinc contents are about normal – approximately in between the variations in drilled bedrock well waters in Finland. Sulphate, copper, manganese, iron and zinc concentrations are mainly within the limits that have been given for drinkable water. Iron and zinc contents in drill holes PH101 and PH102 vary significantly compared to the other results. It is interpreted that this may be because of a very slow water flow from the two boreholes. In addition, the walls in the sample location were strongly stained by iron oxide with could have contaminated the water sample.

4 Summary

The Pyhäsalmi mine infrastructure offers a unique 1.4 km deep underground infrastructure for business, research and innovation. The soon ending underground mining will free more space for the reuse activities. Callio – Mine for business is the post-mining phase facility and facility service, provider. They have an exclusive agreement with the Pyhäsalmi Mine Ltd. for exclusive right to reuse, rent and lease mine facilities. Callio Lab is a University of Oulu, Kerttu Saalasti Institute coordinated underground research infrastructure and research network.

The reuse possibilities, even already functioning along with the mining activities, have a major impact in mitigating the effects of the end of underground mining, but also a great possibility to become an innovation hub for the region, country and Europe. The pre-investment plan for the pumped-hydro storage has made the future of the reuse solid.

Through the establishment and growth of the EUL Association in the future, the scope and perspectives of Callio Lab can become bigger, and the potential to research in new fields will grow. The preservation of such a facility is a big challenge. Whether we discuss research and education, cultural heritage preservation, or tourist services, the optimisation of services offered is always a scope.

5 References

1. Callio - Mine for Business [Internet]. 2021. Available from: https://callio.info
2. Callio Lab [Internet]. 2021 [cited 2021 Apr 20]. Available from: https://calliolab.com/facilities-2/facilities/
3. Jalas P, Enqvist T, Isoherranen V, Joutsenvaara J, Kutuniva J, Kuusiniemi P. Callio Lab, a new deep Underground Laboratory in the Pyhäsalmi mine. In: Journal of Physics: Conference Series. 2017.
4. Callio Lab [Internet]. Available from: https://calliolab.com
5. Enqvist T, Keränen P, Peltoniemi J, Joutsenvaara J, Jämsén T, Kulju T, et al. Research options in the pyhäsalmi underground facility. Nucl Phys B - Proc Suppl. 2005;143(1-3 SPEC. ISS.):561.
6. Jämsen T, Elo A-M, Kangas J, Mursula K, Peltoniemi J, Usoskin I ~G., et al. A new multilevel experiment MUG for observing muon fluxes underground. Int Cosm Ray Conf. 2001 Aug;3:1250.
7. Enqvist T, Mattila A, Föhr V, Jämsén T, Lehtola M, Narkilahti J, et al. Measurements of muon flux in the Pyhäsalmi underground laboratory. Nucl Instruments Methods Phys Res Sect A Accel Spectrometers, Detect Assoc Equip. 2005 Dec 1;554(1–3):286–90.
8. Kuusiniemi P, Bezrukov L, Dzaparova I, Enqvist T, Fynbo H, Inzhechik L, et al. Performance of tracking stations of the underground cosmic-ray detector array EMMA. Astropart Phys. 2018 Nov 1;102:67–76.
9. Patzak T. LAGUNA-LBNO: Large apparatus studying grand unification and neutrino astrophysics and long baseline neutrino oscillations. J Phys Conf Ser. 2012;375:42056.
10. Trzaska WH, Enqvist T, Joutsenvaara J, Kalliokoski T, Kokko E, Kuusiniemi P, et al. Advantages of locating LAGUNA in Pyhäsalmi mine. Prog Part Nucl Phys. 2011;66(2).
11. Tonazzo A. The LAGUNA-LBNO Project. Nucl Part Phys Proc [Internet]. 2015;265–266:192–4. Available from: http://www.sciencedirect.com/science/article/pii/S2405601415003910
12. Salmelainen J, Ström J, Cristiá S, Hatakka L, Tirinen J, Westerlund G, et al. LAGUNA-LBNO EXTENDED SITE INVESTIGATION AT PYHÄSALMI, FINLAND Deliverable 9 Site investigation summary. 2014.
13. Jędrzejczak K, Debicki Z, Kasztelan M, Marszal W, Orzechowski J, Przybylak M, et al. The BSUIN project. PoS. 2019;ICRC2019:523.
14. Mischo H, Fuławka K, Joutsenvaara J. European Underground Laboratories Association EUL-An International Partner for Underground Research Opportunities. In: EGU General Assembly Conference Abstracts. 2021. p. EGU21--7730.
15. Elger K, Lauterjung J, Ulbricht D, Cocco M, Atakan K, Bailo D, et al. Implementation of the European Plate Observing System (EPOS) Infrastructure. 2016;
16. Franklin JM, Gibson HL, Jonasson IR, Galley AG. Volcanogenic massive sulfide deposits. In: Economic Geology One Hundredth Anniversary Volume 1905-2005. Society of Economic Geologists, Inc., Littleton, Colorado; 2005. p. 523–60.
17. Candela PA. Ores in the earths crust. Treatise on geochemistry. 2003;3:659.

18. Shanks WCP, Thurston R. Physical volcanology of volcanogenic massive sulfide deposits. Volcanogenic massive sulfide Occur Model US Geol Surv Sci Investig Rep 2010-5070-C, chap 5. 2012;345.

19. Cathles LM. What processes at mid-ocean ridges tell us about volcanogenic massive sulfide deposits. Miner Depos [Internet]. 2011;46(5):639–57. Available from: https://doi.org/10.1007/s00126-010-0292-9

20. Morgan LA, Schulz K. Physical volcanology of volcanogenic massive sulfide deposits. In: Scientific Investigations Report 2010-5070-C. U.S. Department of the Interior, U.S. Geological Survey; 2012. p. 40.

21. Rogers N, van Staal C, Skulski T, Piercey SJ, McNicoll V. Timing and tectonic setting of volcanogenic massive sulphide bearing terranes within the Central Mobile Belt of the Canadian Appalachians. In.

22. Monecke T, Petersen S, Hannington MD, Grant H, Samson IM. The Minor Element Endowment of Modern Sea-Floor Massive Sulfides and Comparison with Deposits Hosted in Ancient Volcanic Successions. Rare Earth Crit Elem Ore Depos. 2016 Oct 14;

23. Mäki T, Kousa J, Luukas J. The Vihanti-Pyhäsalmi VMS Belt. Miner Depos Finl. 2015 Jan 1;507–30.

24. Hannington MD, Ronde CEJ De, Petersen S. Sea-Floor Tectonics and Submarine Hydrothermal Systems. One Hundredth Anniv Vol. 2005 Oct 14;

25. Herzig PM, Hannington MD. Input from the Deep: Hot Vents and Cold Seeps. Mar Geochemistry [Internet]. 2006 [cited 2021 Nov 17];457–79. Available from: https://link.springer.com/chapter/10.1007/3-540-32144-6_13

26. Economou-Eliopoulos M, Eliopoulos DG, Chryssoulis S. A comparison of high-Au massive sulfide ores hosted in ophiolite complexes of the Balkan Peninsula with modern analogues: Genetic significance. Ore Geol Rev. 2008 Jan 1;33(1):81–100.

27. Yeats CJ, Hollis SP, Halfpenny A, Corona JC, LaFlamme C, Southam G, et al. Actively forming Kuroko-type volcanic-hosted massive sulfide (VHMS) mineralization at Iheya North, Okinawa Trough, Japan. Ore Geol Rev. 2017 Apr 1;84:20–41.

28. Petersen S, Lehrmann B, Murton BJ. Modern Seafloor Hydrothermal Systems: New Perspectives on Ancient Ore-Forming Processes. Elements. 2018 Oct 1;14(5):307–12.

29. Herzig PM, Hannington MD. Polymetallic massive sulfides at the modern seafloor a review. Ore Geol Rev. 1995 Dec 1;10(2):95–115.

30. Doyle MG, Allen RL. Subsea-floor replacement in volcanic-hosted massive sulfide deposits. Ore Geol Rev. 2003 Oct 1;23(3–4):183–222.

31. Korja A, Lahtinen R, Nironen M. The Svecofennian orogen: a collage of microcontinents and island arcs. Geol Soc London, Mem [Internet]. 2006 Jan 1 [cited 2021 Nov 17];32(1):561–78. Available from: https://mem.lyellcollection.org/content/32/1/561

32. Lahtinen R, Korja A, Nironen M. Chapter 11 Paleoproterozoic tectonic evolution. Dev Precambrian Geol. 2005 Jan 1;14(C):481–531.

33. Imaña M, Heinonen S, Mäki T, Häkkinen T, Luukas J. 3D modeling for VMS exploration in the Pyhäsalmi district, Central Finland in. In: Proceedings of the 12th Biennial SGA Meeting. 2013. p. 12–5.

34. Eilu P (ed). Mineral Deposits and Metallogeny of Fennoscandia. Geological Survey of Finland, Special Paper 53. Econ Geol. 2012 Aug 1;107(5):1075–6.

35. Roberts MD, Oliver NHS, Lahtinen R. Geology, lithogeochemistry and paleotectonic setting of the host sequence to the Kangasjärvi Zn-Cu deposit, central Finland: implications for volcanogenic massive sulphide exploration in the Vihanti–Pyhäsalmi district. 2004 [cited 2021 Nov 18]; Available from: http://www.geologinenseura.fi/bulletin/Volume76/Roberts.pdf

36. Mäki T, Kousa J, Luukas J. The Vihanti-Pyhäsalmi VMS Belt. In: Mineral Deposits of Finland. Elsevier Inc.; 2015. p. 507–30.

37. Haozhe X, Pengxian F, Kaifeng J, Ang L. Reviews on the Failure Mechanism and Stress Condition of Rock Core Discing.

38. Rockplan, 2014a. LAGUNA-LBNO Extended Site Investigations. Pyhäsalmi, Finland. Deliverable 2: In Situ Stress Measurements. A report to University of Oulu.

39. LAGUNA-LBNO Extended Site Investigations at Pyhäsalmi, Finland. Deliverable 4: Mechanical, thermal and radiogenic properties of rock samples.

40. Polaczek-Grelik K, Walencik-Łata A, Szkliniarz K, Kisiel J, Jędrzejczak K, Szabelski J, et al. Natural background radiation at Lab 2 of Callio Lab, Pyhäsalmi mine in Finland. Nucl Instruments Methods Phys Res Sect A Accel Spectrometers, Detect Assoc Equip. 2020 Jul 21;969:164015.

41. Szkliniarz K, Kisiel J. Natural radioactive background characterisation of the Uls [Internet]. 2020. Available from: http://bsuin.eu/wp-content/uploads/2021/01/Final_Report_A2.2.pdf

42. Pohuliai S, Sokolov A, Gostilo V, Joutsenvaara J, Puputti J. Measurements of gamma-ray background radiation in Pyhäsalmi mine. Appl Radiat Isot. 2020 Jul 1;161:109166.

43. Gostilo V, Sokolov A, Pohuliai S, Joutsenvaara J. Characterisation of the natural gamma-ray background in the underground Callio Lab facility. Appl Radiat Isot. 2020 Feb 1;156:108987.

44. Pohuliai S, Sokolov A, Gostilo V, Joutsenvaara J, Puputti J. Measurements of gamma-ray background radiation in Pyhäsalmi mine. Appl Radiat Isot. 2020 Jul 1;161.

45. Abdurashitov J. N. GVNMVLSAAYVEPJKT. Measurement of Neutron Background at the Pyhasalmi mine for CUPP Project, Finland. arXiv:nucl-ex [Internet]. 2006; Available from: arxiv:nucl-ex/0607024

46. LAGUNA-LBNO Extended Site Investigations. Pyhäsalmi, Finland. Deliverable 5: Groundwater sampling and analysis.