EMPOWERING UNDERGROUND LABORATORIES NETWORK USAGE

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

SITE DESCRIPTION AND DATA OF THE Reiche Zeche

Site services, Characteristics and Data

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1 Aim and Introduction

This report provides an overview of the features, properties and services of the Reiche Zeche mine 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 Reiche Zeche mine, 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.

Research and Education Mine "Reiche Zeche"

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2 Overall description of the Reiche Zeche

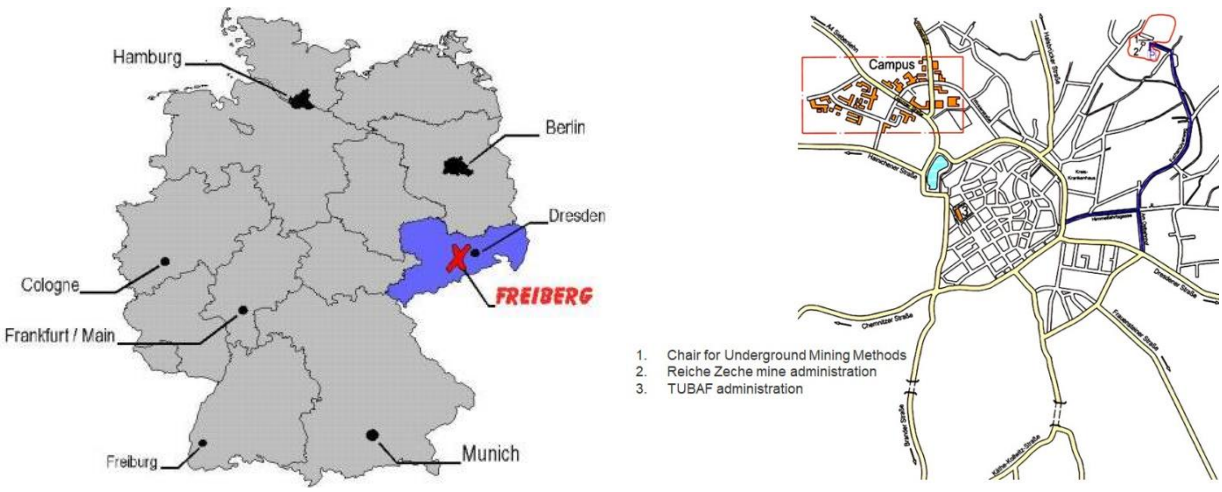
2.1 Location

2.1.1 Geographical settings

The Research and Education Underground Facility "Reiche Zeche" (Forschungs- und Lehrbergwerk – FLB, in German) is located on the edge of the Erzgebirge in the municipality of Freiberg. Freiberg is situated in the centre of the state of Saxony between Dresden and Chemnitz in Germany, and close to the Czech border with around 40km to each side (Fig. 1a). The town lies on the northern declivity of the Ore Mountains (Erzgebirge), with the majority of the borough west of the Eastern or Freiberger Mulde river. Its centre has an altitude of about 412 m above mean sea level.

Freiberg is located about 31 kilometres (19 miles) west-southwest of Dresden, about 31 kilometres east-northeast of Chemnitz, about 82 kilometres (51 miles) southeast of Leipzig, and about 179 kilometres (111 miles) south of Berlin and about 120 kilometres (75 miles) northwest of Prague.

The main entrance of the mine that is the vertical shaft "Reiche Zeche" is located at the North-East part of the city, at a walking distance of 20-25 minutes from the center of Freiberg. The official coordinates of Reiche Zeche are: 50° 92' 85.8" North / 13° 35' 73.3" East.



(a) (b)

Figure 1. a) Location of Freiberg in Germany and (b) Location of the FLB „Reiche Zeche" Mine at the suburbs of Freiberg (Tu Bergakademie, Freiberg, 2021).

Apart from the main shaft that provides access to the underground mine, the hill of Reiche Zeche hosts a number of other facilities such as university departments, laboratories and small companies (Fig. 2). For instance, the department of Underground Mining Methods of TU Bergakademie Freiberg is situated exactly next to the Reiche Zeche shaft. The chair of the department, Univ.-Prof. Dr.-Ing. Helmut Mischo (https://tu-freiberg.de/fakultaet3/tiefbau/helmut-mischo) is also the director of the mine.

Figure 2. Aerial view of the Reiche Zeche hill (Mischo, 2019).

2.2 Use and Access

2.2.1 The original purpose and current use

Mining in Freiberg has a long history. Silver ore was first discovered in Freiberg at 1168 A.C. by farmers who were cultivating the land (Figure 3). This year is officially recorded as the founding date of the city of Freiberg. The discovery of silver attracted miners from Lower-Saxony (a state in northwest Germany bordering the North Sea), who started minng of near surface parts of the deposit, mainly galena with high silver content. At the beginning, the mining methods were primitive and labour intensive (shovels, chisel and iron tools), while the biggest problem the miners had to face was the removal of inflowing water from the surface mining operations.

Due to the presence of water and also the fact that the inclined deposit had a tendency to go deeper, soon enough, the miners shifted to underground mining techniques. Around 1300 A.C. a significant amount of adits had been constructed to remove the inflowing water to the nearby valley of the river Mulde and to give more access to the deposit.

In the centuries to follow the development of the underground network was phenomenal; mining was the most profitable occupation in the area; silver was the main source for currency (coins) back then, and thus it was considered a very valuable metal. The fact that the deposit did not belong to a king or any other rich person in the area attracted more and more people to come and work. Even the name of Freiberg (Free Mountain) implied that everyone could get a permit to mine, produce his own silver and sell it. The only obligation was to pay taxes to the city of Freiberg. Consequently, a huge number of small mines were developed for the exploitation of this vast deposit.

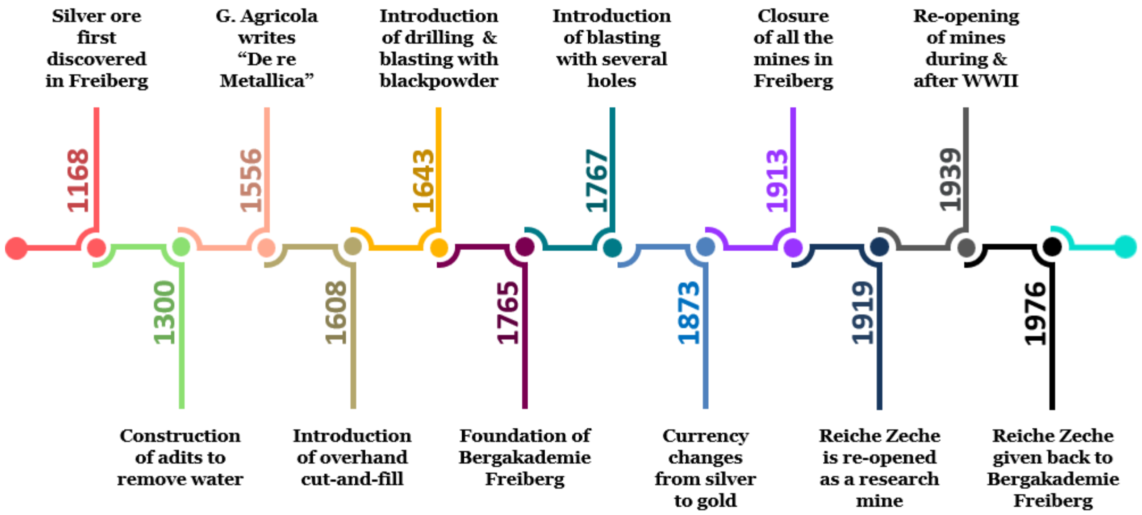


Figure 3. Timeline of the most significant activities at Reiche Zeche during the whole life of the mine (Barakos, 2017).

The small scale mining operations were expanded covering a big area that now lies beneath the whole city of Freiberg. In fact there are still some abandonded shallow shafts in the basements of old houses that were providing access to the upper levels of the underground mining openings.

A lot of pioneering mining technologies had been introduced in Freiberg. For example, the overhand cut-and-fill mining method was introduced in 1608, while (hand-)drilling and blasting with black powder was introduced in 1643. In turn, the productivity increased significantly until the beginning of the 20th century. In 1871, the German Empire introduced the "coin-reform". This meant the replacement of the silver currency to gold until 1878, thus resulting in a significant drow of the value of silver. Consequently, all mines in Freiberg were closed until 1913.

A few years later, in 1919, the shafts of Reiche Zeche and Alte Elisabeth, as well as the surrounding underground openings were given for research and teaching purposes to the Bergakademie Freiberg that had already been founded since 1765.

Due to WWII, several of the former mines became operational again in 1937. Their operation continued even after the end of the war from the former German Democratic Republic (GDR) under the auspices of the Soviet Union. All operations seized in 1969 and a few years later (1976) the mine facilities were given once again to Bergakademie Freiberg for scientific and educational purposes.

After the unification of Germany, the university was given its current official name (Technical University Bergakademie Freiberg) and the mine facilities belong to the university. The Research and

Education Underground Facility "Reiche Zeche" (Forschungs- und Lehrbergwerk – FLB) serves research, training and educational purposes and is used by many research institutions, industrial companies, and universities. The facilities are used for developing new technologies, testing production methods, new materials, or obtaining reference materials for their databases and practical training of students in mining and surveying operations.

Though identified as a research underground facility, FLB is also licensed to operate as an active mine. The mine site is also open to the general public for visits and underground tours. Approximately 20,000 people are visiting the mine every year. In July 2019, the UNESCO World Heritage Committee decided to include FLB in the list of UNESCO World Heritage sites.

2.2.2 Available infrastructure

It is estimated that a total of 1,270 km of underground horizontal openings had been created during the whole life of the mines. These openings cover an area of 54 km^2 (4.12 km2 on the surface) in 15 levels down to a depth of 750 m.

Since 1967 when mining operations stopped, the pumping of inflowing water from the mine had become very expensive. Hence, in 1969 pumping of water from deeper levels stopped and the mine was let to flood. For this reason all mines had been flooded up to the level of the adit "Rothschönberger Stollen" – i.e. a depth of about 230 m (at shaft "Reiche Zeche"). This adit and a number of adits to the valley of the river Mulde (depth about 100 m) are nowadays responsible for the de-watering of the mine.

Turbines had been installed since 1914 at the shaft "Dreibrüderschacht" in a depth of 270 m (Rothschönberger Stollen), which used the water for the production of electrical energy for the city of Freiberg. The idea was to use these turbines again, but the big flood of 2002 in Saxony resulted in the collapse of the adit Rothschönberger Stollen and no reconstruction has been realised since then. Consequently for a research, for teaching and visiting only parts down to 230 m depth are available. For further research mostly related to mining under water, additional parts in the shafts to greater depths are also available.

Since 1981 additional openings had been prepared for a use. For this reason recently roughly 20 km of openings are steadily controlled and immediately available for a use, the 14 km of which are around the shaft of Reiche Zeche. Furthermore several km of openings (approximately 129 km) are inspected and are accessible but nor regularly controlled.

There are five levels accessible to the depth of 230 m (Figure 4). The main level (Level 1 - 1. Söhle) is at 150 m, where most of the research infrastructure is installed. Other primary levels in the mine are the Adit Level at the depth of 100 m, where narrow openings are used mainly for tours for visitors and for educational purposes, while there is also Level 3 at 200 m depth that is mainly used for research.

Currently (2021) there are 33 research laboratories, as well as classrooms and training facilities (Figure 5) inside the underground mine Reiche Zeche (Figure 6). Most of these facilities are run by several departments of TU Freiberg, while some others are run by external partners.

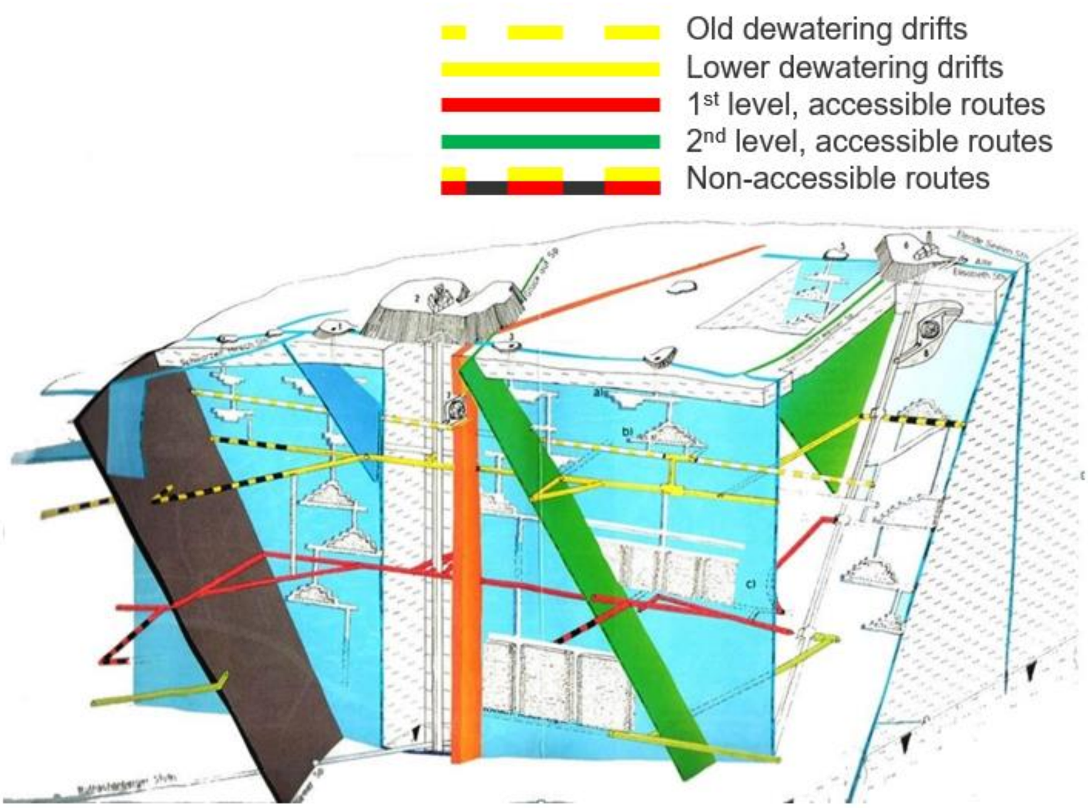


Figure 4. A sketch of the underground openings around the shafts of Reiche Zeche and Alte Elisabeth (Dr. Herbert Pforr, no date available).

Figure 5. Training classroom „Lehrpfad“ with stationary presentation equipment; One of three training classrooms in the mine (TU Bergakademie Freiberg, 2021).

Pos.	Bezeichnung	Nutzung
1	Praktikumsgebiet Markscheidewesen	Lehre
2	Luttenversuchsstand	Lehre, Forschung
3	Aromatenlager	Forschung
4	GFZ-Bohrgestängeversuchsstand	Forschung
5	Real Time Mining	Forschung
6	Prüfbahn	Lehre, Forschung
7	In-Situ-Laugungsversuchsstand BioHydroMetallurgisches Zentrum (BHMZ)	Forschung, Lehre
8	Vortriebsort	Lehre
9	Living Lab	Forschung
10	Hochdruckforschungszentrum (Sprengkammer)	Forschung
11	Klimakammer	Forschung
12	GFZ-Versuchsstand Geophysik	Forschung
13	Versuchsstand Geophysik	Forschung
14a	Seilversuchsstand (Röschensohle)	Forschung
14b	Seilversuchsstand (1. Sohle)	Forschung
15	Diffusionsversuchsstand	Forschung
16	Rohrleitungsversuche	Forschung, Lehre
17	Korrosionsversuchsstand	Forschung
18	Stimtec	Forschung
19	Datenübertragung im Fels	Forschung
20	Seismograph	Lehre, Forschung
21	Praktikumsgebiet Magnetik / Gravimetrie	Lehre
22	BSUIN – Netzwerke für Untertageforschungsinfrastrukturen	Forschung
23	Entwicklung Bohrtechnik	Forschung
24	Praktikumsgebiet Kartierung	Lehre
25	Praktikumsort Schachtfördertechnik	Lehre
26	Praktikumsort Vortrieb	Lehre
27	Praktikumsgebiete Wetterrmesstechnik	Lehre
28	Messstände Messung Grubenwasser	Lehre, Forschung
29	Vodamin II	Forschung
30	Schachtlotung	Lehre
31	Aridua	Forschung
32	MINERS	Lehre
33	RFCS Hydrocoal	Forschung

Figure 6. List of the current (2021) research and training facilities in the underground mine Reiche Zeche (Mischo 2021).

There are no large measurement rooms in the underground mine, only the old water wheel room, lecture halls and event rooms.There are several spaces in the mine with dimensions of approximately 2.20 x 2.30 m.

There is access (in certain places in the mine) to:

- high-speed internet(10 Gigabit-LAN) via glas-fibre cable is available at certain locations and can be installed to almost every location in the mine,
- the main voltage in the subsurface is 400 V. With certain transformer 230 V is available. Recently a new power line was installed. The used system is an IT-net (Isolé Terre) (per IEC 60364-3: unearthed system: IT System),
- wired telephone system,
- lighting is available in all research infrastructures and most of the main openings at the 1st Level,
- railway tracks, railway for material and person transport; transportation provided by previous announcement of service required,
- water from the supply system is available in the Reiche Zeche shaft near area and at some location in the main drifts. The water from these lines is not drinkable; it comes from an underground basin on upper levels to the water supply system and is almost neutral in pH (not acidic),
- compressed air lines are available at some locations in main drifts.

2.2.3 Current ownership and organisation

Because of the closure of all mines and the German reunification in 1990 (in which the German Democratic Republic (GDR) became part of the Federal Republic of Germany (FRG) to form the reunited nation of Germany), the legal responsibility of the Reiche Zeche mine facilities was passed to the German federal state. There was no legal person or enterprise which had any responsibility. So, the Mining Authorithy took the responsibility initially for the adit “Rothschönberger Stollen”. Yet, TU Bergakademie Freiberg was still running the openings around Reiche Zeche and the question arose whether the university as “owner” of the research mine is a legal successor of the old GDR-enterprise. Finally it was clarified, that the adit and possible dangers, rehabilitation etc. is in the responsibility of the Mining Authority. The TU Bergakademie Freiberg has the allowance to use and extent its research mine to a national and European research mine, currently under the Federal Mining Act (BBergG), the General federal mining ordinance, and the Saxonian mining ordinance.
Consequently, there is a supervision by the Mining Authority in combination with the fact that Reiche Zeche is also licenced as an active (producing) mine. This means also the establishment of extended emergency plans, including the introduction of self-rescuers in certain areas. Due to this status the shaft “Reiche Zeche” has been reconstructed within the last years. In fact, a big reconstruction project

was launched in 2021 and is expected to be completed in early 2022. Furthermore, plans for the construction of a third entrance (ramp) are under consideration.

To date, all requirements from the Mining Authority are met. All activities in the mine have to be announced or approved by the Mining Authority – as usual in any other producing mine in the world. Some approval is easier because the “Forschungs- und Lehrbergwerk” is only typically considered as a producing mine.

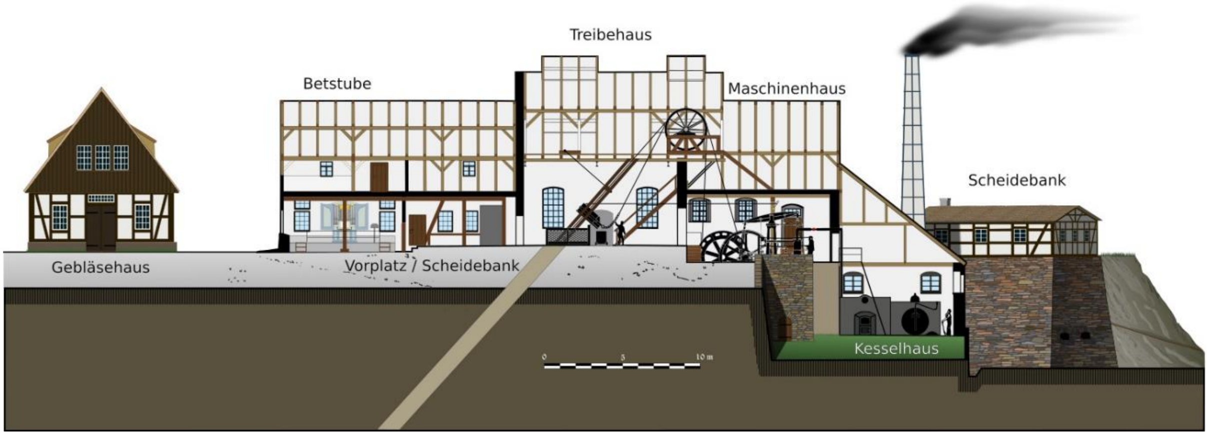
Nevertheless, any mining plan has to be handed over and/or be approved by the Mining Authority. As usual, this means a certain time is necessary from an idea to the final permission for certain works.

- Status of the UL: Cooperation under public law as part of Techical University Bergakademie Freiberg,
- Owning Institution: Saxon mining authority is a bundling authority. All other authorities are contacted via the mining authority; Applicable language is German,
- Relevant law jurisdiction: Federal Mining Act (BBergG), General federal mining ordinance, saxonian mining ordinance,
- Operator: Techical University Bergakademie Freiberg (tu-freiberg.de/lfbw),
- Contact person: Professor Dr.-Ing. Helmut Mischo (helmut.mischo@mabb.tu-freiberg.de).

2.2.4 Underground access

Access to the mine is vertical and possible only through shafts. With the re-establishment and use of the mine facilities for research, training and education since the 1980s, the only remaining accesible shafts had been the shaft “Reiche Zeche” and the shaft “Alte Elisabeth” (Fig. 7a & b).

(a)



(b)

Figure 7. (a) A view of the Alte Elisabeth facilities (Dr. Weyer, 2021) and (b) a chematic representation of the surface installations showing the position of the inclined shaft (modified after Fritz Bley, 1917).

Beside these shafts there are several shafts which are at least partly accessible, but either locked or sealed at or near the surface (Fig. 8). Furthermore, these other shafts and openings (mainly adits) are not regularly controlled and ventilated. Hence, for teaching, research and access of visitors only openings within the former mining fields of the “Reiche Zeche mine” and “Alte Elisabeth mine” could be used.

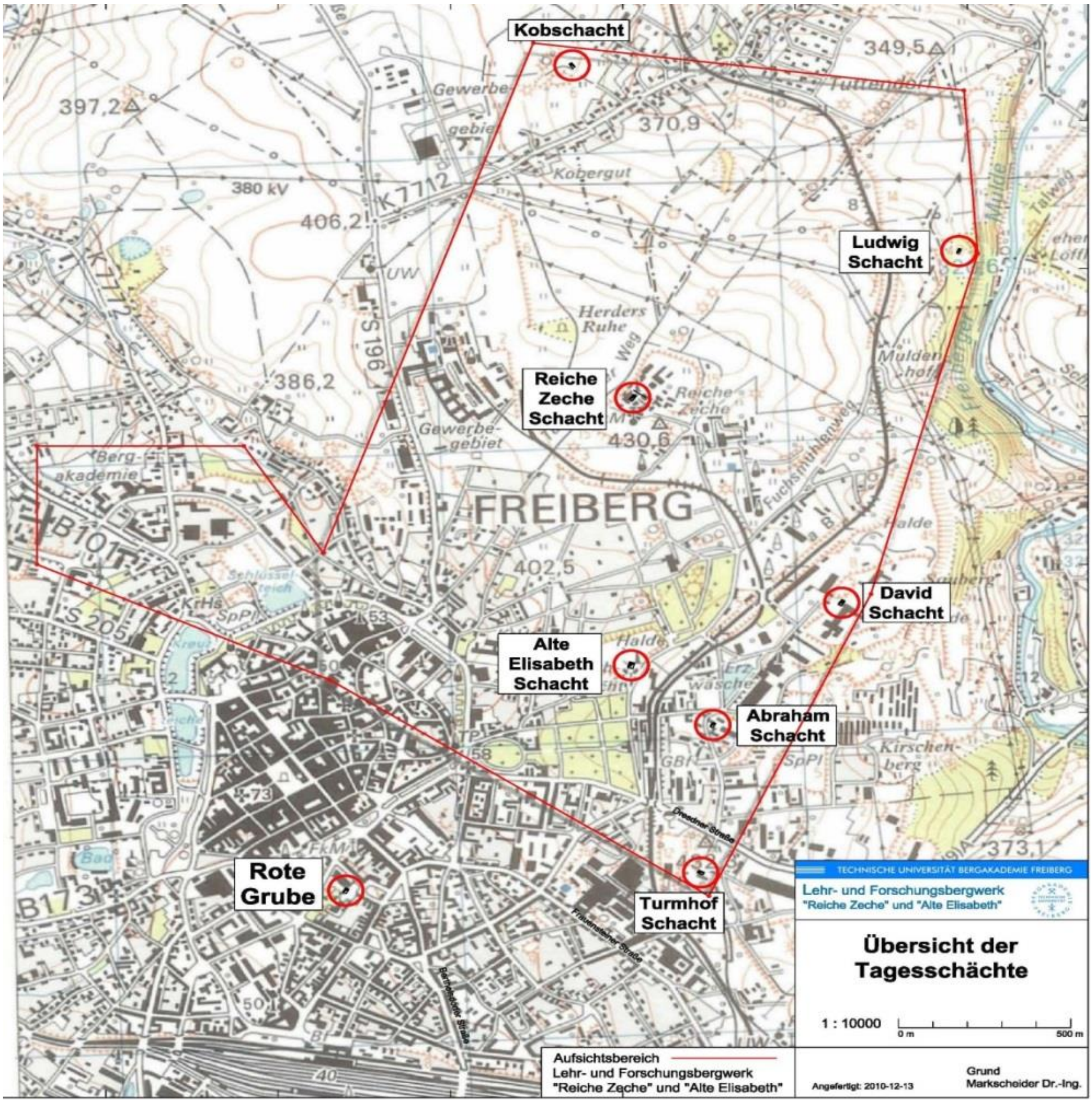


Figure 8. Overview of the main shafts in the surrounding area of the mine (TU Bergakademie Freiberg, 2021).

Although connected at different levels, both shafts had been supporting the production in individual mines when they were founded. The shaft "Reiche Zeche" was first used for "mining engineering and machines" and the shaft "Alte Elisabeth" for surveying. Until the replacement of the hoisting machine in 1981 all students had to enter the mine via the inclined shaft "Alte Elisabeth" (Figure 9), tenderly named "Alte Elise" or "Alte Elli". For this reason the research mine was often reffered to as "Lehrbergwerk Alte Elise" or "Lehrbergwerk Alte Elisabeth" ("Teaching Mine Alte Elisabeth").

Figure 9. The engine house of the Alte Elisabeth shaft with a balancing steam engine (left) and a water column engine (right) (TU Bergakademie Freiberg, 2021).

After the replacement of the hoisting machine from the shaft “Turmhof Schacht” to the shaft “Reiche Zeche” the new entrance was the shaft “Reiche Zeche”. Consequently people spoke about the teaching mine “Lehrbergwerk Reiche Zeche”. The Reiche Zeche shaft (Fig. 10) is mainly used to provide access for people inside the mine and to deliver materials and equipment for the mine.

Figure 10. The double cage system at the Reiche Zeche shaft (Barakos, 2021).

It is a bottleneck in weight and size, but weights of around 1.5 t are not a problem (the test weight for a hoist is around 2 t). The shaft uses a double cage system and the size of each inner hoist cage is approx: 0.8m x 1.5m x 1.7m. Some parts of the hoisting cages are only taller in the middle. Each cage can carry up to 6 people. UL also offers two locomotives, which run on 600 m long tracks, the width of the galleries are 2.2 x 2.2 m.

A 3D visualization of the Reiche Zeche can be found at https://sketchfab.com/3d-models/flb-freiberg-8b53a8ad9960494b9d571d2b53a75837. Figure 11 illustrates the 3D sketchfab model of the underground mine network, as well as the two main shafts of the mine (1. Reiche Zeche; 2. Alte Elisabeth).

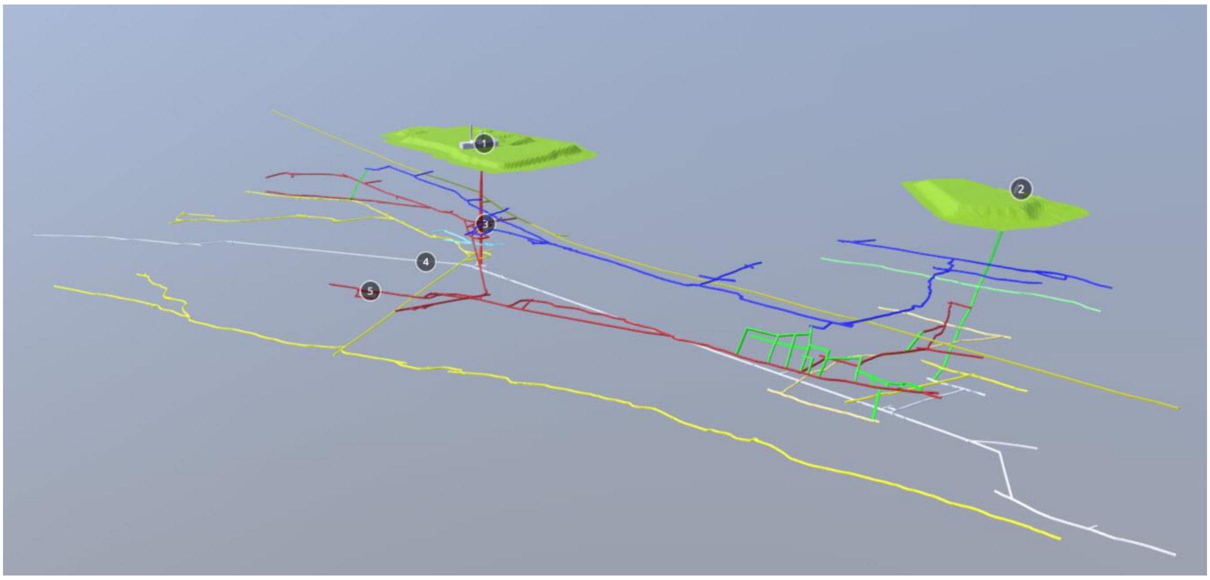


Figure 11. 3D sketchfab model of the Reiche Zeche.

2.2.5 Commuting

As already mentioned, the underground laboratory FLB is located in the municipality of Freiberg, between Dresden and Chemnitz. Each of these cities lies 40 kilometres away from Freiberg. You can get to Reiche Zeche from Dresden by car in about 45 minutes either via the A4 highway (Autobahn) or via the B173 motorway (Fig. 12). From the A4 highway (exit 75 – Siebenlehn) you have to drive about 17 kilometres on the federal road 101 to Freiberg.

Alternatively, there is at least once per hour a train leaving Dresden or Chemnitz towards Freiberg. The train journey from Dresden Hauptbahnhof to Freiberg (Sachs) takes around 40 minutes. Freiberg (Sachs) station is located approximately 3 km from UL (35 minutes on foot). Cabs are available outside the train station. There is a bus connection also available. The name of the bus stop at the train station is "Freiberg (Sachs), Bahnhof". Taking the bus Linie D, will drive you to the bus stop “Freiberg (Sachs), Fuchsmühlenweg/Reiche Zeche“ in approximately 15 minutes.

The nearest international airports are in Dresden (approx. 50 km from UL), Leipzig (approx. 120 km), Prague (approx. 140 km), and Berlin (approx. 210 km) (fig. 12).

Figure 12. How to access to Freiberg via car, train and airplane (TU Bergakademie Freiberg, 2021).

2.3 Research, innovation and cooperation possibilities

2.3.1 Innovation and research

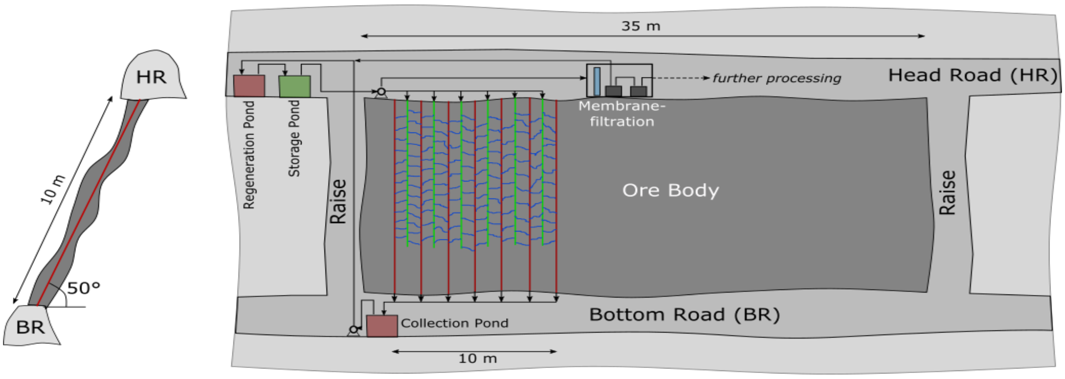
The diversity of uses (for cultural, educational, research and training purposes) makes FLB a unique asset; the mine is used to develop new technologies, production methods and new materials by companies and research units. The mine is also used to train mining and surveying students. The activities are aimed at developing the mine as a European platform for improving mining techniques and education.

More than 30 research laboratories have been set and operating underground not only from different departments of TUBAF, but from external research organisations as well. Though identified as a research underground facility, FLB is also licensed to operate as an active mine.

Some notable research activities that take place in FLB include:

- Bio-hydrometallurgical leaching in ore formations (BHMZ- https://tu-freiberg.de/forschung/bhmz) (Fig. 13a-c)
- High-resolution geophysical exploration systems (Deutschen GeoForschungsZentrum-GFZ)(Fig. 14a-d)

- Developing decentralized communication and data transmission systems
- Optimisation of of operational and work safety conditions
- Real-Time Mining, Big Data management
- Submarine mining (Fig. 15)
- Robotics in mine planning optimisation (https://tu-freiberg.de/node/29068) (Fig. 16)
- New technologies, ventilation, automation, IoT, robotics (Mining 4.0)



(a)

(b)

(c)

Figure 13. (a) Drawing of the bio-hydrometalurgical facility in the FLB, (b) drilling of boreholes from the hearoad towards the bottomroad, (c) controlling station of the collection pond at the bottomroad of the BHMZ facility (TU Bergakademie Freiberg, 2021).

(a)

(b)

(c) (d)

Figure 14. (a) the entrance to the inclined opening that leads to the geophysics underground laboratory, (b) the drilling chamber in the GFZ, (c) the inclined opening giving access to GFZ from the above, (d) Vertical drilling DN 210 at a depth of 70 m (GFZ, 2021).

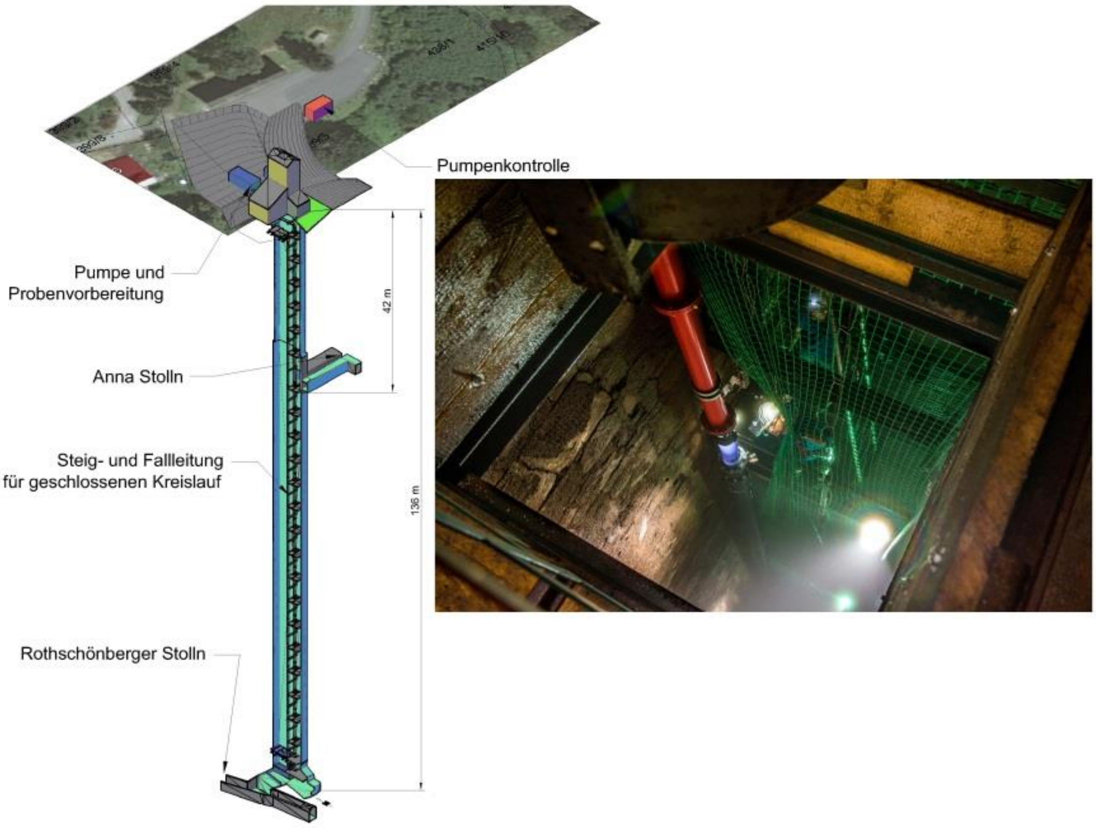


Figure 15. Simulation and actual model tests for submaring mining and haulage for deep sea environments in flooded shafts at Reiche Zeche (TU Bergakademie Freiberg, 2021).

Figure 16. Application of Robotics in underground mining conditions (TU Bergakademie Freiberg, 2021).

FLB is a Regional & International Research Cluster (Fig. 17). The facilities offer a close-to-reality R&D environment with technical and scientific support. This UL serves as an ideal partner for industry, research institutions and universities.

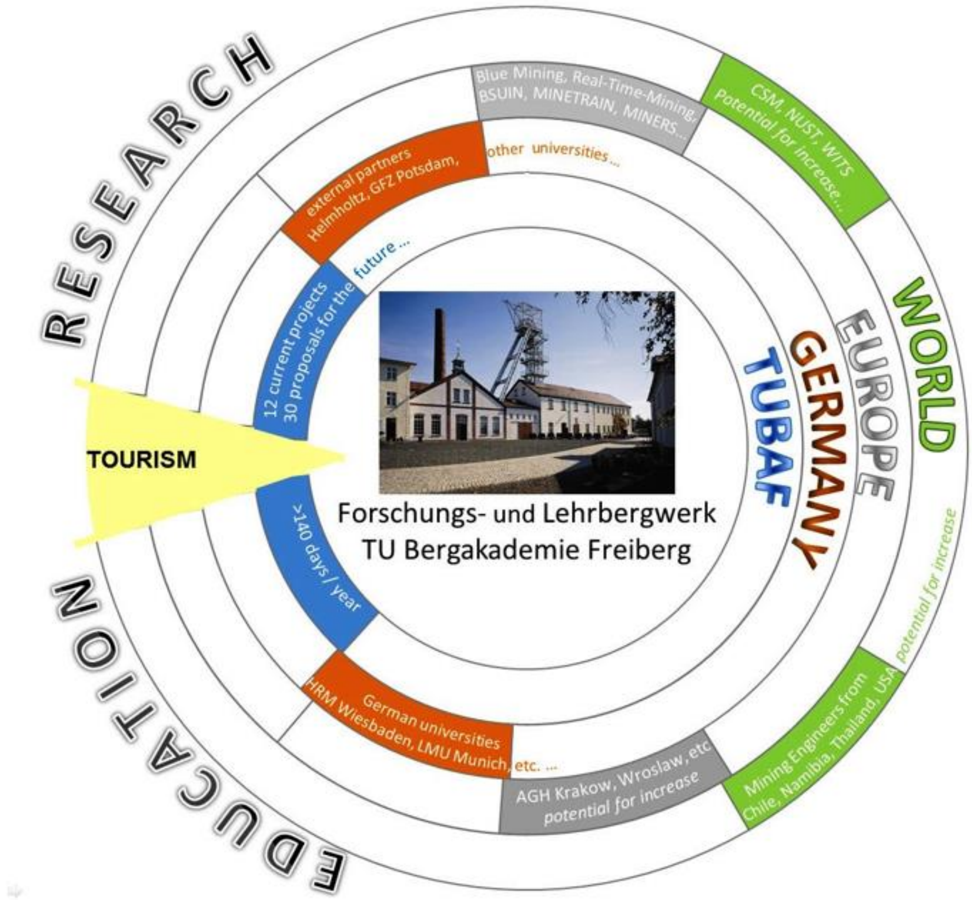


Figure 17. Diverse activities at FLB (TU Bergakademie Freiberg, 2021).

2.3.2 National and international cooperation

Research / training is conducted in the underground laboratory as part of national cooperation by many research institutions, industrial partners and universities. The FLB is currently collaborating with:

- 48 international partners from 26 countries (Fig. 18)
    - 21 partners from industry
    - 27 universities and research institutions

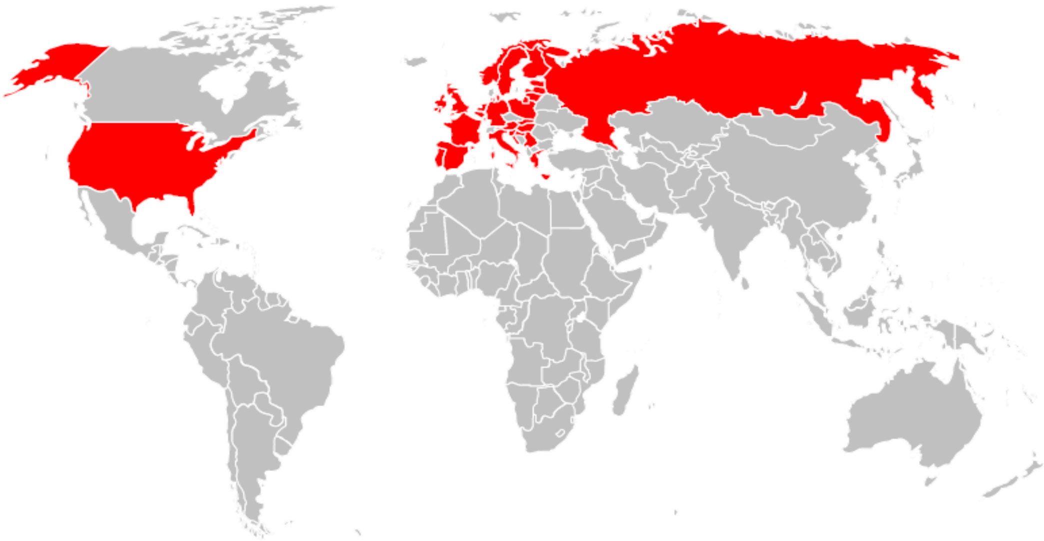


Figure 18. International research partners at theFLB in 2019.

There is close collaboration with other underground research facilities in Europe and around the world. The Reiche Zeche UL belongs to the European Underground Laboratories Association. In addition there is cooperation with Edgar mine, the Colorado School of Mines Experimental Mine, (https://mining.mines.edu/edgar-experimental-mine/) in Colorado, USA.

In addition, FLB offers education not only to German/German speaking undergraduate and postgraduate students. There are international students from 41 countries around the world having research and educational access at the underground facilities in Freiberg (Fig. 19).

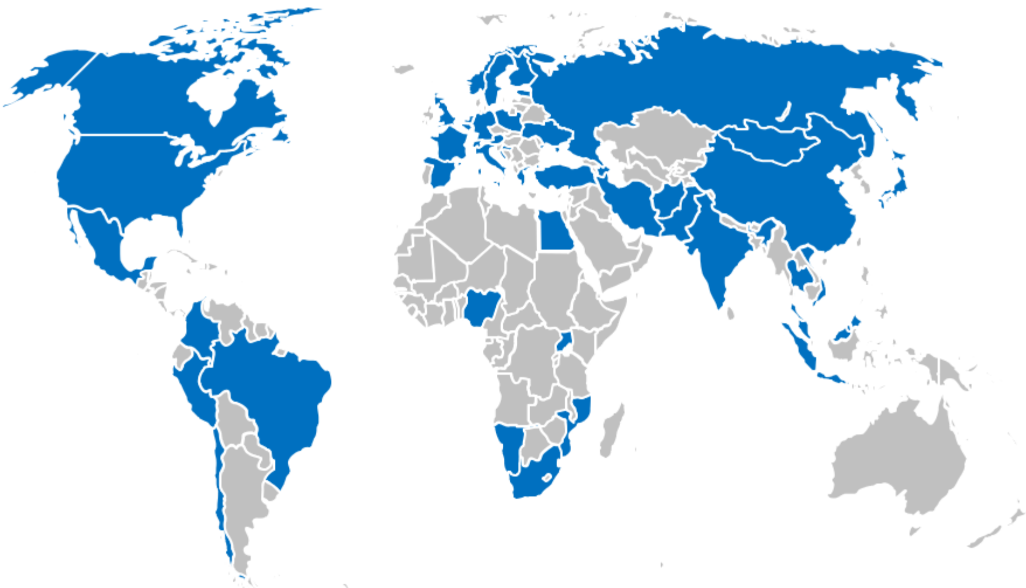


Figure 19. Origin of international students at theFLB in 2019-2020.

2.4 Support at the site and available database

2.4.1 Project handling, competencies and quality control

FLB belongs to TU Bergakademie Freiberg under the auspices of the Mining Authority of Saxony. The structure of the management is described in Figure 20:

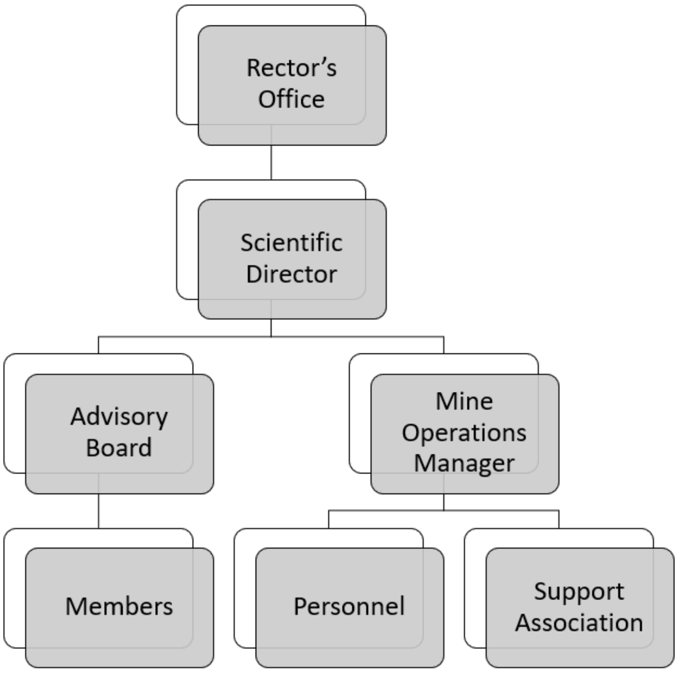


Figure 20. Structure of the management for FLB.

The rector's office is the principal authority that runs the Research and Education Mine Reiche Zeche (FLB). The scientific director of the mine is Prof. Dr.-Ing. Helmut Mischo, who is also the head of the department for Underground Mining and Special Civil Engineering of TU Bergakademie Freiberg. The Scientific Director represents the central institution externally and towards the organs and functionaries of the TU Bergakademie Freiberg. The scientific director's work is supported by the advisory board of the mine and the mine operations manager. The performance of the duties of daily mine operations shall be the responsibility of the Mine Operations manager that is Dipl.-Ing. Frank Reuter. On the other hand, the tasks of the advisory board are:

- Advice and support for projects requiring a business plan
- Advice and support in the preparation and production of underground operating points for teaching and research purposes
- Advice and support on safety-related problems

The regulations that govern the management and operation of FLB can be found here (in German language):
https://tu-freiberg.de/sites/default/files/media/lehr--und-forschungsbergwerk-reiche-zeche-und-alte-elisabeth-2989/ordnung_rz.pdf
Underground openings and spaces are to be used by university departments and/or be rented as facilities to external partners/clients for experiments, tests, research activities and other activities that may take place in an underground environment with specific weather conditions. Stakeholders shall declare their interest to the Scientific Director of the mine, who in turn shall inform the rector's office and decide based on their consulting.

2.4.2 Database

FLB has a long history that is well documented in detail. There are numerous data sets for the surface facilities, the underground openings, geological, geophysical and geochemical surveys from different periods of the life of the mine.

A sample of gathered literature and sources is listed hereinafter:

(1)	Author collective under the direction of Günter Freyer	Freiberger Land - results of the local history inventory in the area around Langhennersdorf, Freiberg, Oederan, Brand-Erbisdorf and Weißenborn; Akademie-Verlag Berlin 1988
(2)	Murawski, H .; Meyer, W.	Geological dictionary, Ferdinand Enke Verlag Stuttgart 1998
(3)	Wagenbreth,O.; Wächtler, E.	Freiberg mining, technical monuments and history; German publisher for basic industry, 1986
(4)	Muzeniek, P.	Drawing miner
(5)	Jobst, W .; Rentsch, W.; Schubert, W .; Trachbrod, K.	Mines in the Freiberg region; Media center of the TU Bergakademie Freiberg, 1993
(6)	Prescher, H.	Georgius Agricola Personality and Work for the Mining and Metallurgy of the 16th Century, VEB Deutscher Verlag für Grundstoffindustrie, Leipzig 1985
(7)	Naumann, F.	Georgius Agricola mountain scholar, naturalist, humanist Sutton-Verlag 2007
(8)	Wagenbreth, O.	125 years of Rothschönberger Stolln, Freiberg 2002
(9)		www.bergbautradition-sachsen.de
(10)	Pforr, H .; Schützel, H.; Baumann, L.	Excursion guide to the teaching pit "Alte Elisabeth", volume 2/3 Bergakademie Freiberg 1985

(11)	Haubold, O. Copy (German writing) Fischer, K.	Entertainment supplement from the Freiberger Anzeiger, Sunday, August 18, 1935
(12)	Mischo, H. (ed.)	Entdecker Unter Tage 1919-2019: 100 Jahre Forschungs- und Lehrbergwerk

Among detailed literature, there are numerous articles in Journals, papers in conferences, reports, students' theses and personal recordings that describe the history of this UL. For example, the galleries and openings around the Reiche Zeche shaft (main area) have been mapped in detailed and were digitized (using Maptek Vulcan) since 2014, in the context of a diploma thesis.

In addition, The Freiberg Mining Archives (https://www.staatsarchiv.sachsen.de/bergarchiv-freiberg-3988.html) has been founded and in there about 4500 linear meters of written material are kept, including about 65,000 maps, plans and outlines, and about 30,000 photos, as well as a special mining history library with about 21,000 volumes, in Freudenstein Castle in Freiberg. The mining archive can be traced back to 1679. A very big part of the archive is already digitized (more than 70.000 pieces including documents, maps and photos).

3 Site description data and data properties

3.1 Bedrock geological data and properties

3.1.1 Geological data and tectonics

The geological data and description hereinafter comes directly from the following publication:

Laura J. Swinkels, Jan Schulz-Isenbeck, Max Frenzel, Jens Gutzmer, Mathias Burisch; Spatial and Temporal Evolution of the Freiberg Epithermal Ag-Pb-Zn District, Germany. Economic Geology 2021;; 116 (7): 1649–1667. doi: https://doi.org/10.5382/econgeo.4833

Regional geology

The Erzgebirge metallogenic province (Fig. 21B) forms the northern tip of the Bohemian Massif, part of the Variscan orogen in central Europe. The Variscan orogen resulted from the collision of Gondwana and Laurussia between 400 and 340 Ma (Kroner et al., 2010). The Erzgebirge consists of a diverse suite of metamorphosed nappe stacks, with Cadomian and Paleozoic protoliths forming a large SW-dipping anticline (Romer et al., 2010; Rötzler and Plessen, 2010). The metamorphic units were subsequently intruded by syn- to latecollisional granitoids between 336 and 315 Ma, followed by postcollisional bimodal magmatism (305–270 Ma; Kroner et al., 2010; Hoffmann et al., 2013; Kroner and Romer, 2013; Zhang et al., 2017). The late Carboniferous and early to middle Permian were characterized by intense rifting, volcanism, and basin formation (e.g., Döhlen basin; Gaitzsch et al., 2010; Schneider and Romer, 2010). The youngest record of Permian silica-rich volcanism is dated at ~270 Ma (Schneider and Romer, 2010; Hoffmann et al., 2013). Continued subsidence during the Mesozoic led to burial of the basement units underneath thick sedimentary sequences (Ziegler, 1990). Eventually, in the Cenozoic, the formation of the Eger Graben rift resulted in the exhumation of the Variscan basement and associated hydrothermal deposits (Ziegler, 1990; Ziegler and Dèzes, 2007).

The Erzgebirge is host to numerous types of ore deposits (e.g., Baumann et al., 2000; Haschke et al., 2021; Reinhardt et al., 2021; Guilcher, in press). Most prominent among these are magmatic-hydrothermal deposits such as skarns (Schuppan and Hiller, 2012; Bauer et al., 2019b; Burisch et al., 2019b; Korges et al., 2020; Reinhardt et al., 2021), greisens (Štemprok, 1967; Zhang et al., 2017; Korges et al., 2020), and epithermal veins (Bauer et al., 2019a; Burisch et al., 2019a).

District geology

The Freiberg district is located in the northeastern part of the Erzgebirge (Fig. 21). The predominant lithology is a Neoproterozoic composite gneiss unit, comprising biotite-plagioclase orthogneiss (locally referred to as lower gray gneiss) and biotite-muscovite-plagioclase paragneiss (locally referred to as upper gray gneiss; Tichomirowa et al., 2012). The gneiss units form an ellipsoid-shaped (dome-like) body, which is overthrusted by mica schists in the northwest and phyllites in the north and northeast and bordered by other gneiss units in the south and west (Fig. 21C). In the north, gneiss, mica-schist, and phyllites are locally alternated with metagabbro, serpentinite, and amphibolite schist (Baumann, 1965; Baumann et al., 2000).

East of the town of Freiberg, the gneiss units were intruded by the late Variscan (ca. 325–320 Ma) Niederbobritzscher biotite granite (Tichomirowa, 1997). The granite is accompanied in the east by a rhyolitic unit of the Tharandter Wald Volcanic Complex (ca. 320 Ma; Breitkreuz et al., 2009). Numerous rhyolite/microgranite and lamprophyre dikes crosscut the metamorphic units in the area (Müller, 1901; Baumann, 1965; von Seckendorff et al., 2004; Abdelfadil et al., 2014).

Hydrothermal mineralization in the Freiberg district

Three fundamentally different types of hydrothermal veins have been recognized in the Freiberg district: (1) epithermal polymetallic sulfide-quartz-carbonate veins, (2) fluoritebarite-quartz-Pb-Zn veins, and (3) less abundant five element (Bi-Co-Ni-Ag-As) veins (Müller, 1901; Baumann et al., 2000; Bauer et al., 2019a; Burisch et al., 2019a; Ostendorf et al., 2019). This study focuses only on the economically dominant polymetallic sulfide-quartz-carbonate veins, which are probably related to Permian magmatic-hydrothermal activity (276 ± 16 Ma; Ostendorf et al., 2019). The fluorite-barite and native metal-arsenide veins are significantly younger and have been tentatively associated with the opening of the northern Atlantic (Ostendorf et al., 2019).

Polymetallic epithermal mineralization in the Freiberg

district occurs in steeply dipping N-S– and NE-SW–trending veins that are hosted by gneiss, mica-schist, metagabbro, and less commonly phyllites. Mineralization can typically be traced over large vertical extents (>1 km; Kraft and Tischendorf, 1960). Three mineral associations have historically been distinguished within the epithermal Ag-Zn-Pb veins of the Freiberg district: (1) a base metal-sulfides-quartz association, referred to as “Kiesige Bleierzformation” (kb), comprising mainly sphalerite, galena, arsenopyrite, pyrite, pyrrhotite, and chalcopyrite, (2) a sphalerite-Ag-sulfides-carbonate association (“Edle Braunspatformation”; eb) with sphalerite, galena, fahlore, and silver sulfosalts, and (3) an Ag-sulfides-quartz association (“Edle Quarzformation”; eq) with abundant silver sulfosalts, acanthite, arsenopyrite, pyrite, galena, sphalerite, and Sb sulfides (Müller, 1901).

Individual veins commonly comprise multiple generations of vein infill that may represent several distinct mineral associations. The predominant association, however, varies systematically on the district and vein scale (Müller, 1901; Burisch et al., 2019a). The base metal-sulfides-quartz association is the dominant vein fill in the central part of the district. The sphalerite-Ag-sulfides-carbonate association is most prominent at the historical mining camps of Brand-Erbisdorf and Kleinvoigtsberg, 6 km south and 10 km north of the town of Freiberg, respectively (Fig. 21; Müller, 1901; Burisch et al., 2019a). The Ag-sulfides-quartz association prevails in the peripheral sectors and shallow vein sections (Müller, 1901; Burisch et al., 2019a). Veins that comprise Ag-sulfides-quartz infill commonly also contain discrete Sb sulfides, such as stibnite and berthierite, which typically occupy a shallower position in the veins than the major Ag mineralization (Burisch et al., 2019a). The intensity of host-rock alteration is variable and mostly characterized by silicification and sericitization (muscovite) with some disseminated pyrite, arsenopyrite, galena, and rarely chlorite (Rösler and Kühne, 1970). However, a comprehensive study on host-rock alteration in the Freiberg district has never been conducted.

Geochronologic, petrographic, geochemical, and microthermometric observations indicate a magmatic-hydrothermal origin of much of the Freiberg epithermal district, affiliated with early Permian magmatism (Bauer et al., 2019a; Burisch et al., 2019a; Ostendorf et al., 2019). However, a causative intrusion has not yet been identified. Attempts to intersect a potential intrusion by drilling during Sn exploration campaigns in the 1950s and 1970s were unsuccessful as all five drill holes with final lengths of 1,110, 1,317, 1,745, 1,826, and 1,061 m, respectively, did not intersect an intrusive body.

Notably, abundant veins with base metal-rich mineralization were still present at the final depths of these drill cores (Kraft and Tischendorf, 1960; Krutak, 1980).

Sectors of the Freiberg district

The Freiberg district has been subdivided into five sectors based on geography (Fig. 21C) and distinct mineralogical and geochemical variations (Baumann et al., 2000). In the following, background information on the most important mines and characteristics of the ore deposits of each sector are briefly introduced.

Central sector: The central sector, including the towns of Freiberg and Brand-Erbisdorf, comprises the deepest and largest underground mines of the district (down to 600 m below surface). Abundant N-S– to NE-SW– and E-W–striking hydrothermal veins form a dense fracture network with individual veins traceable over ~5 km along strike. Vein thickness may reach up to 4 m but usually ranges between 0.1 and 0.8 m (Müller, 1901). The base metal-sulfides-quartz association is the most prominent vein infill in the central sector (e.g., Himmelfahrt mine, Freiberg) and is associated with elevated concentrations of Cu, Sn, and In (up to 71,000, 13,000, and 1,560 g/t, respectively; Müller, 1901; Seifert and Sandmann, 2006). In the southern part of the central sector (Brand-Erbisdorf) the sphalerite-Ag-sulfides-carbonate association prevails, commonly crosscutting or coating the paragenetically older base metal-quartz association (Müller, 1901). Because of the dominance of the sphalerite-Ag-sulfides-carbonate association, the Himmelsfürst mine (BrandErbisdorf) was one of the economically most significant mines of the entire Freiberg district (Müller 1901; Seifert and Sandmann, 2006).

Northern sector: The northern sector includes the historical mining camps of Kleinvoigtsberg, Großvoigtsberg, Obergruna, Siebenlehn, Reinsberg, and Mohorn (Fig. 21C). Hydrothermal veins mainly strike northeast-southwest, can be traced along strike for up to 2 km, and have thicknesses between 0.1 and 4 m. The veins in the northern sector are often found in the contact zone between gneiss and schist and tend to be less continuous along strike and dip than in the central sector; they frequently split or pinch out and locally form stockwork-like swarms of veinlets. The shallow levels of the veins in this sector are dominated by an Ag-sulfides-quartz association, whereas at deeper levels the sphalerite-Ag-sulfidescarbonate and the base metal-sulfides-quartz associations prevail (Müller, 1901; Baumann, 1965; Baumann et al., 2000).

The Alte Hoffnung Gottes mine near Kleinvoigtsberg was the economically most significant mine in the northern sector and was mined to depths of 560 m below surface (Müller, 1901; Baumann, 1965). The area of Reinsberg comprises several small mining camps with the Emanuel mine, which was mined to depth of 310 m below surface, as the most significant operation (Müller, 1901; Baumann, 1965).

Western sector: The Neue Hoffnung Gottes mine close to the town of Bräunsdorf was the most important operation in the western sector (mined down to 290 m below the surface). Similar to the northern sector, hydrothermal veins strike mainly northeast-southwest. In contrast to other sectors, veins are often hosted by what has been described as a graphite-rich schist unit (Müller, 1901; Baumann, 1965; Baumann et al., 2000; Burisch et al., 2019a). Within the ~300-m vertical profile of the Neue Hoffnung Gottes mine, a distinct vertical zoning has been recognized, which includes a shallow Sb quartz cap grading into Ag-sulfides-quartz association with increasing depth (Burisch et al., 2019a).

Southern and eastern sectors: Historical mining operations were much smaller in the southern and eastern sectors of the Freiberg district. Veins are characterized by abundant Ag-sulfides-quartz mineralization. An increase of base metals at depth is reported and is locally associated with economic Cu and Sn mineralization (Müller, 1901; Baumann, 1965).

The major operations in the southern sector were the Friedrich August and Friedrich Christoph mines, southeast of the town of Frauenstein. These operations targeted an ~200- × 2,000-m swarm of N-S–striking veins. The operations were limited to depths of 170 m below surface (Müller, 1901).

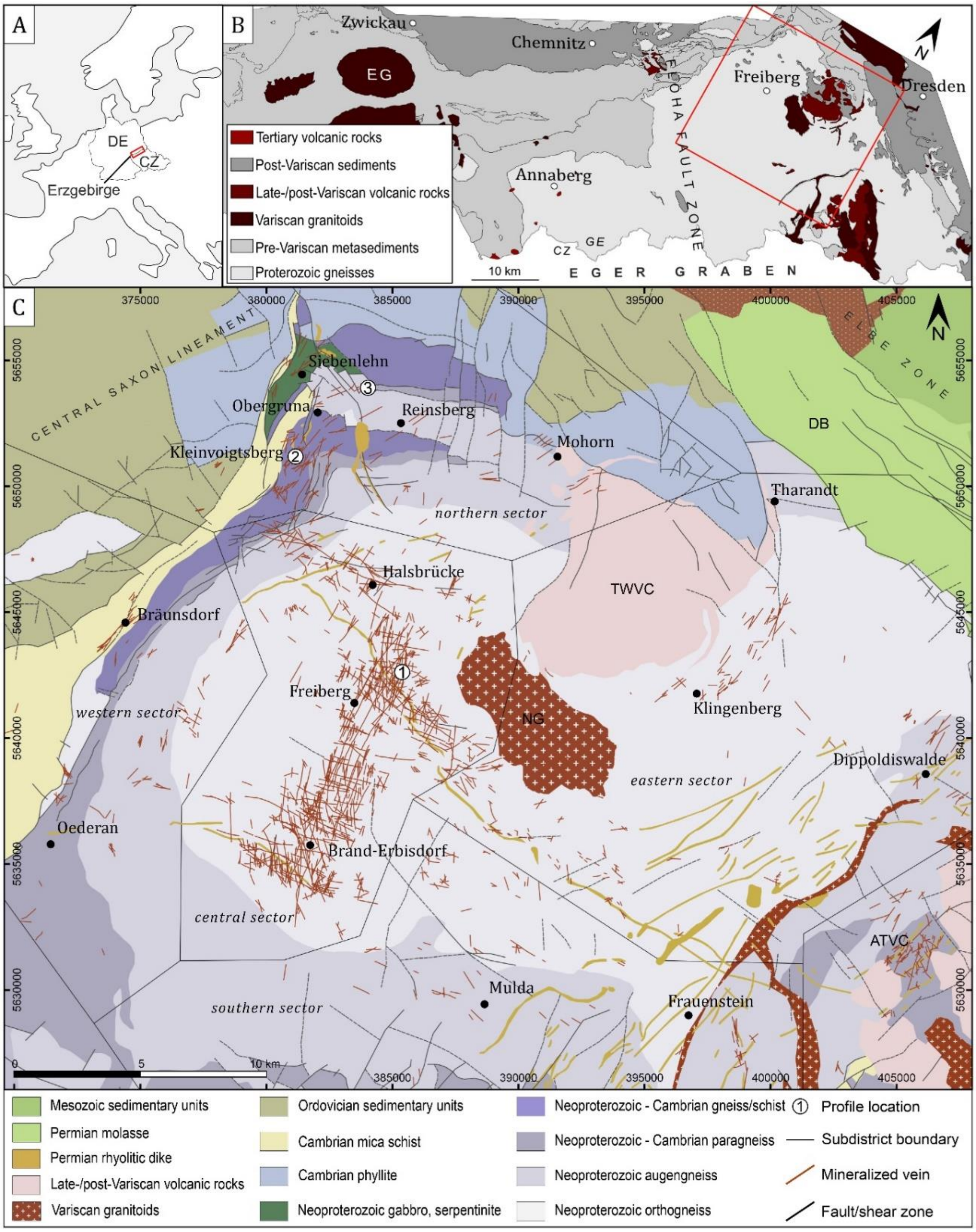


Figure 21. Overview map of the study area. (a) Location of the Erzgebirge at the border between Germany (DE) and the Czech Republic (CZ). (b) Simplified geologic map of the Erzgebirge after LfULG (1994). (c) Simplified geologic map of the Freiberg district based on Hoth et al. (1980), with ATVC = Altenberg-Teplice Volcanic Complex, DB = Döhlen basin, EG = Eibenstock granite, NG = Niederbobritscher granite, TWVC = Tharandter Wald Volcanic Complex. Known hydrothermal veins are indicated as red lines (Swinkels et al., 2021- https://doi.org/10.5382/econgeo.4833).

3.1.2 Major rock type(s)

The Freiberg district hosts one of the largest series of epithermal polymetallic vein deposits in Europe. Six distinctive mineral associations have been recognized within the Freiberg epithermal veins; sphalerite-pyrite-quartz and galena-quartz±carbonate associations are most abundant in the central sector, as well as in the deepest sections of veins on the periphery of the district. A high-grade sphalerite-Ag-sulfides-carbonate association occurs laterally between the central and peripheral sectors and at intermediate depth in veins on the periphery. Shallow and peripheral zones are dominated by an exceptionally Ag-rich Ag-sulfides-quartz association, whereas the shallowest veins locally comprise Ag-poor stibnite-quartz and quartz-carbonate associations.

Fluid inclusion assemblages returned low salinities (<6.0 wt % NaCl equiv), and homogenization temperatures successively decrease from ~320°C associated with the proximal and deep sphalerite-pyrite-quartz association, to ~170°C related to the distal and shallow Ag-sulfides-quartz association.

The architecture of the Freiberg district is related to the temporal and spatial evolution of magmatichydrothermal fluid systems, including boiling and concomitant cooling, as well as CO_2 loss. Constraints on the paleodepth indicate that the veins formed between 200 and 1,800 m below the paleowater table. High-grade Ag ore occurs over a vertical interval of at least 500 m and is bracketed by shallower stibnite-quartz and barren quartz, and deeper base metal-sulfide-quartz zones.

The ore veins have an average thickness between 20 and 40 cm, while their length (strike) could be several hundreds of meters. The inclination of the deposit is between 30° and 90°, most ore veins in the FLB have 40° to 60° inclination.

Main minerals and metals found in this formation are (Fig. 22):

- Galena
- Sphalerite
- Pyrite
- Chalcopyrite
- arsenopyrite
- quartz.

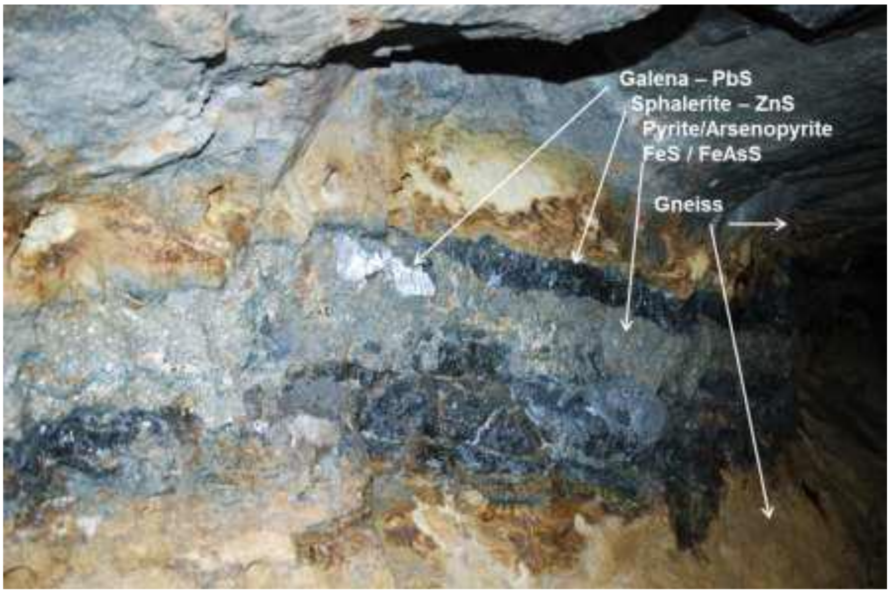


Figure 22. Typical mineral composition at Reiche Zeche (Weyer, 2018).

The polymetallic deposit exploited in Freiberg includes several other minor metals as well, many of which are included in the critical raw materials list as this has been defined by the EU. For instance sphalerite is now in the focus of several research activities, due to its yield on indium and germanium.

3.1.2.1 Mechanical properties and conditions

The stability of the openings and necessary support depend on the location inside the mine. To begin with, there is a difference between openings within the host rock (gneiss) and openings within veins, faults or fractures. Openings within gneiss are generally very stable and do need zero or only limited support. Smaller cross-sections have remained stable over the centuries without any rock fall or damage. Characteristic examples are some old openings on the adit level, which were mined with chisel and iron (i.e. before the introduction of drilling and blasting; meaning that these openings are since the 18th century and before). The search for ore veins from “Hauptstollngang” started in 1721. The resulting openings “Auferstehung Christi” are accessible and are shown during visitors’ tours to the public. The openings look like they were mined recently. The cross section is roughly 60 cm width and 1.80 m height. In such old openings heights can go down to 1.20 m or even less.

Nevertheless, drifts which have been opened up until the closure of all mines in 1969 are also considered as very stable. In some cases no support or only single roofbolts can be found on the handwall and footwall. In the Reiche Zeche shaft near area and the main drifts on the 1st Level (150 m) more roofbolts have been set although nor really necessary in geotechnical terms. A main reason for having placed these roofbolts is to give non-mining visitors a better feeling of safety. Another reason is that in 1990 hundreds of roofbolts were given to the mine.

In the stopes the situation is often different. Although temporary safe, – as required by the law – special attention is deemed necessary. The ore vein itself has different geotechnical and mechanical properties. But more important are the boundary conditions. The ore vein can either be hard, and thus the contact to the gneiss is hard and solid as well. On the other hand, movements and reactions after the formation of the ore veins could have formed a layer of clay that has not enough strength. This was used to break the ore vein from the host rock. Nevertheless, this increases the risk of rock fall. During operation times (until 1969) this danger was known as "Sargdeckel" (coffin lid), because massive parts of rock or ore vein could suddenly fall down. Such parts had a weight of some tons and were of course deadly.

Contrary to the aforementioned, the roof had to be stable only for a few days, due to the advancement of the operations; the next slice was mined and a new roof was created. Nowadays, all accessible stopes and also all accessible parts of the entire mine are secured. For this reason one can find stopes with a lot of timber support (Fig. 23) but also stopes without support, depending on the stability of the system host rock – ore vein.

Inside the drifts smaller ore veins or faults can cross the opening. Here similar conditions like in the stopes are evaluated. Such regions inside the mnie have to be partly secured. Bigger openings, which have been created in the last decades are secured by a system of rockbolts, meshes and shotcrete, as it generally happens in most underground mines and tunnels.

Special attention is also given to vein drifts, where no safety pillar was left up to the first stope (slice). If the vein drift was supported using steel (old rails), then the acidic water could have lead to a faster corrosion of the material during the years. On the steel buntons lies mined waste rock from the stope, i.e. roughly a 50 m high column of rock (backfill). If timber is rotted or steel is rusted, tons of backfill can fall into the drift. Therefore, such parts are constantly monitored and further secured if necessary.

Figure 23. Timber support in parts of the Reiche Zeche undergound mine (Dr. Weyer, 2012).

3.1.2.2 Thermal properties and conditions

The altitude of the city of Freiberg is roughly 400 m. The average temperature on surface is about 7.3 °C. Seldom temperatures can reach -25 °C in winter and 30 °C in summer. These temperatures on the surface can only influence the underground temperature in some of the openings that are not too far away from the intake shaft “Alte Elisabeth”. This has been proved by temperature measurements inside the mine. Despite temperatures between -25 °C and 32 °C at the surface the underground air-temperature after about 700 m is almost constantly 11 °C and constantly 11 °C after 1800 m. Therefore, temperatures between 10 °C and 12 °C – depending on the location – must be expected in the mine openings.

The relative humidity is constantly measured in parallel to the measurement of the temperature. The relative humidity has also constant values a few hundreds of meters away from the intake shaft. In summer time the relative humidity is increasing, obviously because warm air cools down when entering the mine atmosphere. In winter times cold air becomes warmer inside the openings, thus decreasing its relative humidity. In addition, inflows of water, dropping water from the roof and wet rocks increase the relative humidity. Already after 700 m away from the intake shaft values between 97 % - 98 % relative humidity could be measured. Condensation appears already at this percentage.

The barometric pressure is comparable to the barometric pressure on surface. In theory it is lower, than the average barometric pressure on sea level. So, the average barometric pressure on surface is about 965 hPa. Consequently the barometric pressure at a depth of 150 m is around 985 hPa and at a depth of 200 m is around 990 hPa. (Standard pressure on surface is defined as ICAO standard atmosphere at 15 °C giving 1013.25 hPa.) Hence, the differences to the given values for the atmosphere on surface are negligible for any work or any instrument. Even for calculations of the density it is normally not necessary to measure or recalculate the exact barometric pressure.

The FLB is ventilated by a forcing ventilation system. The main mine fan is located in the inclined shaft "Alte Elisabeth". A forcing ventilation system is required by the Mining Authority mainly under consideration of aspects of radiological protection. As a matter of fact the natural radiation in magmatic rocks is higher than in sedimentary rocks. Furthermore the radiation in ore deposits is generally higher than in rock without ore. This applies for all ore mining operations all over the world, special dangers and regulations apply for mining of radioactive ores.

Compared to big operating mines the total length of ventilation-controlled openings is small. In the past no diesel driven loaders or other vehicles have been used. Therefore, the required volume flow through the mine is smaller than in mines with diesel equipment. As already mentioned, there are plans for a 3rd access with diesel driven equipment which also requires a change in the volume flow and the installation of a new main mine fan.

Currently about 600 … 900 m3/min of fresh air enter the mine. The main exhaust airway is the shaft "Reiche Zeche". Due to several connections to old abandoned openings including shafts, adits and raises only up to 2/3 of the volume flow leaves the air through the shaft "Reiche Zeche"; the remaining amount reaches the surface via other old openings outside of the controlled area of the mine.

The cross section of (most of) the existing openings starts from less than 1 ^{m2} at some locations in the adit level (visitors, education) to about 5 - 6 m^2 in regular drifts at the 1st and 3rd Level. The cross section in stopes is theoretically 1.25 m^2 required during operation time until 1969. Depending on the location, bigger and smaller cross sections are possible. Testing fields and research facilities can have bigger dimensions and have been mined or extended to the required cross section (also 20 m^2 and more) but the drifts to or from the testing fields are again in the range of about 5 - 6 m^2.

During the controlled decommissioning and flooding of the tunnels after mining concluded, nature reclaimed parts of the mine. Shafts and tunnels which once led miners through the mine are now filled with water. While part of this water is due to precipitation that has seeped down from the surface, the other part is from deep-lying groundwater. Water from tunnels deep within the mine can rise through the mine's shafts, as has occurred in the main shaft of the Reiche Zeche, the „Himmelfahrt Fundgrube", for example. Here, geothermal energy is transported with the water from a depth of 750 m to only 228 m below the surface, yielding water temperatures of approximately 19°C year-round. The water then flows into a cooler underground drainage tunnel, the Rothschönberger adit. The university's geothermal energy system at the Reiche Zeche makes use of this energy for heating and cooling purposes (Fig. 24).

In Winter, the 19°C mine water is pumped to two underground heat exchangers, which are connected with an intermediate heating loop. This heating loop transfers the heat to the surface, where the warm water stream is divided. The temperature of one fraction is increased to 60°C using heat-pump technology, while the other fraction is used for cooling of the computer labs and server rooms. In summer, the cooling system switches to pumping the cooler 14°C water from the Rothschönberger adit above ground. Thus, the water cools several laboratories, server rooms and offices energy efficiently. With the two installed heat pumps, a heating load of 175 kW can be achieved. By using the cool water from the Rothschönberger adit directly, the cooling load can reach 100 kW [1,2].

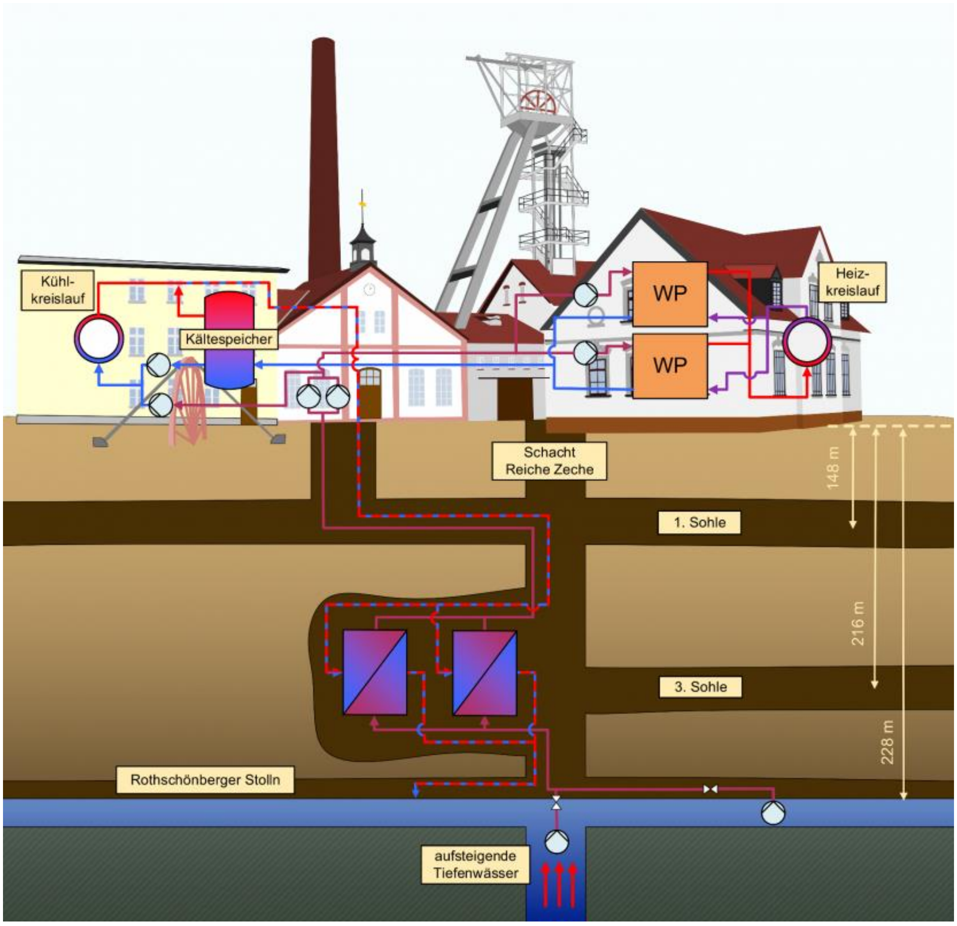


Figure 24. Geothermal mine water system Reiche Zeche Freiberg (TUBAF, 2021).

Summer Operation (Cooling Mode)

- Pumping of water from the Roth-schön-berger adit primarily for the cooling
- Discharge of the mine water, which has been warmed-up by absorbing heat in the cooling loop, back into the Roth-schön-berger adit with enough distance from the suction point
- Direct cooling of laboratories, server rooms, and offices

Winter Operation (Heating Mode)

- Use of water from the Reiche Zeche mine shaft primarily for heating
- Heat pumps increase the temperature of the water for heating and warm water supply
- Cooling is also required for laboratories and server rooms in winter
- Support of cooling by recycling the cooled water from the heating loop

3.1.2.3 Radionuclide data

Radionuclides are of importance for both occupational safety and for users looking for low natural background radiation environments.

In the Freiberg mining district no minable radioactive ores have been found. It is a “normal” lead-zinc deposit with no special danger. Nevertheless, in magmatic and metamorphic rocks (like gneiss) there is natural radiation detected that can reach levels up to 6ppm.

3.1.3 Data sources

3.1.3.1 Surface data

Surface data (ground magnetic, resistivity and seismic surveys) about the FLB and surrounding areas are available upon request to the Deutsches Geoforschungszentrum (GFZ) of the Helmoltz-Zentrum Potsdam (https://www.gfz-potsdam.de/sektion/geomechanik-und-wissenschaftliches-bohren/infrastruktur/gfz-untertagelabor-freiberg/). Additional data can as well be found in the Bergarchiv Freiberg (https://www.staatsarchiv.sachsen.de/bergarchiv-freiberg-3988.html), as well as at the Institute of Geophysics and Geoinformatics of TU Bergakademie Freiberg (https://tu-freiberg.de/en/geophysik/institute/institute-of-geophysics-and-geoinformatics). Furthermore, there is extened published literature available via the worldwide web.

Respective information regarding bedrock maps and other surface data can be found in the Bergarchiv Freiberg (https://www.staatsarchiv.sachsen.de/bergarchiv-freiberg-3988.html), as well as at the Institute of Geology of TU Bergakademie Freiberg (https://tu-freiberg.de/en/geo). Furthermore, there is extened published literature available via the worldwide web.

3.1.3.2 Borehole data

Rock mechanics data about the FLB are available upon request at the Institute of Drilling Engineering and Fluid Mining of TU Bergakademie Freiberg (https://tu-freiberg.de/en/fakult3/tbt/institute/institut-fuer-bohrtechnik-und-fluidbergbauengl). Furthermore, there is extened published literature available via the worldwide web.

3.1.3.3 Underground data

Underground data about the FLB are available upon request to the Bergarchiv Freiberg (https://www.staatsarchiv.sachsen.de/bergarchiv-freiberg-3988.html), as well as at the Department of Underground Mining and Special Civil Engineering of TU Bergakademie Freiberg (https://tu-freiberg.de/en/fakultaet3/tiefbau). Furthermore, there is extened published literature available via the worldwide web.

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

Rock mechanics data about the FLB are available upon request to the Bergarchiv Freiberg (https://www.staatsarchiv.sachsen.de/bergarchiv-freiberg-3988.html), as well as at the Department of Geomechanics, rock mechanics and rock engineering of TU Bergakademie Freiberg (https://tu-freiberg.de/en/fakultaet3/gt/felsmechanik/rock-mechanics). Furthermore, there is extened published literature available via the worldwide web.

Respective data related to petrography can be found in the Bergarchiv Freiberg (https://www.staatsarchiv.sachsen.de/bergarchiv-freiberg-3988.html), as well as at the Institute of Geology of TU Bergakademie Freiberg (https://tu-freiberg.de/en/geo). Furthermore, there is extened published literature available via the worldwide web.

3.1.3.5 Natural background radiation data

Forcing ventilation is mandatory at the underground openings of Reiche Zeche due to the existence of natural occurring radioactive material (NORM). According to the German Law and in compliance with international regulations workers have to be controlled (be carrying always a dosimeter) if an effective dose of 6 mSv/year can be reached.

Even though the measured radiation levels inside the mine (FLB) are much lower than the aforementioned limit, monitoring and controls are performed regularly. In the working areas and testing fields the effective dose is normally less than 1 mSv (/y). Only in unventilated areas and the abandoned mining openings outside of the FLB the effective dose can rise up to more than 100 mSv/year.

Besides the data collected in the dosimeters that the permanent workers of the mine are carrying, measurements are taken in regular intervals in the context of research projects and practical training of university students.

For instance, natural radioactivity measurements were taken in 2018 in the context of the BSUIN project (http://bsuin.eu/) at two locations: the server room near the Reiche Zeche shaft and a bare cave near the Alte Elizabeth shaft. In addition, for a deeper analysis of the study site, rocks and water samples were collected for laboratory analysis at the Institute of Physics of the University of Silesia in Katowice. The measurement results (neutron flux, gamma-ray flux, effective dose rate, count rate, the radon concentration in air, and radioisotopes concentration in water ($^{234,238}U$, $^{226,228}Ra$) and rock ($^{234,238}U$, $^{226,228}Ra$, ^{40}K) samples are available in the A2.2 activity report of the BSUIN project (Scheme_of_Reiche_Zeche_mine_devoted_to_natural_background_radiation_(NBR)_characterization) and have been published in several scientific papers and presented at several international conferences.

Further recent measurements can be found in published papers and students' theses:

Yildirim, O. (2019). New quick erect stopping system for underground mines: A technical, economic and environmental assessment of a newly developed ventilation and gas proof sealing system for the application in different mine settings, M.Sc. Thesis, Technical University Bergakademie Freiberg. 104p.

Dehnert, J., Stopp, J., Windlisch, P. and Schönherrt, B. (2020). Quick-erect stopping system for radiation protection and mine rescue in small-scale mining, *Mining, Metallurgy & Exploration*, *37*(2020): 1807-1817. https://doi.org/10.1007/s42461-020-00261-2

3.2 Hydrological data and properties

3.2.1 Hydrogeological data and properties

3.2.1.1 Description of data

Hydrogeological data about the FLB and surrounding areas are available online for download from the Sächsisches Landesamt für Umwelt, Landwirtschaft, und Geologie (LfUG) (https://lfulg.sachsen.de/). Several maps and research studies can also be found in the Bergarchiv Freiberg (https://www.staatsarchiv.sachsen.de/bergarchiv-freiberg-3988.html), as well as at the Dept. of Hydrogeology and Hydrochemistry of TU Bergakademie Freiberg (https://tu-freiberg.de/geo/hydro).

Besides, there are numerous of research studies and publicatons available on the worldwide web.

3.2.1.2 Description of properties

Ground water that can flow into the mine is something usual in underground facilities. In the case of the Freiberg underground laboratory there are parts which are relatively dry, yet other parts that are semi- or totally flooded. There are also a few meters of openings with steadily dripping water. Most other parts of the mine have no steadily dripping water. Nevertheless walls, roof and faces can be wet. Relative humidity is very high >95%).

Rothschönbergerstolln (RSS), the deepest drainage adit, is supplied with water from the southern Erzgebirge mountains, which enters the Drei Brüder Schacht by way of the Constantinschacht, eventually flowing down into the RSS. Some of this water goes very deep within the flooded area, and when it comes back up again at the Reiche Zeche Schacht, it can carry traces of low pH level waters. This water then drains and is discharged 18 km north into the Triebish and Elbe Rivers.

In almost every drift water channels are located at one side of the opening (Figure 25). The water in these channels can flow or stand almost still. Depending on the location the quality of the water is different. In some openings stalactites and stalagmites have been formed in the course of the years. Compared to caves this process is very fast. On the adit level there is a 30 years old cable which is completely included in newly formed stalactites. This shows that minerals are transported by the water.

Figure 25. Typical water channels on the side of one of the openings on the 1st Level at FLB (Dr. Barakos, 2020).

3.2.2 Hydrogeochemical data and properties

3.2.2.1 Description of data

Water quality data about the FLB and surrounding ecosystems are available online for download from the Sächsisches Landesamt für Umwelt, Landwirtschaft, und Geologie (LfUG) (https://lfulg.sachsen.de/) . Apart from that, there are numerous of research studies and publicatons available with measurements and analyses related to the hydrochemical properties in Freiberg.

3.2.2.2 Description of properties

Depending on the mineralization of the water reactions may take place if the water leaves the rock. As a result one can find water with white, yellowish, brown, red and black color. Most often these are precipitate reactions due to the reduced pressure when the water comes out of the rock (Figure 26).

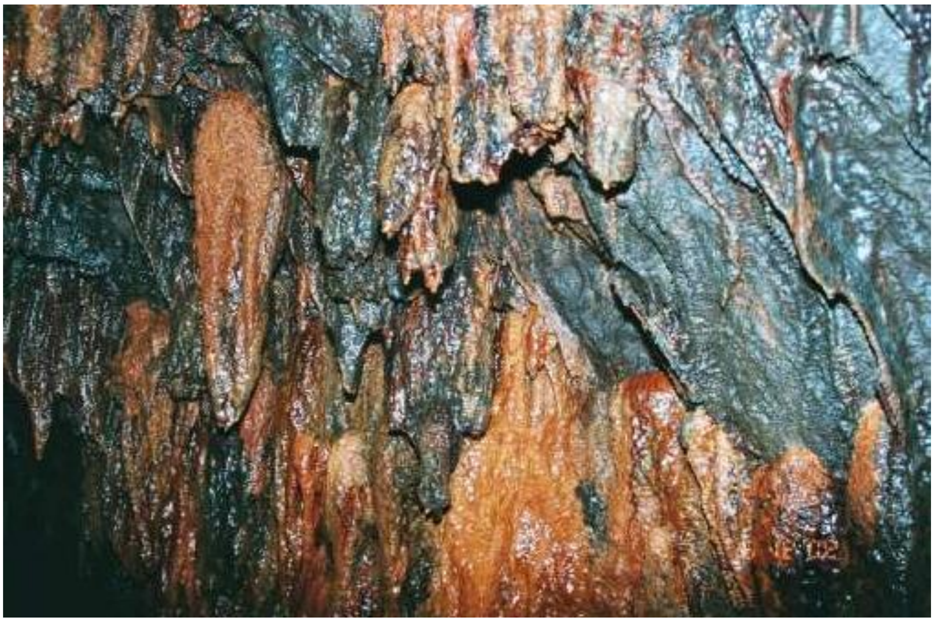


Figure 26. Stalagtites at "Rothschönberger Stollen" (Dr. Weyer, 2018).

Sometimes the water looks black but in reality it is clean. That is because black matter – most often manganese – settled on the bottom of the channel. In the same way other colors from other minerals or metals can appear. In limited cases the water seems to stand still. On one hand this could be because of very low velocities of the water or due to very thin layers of material on the water surface. The quality of the water depends on the location. Reiche Zeche has exhibited pH levels all across the board, with lower pH levels perhaps attributed to upwelling of deep waters from the flooded levels of the mine nearly 700m under surface.

There are a few locations where the pH value of the water is between 2 and 3. This happens if small amounts of water run through an ore vein. The water becomes acidic and dissolves iron, resulting to a blood red colour. This can be seen in some stope-areas where the water almost stands still (Figure 27).

In other areas the pH value of the water is almost 7. This is a strong indication that this water had no contact with ore veins (or at least no longer contact) and probably comes from the surface or from ground water. In case of the stope "Wilhelm Süd" at the 1st Level, these two locations are only 50 m apart. The mine is de-watered by adits to the river Mulde and the deep adit "Rothschönberger Stollen". Of course these adits de-water the entire region. The content of elements in the water of the adit "Rothschönberger Stollen" is given below.

It is often written that there are dangerous heavy metals in the water. Compared to the allowed content in drinking water some limits are exceeded. According to the limitations for allowed concentrations in waste water from industrial plants all values are within the limits and reach mostly only 1/10 of the allowed limit.

Figure 27. Stagnant water with a characteristic blood red colour (Dr. Weyer, 2018).

Iron is clearly one of the dominant systems controlling metal presence in the mine. In still water it is present in ferrous form and in high concentrations. In flowing water it is generally present in ferric form and precipitating out of solution at pH>4.5 and high oxygen conditions, and therefore exists at extremely low concentrations. Aluminum concentration is dependent upon K, Na, or Pb based jarosites at pH<2.5.

The sulfate system is the other dominant system that controls metal presence in the mine. High sulfate concentrations had been detected in still water samples, often in excess of iron concentrations as no natural process can fully eliminate sulfate from waters. Sulfate concentrations are lower in flowing water, where oxygen concentrations are clearly higher, as are temperatures and pH levels, but concentrations of Pb, Fe, Zn, and Cu are usually low. The reverse trend is observed in still water; higher concentrations of Fe, Zn, Pb, Cu at lower pH levels and temperatures.

4 Summary

FLB is a fully functioning and economically sustainable underground laboratory, which makes it a unique facility. The diversity of uses (for cultural, educational, research and training purposes) makes the mine site a significant asset not only for TU Bergakademie Freieberg but for the city of Freiberg as well.

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