Master's Thesis

Reuse of tunnel excavation material – real-time measurements and decision-making on the construction site of Research@ZaB – Zentrum am Berg – an underground research facility in Eisenerz, Austria

Irina Maria Seidler, BSc.

Leoben, February 2018

Affidavit

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet.”

Leoben, February 2018

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Abstract

Tunnel excavation material is still usually dumped in landfills instead of putting the raw material excavated through construction to reuse. Valuable raw materials are mined as a byproduct of tunneling and should be used to their maximum extent. Landfilling is not cost effective when compared to reusing the material and also has a negative impact on the environment. With this thesis, an attempt for a holistic approach of reutilization of tunnel muck is made.

For repurposing excavation material, it is important to analyze the material on site in real-time for decision making. Therefore, a part of this thesis is the evaluation and comparison of elemental and mineralogical analyzation methods on samples taken from the Research@ZaB. The purpose of the analytical unit is to analyze the excavation material in real-time.

LIBS (laser-induced breakdown spectroscopy) and NIR (near-infrared) spectroscopy show great potential. Additionally, photo-optical particle analysis is introduced because grain size and shape of tunnel muck are key factors for certain types of reuse. Taking into account these boundary conditions, the analytical unit for the Research@ZaB was planned. This unit consists of a jaw crusher, a sampler, a separator, a LIBS analyzer and a photo-optical particle analyzer. The flexible and modular design of the analytical unit allows for potential addition of other measurement systems including NIR spectroscopy.

Furthermore, tunnel muck in Austria is treated as waste. This governmentally imposed regulation is a major issue when it comes to repurposing excavation material. It prohibits the direct reuse of excavated material. During this thesis, a closer look will be given on that matter. Additionally, two contractual models for the different reuses in relation to varying lithologies were designed. One model is a decision tree model the other one is a matrix model based on the tunneling class matrix according to ÖNORM B 2203-1.

The work of this thesis is the first step towards a more sustainable tunneling industry but further research and a more detailed design of the analytical unit are necessary.

Zusammenfassung

Tunnelausbruch wird in der Regel immer noch auf Deponien abgelagert, anstatt das ohnehin durch den Bauprozess gewonnene Material wieder zu verwerten und damit der Tunnelbauindustrie zu einer nachhaltigeren Zukunft zu verhelfen.

Wertvolle Rohstoffe werden als Nebenprodukt des Tunnelbaus ohnehin abgebaut und ihr Potential sollte vollkommen ausgeschöpft werden. Deponierung ist im Vergleich zur Wiederverwendung des Materials nicht kosteneffektiv und hat negative Auswirkungen auf die Umwelt. In dieser Diplomarbeit wird versucht, einen ganzheitlichen Ansatz für die Verwertung von Tunnelausbruch zu finden.

Für die Wiederverwertung von Aushubmaterial ist es wichtig, das Material vor Ort in Echtzeit zur Entscheidungsfindung zu analysieren. Ein Teil dieser Arbeit beschäftigt sich daher mit der Auswertung und dem Vergleich von elementaren und mineralogischen Analysemethoden anhand von Proben aus dem Research@ZaB. Die Aufgabe der Analyseeinheit ist es, dass Ausbruchsmaterial in Echtzeit zu analysieren.

LIBS (laser-induced breakdown spectroscopy) und NIR (near-infrared) Spektroskopie beweisen das größte Potential für diese Verwendung. Darüber hinaus wird die photo-optische Partikelanalyse vorgestellt, da Korngröße und -form einen Schlüsselfaktor für bestimmte Arten der Wiederverwendung darstellen. Unter Berücksichtigung dieser Randbedingungen wurde die Analyseeinheit für das Research@ZaB geplant. Diese Einheit besteht aus einem Backenbrecher, einem Probenehmer, einem Separator, einem LIBS-Analysator und einer Anwendung für die photo-optische Partikelanalyse. Der flexible und modulare Aufbau der Analyseeinheit ermöglicht eine Ergänzung anderer Messsysteme einschließlich der NIR-Spektroskopie.

Darüber hinaus wird Tunnelausbruchsmaterial in Österreich per Gesetz als Abfall behandelt. Die Behandlung dieser gesetzlichen Einschränkung ist wichtig, wenn es um einen ressourcenschonenden Umgang von Ausbruchmaterial geht, denn sie verbietet eine direkte Wiederverwendung. Zusätzlich wurden zwei verschiedene Vertragsmodelle für die Wiederverwendung von Tunnelausbruch in Zusammenhang mit variierenden Lithologien entworfen. Eines der Modelle basiert auf einem Entscheidungsbaum, das andere ist ein Matrixmodell angelehnt an die Vortriebsklassenmatrix der ÖNORM B 2203-1.

Diese Arbeit ist der erste Schritt in Richtung einer nachhaltigeren Tunnelbaubranche, aber weitere Forschung und ein detaillierteres Design der Analyseeinheit sind notwendig.

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1 Introduction

Resource efficiency has moved into focus over the last years due to the growing awareness that our world has limited non-renewable natural resources such as mineral resources. There is no unrestricted access to raw materials, which are crucial for construction, e.g. concrete production. The construction of underground structures is increasing and produces a huge amount of excavation material that is mostly used for landfilling. It becomes obvious that in order to maintain our natural resources, excavation material needs to be seen as a raw material whose purpose does not lie in landfilling solely. Valuable raw materials are mined as a byproduct of tunneling and should be used to their maximum extent.

In Figure 1 the shares of selected groups of waste in Austria in 2014 are shown. Excavated material accounted for 54 % of the total waste which was about 57 million tons. Approximately 30 million tons of waste from excavated materials were produced. This results in an increase by 29 % from 2011 to 2014. Of this amount, about 7 million tons were re-used and an estimated amount of 5 million tons were used for landscape corrections and construction of dams. About 18 million tons were deposited in landfills. Excavated material that is used in the immediate vicinity of construction sites does not count as waste and is therefore not part of these numbers. (Bundesministerium für Land- und Forstwirtschaft, 2015)

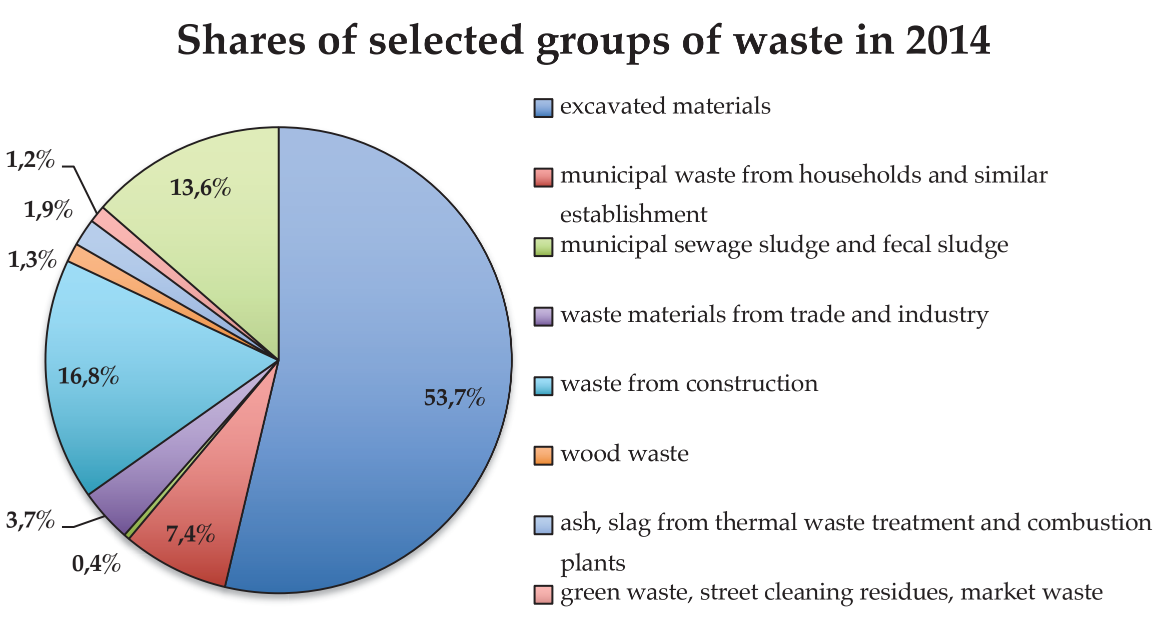


Figure 1: Shares of selected groups of waste in Austria in 2014 (Bundesministerium für Land- und Forstwirtschaft, 2015)

Not only is the reuse of tunnel excavation material important for resource efficiency but also in terms of the environmental impact of tunnel structures and cost reduction.

Using excavation material for example as an aggregate for concrete production decreases the CO_2 emission caused by trucks transporting gravel from a quarry to the construction site. Moreover, trucks are responsible for damage of pavement, disturb noise sensitive areas and are a negative factor of safety on the streets (Shiau and Chuang, 2012). If the excavation material is reused the emissions and pollution from the production of a material that would have been used instead are eliminated.

In addition, repurposing of the excavated raw material reduces costs. These costs can be divided into three groups:

- Saving money by not buying a new product:
  If the material were used on site as for example an aggregate for concrete or shotcrete production the costs of buying an equivalent material elsewhere would be eliminated. However, one needs to take into account that there are costs involved in the processing of the material such as the investment costs for a crusher or sorter.
- Selling the excavation material:
  If there is material that can be sold to another industry even secondary income can be generated.
- Saving money by not depositing:
  If the material is not reused it has to be deposited in landfills. In Austria, there are different classes for landfilling (depending on the properties of the excavation material) and for each class the owner has to pay a different price per tonnage. Thus, finding a purpose for the excavation material does mean that these costs can be eliminated.

Under these aspects, determining when and how excavation material can be reused can have a high impact on the cost efficiency of a tunneling project.

After a first estimation on possible reuses during the design phase it is important for the construction phase to analyze the material in real-time so decisions can be made accordingly. Since sudden changes in geology are not uncommon in tunneling projects, a quick way for categorizing the material is important. Separating the excavation material according to its varying properties is necessary. The sooner the separation the easier the process. Another aspect is, that for now, the material is stored in intermediate deposits before it can be dumped in landfills because it can take weeks for laboratories outside of the construction site to analyze the material. With real-time analysis, less space for intermediate deposits would be necessary because of fast decision making.

Moreover, in order to repurpose tunnel muck outside of the construction site there must be a market for it. If there is no demand for a special raw material it becomes increasingly difficult to sell it. For one thing, this can be achieved by offering the material for a low price or by even giving it away only by the cost of transportation. However, one must keep in mind that it can have a negative impact on small businesses in the local raw material sector when there suddenly is an oversupply of cheap material caused by big construction companies. Therefore, the market is to be evaluated in an early stage of a project to define possible reutilization early on and plan the process of repurposing the material accordingly.

However, the characterization of the material and the market are not the only obstacles on the way for a proper reuse of tunnel excavation material. In Austria, especially the legal state of tunnel muck is a key factor. For now, it usually is considered as waste and may only be reused on-site. This limits the possibilities of repurposing the material. To further examine this matter, the legal aspects will be discussed in chapter 5.1.

The aim of this Master's thesis is to show an efficient way for how to analyze the elemental and mineral properties of excavation material and to find a solution for implementing the reuse of muck in the construction contract.

One of the key challenges in reusing excavated material is the proper and time-effective evaluation of the material. Therefore, a unit for the Research@ZaB in Styria, Austria, using different types of online analysis methods was designed. The final design including the stages of planning is shown in chapter 4. However, in order to choose the right methods for analyzing tunnel muck samples were taken from the Research@ZaB, an underground research facility at the Erzberg in Styria. With these samples different analyzers were tested and evaluated. The focus was on elemental and mineral properties of the material and grain size distribution and shape. The results from this chapter led to the design of the analytical unit.

In chapter 2, these different methods are explained and in chapter 3 they are evaluated with samples from the Erzberg.

Since there is only little experience in how to implement these new methods into a construction contract, two models were created in this thesis and are presented in chapter 5.3.

2 Theoretical Basis for Analysis of Tunnel Excavation Material

As mentioned in the introduction, in order to determine a proper handling and reuse for tunnel excavation material on site it is important to evaluate the material properties such as elemental and mineral composition.

Geological properties throughout construction can change quickly which is why the methods used for investigating the material must show results in real-time. For this reason, inline or online and in-situ analysis is necessary. The main difference between inline and online analytics is that for inline analytics no sampling is required while for online analytics often a bypass is necessary.

With online analytics, a continuous relation between obtained information and properties of the process or product is possible. Usually the sample is measured on a bypass. The essential condition for online measurement is that the time in which process and product properties change is longer than the time it takes to obtain analytical data, convert it into information, and send it to a central computer or process control system. Inline analytics is used to directly provide information about process or product properties. The measuring unit is directly installed in the product stream. Online and inline analysis have common advantages and disadvantages. They both work fast and no manual sampling is required but are cost intensive and extensive calibration is needed. However, since with inline measurement no sampling is necessary it is less prone to errors and measurements are not biased due to the chosen sampling method. (KESSLER, 2006)

For a holistic determination of the properties of tunnel muck different methods need to be combined. Elemental analyzation or mineralogical analysis of the construction material alone are not sufficient. The two of them combined however provide wider range of information. Additionally, grain size and shape need to be analyzed as well, as they often play a major role in repurposing tunnel muck (e.g. aggregate for concrete or shotcrete).

With his dissertation REAL-TIME MATERIAL ANALYSIS AND DEVELOPMENT OF A COLLABORATION AND TRADING PLATFORM FOR MINERAL RESOURCES FROM UNDERGROUND CONSTRUCTION PROJECTS, ERBEN (2016) evaluated methods for the analysis of tunnel excavation material during construction for the purpose of reutilization. Two main points of his thesis were:

- to develop an objective approach for evaluation and comparing various material analysis technologies with different measurement principles;
- and to examine and rate chemical and mineralogical online material analysis technologies with respect to tunneling, based on a round robin test.

Optical grain size and shape, elemental, and mineralogical analysis methods cover the most essential parameters for fundamentally characterizing excavated material. A round robin or ring test was performed to compare chemical and mineralogical analysis methods with completely different measurement principles. Resulting from Erben's thesis, for determination of the elemental composition of tunnel muck LIBS (Laser-Induced Breakdown Spectroscopy) is the most suitable one. For the mineral analysis NIR (Near-Infrared) spectroscopy achieved the best results but also LIF (Laser-Induces fluorescence) spectroscopy seemed promising. Not only the composition of the material is important for reusing tunnel muck but also the grain size distribution and shape which according to ERBEN (2016) can be achieved with photo-optical methods.

Chapter 2.1 and chapter 2.2 will explain the following methods and their application:

- LIBS
- NIR spectroscopy
- LIF spectroscopy
- Photo-optical grain size and shape analysis

2.1 Spectroscopy Methods

> *Spectroscopy is the study of the interaction of electromagnetic radiation with matter. There are three aspects to spectroscopic measurement: irradiation of a sample with electromagnetic radiation; measurement of the absorption, spontaneous emission and scattering (Rayleigh elastic scattering, Raman inelastic scattering) from the sample; and analysis and interpretation of these measurements.* (GAFT ET AL., 2005)

The methods which use the same underlying principle of spectroscopy studied in this thesis are LIBS, NIR and LIF.

2.1.1 Laser-Induced Breakdown Spectroscopy (LIBS)

LIBS (also sometimes referred to as laser-induced plasma spectroscopy - LIPS) is a type of atomic emission spectroscopy for elemental analysis. It is a technique that analyzes the spectral emission from laser-induced plasmas and can detect all chemical elements in any material whether it is a liquid, solid or gas. With LIBS qualitative as well as quantitative measurement results are retrieved. However, to obtain accurate results proper calibration is critical. Typical detection limits for LIBS are in the µg/g range. (HARMON ET AL., 2013). According to GAASTRA & KÜCH (2014), Nd:YAG (neodymium-doped yttrium aluminum garnet) lasers with a fundamental wavelength of 1064 nm (highest energy density at this wavelength) and a pulse peak power up to 5 MW are usually used for LIBS applications.

Working principle (Figure 2) (BOHLING ET AL., 2010):

The beam of a high energy laser pulse is focused on the surface of a sample (Figure 2, a) for about a few nanoseconds. The diameter of the surface the beam is focused on is about some 10 ns. Because of the high intensity of the excited radiation, parts of the surface are heated (b, d), then evaporated (c) and partly ionized (e). For a very short period of time high temperatures in the range of 10.000 °C occur. Because of the short time for interaction and ablation there is nearly no heat transport into the medium itself. The intensities during excitement are in the range of some 100 GW/cm². Due to the high temperature, locally bonds between molecules get broken and the single atoms are ionized. A plasma forms that on the inside consists of ionized atoms and electrons but on the outside is neutral. After the excitement, the plasma cools down and in the first stage which only consists of some microseconds the free electrons recombine. Then the plasma mainly emits broadband bremsstrahlung (f). Following this, a discrete line spectrum forms from ions and atoms (g) and later on also molecules (h). The analysis of the spectrum gives information of the stoichiometric composition of the sample.

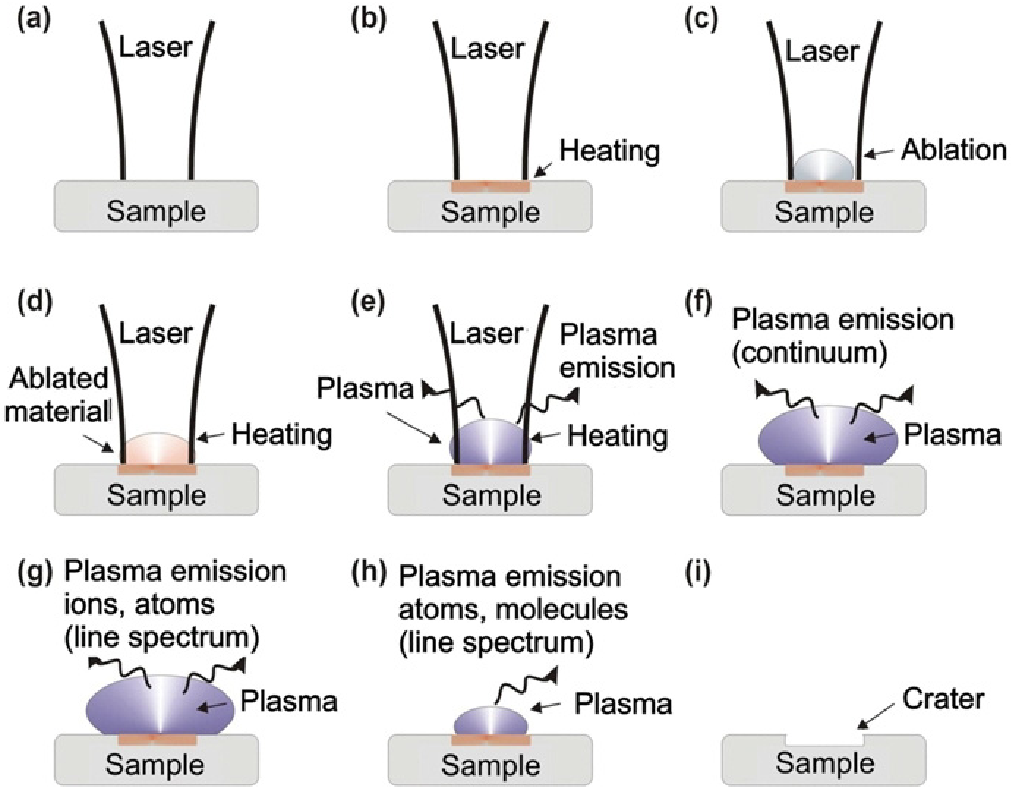


Figure 2: Working principle of LIBS (BOHLING ET AL., 2010)

Advantages and disadvantages of LIBS (BOHLING ET AL., 2010):

One of the advantages of LIBS is that there is no need for sample preparation unlike in many other common techniques such as for example microprobe, X-ray florescence, instrumental neutron activation analysis or atomic absorption spectrometry. LIBS can be used in labs as well as on site. Fully automated data evaluation in real-time is possible with it, and the system works contact-free. Qualitative and quantitative results can be obtained. To sum up, the method works online, inline and in-situ and due to its highly versatile technique LIBS can be used in a variety of different sectors and in laboratories as well as in the field.

However, for a successful implementation of LIBS, calibration with reference material is essential which generally requires a high number of samples (around 100). Furthermore, it needs to be taken into account that this technique only scans a small area. The sample surface therefore must be representative of the entire material. Since LIBS operates in real-time it, for example, can be used for analyzing a material stream. According to BOUSQUET ET AL. (2008) another limitation is that if the water content of a material is too high the water interferes with the measurement because in a wet sample, most of the laser energy is used to vaporize the water instead of ablating the sample itself.

2.1.2 Near-Infrared (NIR) Spectroscopy

Near-infrared (NIR) spectroscopy is a fast and nondestructive analytical technique that usually does not require sample preparation. It is versatile because if samples contain bonds such as C−−H, N−−H, or O−−H, and if the concentration of the analyte exceeds about 0.1%

of the total composition, then it is very likely to yield good results. It is used for analysis of mineralogical components of a material. (BURNS & CIURCZAK, 2007)

Near-infrared is the area of the light of a wavelength roughly between 700 and 3000 nm which is close to the range of visible light (380 – 700 nm). NIR Spectroscopy enables the determination of molecular compositions of surfaces or also quantitative analysis of compounds in mixtures. Analysis of solid, gaseous and liquid material, organic, inorganic and polymer materials is possible. Exceptions to this are materials that are NIR-inactive or have a black surface because all radiation either gets absorbed or reflected. (SCHROPP ET AL., 2014)

Working principle:

When the surface of a sample is irritated by a near-infrared light source photons are absorbed and cause a transition of energy to an exited state. The absorption process depends on the composition of the material of the sample. Therefore, information about a particular composition can be obtained. (SCHROPP ET AL., 2014)

The most commonly used type of spectrometer is a Fourier-transform IR-spectrometer (FTIR), also referred to as the Michelson Interferometer. It consists of an irradiation source, an interferometer and a detector. It requires a computer for data processing in order to obtain a NIR spectrum. The principle is that the radiation of a source travels through the interferometer to the sample while the reflected radiation is measured by a detector. For these measurements, a halogen lamp is often used as a polychromatic radiation source. This lamp can be a mercury or tungsten lamp and has a wide spectral range to cover the complete NIR range. The setup of a Michelson Interferometer is shown in Figure 3. (SCHROPP ET AL., 2014)

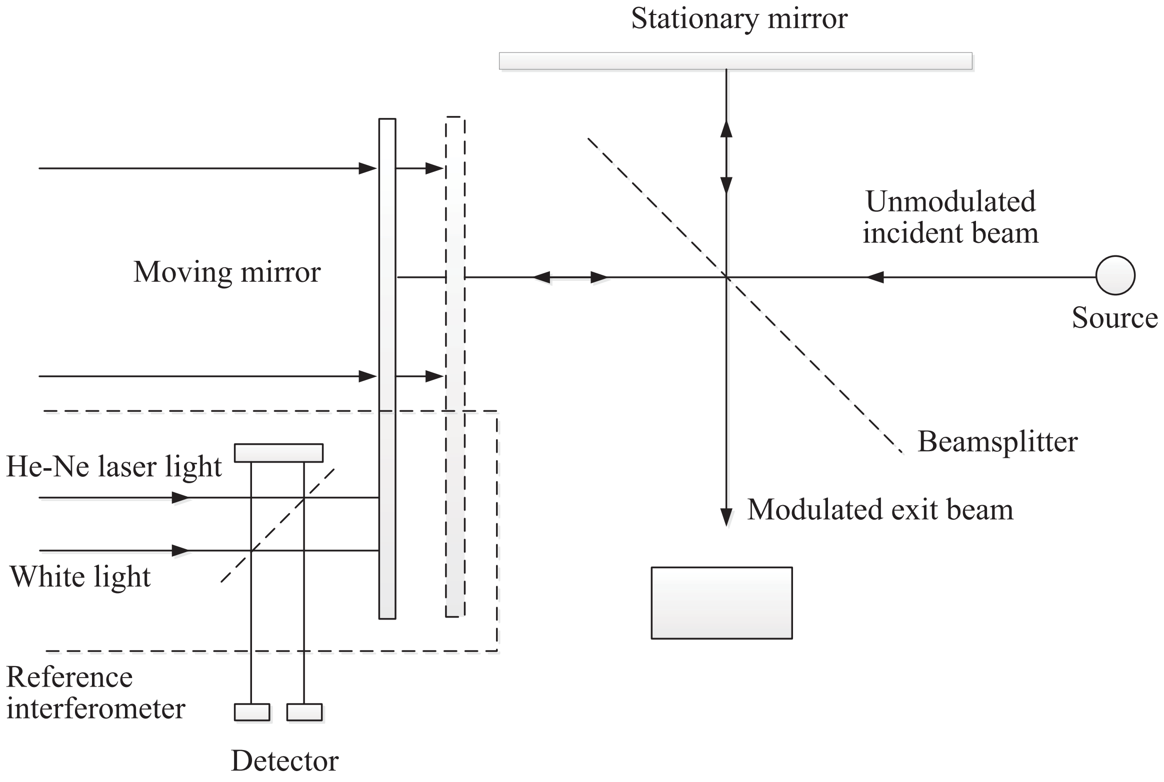


Figure 3: Setup of FTIR Spectrometer or Michelson Interferometer (SCHROPP ET AL., 2014)

Physical background (SCHROPP ET AL., 2014):

One atom has three degrees of freedom because it moves along the three Cartesian coordinate axes. A molecule which has n atoms therefore has 3n degrees of freedom. Within these degrees of freedom, three describe the molecule's motion through space and three more are necessary to describe the molecular rotation. This leads to the definition that 3n – 6 degrees of freedom are fundamental vibrations (also called modes of vibration) for non-linear molecules. For linear molecules only 2 degrees of freedom are required to describe the motion of rotation. Because of that linear molecules have 3n – 5 degrees of freedom. However, fundamental vibration usually does not cause NIR activity, because the total number of vibration shows modes which have no influence on the NIR spectrum. Most bands of the NIR spectra are created by interactions, combinations or differences of these fundamental frequencies. Characteristic absorption bands are created by overtones and combinations of different vibration types. Overtones are multiples of fundamental vibration. The number of overtones is in direct relation with the intensity of the NIR spectra; The higher the number of overtones the higher the intensity of the spectra. If two fundamental vibrations interact combination bands arise. The combination bands are influenced by radiations at the combined wavenumber. They create a NIR spectrum that is specific for a distinctive material.

Turning to the applicability of this method it needs to be mentioned that NIR measurements can be divided into passive and active approaches. For the tunneling industry, the active approach is applicable. Using the active technique, the analyzed material gets actively irradiated. The reflected or transmitted radiation then is detected by suitable detectors. The passive approach is when emitted radiation is detected from a material that has not been irradiated. This method is for example used for night-vision-devices or UAV applications. The principle behind NIR spectroscopy is an interaction between electromagnetic radiation and the molecular structure on a material's surface. The result of these interactions are the vibrational transitions mentioned above.

A spectrometer detects the reflected radiation including absorption bands. Examples of NIR spectra for the iron minerals goethite ($FeOOH$), hematite (Fe_2O_3), jarosite $KFe[(OH)_6 | (SO_4)_2]$ and pyroxene ($Ca,Mg,Fe,Al,Na,Li[Si_2O_6]$) are shown in Figure 4 as they only show little difference in their elements but high differences in their reflectance.

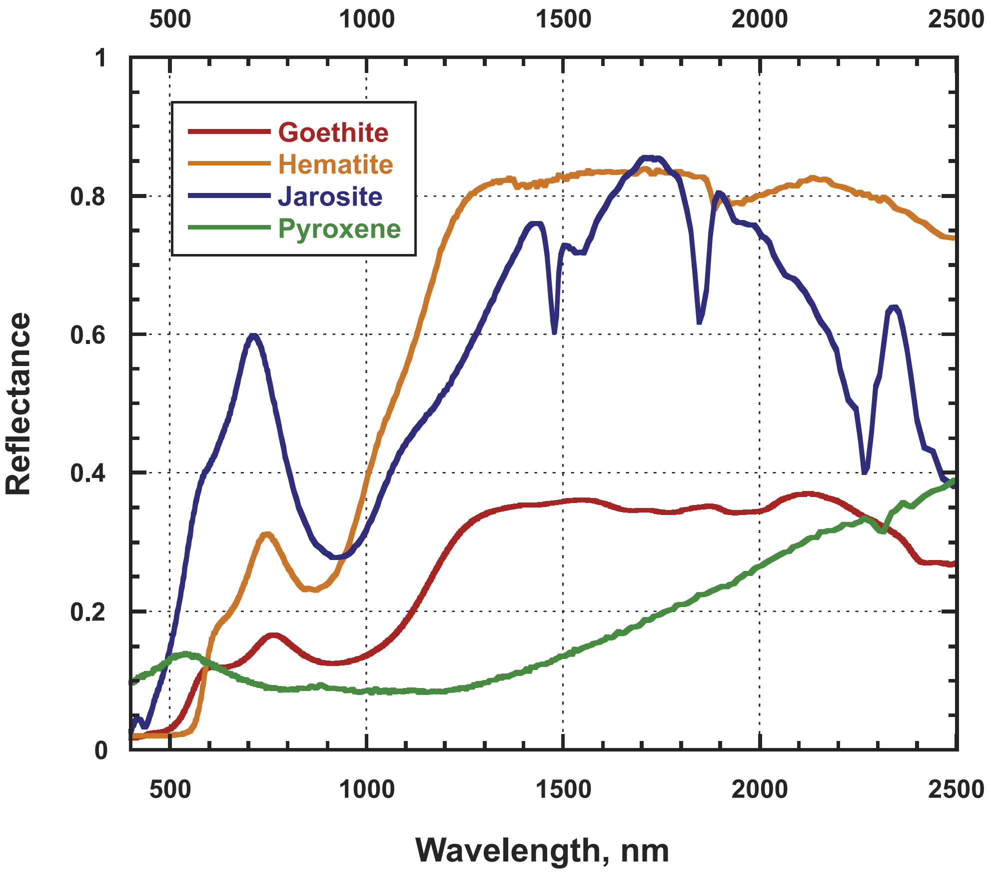


Figure 4: Reflectance spectra of four iron minerals (GOETZ ET AL., 2009)

Advantages and disadvantages of NIR spectroscopy:

NIR spectroscopy is very fast compared to other analytical techniques (often taking less than 1 s). Another advantage is that it is nondestructive and often no sample preparation is needed. With NIR qualitative and quantitative measurement results are obtainable. However, in order to achieve good results the instrument/computer is required to be calibrated thoroughly, which generally is very time consuming. (BURNS & CIURCZAK, 2007)

2.1.3 Laser-Induced Fluorescence (LIF) Spectroscopy

Laser-induced fluorescence (LIF) spectroscopy is luminescence spectroscopy. It is a molecular vibration analysis for mineralogical analyzation purposes in which molecules of a material are activated by high pulses of laser light and therefore get excited and start vibrating. This results in light emission with a lifetime up to 10 ns which is called fluorescence. Each material can be characterized by the wavelength of its fluorescence. LIF spectroscopy as well as the mentioned above LIBS and NIR-spectroscopy is a surface detection technique. (KÜCH & GAASTRA, 2014)

The principle of LIF spectroscopy is based on luminescence of the material. In general, luminescence is a cold emission of light from the range of UV to NIR wavelengths. The emission occurs because electrons are excited to unstable energy levels and emit photons when falling back into their original state. (VINZELBERG, 2008)

According to GAFT ET AL. (2005) luminescence can be divided into fluorescence and slow phosphorescence.

Originally, fluorescence and phosphorescence were defined by the duration of their afterglow which is the duration of excitation after the source of energy has been turned off. The afterglow duration for fluorescence is in the range of 10^5 and 10^9 seconds and the duration for phosphorescence is in the range of milliseconds to minutes or even hours. However, according to a more recent definition phosphorescence is characterized by highly temperature-dependent processes, in which energy is stored after the excitation in intermediate levels and the light emission is triggered only by the rise in temperature. (STEFFEN, 2000)

Working principle:

LIF spectroscopy works on the basis of the generation of fluorescence resulting from excitation by a laser. The process can be divided into three major steps which are

- Excitation of the material using monochromatic light (UV range)
- Detection of emitted fluorescence
- Data processing

The following figure shows the conceptual model of fluorescence.

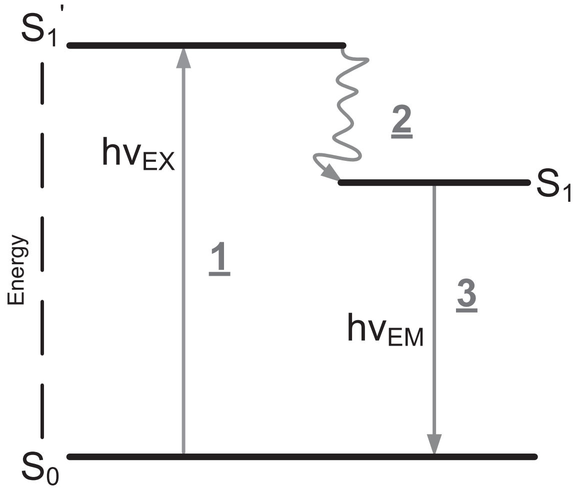


Figure 5: conceptual model of fluorescence (VINZELBERG, 2008)

Molecules show different energy values. A molecule in an S_0 stage is stable. However, if energy gets inserted into a system the molecules are being excited and lifted to a higher energy state (S_1’) because they absorb a photon. Then the excited molecules collide with other molecules and therefore lose vibrational energy until the point that they are at the lowest vibrational state S_1. Afterwards, the molecules change into a stable energy state by emitting a photon. The stable energy state is different for every molecule, which results in different energies of the emitted photons and thus different frequencies. Therefore, it is possible to draw a conclusion about the material from analyzing the frequencies of the emitted photons. (VINZELBERG, 2008)

According to BROICHER (2000) in order to detect fluorescence a monochromatic illuminator or band-pass filter in combination with a photomultiplier is needed.

For determination of the sample material, four parameters need to be investigated. These are absorption, emission, quantum efficiency and decay (BAYER, 2004):

- **Absorption:** In order for a material to emit light it has to be excited at a certain wavelength.
- **Emission:** The emission spectrum characterizes the intensity of the fluorescence for a defined excitation wavelength. The fluorescence can be traced back to the energy differences between the different energy states, so the emission spectrum describes the composition of the material. In most cases, there is not a single maximum in the emission spectrum, but several so-called luminous centers (see Figure 6).
- **Quantum efficiency:** The value of the quantum efficiency represents a specific degree of efficiency, which is influenced by the absorption capacity of the material and the ability to convert the absorbed energy into emitted fluorescence signals.
- **Decay:** The intensity of a fluorescence event decreases after the excitation has ended. This exponential decrease of the emission intensity is described by decay curves. Under normal conditions the lifetime of the emission is only dependent on the excitation intensity and the excited material and thus also a material-specific property (see Figure 7).

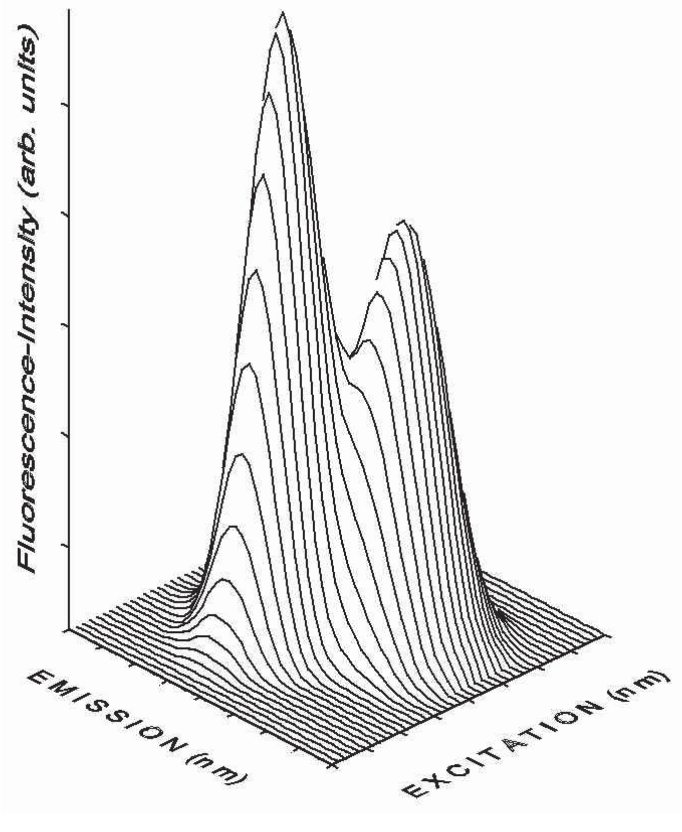


Figure 6: Absorption and emission spectra (BROICHER, 2000)

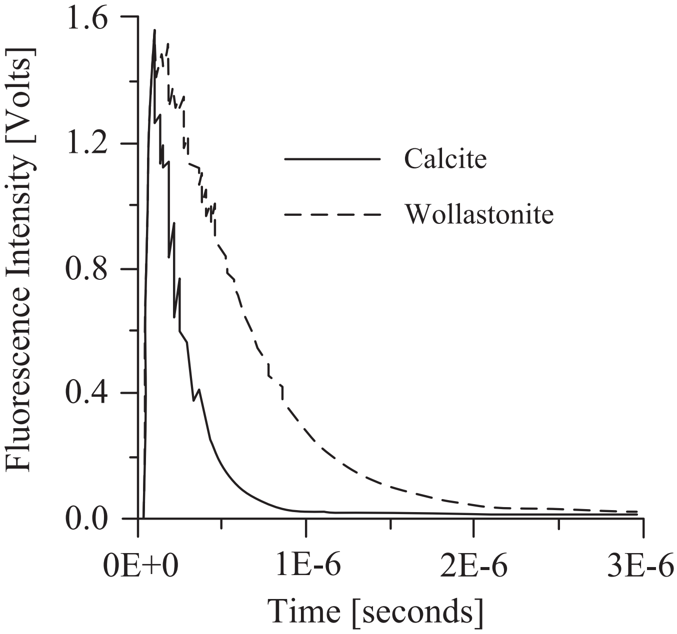


Figure 7: Decay curves for Calcite and Wollastonite (Broicher, 2000)

Advantages and disadvantages of LIF spectroscopy (Broicher, 2000):

The LIF technique works without sample preparation and is a nondestructive, contact-free surface analyzation method. Because it does not destroy the surface, tests are repeatable. LIF spectroscopy can be used in the field because it is insensitive to dust and humidity. However, in order to be able to draw quantitative results the material needs to be homogeneous. Additionally, for field applications LIF can be problematic because it is expensive and complex solutions need to be designed and built for the particular conditions.

LIF spectroscopy cannot be used as a universal method to analyze rock but rock identification it can be applied for quality control, bulk sorting, blending and process control.

2.2 Grain Size and Shape Analysis

There are many different ways to measure the grain size distribution. Sieving which is a mechanical method is widely used in the mining and tunneling industry. For real-time solutions, a photo-optical particle analysis method can be used. With this technique, not only the grain size but also the shape of the particles and their quantity are measured in real-time.

As a representative for the real-time photo-optical particle analysis, the Haver & Boecker system, namely the Haver CPA is chosen.

The Haver CPA measurement method analyses the grain size and shape of non-agglomerated particles by photo-optical means in the range of 10 μm to 400 mm (depending on the application).

Measurement principle:

The measurement principle is based on digital image processing in which a high-resolution digital line scan camera scans the free-falling particles of bulk materials in the back light of a LED light source. The frequency can be up to 28.000 line scans per second. The so produced line scans are combined in an endless data record. Whereas the shadow projections of the particles are evaluated in real-time parallel to the ongoing measurement. With this method, up to 10.000 particles per second can be scanned and analyzed. The following figure (Figure 8) shows the basic setup of the Haver CPA particle analyzers. (HAVER & BOECKER)

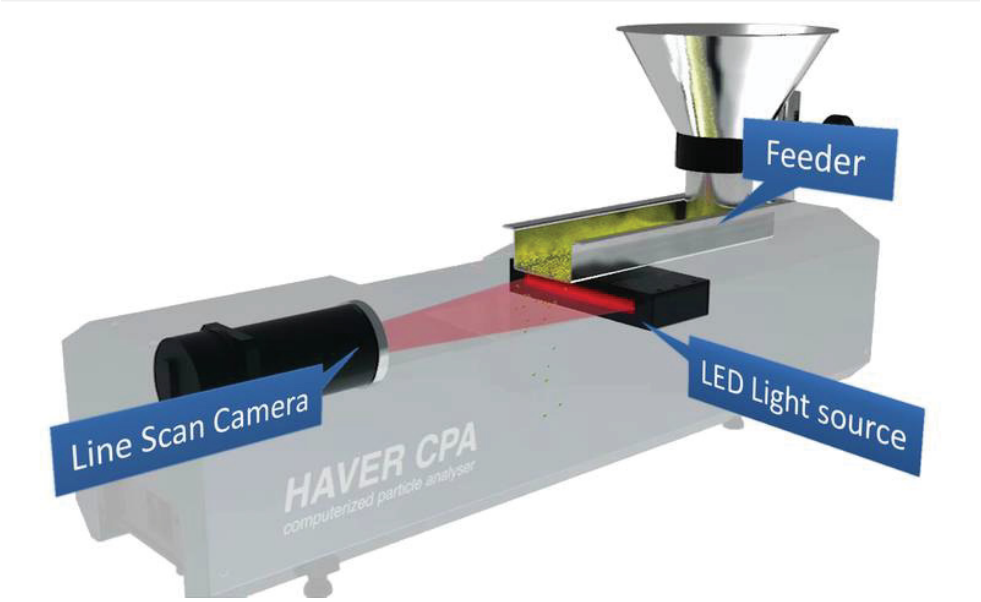


Figure 8: Basic setup of the Haver CPA particle analyzers (HAVER & BOECKER)

3 Analysis of Rock Samples from Research@ZaB

This chapter will compare the different methods for analyzing the tunnel excavation material with samples from the Research@ZaB - Zentrum am Berg, an underground research facility in Eisenerz, Austria.

However, before going into detail about the sample comparison a short introduction into the research facility that is currently under construction is given and its purpose is explained.

3.1 Research@ZaB

The Research@ZaB is a subsurface tunnel system for research on the development on construction methods, materials and equipment such as ventilation and safety systems or fire extinguishing systems that is currently under construction. Testing in a tunnel under real conditions will be possible. In a laboratory, testing is limited and the results are generally not very significant. Even fire testing in real tunnels proves difficult and expensive. The traffic needs to be stopped and tests can only be carried out with a reduced fire load because otherwise structures would be damaged. The so called Zentrum am Berg will be situated in a disused part of the Styrian Erzberg in Eisenerz in Austria. (GALLER, 2016)

The Research@ZaB will work as a research and training facility for the following fields: (GALLER, 2016)

- Research in geotechnics and mining and tunneling industry
- Measurement techniques for geophysics, geotechnics as well as aerodynamics and thermodynamics
- Trainings for emergency response organizations including fire brigade, ambulance services, staff and civil protection
- Research and testing for business partners such as mining and construction suppliers or equipment for safety systems
- Repair and maintenance personnel for training purposes
- Training for future tunnel users, for example new drivers

3.1.1 Project overview

The Styrian Erzberg is a perfect location for the Research@ZaB because on the one hand it has an already existing tunnel system and on the other hand there is a connection to road and rail systems. In addition, the city of Eisenerz is in the vicinity providing additional infrastructure. It is situated in the center of Europe and therefore offers its potential not only to the Austrian tunneling industry but also to the European one. The tunneling work at the Zentrum am Berg comprises two different cross sections; a two-lane autobahn tunnel and a single-track rail tunnel. Both types are constructed as two-tube tunnels in order to provide realistic training conditions for emergency services. The parallel tubes are connected via cross-passages. Furthermore, the Presser tunnel (an old already existing tunnel at the Erzberg) is enlarged from its current cross section which is about 8 m^2 to a typical rail tunnel cross section. This tunnel will work as a test tunnel for further research like tunnel maintenance or fire testing. Parallel to this enlargement of the Presser tunnel an underground test cavern with the dimensions of about 200 m x 1.000 m is planned. Necessary infrastructure such as seminar rooms or operating buildings will be provided nearby. (Galler, 2016)

Each of the twin tube rail and road tunnels is approximately 400 m long and meet with the Presser tunnel in a Y-junction. Figure 9 shows the layout of the tunnels. The two rail tunnels are drawn in blue. They start from the south portal heading north and are connected with two cross-passages. Red marks the two road tunnels running from the west portal in direction east to the Y-junction. The road tunnels are linked with two cross-passages. The test tunnel starts at the Y-junction and runs north to the north portal. It has a length of about 1000 m. Only 300 m of the test tunnel (highlighted in yellow) will be constructed in order to leave room for testing and improving construction methods on the non-excavated part. The highest overburden is in the area of the rail tunnels with 235 m. (GALLER, 2016)

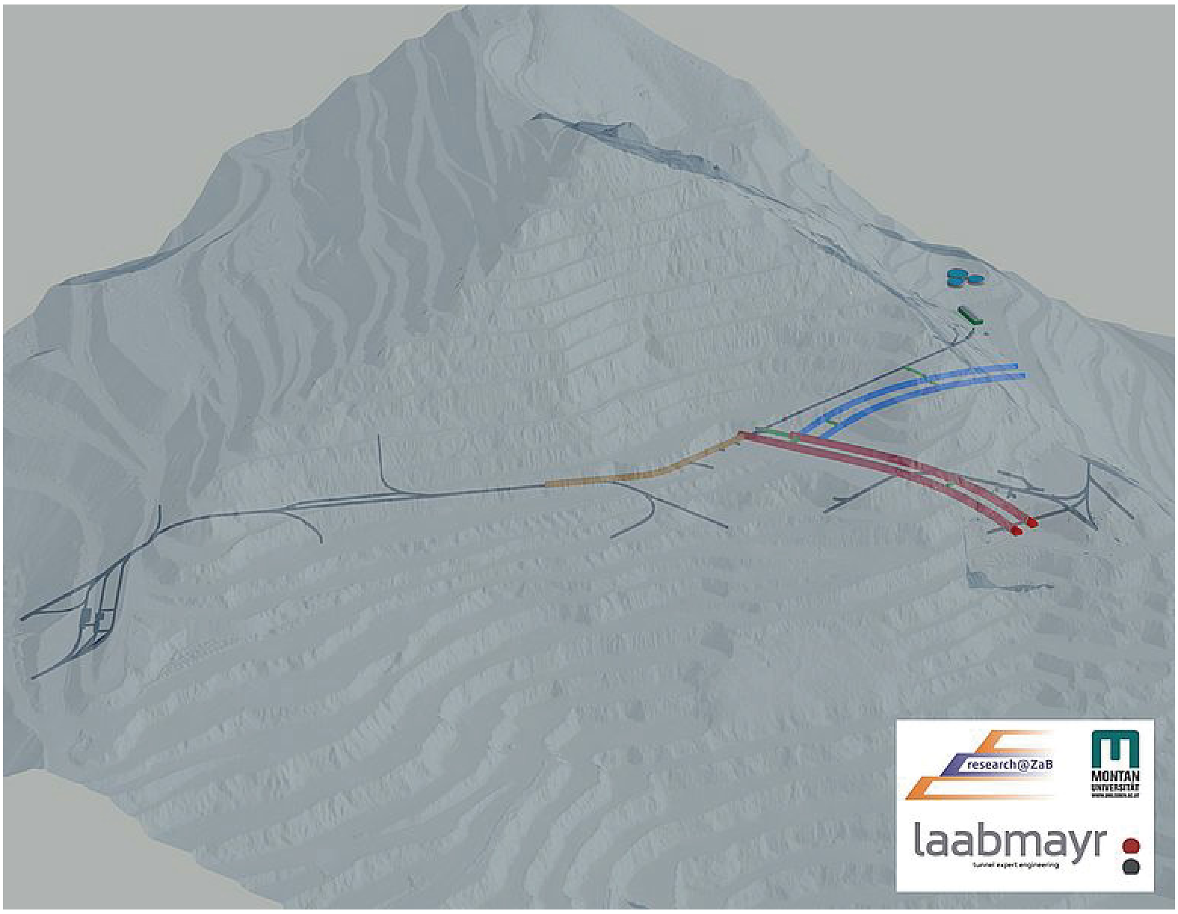


Figure 9: Project overview Research@ZaB (MONTANUNIVERSITÄT LEOBEN)

3.1.2 Geology

The city of Eisenerz is at the northern edge of the northern greywacke zone and the Styrian Erzberg is located in the southeast of Eisenerz. The Erzberg contains the entire strata sequence belonging to the northern area of the Norische Decke which according to the large-scale tectonic structure represents the western flat part in the east of the greywacke zone. Parts of the already existing tunnels are lined with brick-work or partly with concrete. Consequently, it was partly not possible to map the lithography of the tunnel systems. In order to obtain data on the lithologies, maps showing the geological horizontal sections provided by the VA Erzberg GmbH (the company that operates the Erzberg) were studied. The main lithologies are:

- Limestone
- Siderite, Rohwand (massive dolomite and ankerite)
- Blasseneck porphyroid
- Eisenerzer layers (shale, phyllite)

The already lined areas of the northern tunnel can be defined properly from a lithological point of view. During the construction of the tunnel the Eisenerzer layers and porphyroid were already categorized as problematic and had to be supported. Whereas the Sauberger limestone and the ore-bearing limestones were mostly stable without further support. The existing tunnels are mainly damp with in some parts dripping or flowing water ingress. (GALLER, 2016)

3.2 Samples

In April 2017, eight samples were taken from the Kerpely tunnel and the Presser tunnel of the Erzberg. They then were analyzed by a Canadian laboratory (Activation Laboratories Ltd.). Figure 10 is a geological map of the part of the Erzberg where the Research@ZaB is built. The locations of the samples taken are marked with an X.

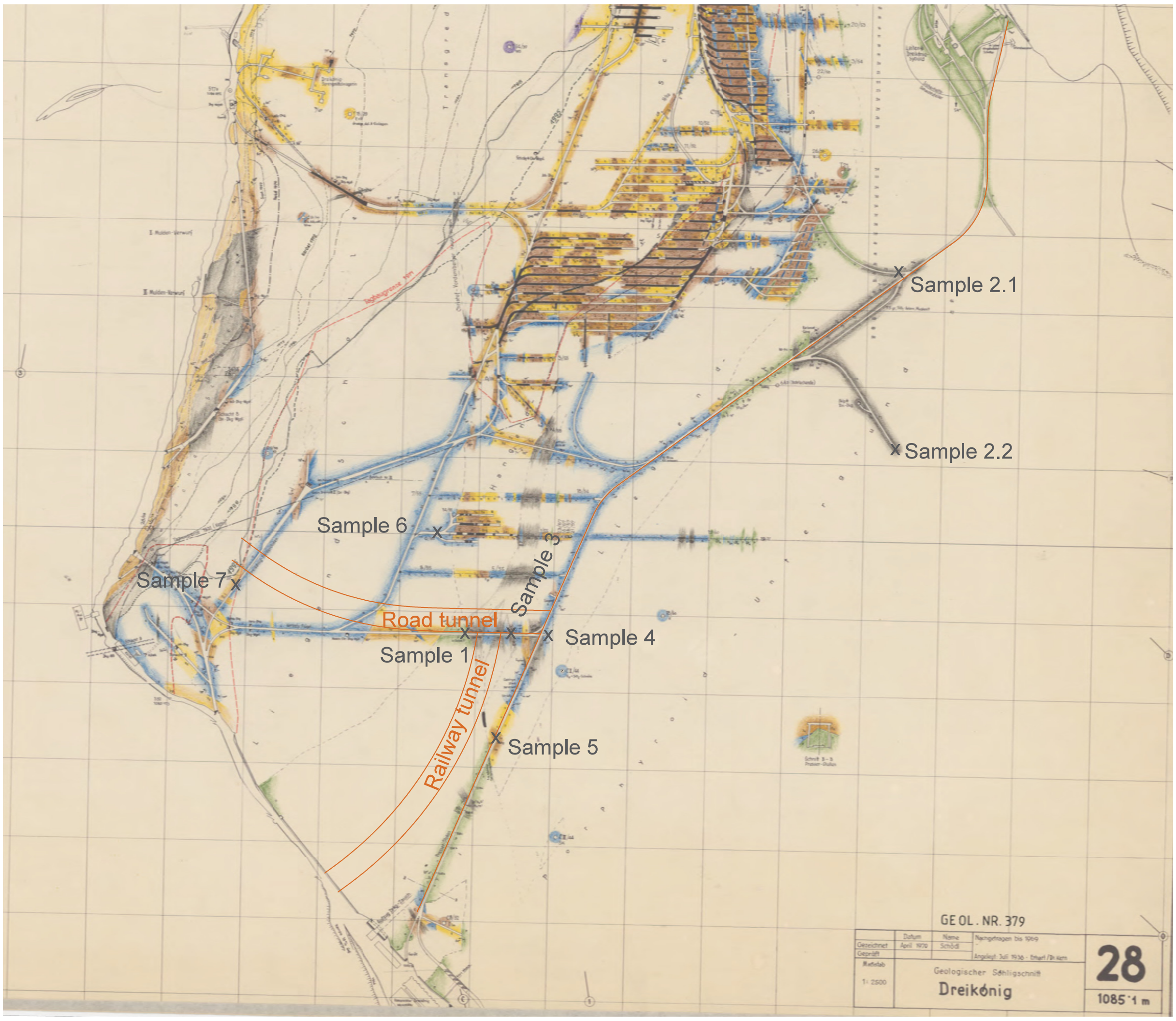


Figure 10: Overview of Erzberg with locations of samples

After taking the samples a pre-determination of their lithology was:

Sample 1:	Porphyroid
Sample 2.1:	Eisenerzer layers, shale
Sample 2.2:	Eisenerzer layers, shale with bands
Sample 3:	Eisenerzer layers
Sample 4:	Sauberger limestone
Sample 5:	Siderite
Sample 6:	Werfener layers
Sample 7:	Siderite

The following pictures show the samples taken from the Erzberg:

Figure 11: Sample 1

Figure 12: Sample 2.1

Figure 13: Sample 2.2

Figure 14: Sample 3

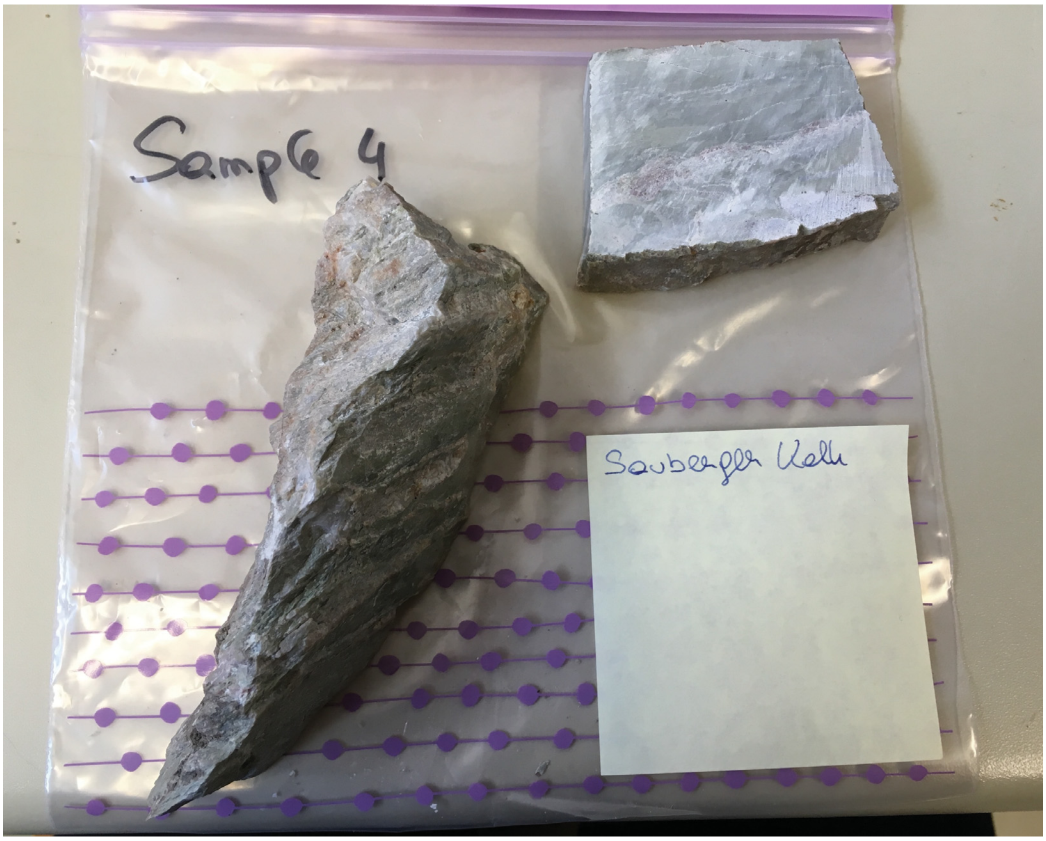


Figure 15: Sample 4

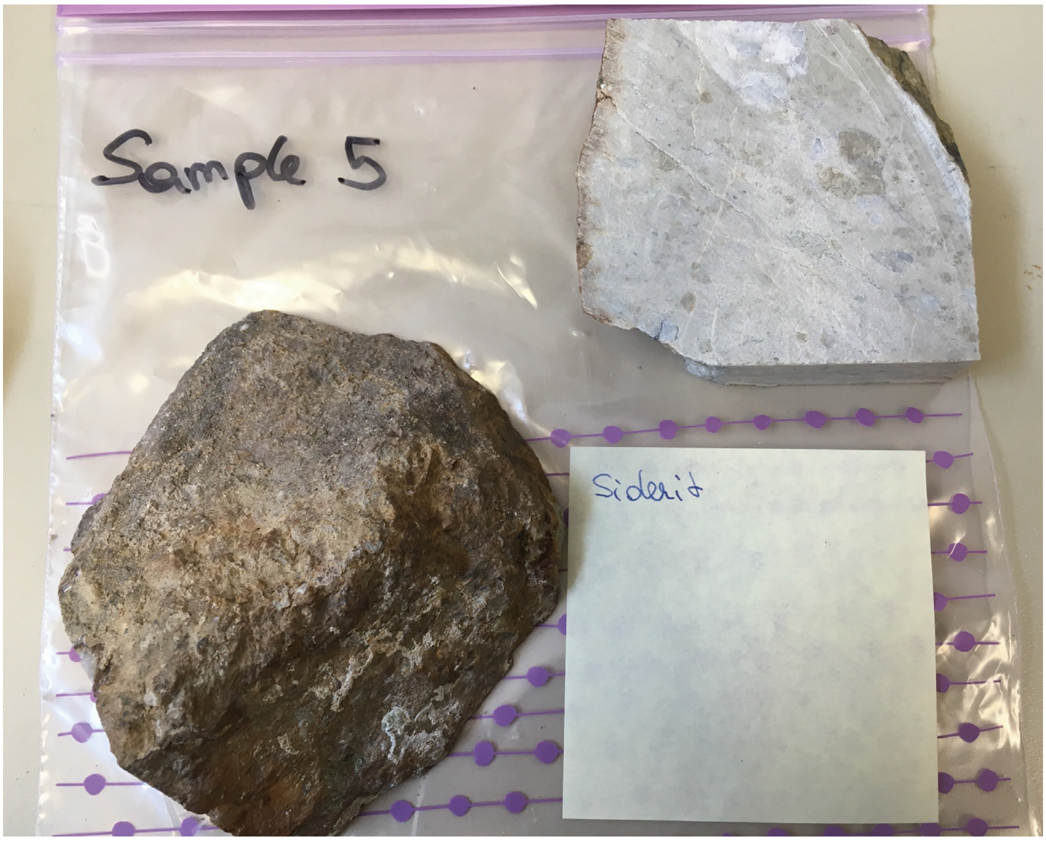


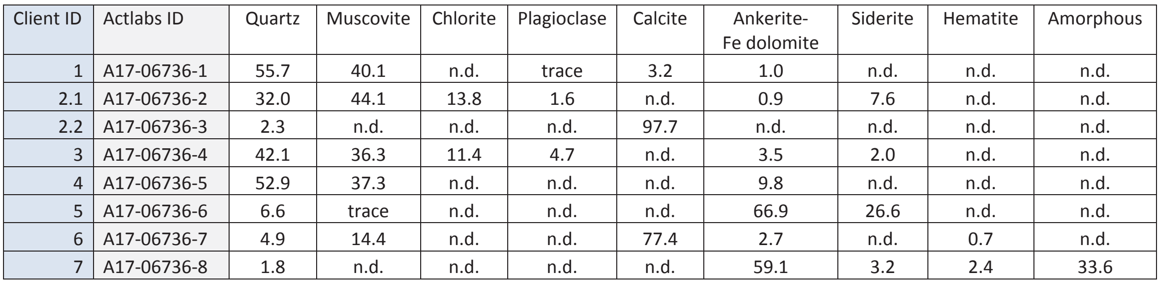
Figure 16: Sample 5

Figure 17: Sample 6

Figure 18: Sample 7

The results from a mineralogical as well as from an elemental analysis carried out by Actlabs are shown in Table 1 and Table 2.

The analysis method used for measuring the mineral abundances was X-ray diffraction. A portion of each pulverized sample was mixed with corundum and loaded into a standard holder. Corundum is added as an internal standard to determine the X-ray amorphous content. The X-ray diffraction analysis was performed on a Panalytical X'Pert Pro diffractometer, equipped with a Cu X-ray source and an X'celerator detector, operating at the following conditions: voltage: 40 kV; current: 40 mA; range: 5-70 deg 2θ; step size: 0.017 deg 2θ; time per step: 50.165 sec; divergence slit: fixed, angle 0.5°. The crystalline mineral phases were identified in X'Pert HighScore Plus, a software for crystallographic analysis, using the PDF-4 Minerals ICDD database. The quantities of the crystalline minerals were determined using the Rietveld method. The Rietveld method is based on the calculation of the full diffraction pattern from crystal structure data. The amounts of the crystalline minerals were recalculated based on a known percent of corundum and the remainder to 100 % was considered X-ray amorphous material. (ACTIVATION LABORATORIES LTD., 2017b)



Client ID	Actlabs ID	Quartz	Muscovite	Chlorite	Plagioclase	Calcite	Ankerite-Fe dolomite	Siderite	Hematite	Amorphous
1	A17-06736-1	55.7	40.1	n.d.	trace	3.2	1.0	n.d.	n.d.	n.d.
2.1	A17-06736-2	32.0	44.1	13.8	1.6	n.d.	0.9	7.6	n.d.	n.d.
2.2	A17-06736-3	2.3	n.d.	n.d.	n.d.	97.7	n.d.	n.d.	n.d.	n.d.
3	A17-06736-4	42.1	36.3	11.4	4.7	n.d.	3.5	2.0	n.d.	n.d.
4	A17-06736-5	52.9	37.3	n.d.	n.d.	n.d.	9.8	n.d.	n.d.	n.d.
5	A17-06736-6	6.6	trace	n.d.	n.d.	n.d.	66.9	26.6	n.d.	n.d.
6	A17-06736-7	4.9	14.4	n.d.	n.d.	77.4	2.7	n.d.	0.7	n.d.
7	A17-06736-8	1.8	n.d.	n.d.	n.d.	n.d.	59.1	3.2	2.4	33.6

Note: n.d. = not detected; amorphous refers to X-ray amorphous material

Table 1: Mineral abundances (wt %) (ACTIVATION LABORATORIES LTD., 2017b)

As the results in Table 1 indicate, sample 1, 2.1, 3 and 4 are similar. They have a high content of quartz and muscovite, which indicates porphyroid. In sample 1 and 4 siderite was not detected. However, sample 2.1 has 7,6 wt% siderite and sample 3 2,0 wt%. In all four samples ankerite was detected.

Sample 2.2 shows a high level of calcite (97,7 wt%) as well as sample 6 (77,4 wt%). However, sample 6 also contains Muscovite with a content of 14,4 wt%.

Samples 5 and 7 are high in ankerite and sample 5 also in siderite which in general correlates with the first estimation of the two samples.

Contrary to expectations, the field estimation of sample 4 first seemed to be wrong, since in the results of Actlabs there was no calcite, while a high content of calcite is a sign for limestone. Instead a high amount of quartz is to be found. However, after LIBS analysis and further investigation which is discussed in chapter 3.3.1 it was found hat the result from Actlabs must have been wrong and that the first estimation of the sample was correct.

From the results of the mineralogical analysis the lithologies of the samples have to be revised:

Sample 1: Porphyroid

Sample 2.1: Eisenerzer layers

Sample 2.2: Eisenerzer layers

Sample 3: Porphyroid

Sample 4: Sauberger limestone

Sample 5: Siderit

Sample 6: Sauberger limestone

Sample 7: Siderit

The elemental analysis was conducted in the following way. A 1 g sample was digested with aqua regia and diluted to 250 ml volumetrically. Appropriate international reference materials for the metals of interest were digested at the same time. The samples and standards were analyzed on an Agilent 700 Series ICP which is an optical emission spectrometer. (ACTIVATION LABORATORIES LTD)

Analyte Symbol	SiO2	Al2O3	Fe2O3(T)	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	LOI	Total
Unit Symbol	%	%	%	%	%	%	%	%	%	%	%	%
Lower Limit	0.01	0.01	0.01	0.001	0.01	0.01	0.01	0.01	0.001	0.01		0.01
Method Code	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP	FUS-ICP
1	71.22	12.88	2.26	0.028	1.44	2.17	0.16	5.38	0.479	0.07	4.17	100.3
2.1	57.37	17.89	8.44	0.133	2.19	0.63	0.53	5.09	0.838	0.14	6.82	100.1
2.2	2.42	0.86	1.02	0.193	0.53	52.21	0.02	0.25	0.044	0.12	42.04	99.69
3	63.44	15.79	5.47	0.086	1.71	1.39	0.55	4.22	0.836	0.13	5.77	99.41
4	67.38	13.24	2.77	0.144	1.97	3.45	0.06	4.46	0.211	0.16	6.58	100.4
5	6.08	1.07	27.95	1.442	5.75	21.35	0.02	0.33	0.049	0.06	35.88	99.97
6	13.18	4.86	2.36	0.099	1.27	40.89	0.04	1.68	0.241	0.07	34.81	99.49
7	2.31	0.33	42.20	2.172	4.65	17.30	0.03	0.09	0.018	0.04	30.83	99.98

Sc	Be	V	Cr	Co	Ni	Cu	Zn	Ga	Ge	As
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
1	1	5	20	1	20	10	30	1	1	5
FUS-ICP	FUS-ICP	FUS-ICP	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS	FUS-MS
7	1	70	30	2	< 20	< 10	40	14	1	< 5
17	3	120	110	16	50	40	40	25	2	24
3	< 1	22	< 20	1	< 20	< 10	< 30	1	< 1	< 5
15	2	130	100	13	50	30	< 30	19	2	20
8	4	28	< 20	3	50	< 10	< 30	17	2	< 5
1	< 1	8	< 20	6	30	< 10	< 30	2	< 1	< 5
6	< 1	30	20	3	< 20	< 10	< 30	7	< 1	< 5
2	< 1	10	< 20	4	30	< 10	< 30	2	< 1	< 5

Table 2: Results from elemental analysis (ACTIVATION LABORATORIES LTD., 2017a)

The elemental analysis correlates with the results from the X-ray diffraction. The chemical formula of quartz is SiO_2. Samples 1, 2.1, 3 and 4 show a high content of silicon. In all four samples iron was detected. Sample 2.1 has the highest content of iron(III) oxide which is 8,44 wt%. Of these four samples, 2.1 it also has the highest content of siderite (7,6 wt%).

Sample 5 and 7 have a high grade of iron. However, sample 7 has the highest wt% of iron(III) oxide, namely 42,20 wt%.

Sample 2.2 and 6 also correlate with the mineralogical analysis. They have the highest amount of CaO. Sample 2 consists of 52,21 wt% CaO and sample 6 of 40,89 wt%.

3.3 Comparison

Based on the results provided by the Canadian laboratory, a comparison between their results and the intended measurement methods (LIBS, NIR and LIF) for the Research@ZaB were conducted to determine the best solution for an online on-site analysis of the excavation material.

3.3.1 Preliminary Analysis with LIBS

The elemental composition of the samples from the Erzberg was measured with MineralLIBS which is an analyzer from SECOPTA analytics GmbH, a German company specialized in LIBS applications. The analyzer used for the sample is called MineralLIBS which is especially designed for measuring the composition of minerals in an industrial environment. Figure 19 shows a schematic sketch of MineralLIBS. The material on the conveyor belt moves from the left to the right. First the height of the material is measured so that afterwards the laser can focus correctly. (Ahsan, 2017)

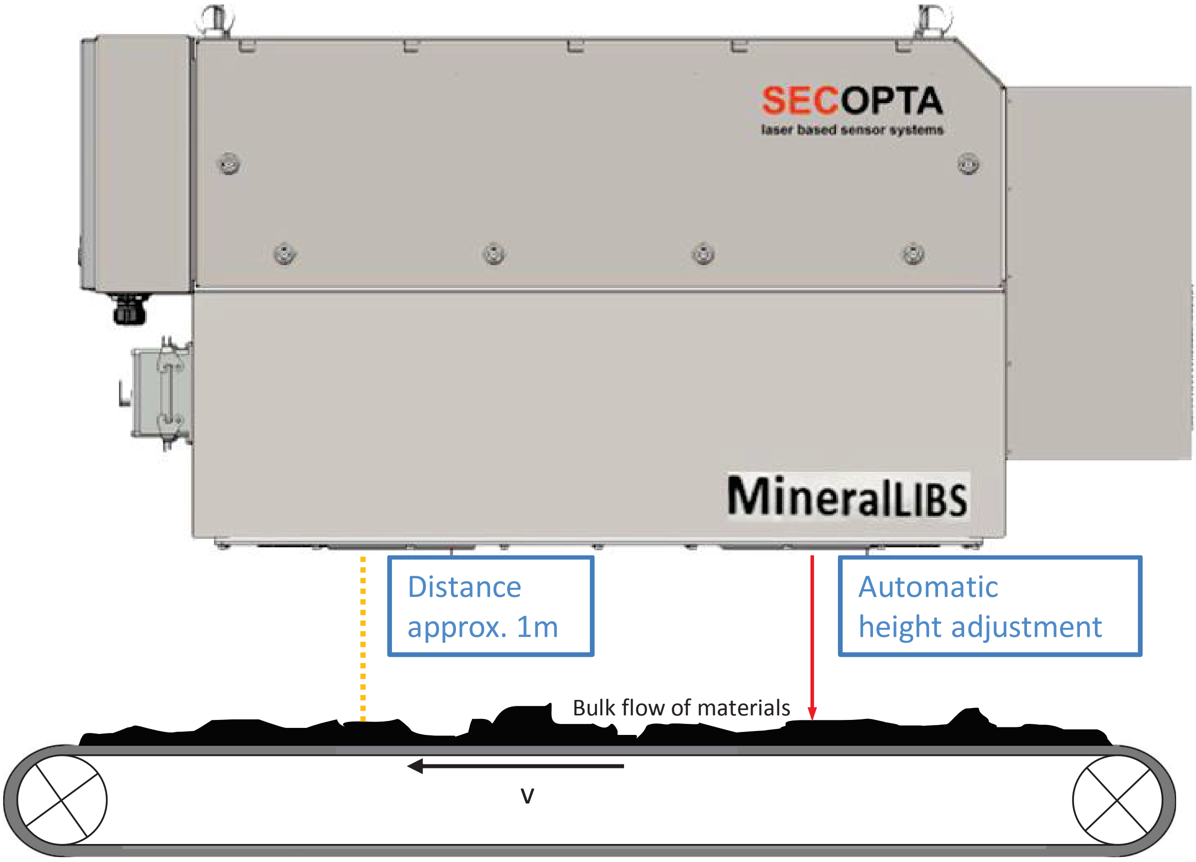


Figure 19: MineralLIBS (Ahsan, 2017)

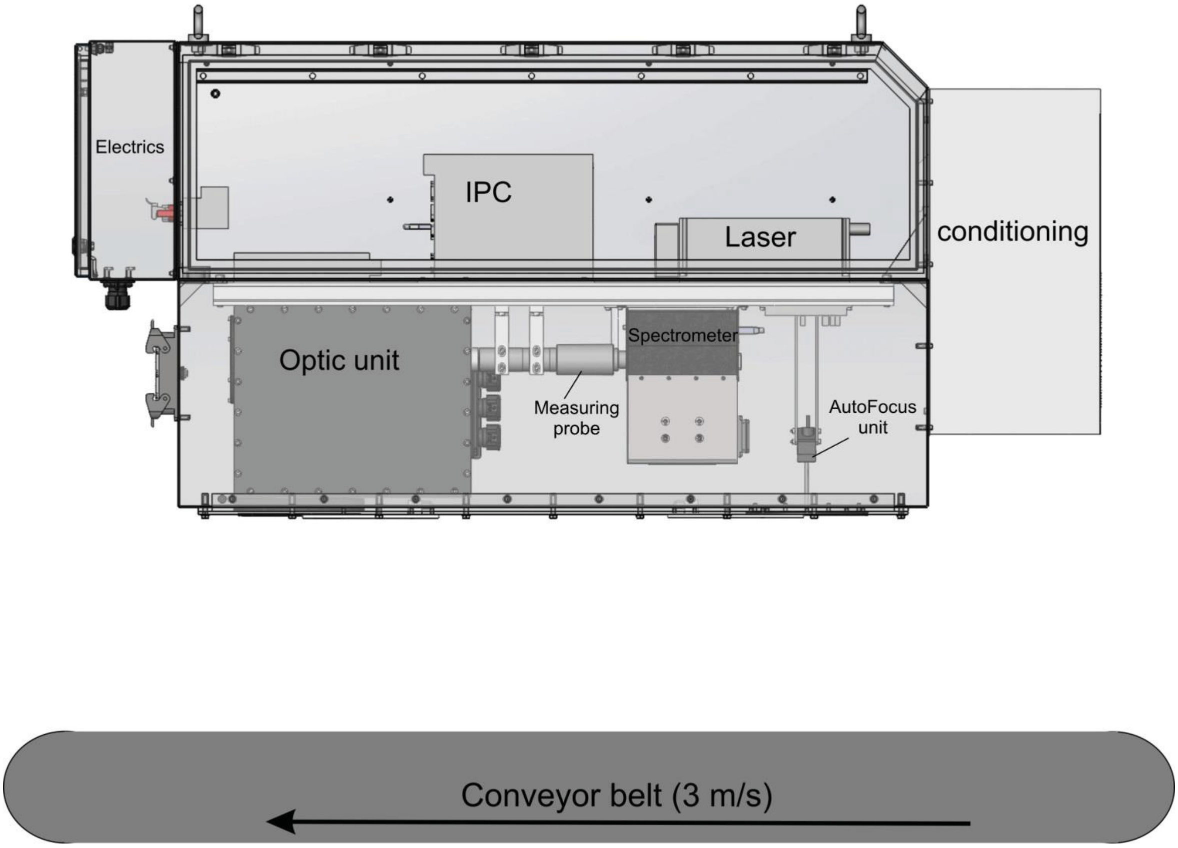


Figure 20: Sketch of the inside of MineralLIBS (Ahsan, 2017)

Figure 20 gives an insight into the inner parts of MineralLIBS. It contains an AutoFocus unit to measure the height of the material stream, a laser with a wavelength of 1064 nm, an optic unit and an industrial PC. The application works with conveyor belt speeds up to 3 m/s.

The laser operates with a frequency of 20-80 Hz. The pulse energy is between 24-40 MJ with a pulse duration of about 8 ns. The results are obtained within milliseconds and more than 350 measurements/s with up to 20.000 measurement points/s are possible. Quantitative results of MineralLIBS are measureable under 0,1 wt% with a relative error of 5 % at 3 m/s conveyor belt speed. (Ahsan, 2017)

For harsh environments MineralLIBS is designed according to IP67. The international protection code is specified in ÖNORM EN 60529:2014. The first digit (6) of IP67 indicates the protection against intrusion of solid particles which in this case is “dust tight”. The second digit provides information about the protection of liquid ingress. 7 stands for “Immersion, up to 1 m depth”. This allows MineralLIBS to be used in an environment like a construction site.

The results, pictured as spectra, of the qualitative analysis of the samples with MineralLIBS are shown in Figure 21 to Figure 30. There are two spectra of sample 7 because there were two measurements. During the first measurement, the sample was randomly placed under the laser. However, for the second one the sample was adjusted in a way that the laser would focus on an area that was predicted to have a high content of iron.

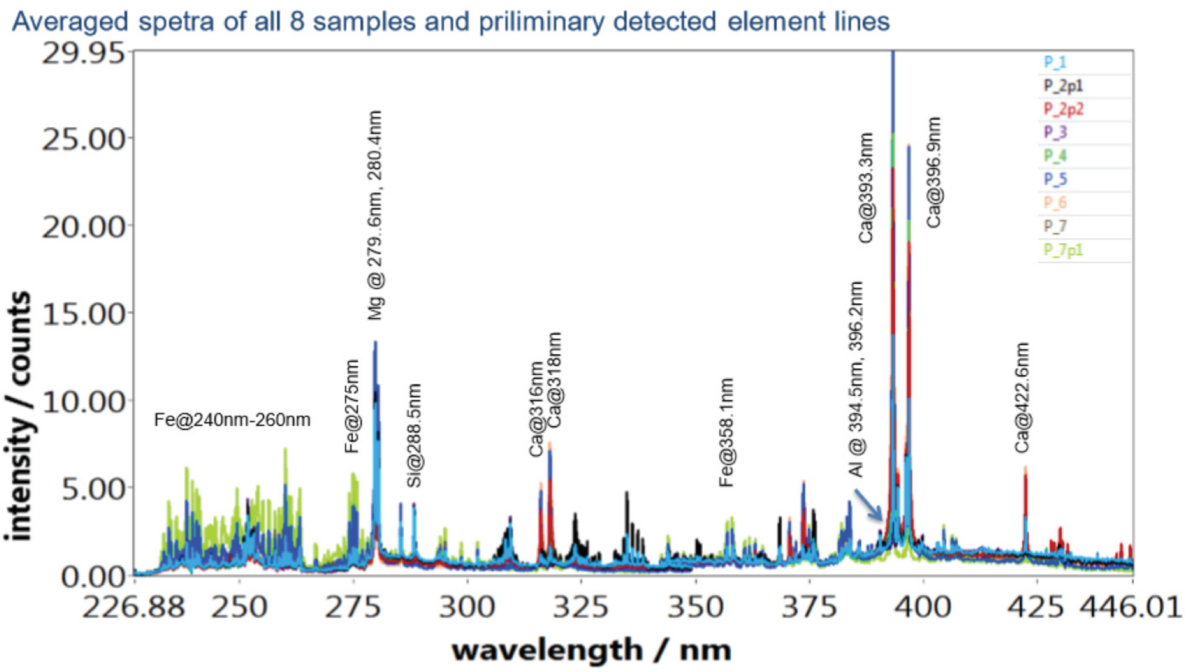


Figure 21: Qualitative overlayed spectra of all samples (AHSAN, 2017)

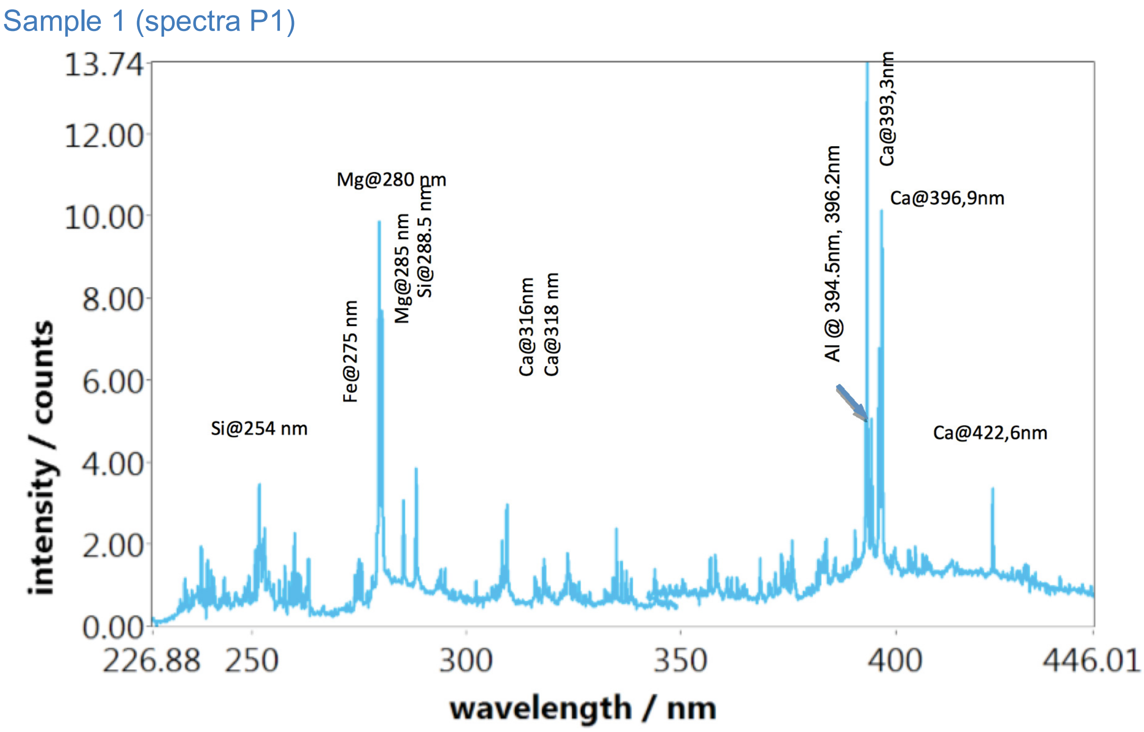


Figure 22: Qualitative spectra of sample 1 (AHSAN, 2017)

Sample 2.1 (spectra P2p1)

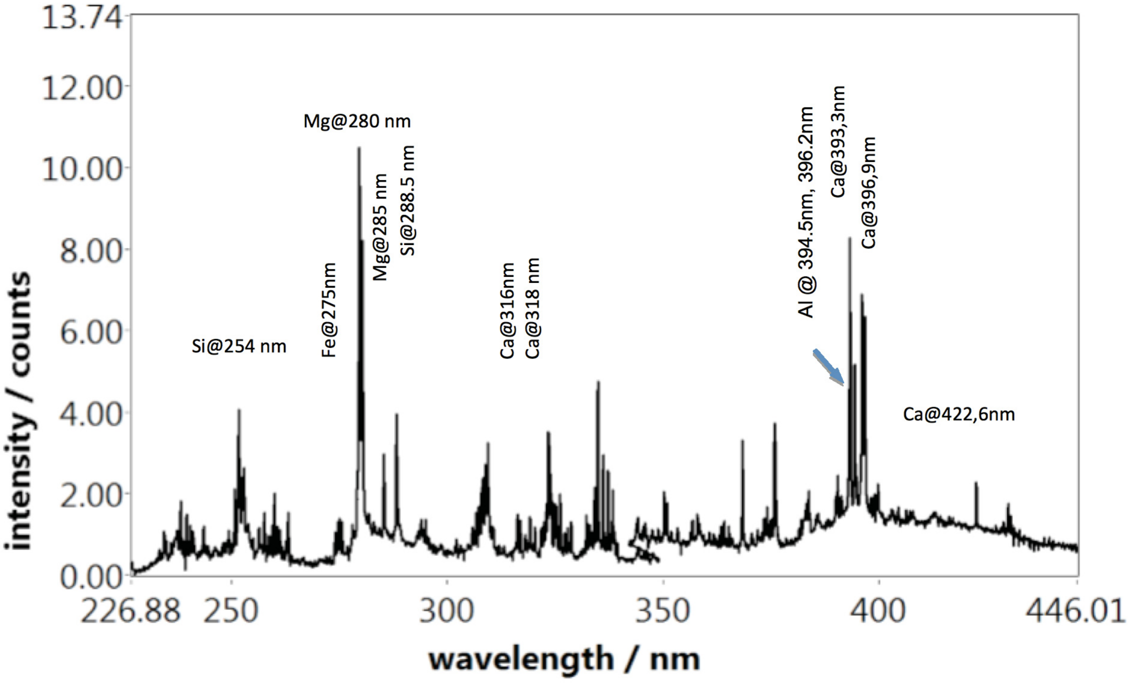


Figure 23: Qualitative spectra of sample 2.1 (AHSAN, 2017)

Sample 2.2 (spectra P2p2)

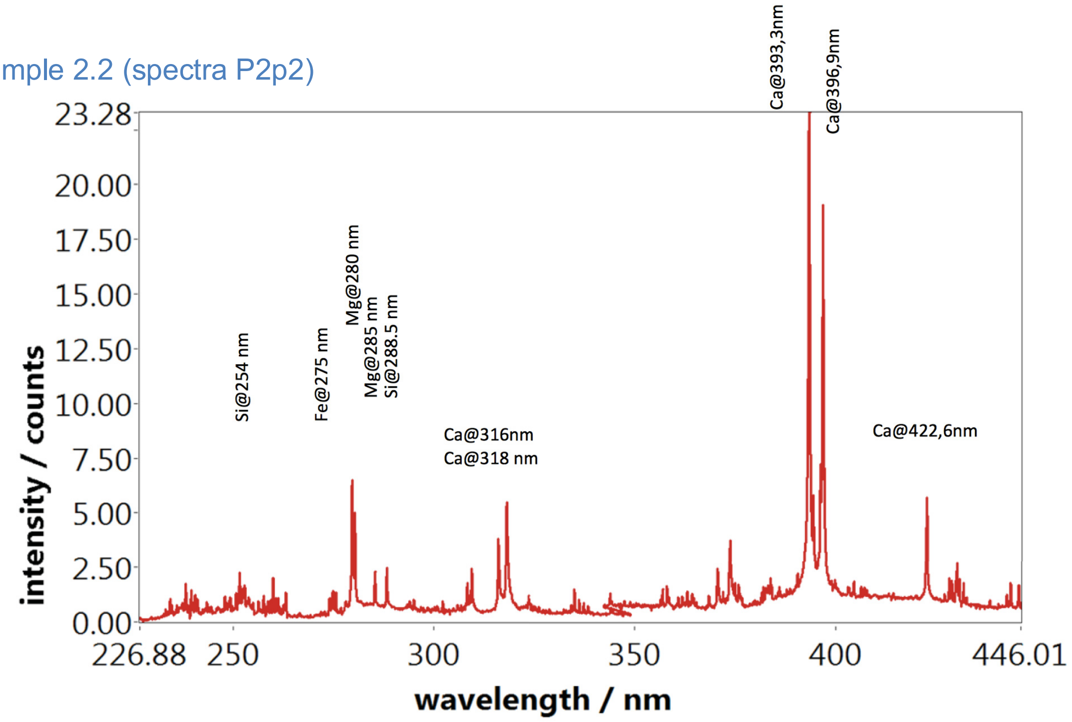


Figure 24: Qualitative spectra of sample 2.2 (AHSAN, 2017)

Sample 3 (spectra P3)

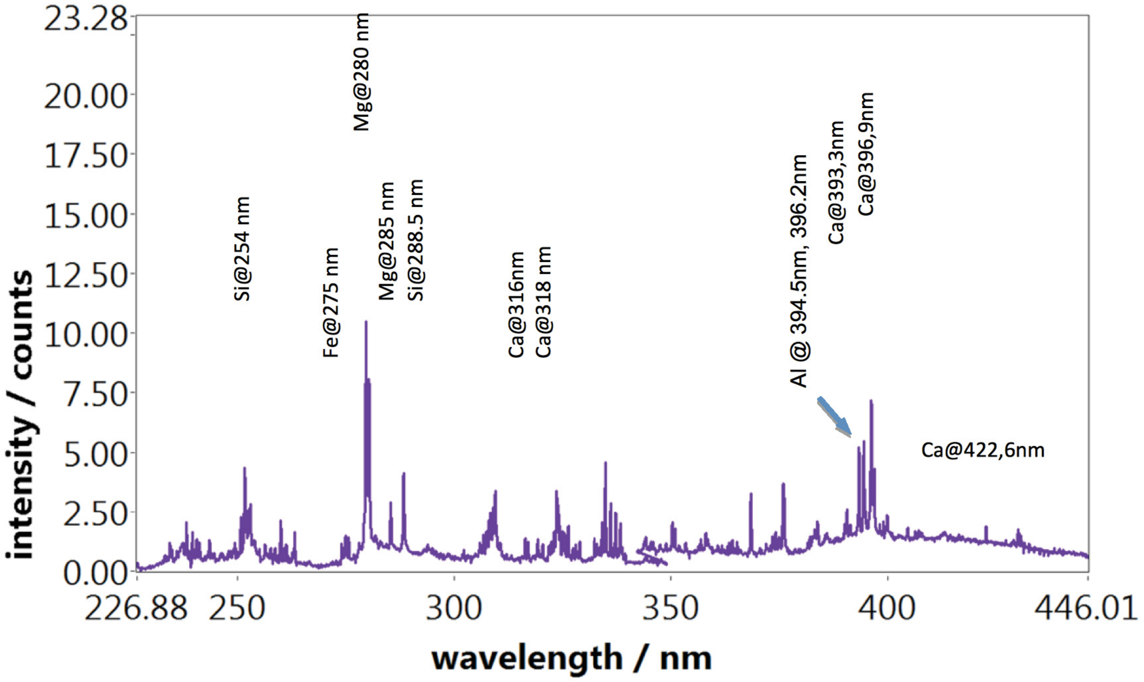


Figure 25: Qualitative spectra of sample 3 (AHSAN, 2017)

Sample 4 (spectra P4)

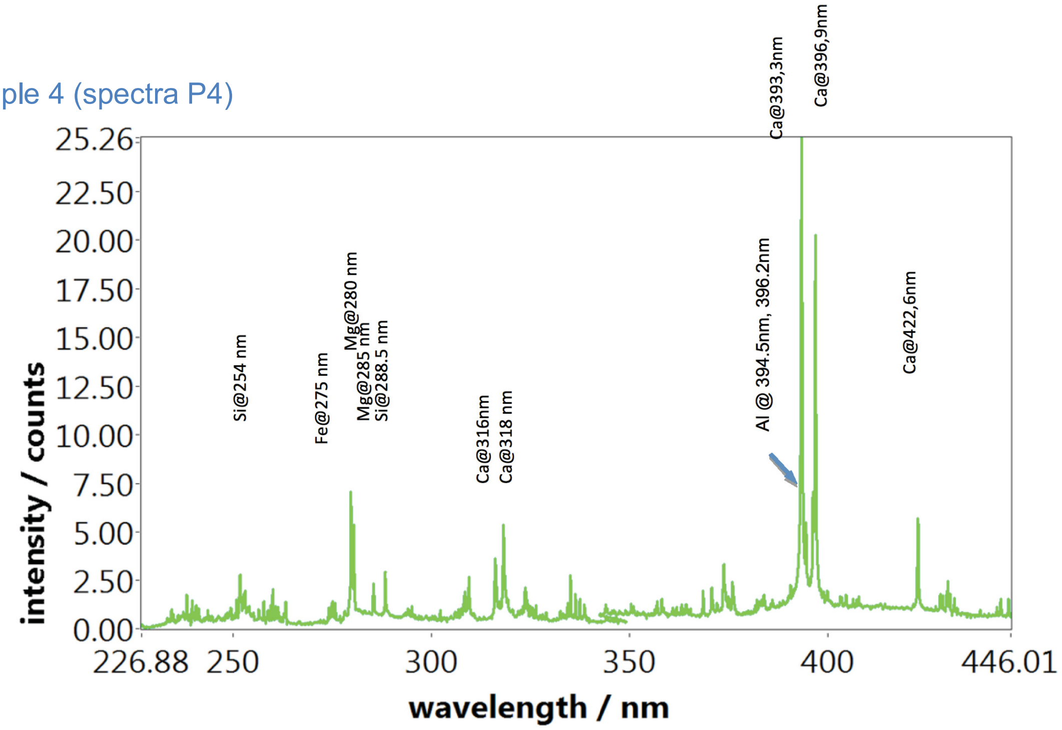


Figure 26: Qualitative spectra of sample 4 (AHSAN, 2017)

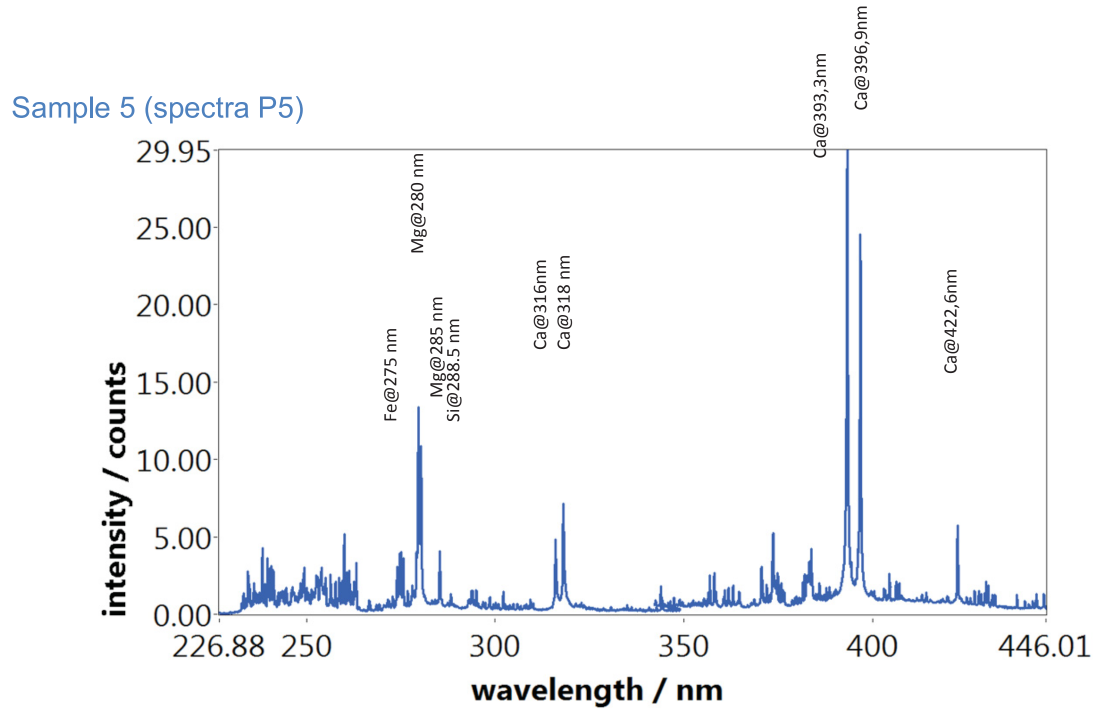


Figure 27: Qualitative spectra of sample 5 (Ahsan, 2017)

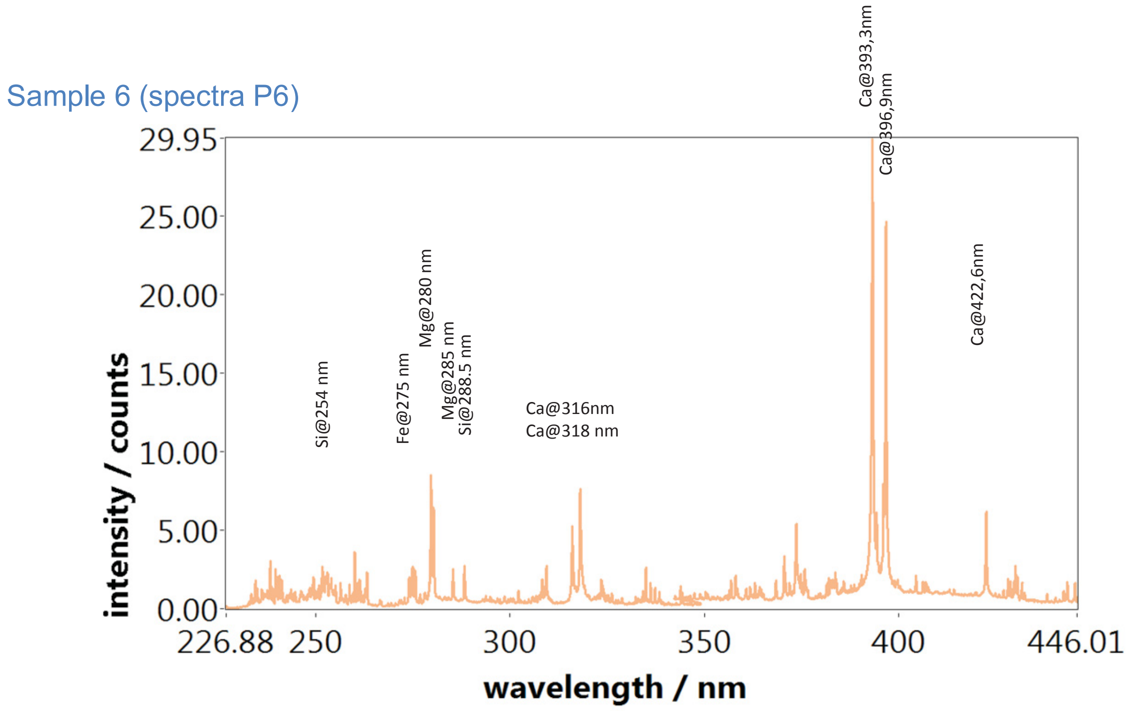


Figure 28: Qualitative spectra of sample 6 (Ahsan, 2017)

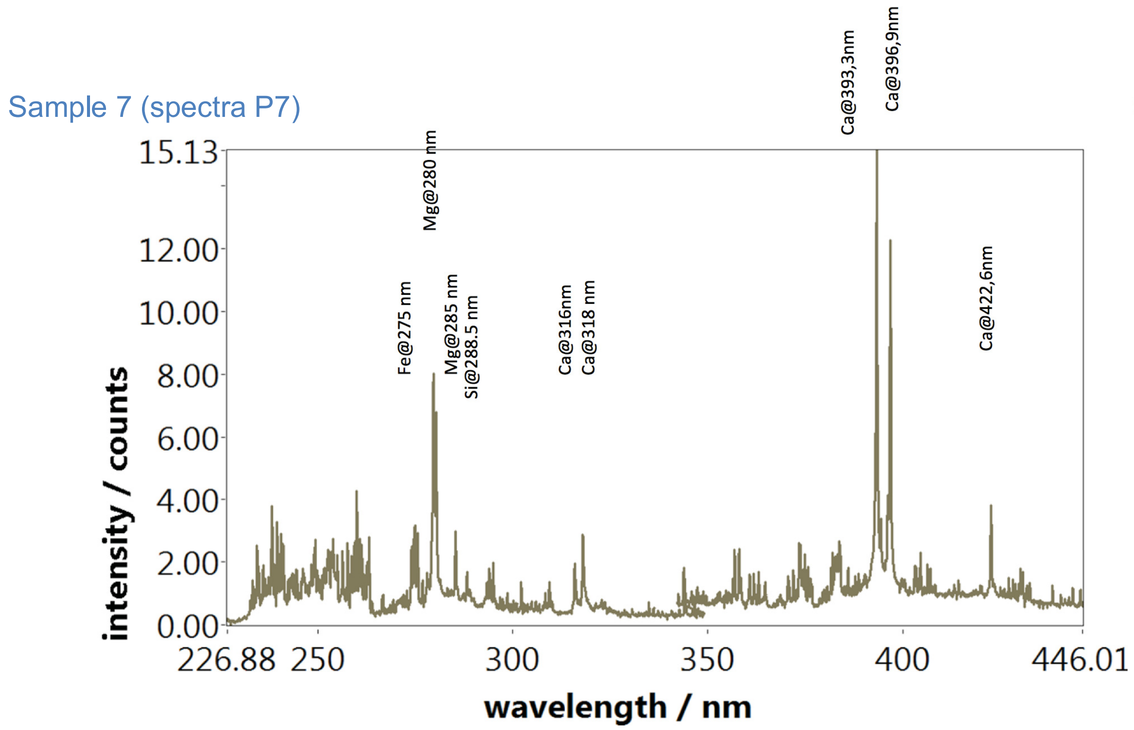


Figure 29: Qualitative spectra of sample 7 (AHSAN, 2017)

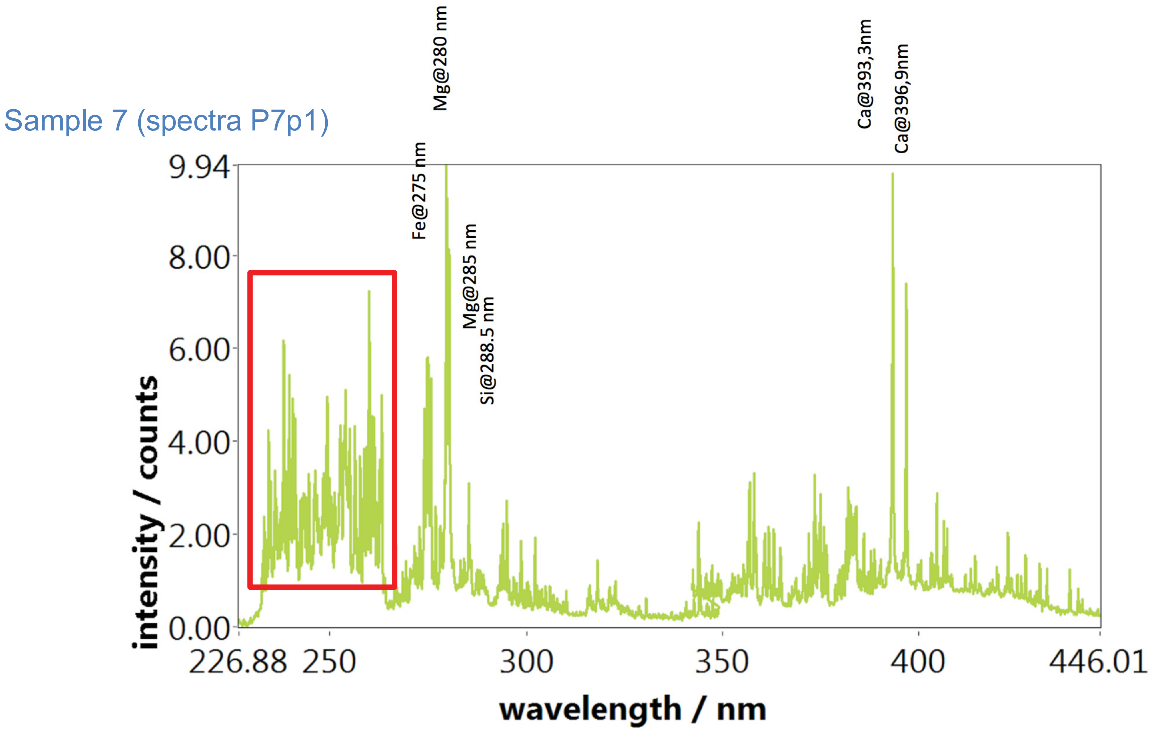


Figure 30: Qualitative spectra of sample 7_1 (AHSAN, 2017)

With the exception of sample 4, the different spectra correlate with the results from Actlabs. Sample 1, 2.1, and 3 show distinctive intensities of silicon (wavelength 254 nm and 288,5 nm) and low intensities of calcium like the results from the analysis of Actlabs. Sample 2.2 and 5 have high calcium intensities (wavelength 393,3 nm, 396,9 nm and 422,6 nm) and also sample 7 provides high peaks of calcium.

Iron intensities are shown as a multitude of peaks in the range of 230-265 nm (highlighted area in Figure 30) and also at 275 nm (AHSAN, 2017). The magnitudes of the peaks in Figure

30 are significantly higher than in Figure 29 although it is the same sample. This is a result of the laser focusing on different areas. The spectra in Figure 29 results from the sample randomly placed under the laser. Then the sample was placed in a way that an area predicted to be rich in iron was in the focus of the laser.

After investigating the spectra of sample 4, suspicion has grown that there was something not right about the results from Actlabs. To find the cause of the differences, the location where the sample was originally taken was revisited. A test with hydrochloric acid (HCl) to see if the rock reacts with it was conducted. Hydrochloric acid reacts with calcium carbonate and this can be seen as instantaneous reaction with the formation of bubbles.

The equation of the reaction of calcium carbonate in hydrochloric acid is as follows:

$$CaCO3(s) + 2\ HCl(aq) \text{ -> } H2O(l) + CO2(g) + CaCl2(aq)$$

The result of this experiment was a strong reaction with hydrochloric acid which indicates that sample 4 has a relative high content of calcium carbonate (the mineral is called calcite). As a conclusion, the results from Actlabs regarding sample 4 need to be ignored. However, since there is no indication that the other samples are wrong (they correlate with LIBS analysis) we can expect that the results are correct.

3.3.2 Preliminary Analysis with NIR

Specim, Spectral Imaging Ltd., a Finnish company focused on hyperspectral imaging conducted NIR spectroscopy measurements on the samples from Erzberg with the aim to evaluate the iron content with mineral mapping. In this study Specim scanned the rock samples with a SWIR (Short-Wavelength Infrared) spectral camera (970-2500 nm) and its specifications are shown in Table 3.

Spectral Range	970 – 2500 nm nominal
Spectral Sampling (distance between bands)	5.6 nm on average
Spectral resolution	12 nm FWHM
Number of spectral bands	279
Number of spatial pixels across swath	384
Spatial resolution on target	0.21 mm
Integration time	2.8 ms
Acquisition rate	182 frames per second
Camera Output	16 bit
Camera Serial Number	430020

Table 3: VNIR-PFD spectral camera specifications (BÄRS, 2017)

The estimation of the iron content is based on GAFFEY (1986). According to her work the iron content in carbonate minerals can be seen as a wide absorption feature (resembling a valley) in the range between 700 nm and 1800 nm while the depth of the absorption is dependent on the iron content. The typical spectra of ferroan calcite and ferroan dolomite are shown in Figure 31.

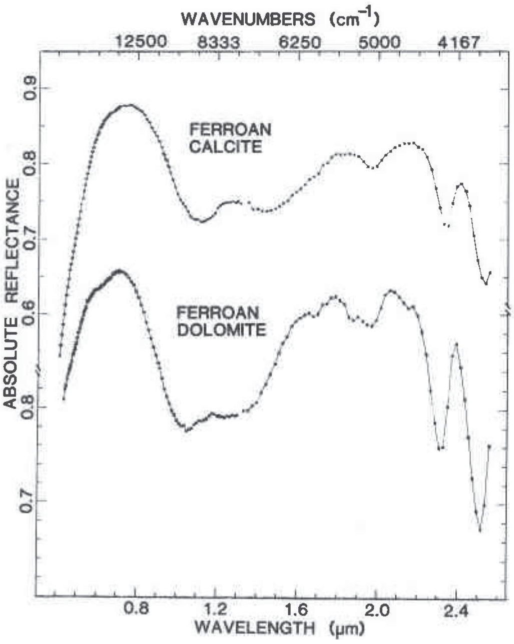


Figure 31: Spectra of ferroan calcite and ferroan dolomite showing difference in shape and position of Fe^{2+} bands (GAFFEY, 1986).

For the Erzberg samples the depth of the feature was simply calculated by subtracting the reflectance of the maximum band near 1700 nm from the minimum value, found at a band close to 1200 nm. The calculated depth is a value between 0 - 1 (or 0 % - 100 %). The greater the depth the higher is the iron content. This is best shown in a colored scale. Black stands for the lowest calculated depth and dark red for the highest. A sample with more red areas has a higher iron content than a sample with less.

This method unfortunately is fairly inaccurate because it does not take into account the global trend of the spectral shape. If the spectral shape is generally downward sloping towards longer wavelengths (e.g. Figure 34), then the value tends to be underestimated and vice versa. For some of the samples, with strong global trends and small FE-absorption features no reliable estimate could be calculated using this method, as the results were negative (see sample 2.1, 2.2 and 3). (BÄRS, 2017)

According to BÄRS, more accurate results could be achieved by first removing the global trend and then possibly fitting an N-degree function to the spectral shape. However, in this limited study the main point is to demonstrate and test the concept and only limited resources were available.

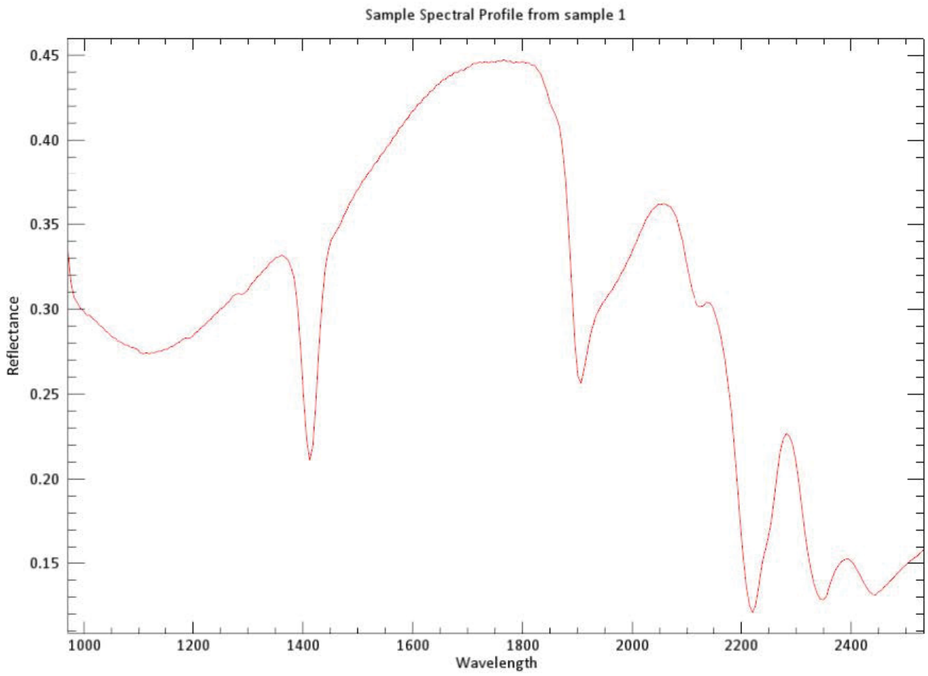


Figure 32: Typical spectrum of sample 1 (Bärs, 2017)

The graph in Figure 32 shows the maximum value of around 1700 nm and the minimum value at 1100 nm. Because of the distinctive difference between the maximum and minimum value the Fe-content of sample 1 was easy to estimate.

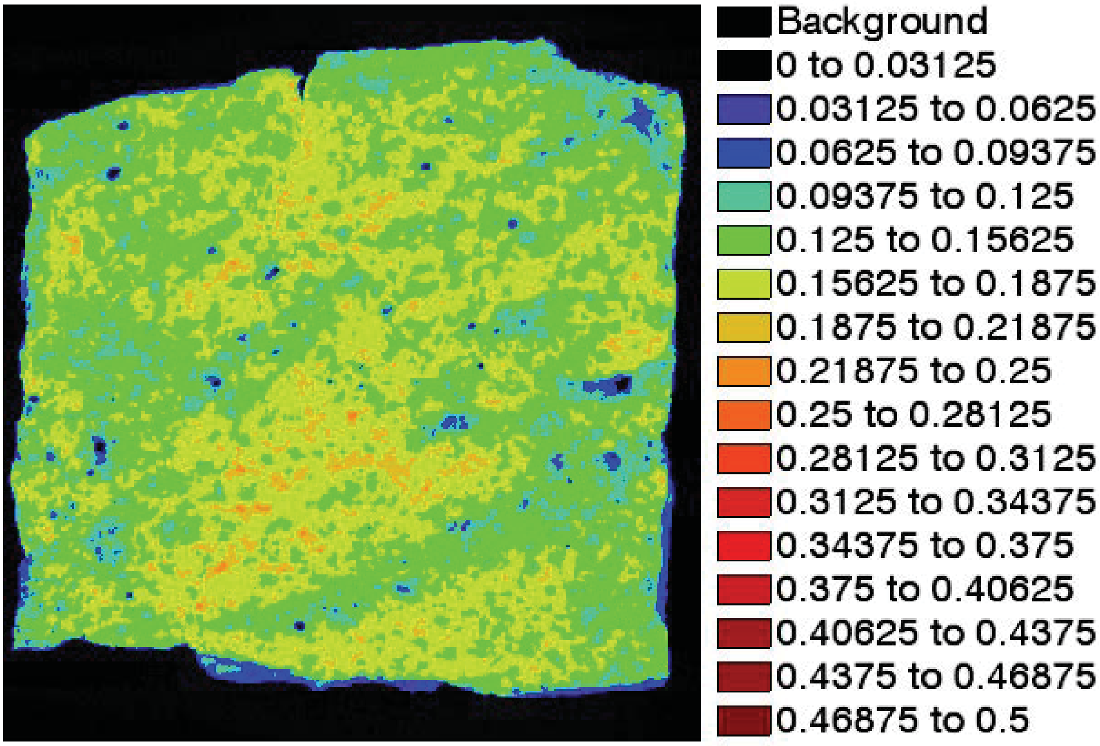


Figure 33: Calculated depth of the spectral Fe-feature of sample 1 (Bärs, 2017)

Regarding Figure 33, note that a greater depth corresponds to a higher content of iron. In this case, areas in orange show the biggest depth and largest Fe-absorption features.

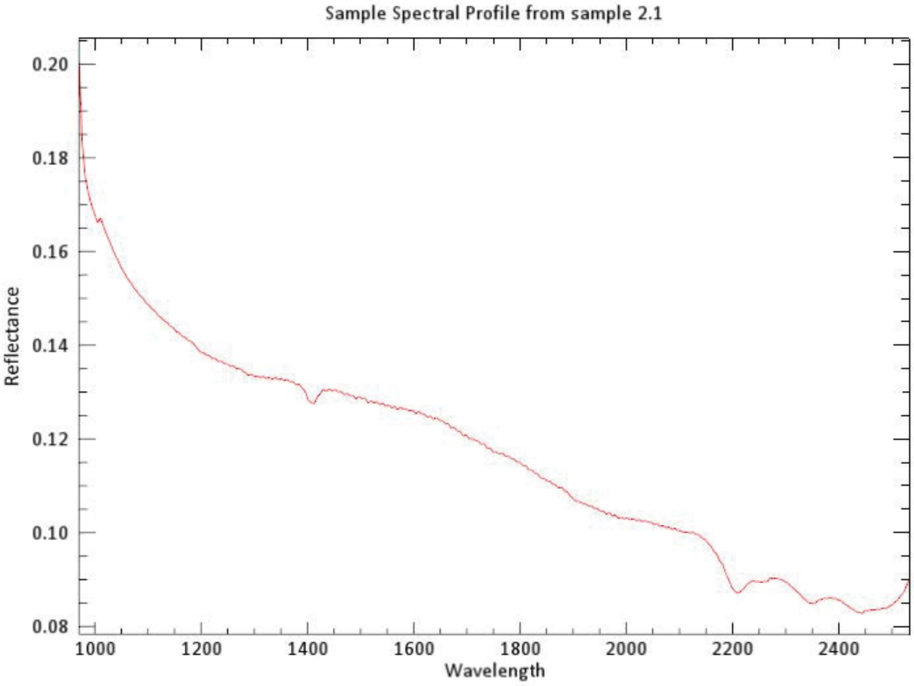


Figure 34: Typical spectrum of sample 2.1 (Bärs, 2017)

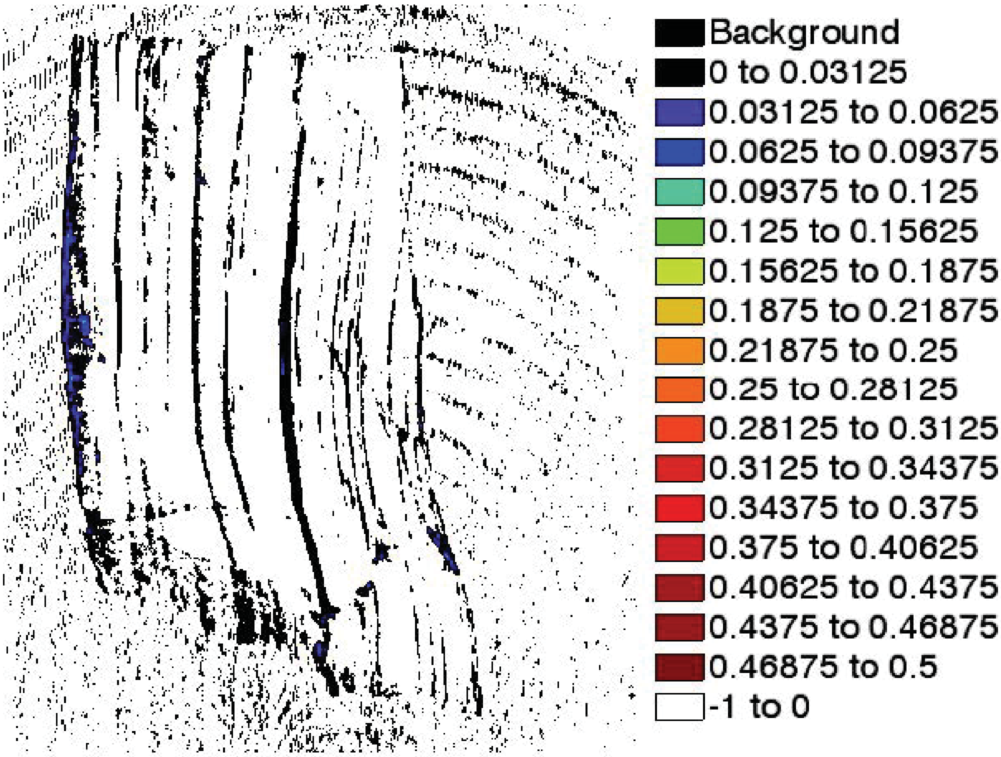


Figure 35: Calculated depth of the spectral Fe-feature of sample 2.1 (Bärs, 2017)

The Fe-content was difficult to estimate because of the global trend in the spectrum. Most of the sample has negative values which the white areas in Figure 35 indicate.

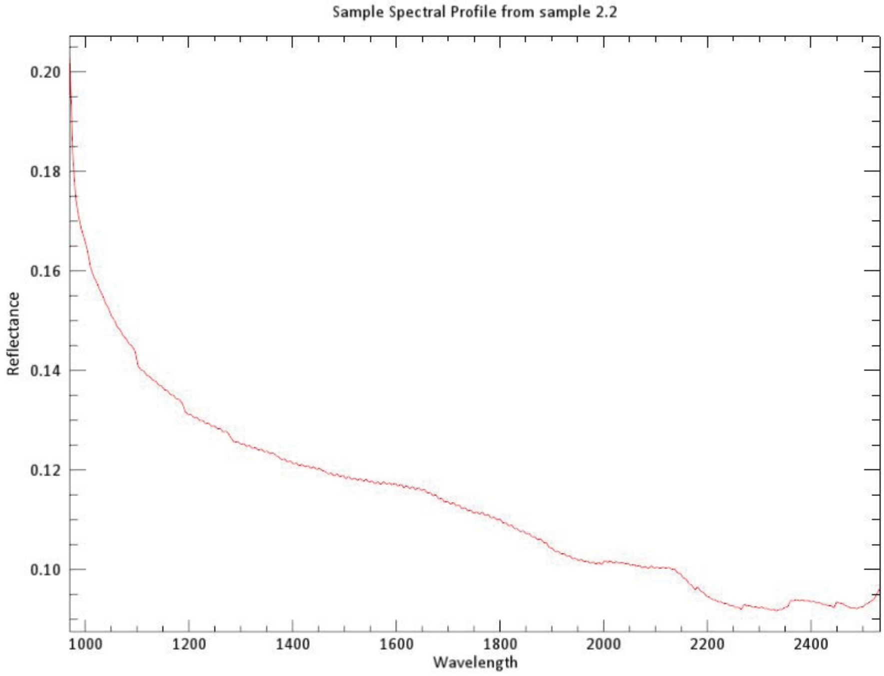


Figure 36: Typical spectrum of sample 2.2 (Bärs, 2017)

Similar to sample 2.1 the Fe-content was difficult to estimate because of the global trend in the spectrum. Sample 2.2 shows a strong decreasing spectral trend over the whole sample. All calculated Fe-absorption depths have negative values which is why an image of the results is not displayed here.

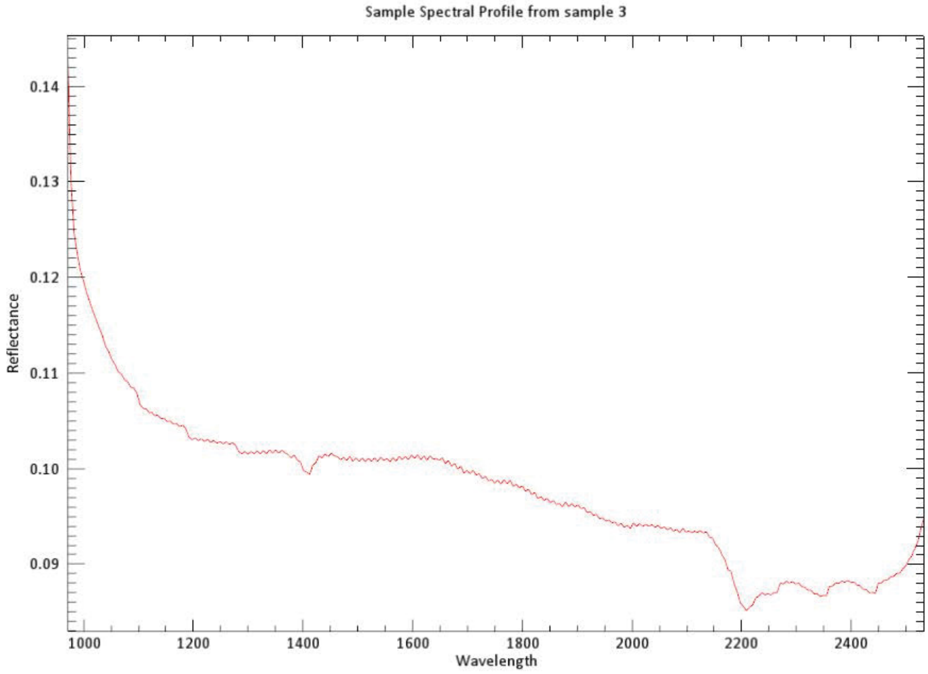


Figure 37: Typical spectrum of sample 3 (Bärs, 2017)

Also, the Fe-content of sample 3 was fairly difficult to estimate because of the same reason as for sample 2.1 and 2.2.

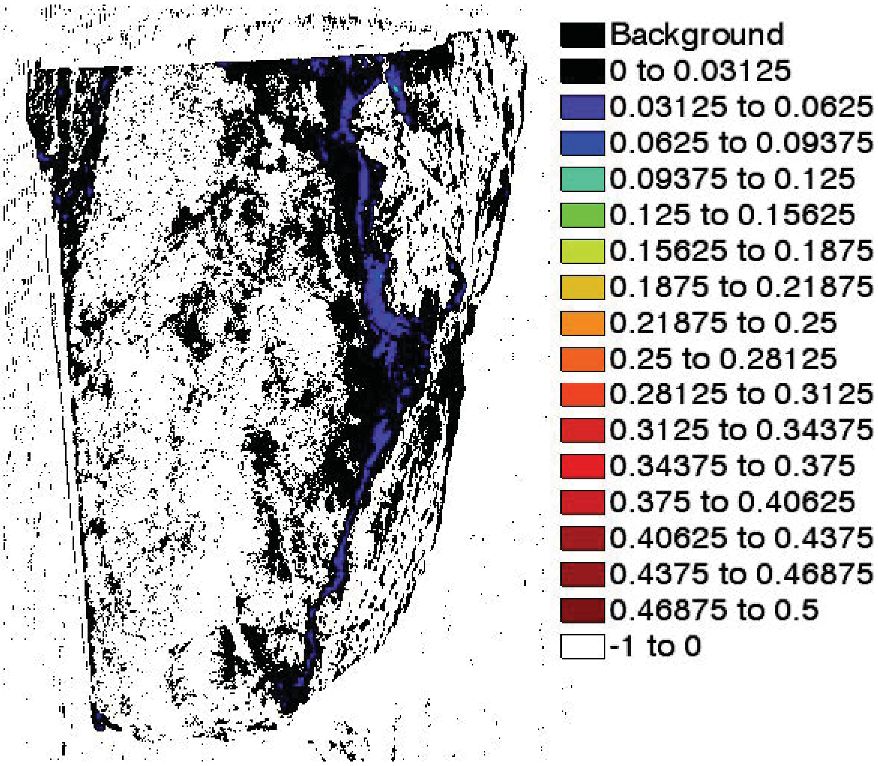


Figure 38: Calculated depth of the spectral Fe-feature of sample 3 (BÄRS, 2017)

Figure 38 shows a high amount of negative values.

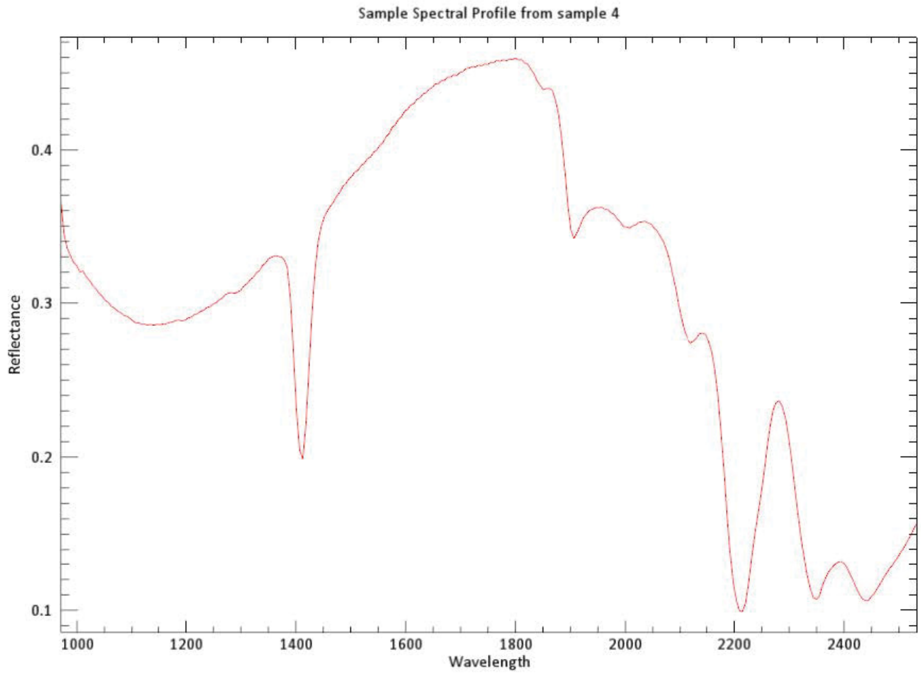


Figure 39: Typical spectrum of sample 4 (BÄRS, 2017)

The Fe-content of sample 4 was easy to estimate and its trend is shown in Figure 39. As a result, there are no white areas (negative values) in Figure 40.

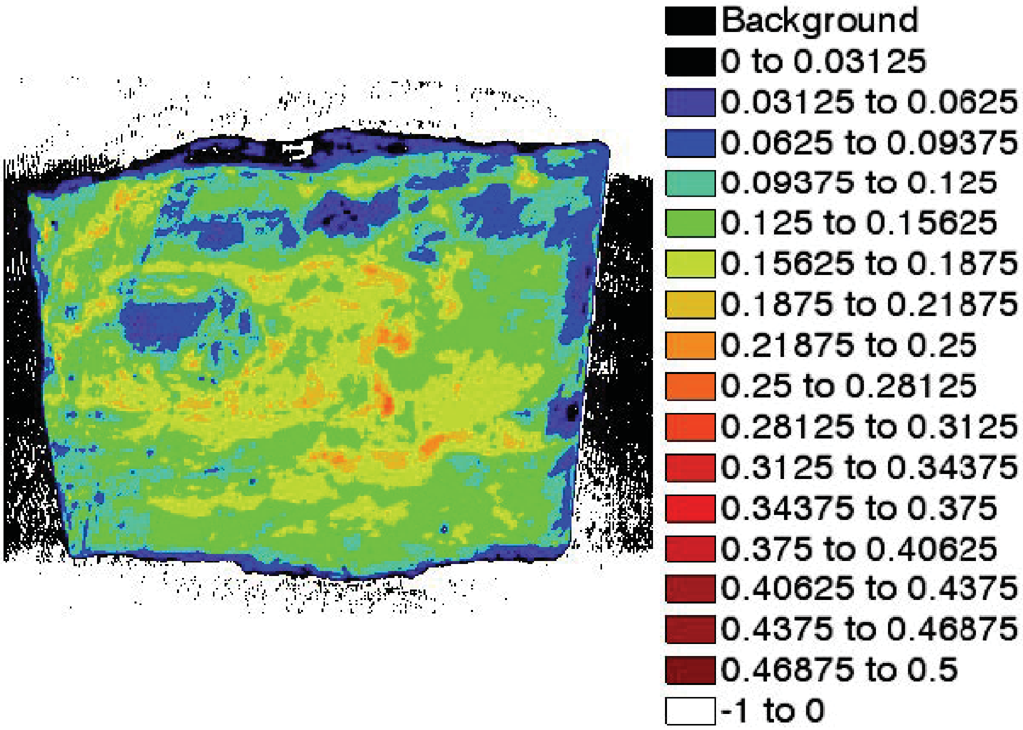


Figure 40: Calculated depth of the spectral Fe-feature of sample 4 (BÄRS, 2017)

Since at the Erzberg iron ore is mostly found in carbonates these results also show that sample 4 is a carbonate and that the first estimation of the rock was correct.

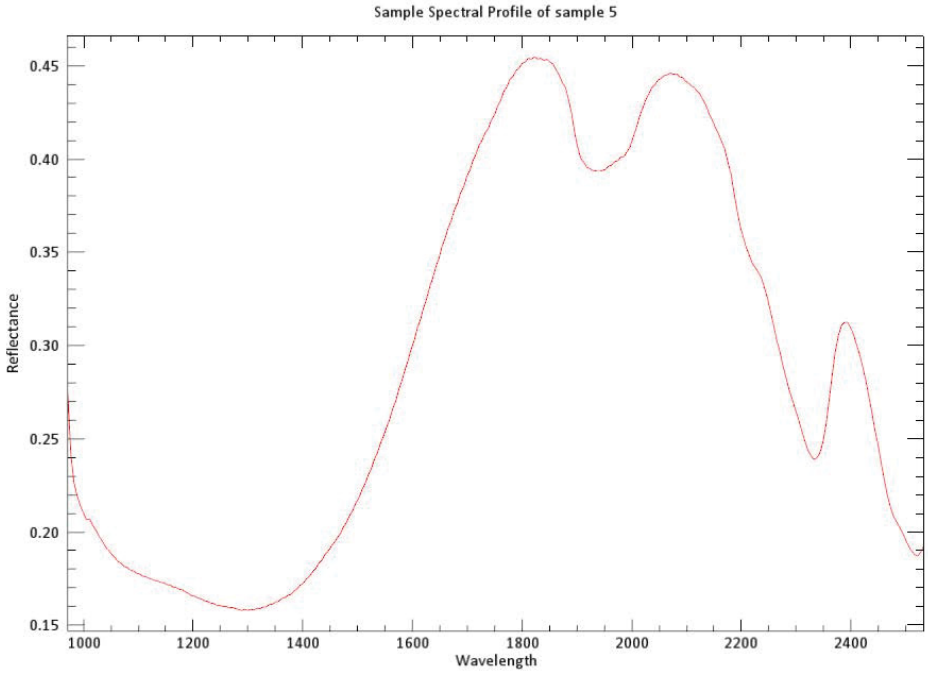


Figure 41: Typical spectrum of sample 5 (BÄRS, 2017)

The Fe-content was easy to estimate. The red color in Figure 42 stands for a bigger depth and a higher content of iron.

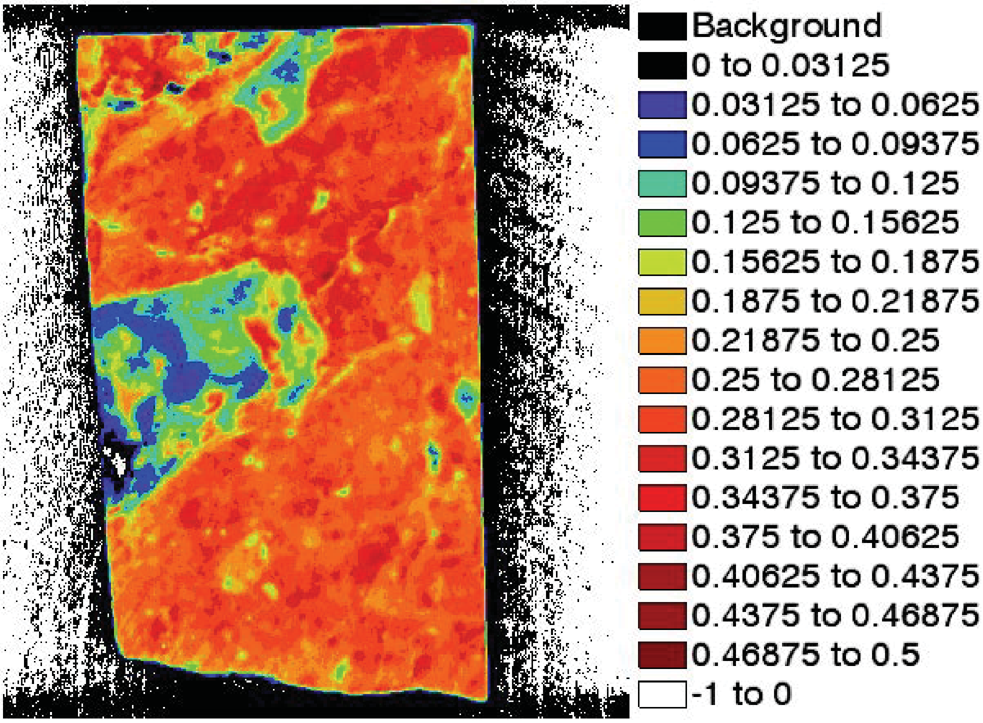


Figure 42: Calculated depth of the spectral Fe-feature of sample 5 (Bärs, 2017)

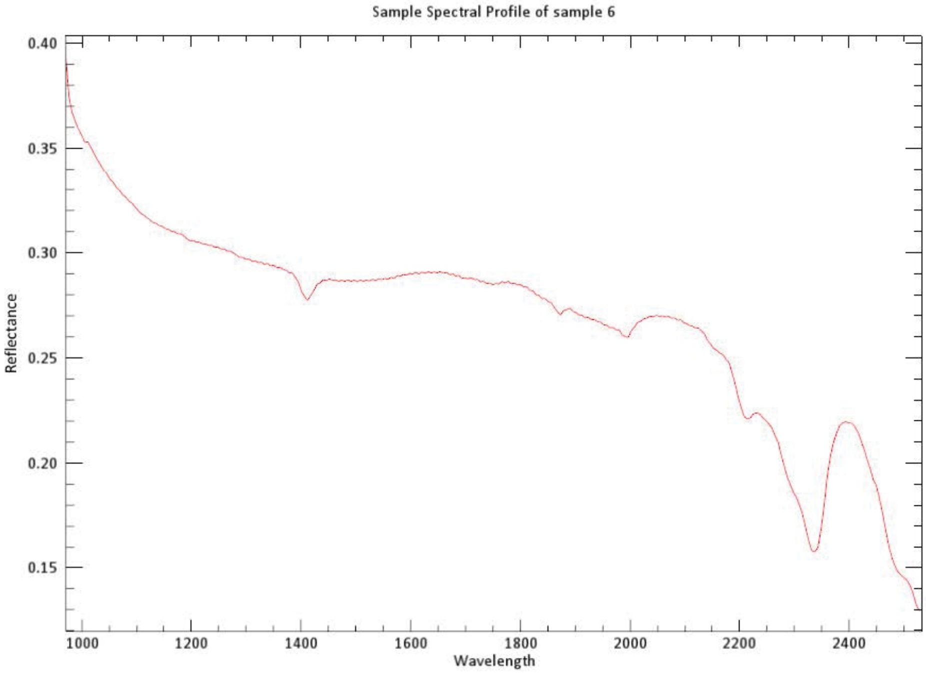


Figure 43: Typical spectrum of sample 6 (Bärs, 2017)

Fe-content of sample 6 was difficult to estimate because of the global trend in the spectrum.

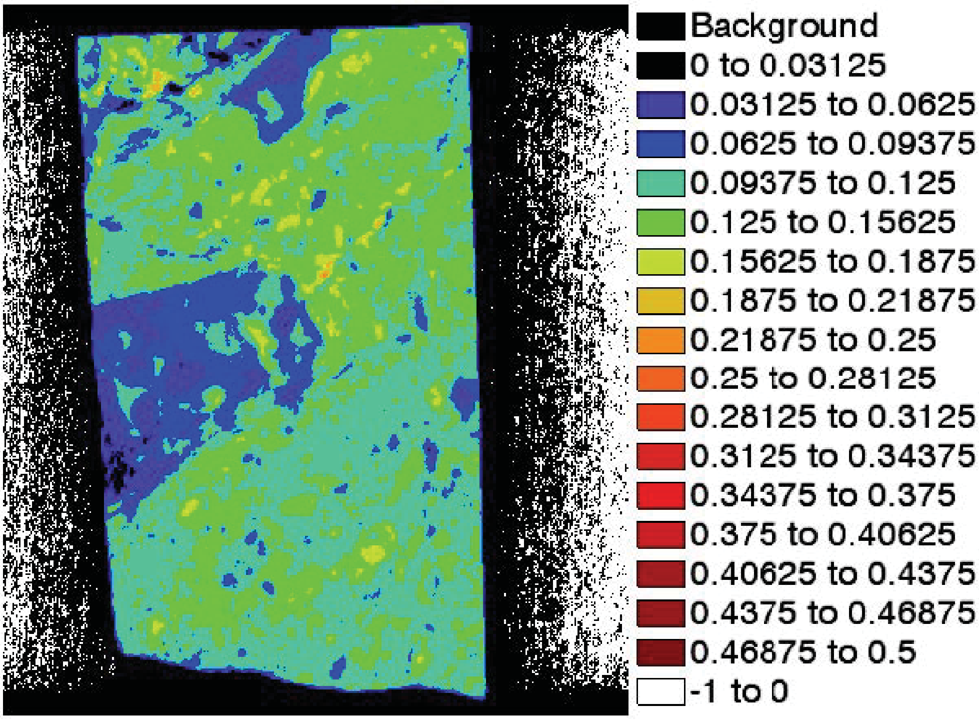


Figure 44: Calculated depth of the spectral Fe-feature of sample 6 (Bärs, 2017)

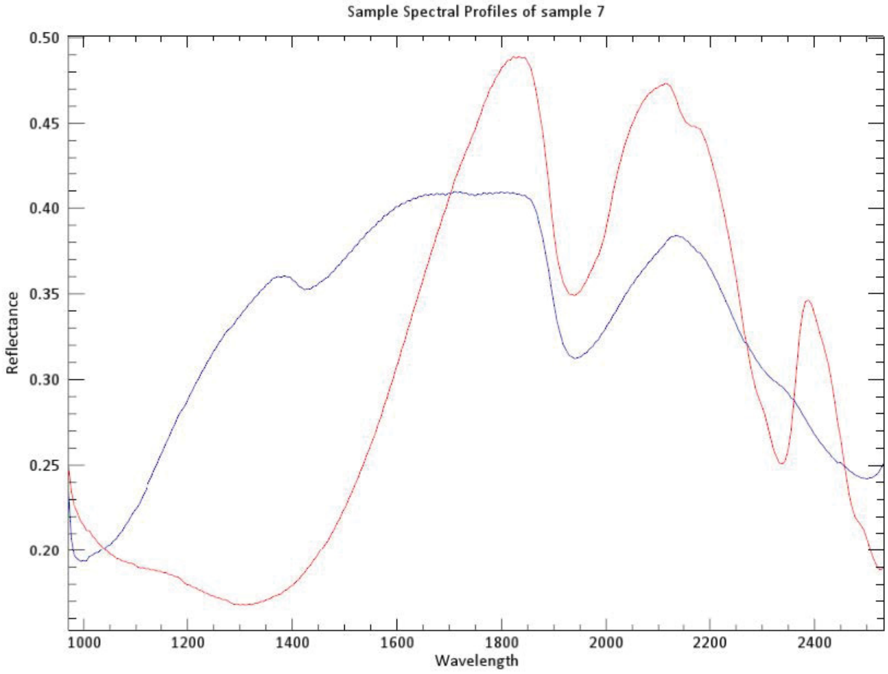


Figure 45: Typical spectra of sample 7, two different areas (Bärs, 2017)

The two curves represent different positions on the sample surface. The red curve is somewhere from the lower third of the sample image, and the blue curve from the upper two thirds of the sample image. The local minima of these curves, between 1000-1400 nm, are at different wavelength positions, one at ~1000 nm and the other at ~1300 nm. This is a clear indication of a difference in mineralogy.

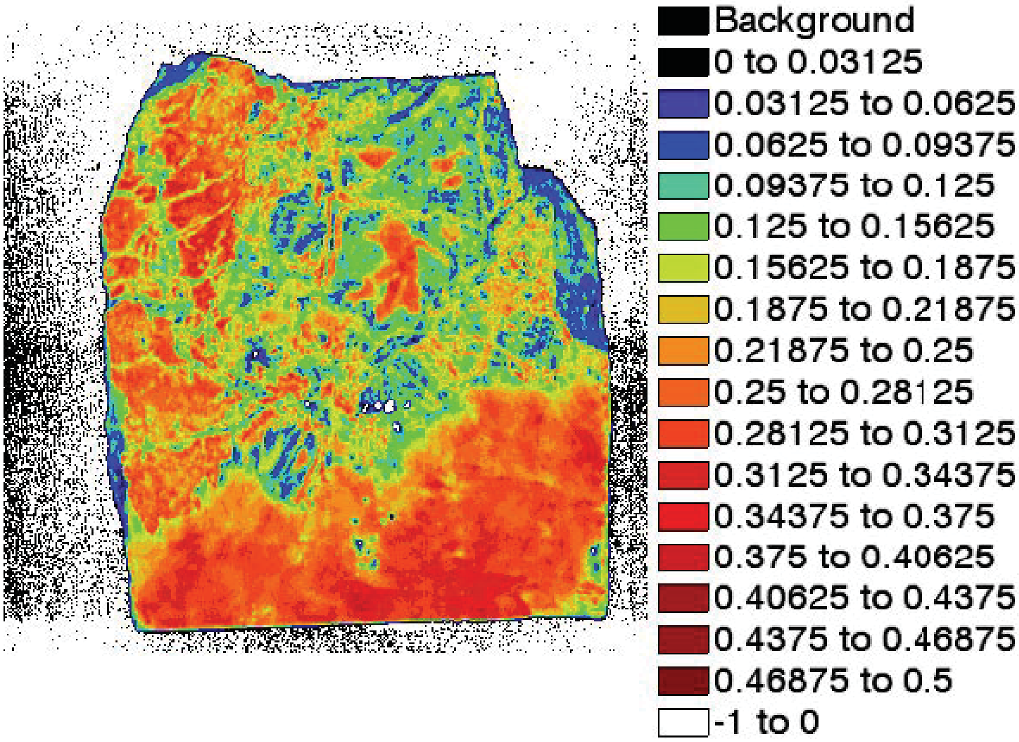


Figure 46: Calculated depth of the spectral Fe-feature of sample 7 (BÄRS, 2017)

3.3.3 Preliminary Analysis with LIF

A small preliminary analysis with LIF was conducted, but the results are too preliminary to be discussed in this thesis. Further research is required in order to be able to evaluate this method.

3.4 Conclusions

After conducting these tests and reviewing the results, the conclusion can be drawn that LIBS is advanced enough to be used in the field. Because it allows to detect all elements and MineralLIBS is designed to work in harsh environments. Additionally, with extensive calibration the content of every element with detection limits in the µg/g range can be measured.

After this quick and preliminary analysis with NIR technology it is obvious that the iron content of a rock can be determined. The question remains if NIR can be used for a wider purpose than only calculation of one property. Further research on this topic is necessary in order to draw a reasonable conclusion and make further decisions.

For the analysis unit at Erzberg it was decided to use LIBS due to the fact that the measurements conducted for this thesis show promising results and that MineralLIBS is advanced enough to be used at a construction site. It is planned to later test NIR methods on the analytical unit since a mineralogical investigation of the excavation material is as important as the elemental.

4 Analytical Unit at Research@ZaB

The main part of this thesis was the design of an analytical unit for the Research@ZaB. The purpose of the analytical unit is to determine the properties of the excavation material once the construction at the Erzberg has started.

Based upon the results of chapter 3, a unit with a LIBS analyzer and a photo-optical particle analyzer was designed.

The analytical unit as it was designed within this thesis was the basis for the planner for the tender design. The drawings were made in Autodesk Inventor, an application for 3D design. It needs to be mentioned that the design of the LIBS analyzer is based on the MineralLIBS of SECOPTA analytics GmbH, the photo-optical particle analyzer is based on the design of the HAVER CPA 4 CONVEYOR from HAVER & BOECKER OHG, the hammer sampler and slotted vessel sampler are based on drawings from Siebtechnik GmbH and a design from SBM Mineral Processing GmbH was used for the jaw crusher.

To demonstrate the planning process of the analytical unit the different design phases are shown in this chapter.

The information on which the design is based can be described as follows:

The excavation material is broken by a jaw crusher into particle sizes smaller than 150 mm. Particles already smaller than 150 mm undergo a primary screening before going through the crusher. The material is only allowed to be moist, not wet because LIBS does not work well with wet material. After calculating the tonnage of excavation material per round, it was decided that the jaw crusher is required to be able to process 150 t/h. For the photo-optical particle analyzer, a bypass is needed and therefore sampling is necessary.

During analysis, the Fe-content of the excavation material has to be assessed in real-time so that afterwards the material containing more than 20 wt% (material A) is separated from the material with lesser Fe-content (material B). Material A then will be transported to the processing facility of VA Erzberg (the owner of the mine), while Material B is used for an expansion of the area in front of the south portal for parking space.

Figure 47 shows an overview of the space in front of the south portal. Its dimensions are approximately 75 m x 30 m. The analytical unit will be placed alongside the embankment. In orange, one can see the expansion for the parking lot.

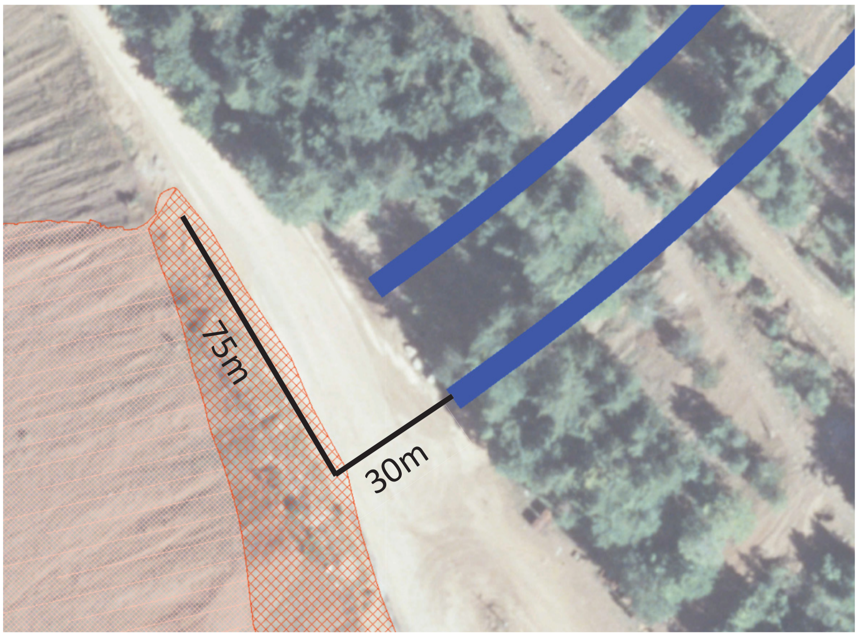


Figure 47: Portal South of Research@ZaB

Figure 48 shows the general process flow for the analytical unit. First the jaw crusher breaks the grains larger 150 mm, then the LIBS analyzer measures the Fe-content. Afterwards through a bypass the material is analyzed regarding its grain size and shape while the main stream gets separated into material A and B.

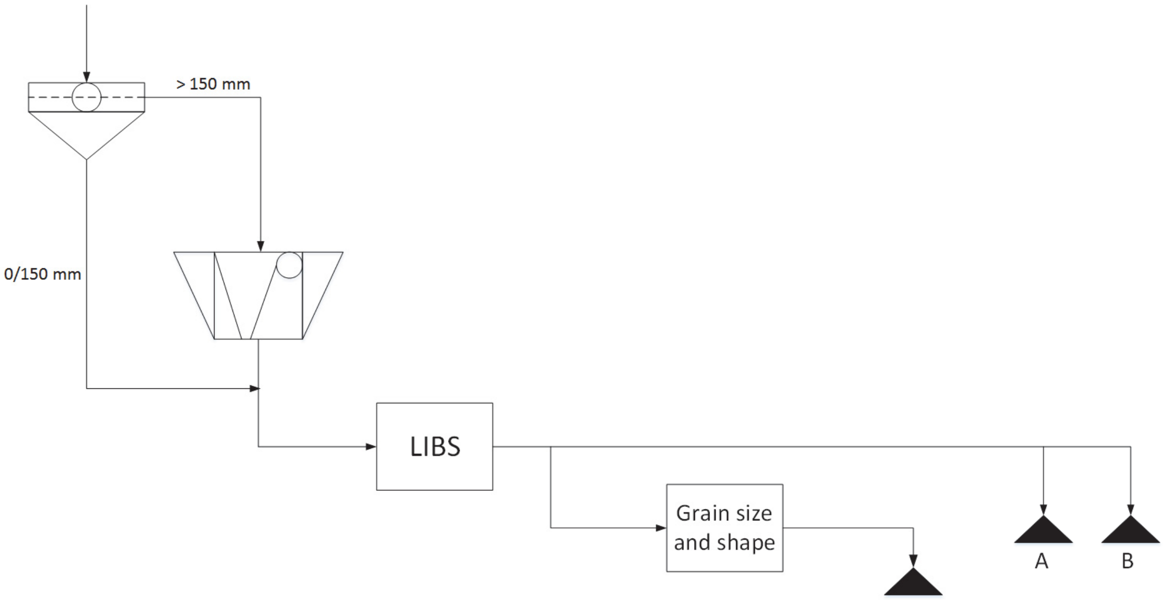


Figure 48: Process flow for analytical unit

In the following chapters (chapter 4.1 to chapter 4.4) the different planning steps are explained.

4.1 Design #1

As shown in Figure 49 the first design contains a jaw crusher followed by the LIBS analyzer. For the photo-optical particle analyzer, a bypass is necessary. In this design, a hammer sampler based on a design by Siebtechnik GmbH (a company specialized in processing and sorting) is used for taking the samples for the bypass.

This type of sampler is used for sampling directly from a conveyor belt. A sampling frame that is closed on one side circulates over the conveyor belt and in doing so takes a sample of a representative cross-section. (SIEBTECHNIK, 2013) Afterwards material A and B are separated through a sorting unit. Dimensions are shown only for design #4 (final design) in Figure 53 to Figure 55.

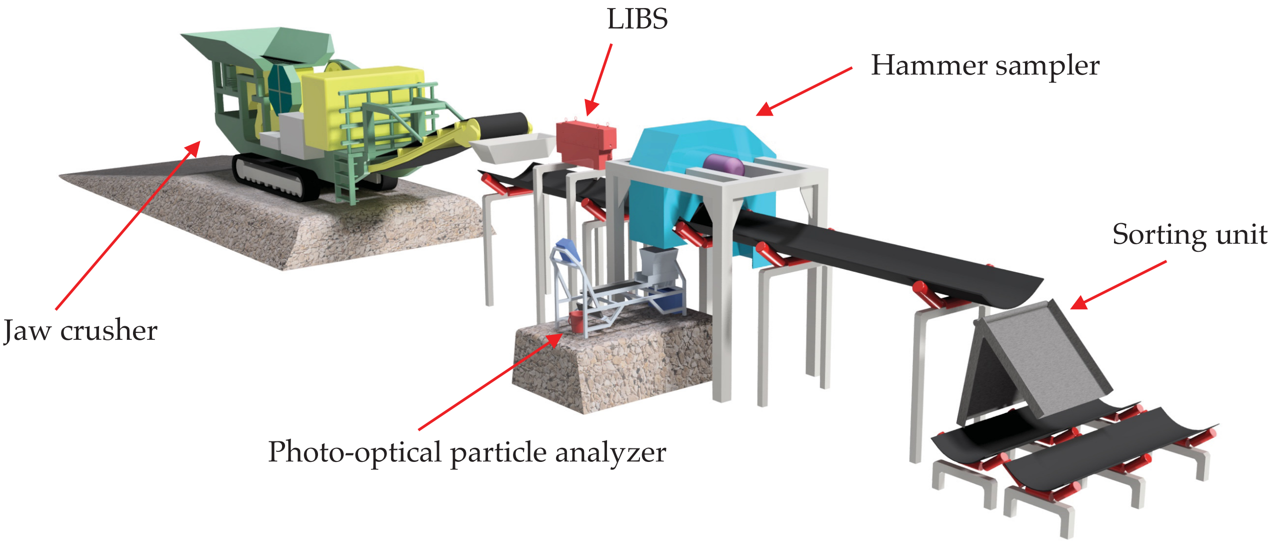


Figure 49: Design #1

4.2 Design #2

The next iteration of the design (Figure 50) led to a smaller space needed for the whole unit. On a construction site, there often is shortage in space and a lot of traffic is going on. This is the reason why for this design phase a smaller design was created. In addition, different sampler and sorter were chosen. The hammer sampler chosen for design #1 can only be used on conveyor belts and therefore needed to be replaced.

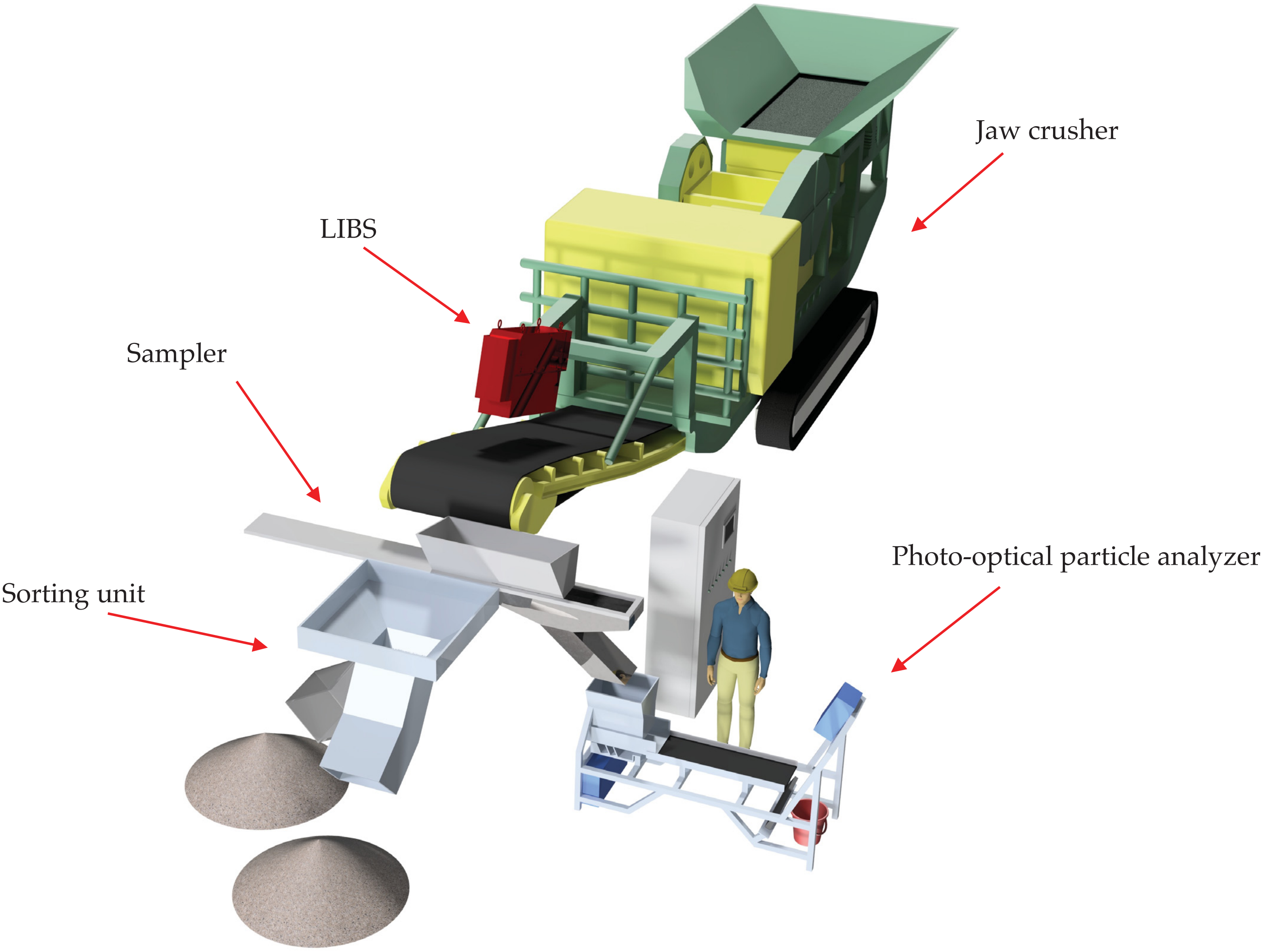


Figure 50: Design #2

4.3 Design #3

For design #3 as shown in Figure 51 it was decided to use a more sophisticated and advanced sampler because the sampler in #2 was not capable of processing a material flow of 150 t/h. This sampler is based on a design by Siebtechnik GmbH and is called a slotted vessel sampler.

According to SIEBTECHNIK (2013) the underlying principle is based on a slotted vessel with a defined intake slot vertical to the dropping material stream. The sampler runs through the material stream and takes a representative sample.

Additionally, the same sorting principle as in design #1 was used.

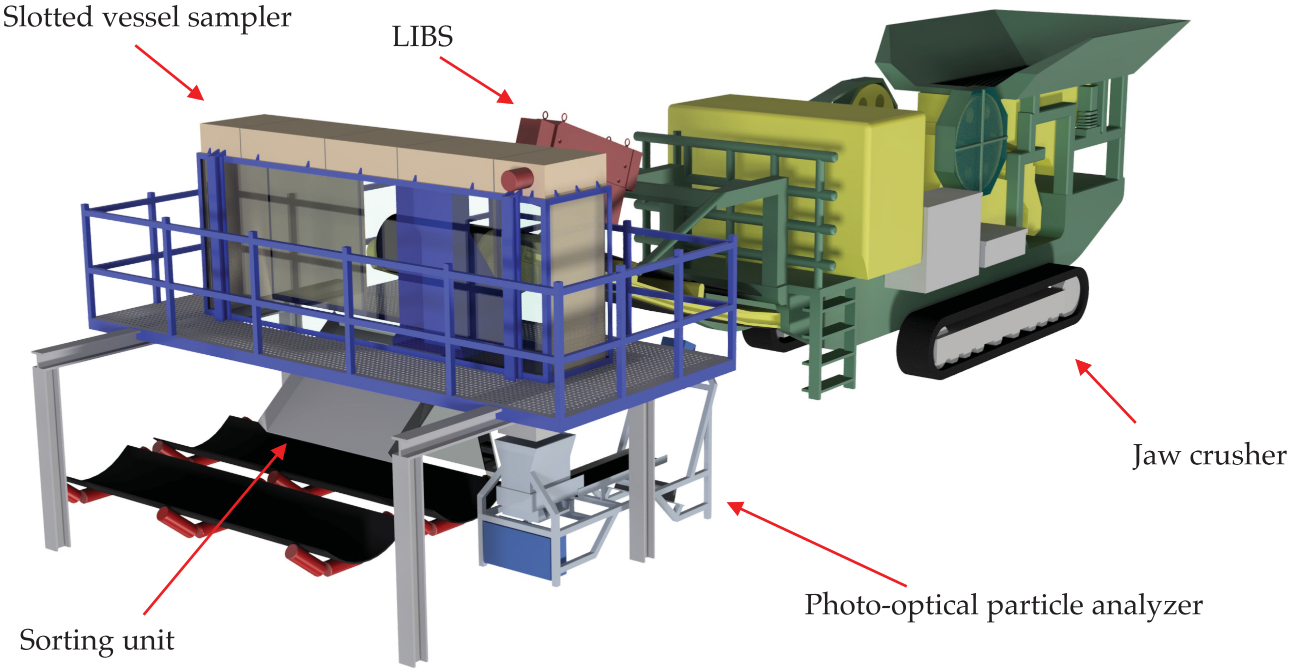


Figure 51: Design #3

4.4 Design #4

After a meeting with engineers from SBM Mineral Processing GmbH it was decided to move the LIBS analyzer back onto the conveyor belt because the vibrations of the jaw crusher would be too high for the laser to focus.

For the tender phase for the Research@ZaB this was the final design.

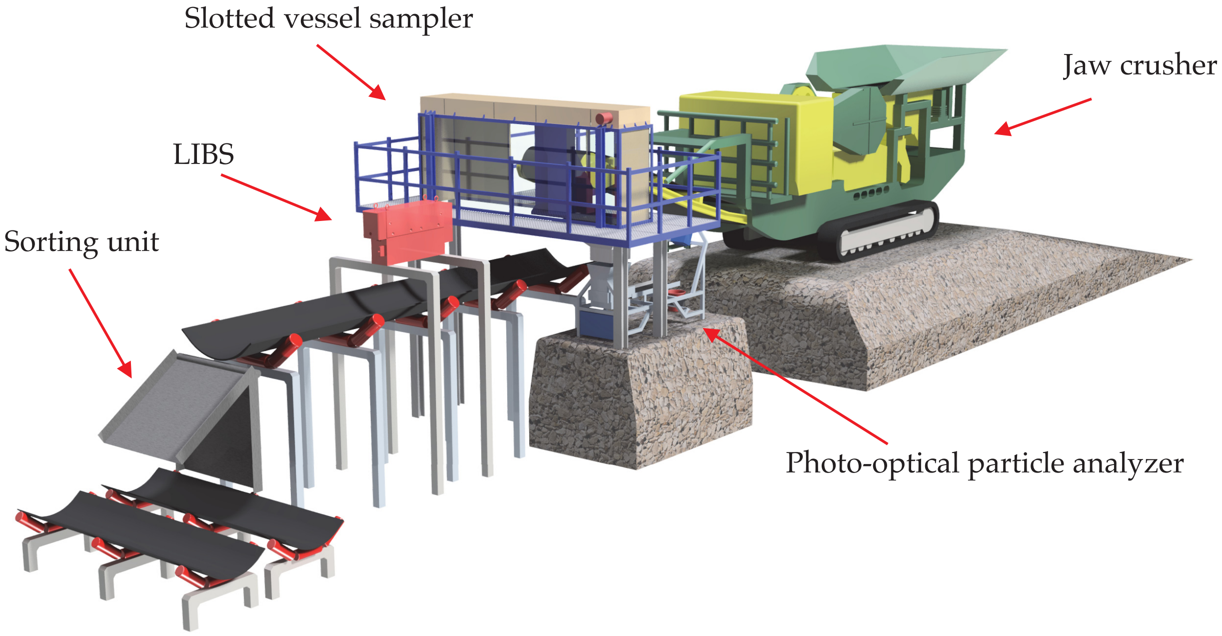


Figure 52: Design #4 – final design

The following figures of design #4 are different views that include general preliminary dimensions. The drawing unit is mm.

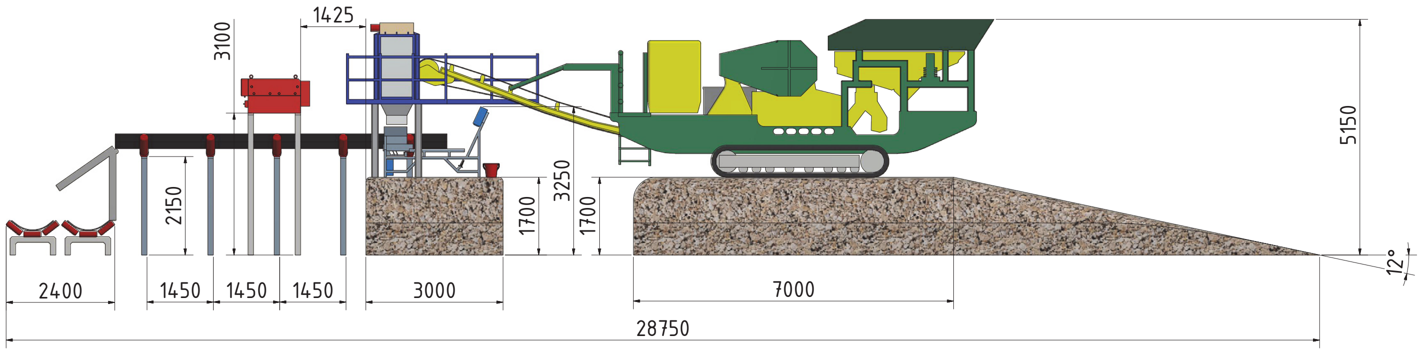


Figure 53: Design #4 view from the front

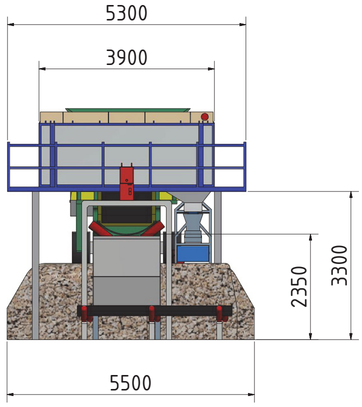


Figure 54: Design #4 view from the left side

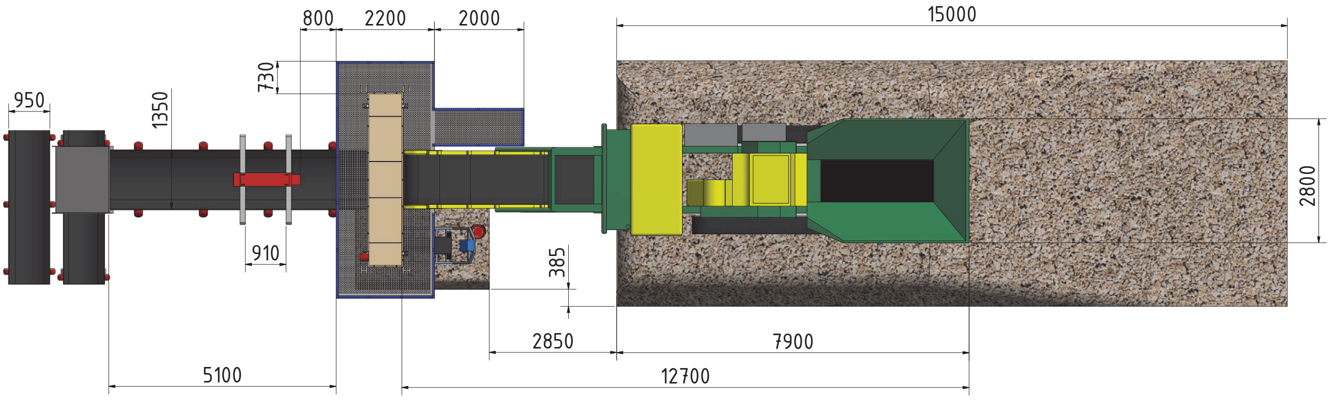


Figure 55: Design #4 view from above

4.5 Conclusion

Since this design is just for the tender phase of the project Research@ZaB and therefore is preliminary, it is proposed that for the construction phase more detailed planning is required. Support from experienced engineers in processing and electrical engineering will be important for a well-thought-out design of the analytical unit. The extra space on the conveyor belt after the LIBS analyzer is purposed for testing and trying out different methods such as NIR or LIF.

For qualitative calibrations for LIBS and NIR a large number of samples is required. A rough estimation is that for a proper LIBS calibration about 100 samples are needed. During the investigation phase of a tunneling project cores are drilled in order to obtain information on the geotechnical properties of the ground. For future projects these cores could also be used as calibration material for qualitative measurements.

5 Contractual Model for the Reuse of Tunnel Excavation Material

Turning to a different part of this thesis, a major issue is that there has not yet been a proper way to implement a possible reuse of excavation material in Austrian construction contracts. After an elemental and mineralogical analyzation of cores in the investigation phase of a project, conclusions on the possible reuse of the tunnel excavation material can be made. The analytical results need to be taken into account in order to determine potential types of reuse. This information is important when drafting the construction contract.

However, before going into detail on a contractual model the legal situation for the repurposing excavation material needs to be considered as it holds a special status in Austria.

5.1 Legal Aspects for the Reuse of Tunnel Excavation Material (Austria)

This chapter is based on the RICHTLINIE VERWENDUNG VON TUNNELAUSBRUCH 2015 (guideline for reuse of tunnel excavation material) and provides an understanding of the legal situation of tunnel muck, especially its waste status and ownership issues.

In Austria, tunnel excavation material is property of the land owner. Generally, the land owner and the party which intends to build a tunnel are two different legal entities. Therefore, at the beginning of a project a clarification under civil law is necessary to solve the issue of ownership.

According to ABFALLWIRTSCHAFTSGESETZ 2002 – AWG 2002 (waste management act) tunnel excavation material counts as waste. A reuse is only possible under certain circumstances. For the AWG 2002 it is important who owns the waste and can decide over it (waste owner).

According to AWG 2002, waste is defined as follows:

„§ 2. (1) Abfälle im Sinne dieses Bundesgesetzes sind bewegliche Sachen,
1. deren sich der Besitzer entledigen will oder entledigt hat oder
2. deren Sammlung, Lagerung, Beförderung und Behandlung als Abfall erforderlich ist, um die öffentlichen Interessen (§ 1 Abs. 3) nicht zu beeinträchtigen.“

This translates to:

§ 2. (1) Waste within the meaning of this Federal Law is movable property,

1. Which the owner wants to discard or has discarded or

2. Whose collection, storage, transport and treatment is required in order not to impair the public interest (§ 1 Paragraph 3).

The intent to dispose in accordance with number 1 is subjective. The removal of the tunnel excavation material from the place of origin is usually an intention to discard. The main purpose is the construction of the structure and not the extraction of the mineral raw material.

Number 2 corresponds to an objective case where the properties of the excavated material are essential. Additionally, the amount of material also effects the public interest.

However, there are also exceptions, but every case has to be examined individually according to AWG 2002:

> *„§ 3. (1) Z 8 (Keine Abfälle im Sinne dieses Bundesgesetzes sind) nicht kontaminierte Böden und andere natürlich vorkommende Materialien, die im Zuge von Bauarbeiten ausgehoben wurden, sofern sichergestellt ist, dass die Materialien in ihrem natürlichen Zustand an dem Ort, an dem sie ausgehoben wurden, für Bauzwecke verwendet werden."*

This translates to:

§ 3. (1) Z 8 (no waste within the meaning of this Federal Act) non-contaminated soils and other naturally occurring materials that have been excavated in the course of construction work, provided that the materials in their natural state at the place, on which they were excavated, are used for building purposes.

Tunnel excavation material is generally not used in the same area (contract section) nor used in its natural state. This exception could only work for loose material which could be used for construction purposes in the contract section where it is excavated. Non-contaminated soil is soil which complies with the threshold values for landfilling class 1 of the DEPONIEVERORDNUNG 2008 (Waste Storage Ordinance).

A contract section in accordance with AWG 2002 is generally the building plot in which the excavation or removal activity has taken place, or respectively, the area covered by the building permit.

Excavation material is used in its natural state if, after being excavated, it is used without further processing like crushing or sieving.

Waste can lose its waste status through permissible reutilization (see § 2 (4) no. 1 and § 5 (1) Abfallwirtschaftsgesetz 2002). The waste status is only lost if there is a concrete reuse which means that there is an actual practical use for the material. Processing alone even if it achieved the desired quality for the purposes of recovery is not enough.

The only way to change the current status would be with an ordinance but there is none for tunnel excavation material yet. However, one is in stage of being designed which should regulate the reutilization and end the waste status of tunnel excavation material in the future.

The AWG 2002 also includes a waste hierarchy:

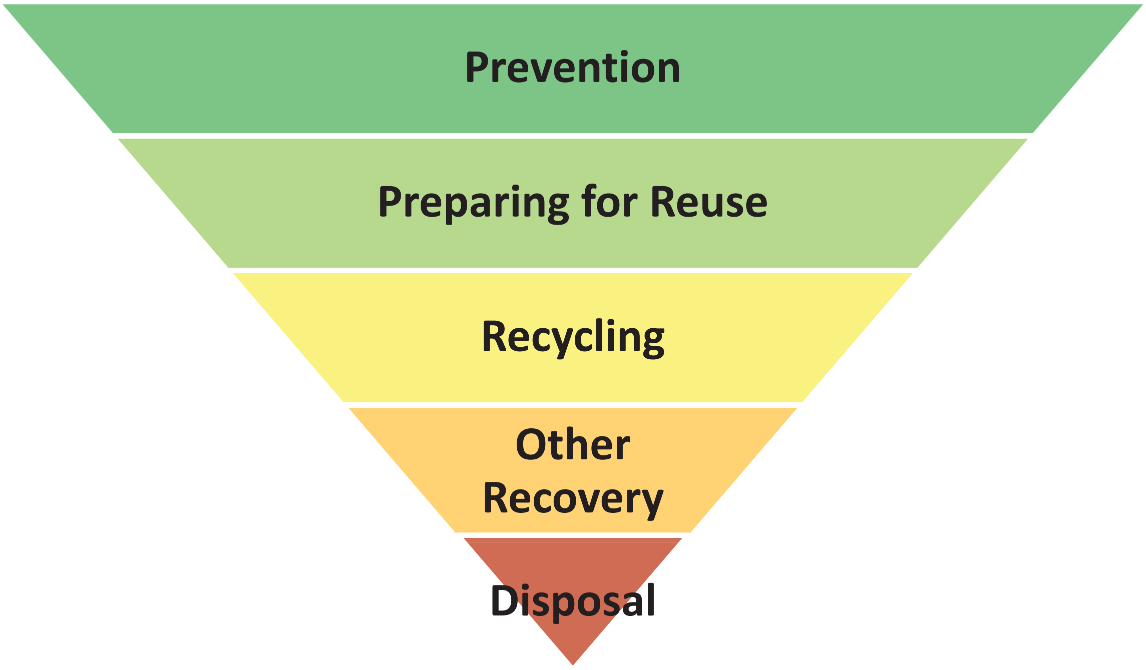


Figure 56: 5-step waste hierarchy (AWG 2002)

This hierarchy makes it obvious that the reutilization of tunnel excavation material should be top priority. Nowadays, most of the material is disposed in landfills which is at the bottom of this hierarchy and should only be the solution if there is no possible reuse.

5.2 Investigation phases according to RICHTLINIE VERWENDUNG VON TUNNELAUSBRUCH 2015

For the reuse of tunnel excavation material information is everything. In the different design phases of a project there are different stages of information. With a more detailed design the knowledge about the geology gets more detailed.

According to RICHTLINIE VERWENDUNG FÜR TUNNELAUSBRUCH 2015 there are four different stages for the investigation of tunnel excavation material. These stages, derived from EUROCODE 7 - GEOTECHNICAL DESIGN - PART 2: GROUND INVESTIGATION AND TESTING (in German: ÖNORM EN 1997-2: 2010 08 15), are:

1. Preliminary study
2. Preliminary investigation
3. Main investigation (Phase A and B)
4. Control Investigation

5.2.1 Preliminary Study

Within the scope of the preliminary study, existing and available information is collected, evaluated and processed for statement on feasibility as well as for the creation of different possible alignments.

The preliminary study is divided into:

- Geology and Geotechnics
- Anthropogenic factors
- Possible reutilization

5.2.2 Preliminary Investigation

The basis for the preliminary investigation is a project, which was created in the scope of the preliminary study. During the preliminary investigation, the different alignments are finalized and evaluated. The result of the preliminary investigation should be the basis for decision-making fon the alignment selection.

From a resource-conserving point of view, a rough assessment of possible material utilization should be carried out and presented as a longitudinal section. In doing so, any anthropogenic and geogenic contaminations have to be considered. Finally, recommendations for the main study are to be given.

5.2.3 Main Investigation

The basis for the main investigation is a selected tunnel alignment with the main characteristics of its structures (e.g. number of tunnel tubes, tunnel cross sections, special structures). These characteristics are increasingly substantiated in the course of progressive tunnel planning.

The main study should provide documents for the official submission and documentation sufficient for the preparation of the tender and the construction design. Generally, the main investigation is divided into two investigation phases, which can be combined if necessary.

Phase A of the main investigation should provide the technical basis for planning and submission. The documents for the official submission must be prepared in such a way that the tunnel project can be assessed by experts (documents that can be approved). This may also require coordination with government experts.

Phase B of the main investigation should cover the requirements of the tender design and, to a large extent, the final design. In this phase, partially already the authority requirements or requirements of official experts are implemented.

Finally, recommendations for the phase of the control investigation are to be given for the respective subject areas.

5.2.3.1 Phase A

In phase A of the main investigation, the investigation measures are to be condensed and supplemented. The result of the investigations is a geological model including information on the basic reusability and landfill-ability. The information includes the ground behavior types according to ÖGG guideline GUIDELINE FOR THE GEOTECHNICAL DESIGN OF UNDERGROUND STRUCTURES WITH CONVENTIONAL EXCAVATION. It also includes the required mineralogical and elemental analysis for the contemplated reuse. For the assessment of effects from waste management and the associated necessary measures, the waste-chemical parameters are to be analyzed according to DEPONIEVERORDNUNG 2008 and ABFALLWIRTSCHAFTSGESETZ 2002. Generally, for the analysis of soil or rock, the full range of parameters (full analysis according to DEPONIEVERORDNUNG 2008 including missing parameters for the assessment of the quality class A2-G according to the Federal Waste Management Plan 2015 (DIE BESTANDAUFNAHME DER ABFALLWIRTSCHAFT IN ÖSTERREICH - STATUSBERICHT 2015)) is advisable.

From the data, obtained measures for the reutilization or disposal (landfilling) of the resulting excavation material are to be assessed by an expert of the respective line of use in coordination with the departments of waste management, design, geology, hydrogeology and geotechnical engineering to work out and finally assess the planning. Finally, the design is to be evaluated.

5.2.3.2 Phase B

In phase B of the main investigation, the focus lies on additional investigation with view on the tender design. Hereby, requirements of the authorities are to be implemented.

5.2.4 Control Investigation

This investigation is carried out during the construction phase and mainly includes fundamental characterizations and testing for quality control.

5.3 Contractual Model

At the Massachusetts Institute of Technology, research for a contractual model was conducted under guidance of Prof. Herbert Einstein.

Two approaches for a contractual model were prepared; a decision tree and a matrix model. As a result of further research the decision tree is stated to be better used in the early stages of design and for the contract and the matrix model is better suited for construction. In this chapter both models are explained.

5.3.1 Contractual Model Based on a Decision Tree

Figure 57 shows the basic outline for the decision tree model. It is first divided into different lithologies. The evaluation on how many and which lithologies are supposed to be encountered during construction, is information that is available early on. After further investigation and exploration, the possible reuse of each lithology can be estimated. With more information available the decision tree gets more branched.

For a more detailed decision tree each reuse class can be divided into different requirements e.g. mineralogical and elemental properties.

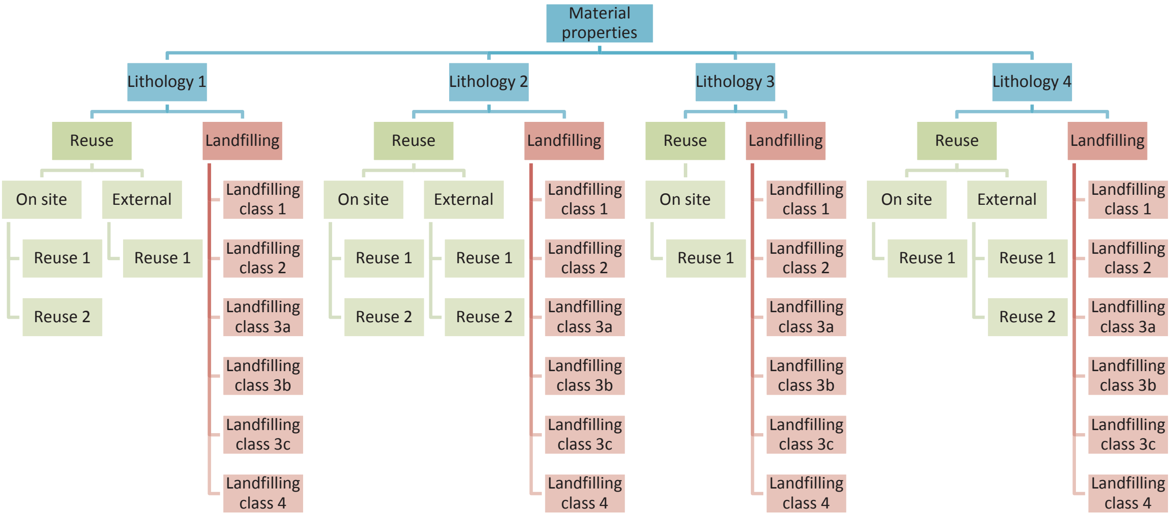


Figure 57: Decision tree, general

If there is no possible reuse, there is always the solution of landfilling. According to DEPONIEVERORDNUNG 2008 there are four landfilling classes. The third class is divided into three more sub-classes.

LANDFILLING CLASS	GERMAN	ENGLISH
Class 1	Bodenaushubdeponie	Excavated-soil landfills
Class 2	Inertabfalldeponie	Inert-waste landfills
Class 3	Deponie für nicht gefährliche Abfälle	Landfills for non-hazardous wastes
Class 3a	Baurestmassendeponie	Demolition debris
Class 3b	Reststoffdeponie	Residual material
Class 3c	Massenabfalldeponie	Mass waste
Class 4	Deponie für gefährliche Abfälle	Landfills for hazardous waste

Table 4: Types of landfills according to DEPONIEVERORDNUNG 2008

Extensive information is needed to pre-evaluate possible reutilization.

In the first stage of a project (preliminary study) information can be obtained from different sources like (RICHTLINIE VERWENDUNG VON TUNNELAUSBRUCH 2015):

- "Geochemical Atlas of the Republic of Austria" and the "Metallogenic Map of Austria Including Industrial Minerals and Energy Raw Materials" from the "Interactive Raw Material Information System IRIS Online"
- Geological maps
- Preexisting results from ground investigations: drilling logs, sounding logs, pits/shafts, borehole tests, laboratory tests, geophysics, geotechnical measurements (e.g. inclinometer)
- Outcrops from site inspection
- Historical maps and literature
- Map of confirmed contaminated sites
- Information about landfillings from the land register
- Information from former construction projects in the vicinity of the project
- Register of potential hazardous sites
- After this evaluation, the next step is to obtain results from core drillings, laboratory tests and in-situ testing

There is a large number of tests that are to be carried out for different reuse purposes. Detailed information in this regard is to be found in the guideline RICHTLINIE VERWENDUNG VON TUNNELAUSBRUCH 2015.

Tunnel excavation material cannot only be used as an aggregate for different purposes on site like concrete, mortar and shotcrete or as backfilling material. It also can be relevant for industrial production. However, if the material is to be used outside of the construction site there are certain things to consider. If there is interest from the raw mineral industry to use the material there are specific requirements. These requirements have to be defined early on. Also, it needs to be specified how much material and at which time is needed. For this matter, special quality control and temporary deposits on site are of great importance. Already in the preliminary design of a tunnel the required space for the construction site is specified.

Moreover, considerations about processing have to be made at an early stage of the project. Cost calculation is necessary for decision making on by whom and where the material is processed. If the construction material is only used as an aggregate the requirements on processing are relatively small – crushing and sieving and eventually washing. However, if more advanced methods are necessary, like for example flotation, it can become more economic to outsource the processing of the tunnel muck for its purposed reutilization.

A preliminary decision tree for the Research@ZaB is shown in Figure 59. It clearly needs to be stated that this is only a preliminary estimation because for now only information from the tender design is available. This assessment is mainly based on longitudinal sections of the geology. The longitudinal section of the east tube of the rail tunnel and the test tunnel is shown in Figure 58. This figure is retrieved from the tender design which belongs to Montanuniversität Leoben.

The different colors stand for different lithologies. Blue colors stand for limestones, green colors for porphyroid and shale. In grey, the Eisenerzer layers are drawn. Brown crosses stand for siderite mineralization and red crosses for ankerite mineralization. Fault zones are shown in red.

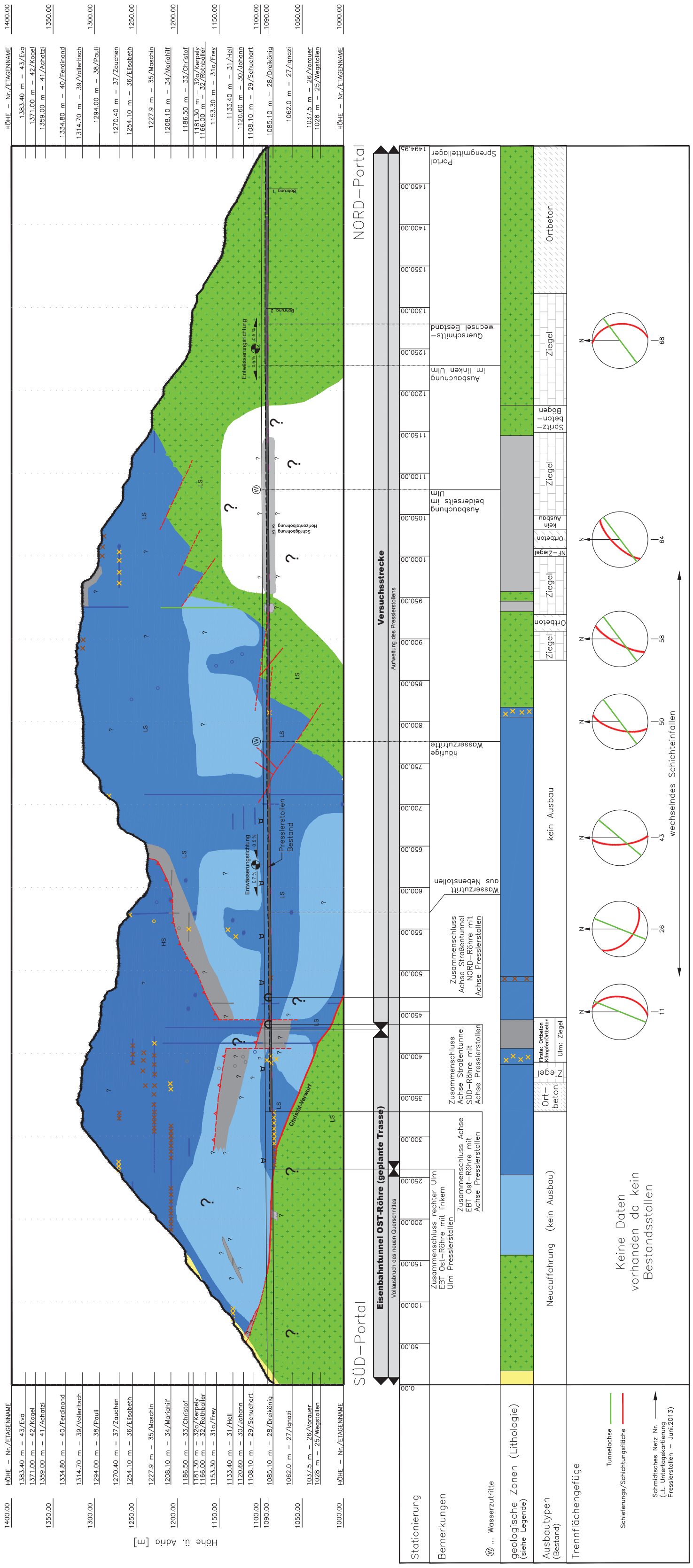


Figure 58: Longitudinal section of the east tube of the rail tunnel and the test tunnel (tender design)

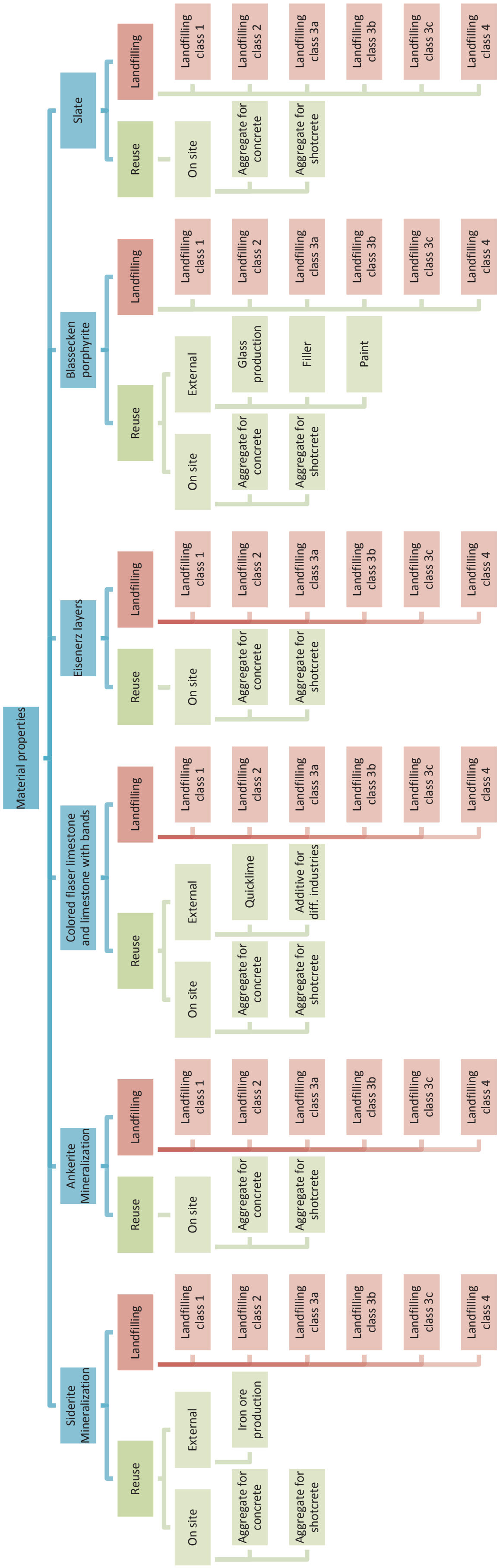


Figure 59: Preliminary decision tree for Research@ZaB

The advantage of this decision tree is that it is very easy to read and that there is no restriction in how detailed it can be drawn. At an early stage of design there is information that is already implementable for the model.

5.3.2 Contractual Model Based on a Matrix

The other approach for a contractual model is in the form of a matrix. The basic outline is shown in the following figure.

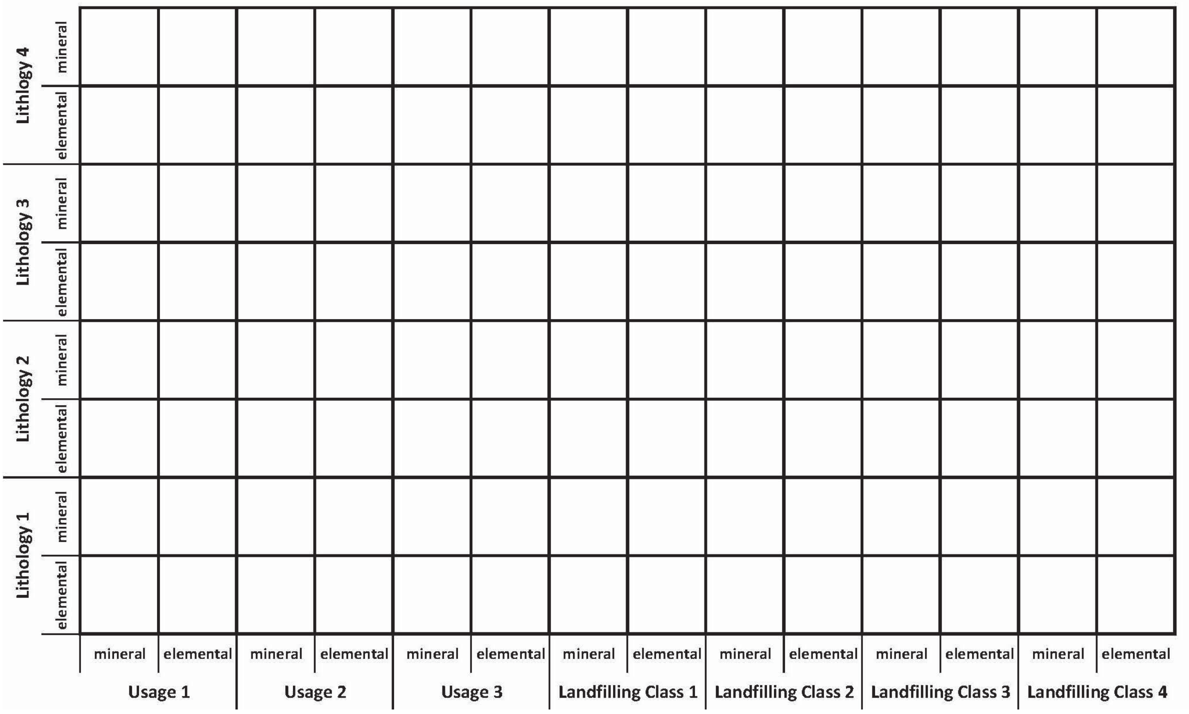


Figure 60: Matrix model, general

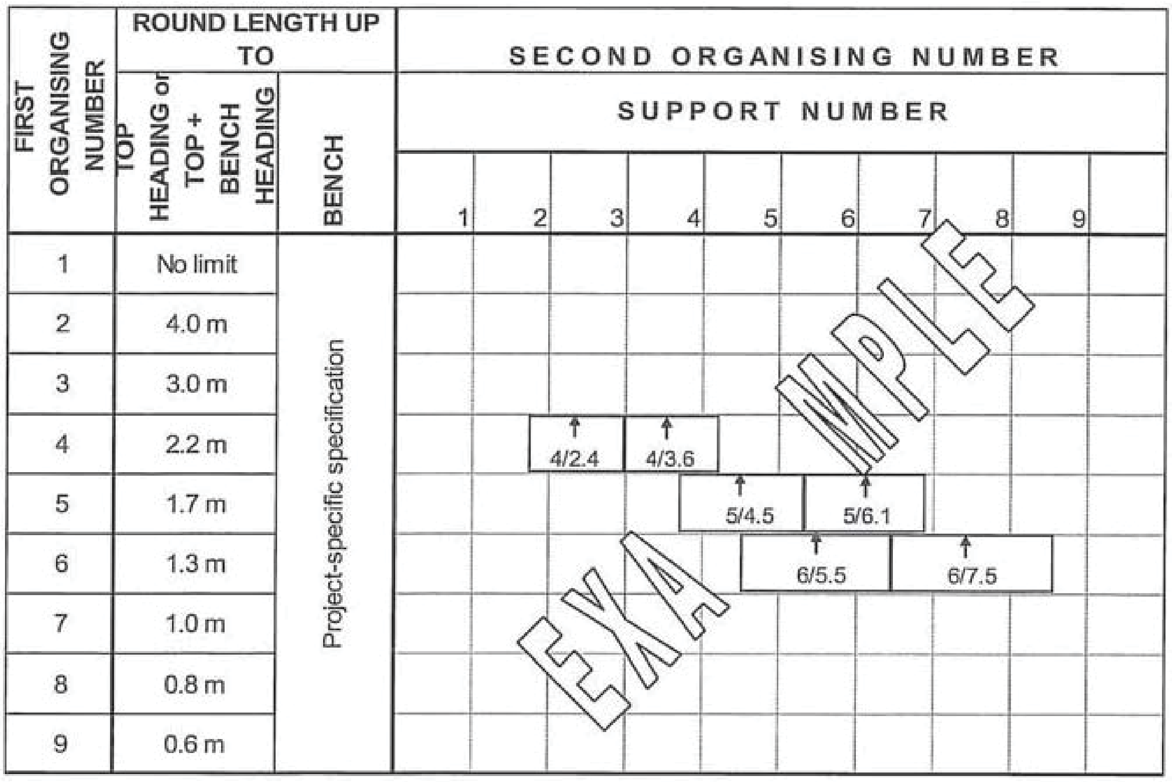
For this model, the x-axis generates the different types of reuse and landfilling classes with their requirements on the material. On the y-axis, the various lithologies with their results from the analysis are shown. If the properties of one lithology overlap with the requirements of a usage class or landfilling class, the area of overlap gets colored.

This model is based on the tunneling class matrix according to ÖNORM B 2203-1: 2001 12 01 UNDERGROUND WORKS - PART 1: CYCLIC DRIVING (CONVENTIONAL TUNNELLING).

The Model for the tunneling classes consists of two numbers, the "First Organising Number" and the "Second Organising Number".

The First Organising Number results from the round length, and the Second Organising Number is calculated from the quantity and type of support elements as well as the cross section. If the calculated Second Organising Number lies outside the scope of the tunneling classes specified in the tender documents, advance rates and excavation unit prices for such tunneling classes can be determined by linear extrapolation.

An Example of a tunneling class matrix is shown in Figure 61.



FIRST ORGANISING NUMBER	ROUND LENGTH UP TO		SECOND ORGANISING NUMBER									
	TOP HEADING or TOP + BENCH HEADING	BENCH	SUPPORT NUMBER									
			1	2	3	4	5	6	7	8	9	
1	No limit	Project-specific specification										
2	4.0 m											
3	3.0 m											
4	2.2 m				4/2.4	4/3.6						
5	1.7 m						5/4.5		5/6.1			
6	1.3 m							6/5.5		6/7.5		
7	1.0 m											
8	0.8 m											
9	0.6 m											

Figure 61: Example of tunneling Class Matrix (ÖNORM B 2203-1)

For the matrix model, also a version for the Research@ZaB was created based on the tender design (see Figure 62).

	THRESHOLD VALUES	Siderite mineralization		Ankerite mineralisation		Colored flaser limestone and limestone with bands		Eisenerz layers		Blassecken porphyroid		Shale	
		mineral	elemental	mineral	elemental	mineral	elemental	mineral	elemental	mineral	elemental	mineral	elemental
Landfilling Class 4	elemental boundaries according to DVO												
Landfilling Class 3c	elemental boundaries according to DVO												
Landfilling Class 3b	elemental boundaries according to DVO												
Landfilling Class 3a	elemental boundaries according to DVO												
Landfilling Class 2	elemental boundaries according to DVO												
Landfilling Class 1	elemental boundaries according to DVO												
Iron production	mineral elemental >20 wt%												
Paint	mineral elemental												
Filler	mineral elemental												
Glas production	mineral elemental												
Aggregate for shotcrete	mineral elemental												
Aggregate for concrete	mineral elemental												

Figure 62: Preliminary contractual matrix model for Research@ZaB

It needs to be mentioned that this is a preliminary example for the Research@ZaB and that there was only little data available.

One particular benefit of this method is that one can spot overlapping areas quickly and that because this model is similar to the tunneling class matrix the users are already used to working with matrices.

Both models, the decision tree and the matrix model tend to get very large when data is implemented. For the present, they are still relative small and it already is very difficult to put them on one sheet of paper.

Moreover, it needs to be said that these models best work when they are directly compared to longitudinal cross sections of the respective tunneling project. The longitudinal cross section makes it easier to fill in the information into the models.

6 Outlook

For the near future, there are some steps ahead for continuing this research. One of them is to acquire funding for the analytical unit. We are currently in the process of applying for research projects funded by the European Commission.

After the financial situation is secured the next step is a precise planning of the analytical unit and its implementation into the Research@ZaB. With this, calibration can start and the way for testing tunnel muck with the analytical unit is set.

As the unit requires an online monitoring system, additionally a webcam needs to be installed that sends a live feed of the material stream and the entire unit to an online mineral trading platform called MineralBay that is currently being developed by the Montanuniversität (Chair of Subsurface Engineering) in cooperation with the INSO – Industrial Software, a research group for industrial software of the TU Wien (Technische Universität Wien). MineralBay is an interactive administration and marketing system for excavated material. Efficient digital processing of the available data on materials, quantities and time parameters of tunnel muck become increasingly important as there is a lot of data collected supporting the process of reutilization and by this upcycling. MineralBay is a platform that brings together owners, suppliers and customers of mineral raw materials in a simple and quick manner. Its purpose is to simplify the exchange and trading of these materials. Users can select and offer raw materials. Product categories and various parameters can be selected. The implementation of online data analysis is planned for the future as well as an online live feed from the analytical unit. (Erben et al, 2015)

To sum up, future research for the analytical unit should consist of a more detailed design with a connection to MineralBay, an assembly on site of the ZaB and testing on site.

Turning to the legal status of construction material, the Austrian government ought to issue an ordinance that changes the waste status of tunnel muck soon. Until then repurposing tunnel excavation material is only possible inside the contract section of the construction site where the material is retrieved and there can be no connection to raw materials industry.

These are the steps to our approach for a more sustainable tunneling industry for future generations.

7 Conclusion

The research of this thesis is supposed to bring us one step further to a more sustainable tunneling industry, and this goal was achieved. Analytical methods were evaluated on samples from the Research@ZaB and an analytical unit was designed for the purpose of characterizing tunnel muck for its possible reutilization. The research has shown that from the tested analytical methods, LIBS and NIR show the most potential for real-time material stream analysis. Although these methods for now will not replace extensive testing with laboratory equipment as it is required by e.g. the DEPONIEVERORDNUNG 2008 they do however make it possible to classify the excavation material for future reuse.

Nevertheless, we are aware that this research has limitations. The first is that the results obtained within this thesis are preliminary. In order to confirm that the different analyzation methods are really applicable in an environment like a tunneling construction site with material whose properties change quickly they have to be tested in exactly these conditions. The second limitation is that there were financial limitations. For qualitative calibrations for LIBS and NIR a large number of samples is required. These samples than have to be analyzed precisely which is quite cost intensive. The LIBS and NIR analysis for this research was gratuitously conducted by SECOPTA analytics GmbH and Spectral Imaging Ltd.

One conclusion of this thesis is that there are analytical methods that can be used for elemental and mineralogical analyzation of tunnel muck that have the potential of being applied at a tunneling construction site. The status of LIBS analysis for our purpose seems to be rather advanced and with proper calibration it should be applicable. NIR on the other hand shows a lot of potential, but we have not found an application yet that is advanced enough to holistically characterize the material. Nonetheless, NIR-based sorting is already available and used in the mining industry.

The design of the analytical unit is the first of its kind and should present the basis for a more detailed design during construction of the Research@ZaB which is the ideal location for conducting further research on this unit. It is designed to leave room for other methods to be tested and applied. However, for now the purpose of this unit is only in analysis of excavation material from the Research@ZaB without putting the material to proper use except for giving it to VA Erzberg or for the extension of the parking lot as mentioned in chapter 4.

Regarding the models for the construction contract it needs to be stated that they for now are relatively imprecise. It is not yet possible to define contractual topics in detail because the legal status of tunnel excavation material has to be changed first. It is, however, an approach that seems to have potential for the future.

In summary, this thesis is a start in the right direction which is a more sustainable tunneling industry. Since the tunnel muck is excavated anyway there is no reason not to reduce waste and put it to proper use and, at the same time, save resources.

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9 List of Figures

10 List of Tables

11 List of Abbreviations

AWG	Abfallwirtschaftsgesetz, waste management act
FTIR	Fourier-transform infrared-spectrometer
ICP	Inductively coupled plasma
IPC	Industrial PC
IR	Infrared
LIBS	Laser-induced breakdown spectroscopy
LIF	Laser-induced fluorescence
LIPS	Laser-induced plasma spectroscopy
Nd:YAG	Neodymium-doped yttrium aluminum garnet
NIR	Near-infrared
SWIR	Short-wavelength infrared
UAV	Unmanned Aerial Vehicle
UV	Ultraviolet
wt%	Weight percentage
ZaB	Zentrum am Berg