Diese Arbeit wurde vorgelegt am Institut für Markscheidekunde

This work was submitted to the Institute of Mine Surveying

Einsatzmöglichkeiten geophysikalischer Messmethoden zur Erkundung und Sicherung von Hinterlassenschaften aus oberflächennahem Altbergbau am Beispiel des ehemaligen Braunkohlebergwerks „Robertshall“

Applications of geophysical measuring methods for the exploration and securing of old mine workings near the surface using the example of the former lignite mine “Robertshall“

Masterarbeit

Master-Thesis

von / prepared by

Hannah Weinbach

1. Prüfer / Examiner 1 **Univ.-Prof. Dr.-Ing. Axel Preuße**
2. Prüfer / Examiner 2 **Dr.-Ing. Heinz-Jürgen Kateloe**

Aachen, 22.12.2021

Abstract

In the former lignite mine "Robertshall" near Hamburg damage to the surface was caused by the collapse of underground cavities originating from old mine workings of a lignite mine which had been in operation between 1920 and 1922. During the investigation of the subsurface by drilling it was noticed that the existing mine plans are incomplete.

If mine plans are missing or incomplete, the risk to protected assets at the surface due to mining damage can often only be reliably assessed by means of indirect methods such as geophysics in reasonable combination with drilling. Within the scope of this work the extend of room-and-pillar caving at the “Robertshall” deep lignite mine was determined by geophysical methods. Subsequent backfilling and securing of the old mine workings are the goals of this exploration.

The simultaneous application of several methods on the selected test profile is not only intended to increase the reliability of the results, but also to gain experience as to which methods are best suited for routine detection under the given geological and mining conditions. The geophysical measurements are supplemented by an evaluation of historical data.

The results of geophysics have led to the prompt and reliable discovery of many drifts that were not included in the mine plan. Compared to the conventional approach of exploration by drilling, the application of seismic measurements saves time and costs. The securing measures could be carried out by the responsible parties and the desired securing success has been achieved so that no further movements of the ground surface are to be expected.

Content

List of figures

List of tables

1 Introduction

During the course of road works by the Landesbetrieb Straßen, Brücken und Gewässer (LSBG) at the Ehestorfer Heuweg in Hamburg, a surface caving occurred in September 2019. The cause was the mine workings of the former lignite mine „Robertshall“. It was in operation until 1922 and is known by means of mine plans.

According to the mine plans, the mine workings of the former lignite mine are located 13 and 17 m below the street Ehestorfer Heuweg and adjacent properties. The areas in the immediate vicinity of the objects requiring securing (road and residential buildings) are now to be explored and secured. Previous work has shown that the exploration of the mine plan has sufficient local accuracy to determine the location of the drifts on site. Furthermore, it is known that sand with isolated layers of brown coal is located above the drifts.

The northern part of the mine workings is located on the territory of the city of Hamburg. The southern part is located on the territory of the State of Lower Saxony. The exploration and securing of the mine workings in the Hamburg area was carried out between September 2019 and February 2020. Subsequently, the process of securing of the Lower Saxony part of the mine below the Ehestorfer Heuweg and nearby residential properties was started in March 2020. As of today, the securing work has not yet been completed.

During the work it became apparent that numerous parts of the mine are not shown on the official mine plan. The mine plan is of great value in evaluating whether the old mine workings pose hazards to the use of the surface. In order to ensure the success of the safety measures, the underground is therefore being investigated using geotechnical- and geophysical methods.

2 Robertshall Mine

This chapter is intended to provide an overview of the old mine workings which have been investigated within the scope of this work. In this context, the historical development of the former lignite mine and the geology related to the deposit will be discussed.

2.1 Historic development

The mining of lignite in the region of central Germany increased in the 18th century. As a result of the growing demand for energy and the already exhausted deposits close to the surface, deep mining was applied. The lignite was mainly used in saltworks, brickworks, glass factories and in the sugar industry. Historic deep lignite mining was carried out using caving methods. This method of extraction involved driving shafts into the deposit, followed by drifts. Within the deposit mining sites with a rectangular layout were then excavated. The excavation chambers were supported with timber, excavated to the planned size and then collapsed by selected mining. Only about 50% of the coal seam could be extracted by this method. In most cases, the mining areas were located under agricultural land and the placement of backfill was therefore not considered necessary. Furthermore, due to the small overburden layer and insufficient technology, the backfill material could not be placed compacted enough to avoid effects on the surface. (Ott, 1976; Hustrulid, 1982; Stefanko, 1983)

At the beginning of the 20th century a lignite deposit was discovered during well drilling on private property in the Hausbruch district of Hamburg. The deposit consisted of a lignite-sand mixture with a lignite content of about 55%. The owner of the property owned the mining rights granted by the Celle Mining Office, which she sold to the Dortmund-based company Gebrüder Stern KG in 1918/1919 (Bergamt Hannover, 1921). After the First World War an increased demand for energy sources arose and made the mining of the rather uneconomic deposit profitable (Meyer-Abich, 1982). At the end of 1919 the "Robertshall" union was formed. This union concluded a supply contract with „Vereinigte Gummiwarenfabrik Harburg-Wien“ (later “Phoenix”). After the erection of a winding tower operations began on March 10, 1920. Lignite was used as an energy source for the process heat required for vulcanization in the production of rubberware. It also served as a raw material for soot, which is the primary aggregate used in tire production. Figure 1 gives an overview of the location and the infrastructure layout of the mine site during operational years. (Hamburgisches Welt-Wirtschafts-Achiv (HWWA) (Ed.), 1949)

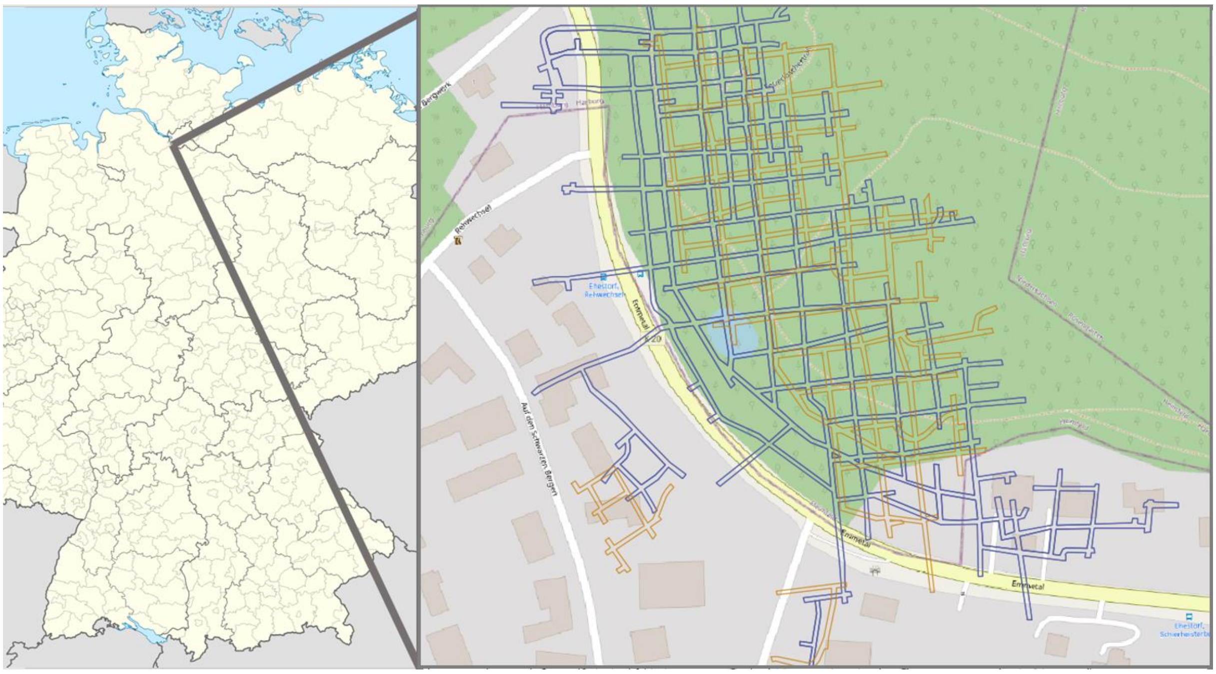


Figure 1 Location of the Robertshall mine and infrastructure in Hamburg/Lower Saxony

The mining of the approx. 8.5 m thick seam was carried out on two levels at depths of 13 m and 17 m, respectively, using the room and pillar caving method. The mined material was transported to the shaft in wagons. After the individual drifts had been excavated the wooden support beams were removed. During excavation and after closure, the drifts were backfilled with hand backfill in the area of the road. This backfilling method results in only a 40-50% fill ratio (Fritzsche, 1962). Due to the sandy subsoil, this led to extensive collapse of the mining areas and therefore mining damage visible at the surface. The high sand content of the deposit made it necessary to wash the coal in a coal washing plant. For this purpose screen drums were used, which utilized the seepage water from the mine workings that was pumped out of the shaft. The subsequently dried coal was first transported to the rubber factory by trucks. Later a cableway was built, which transported the pure coal to the plant. (Bergamt Hannover, 1921)

With the improvement of the situation of the raw materials market and the resulting reduction of the price of coal the mine closed at the end of 1922. By then, it is documented that approx. 80,400 t of lignite sand had been mined. (Bergamt Hannover, 1921)

In the further course of the work, the 13 and 17 m level will be referred to. This term refers to the mine record and not to the actual depth. The depth varies, of course, depending on the location.

2.2 Geology

The upper sediments of the North German Basin were formed by repeated episodes of cold and warm periods in the current ice age, the Quaternary. In the subsurface of the working area, Miocene units (Lower Mica Clay, Lower Lignite Sand, Hamburg Clay, Upper Lignite Sand, Upper Mica Clay) are present. These units form a saddle in the affected area, the axis of which is offset to the west of the course of the Ehestorfer Heuweg. At a depth of between 150 and 200 m, these Miocene units are dicordantly overlain by glacial deposits (sand and boulder clay of the Elster and Saale cold periods). (Hennigsen & Katzung, 2006; Walter, 1995)

The glacial units have partially reworked the Upper Lignite Sands, resulting in the formation of a lignite placer. A placer deposit is a secondary concentration of valuable minerals due to transport processes in sediments, such as sand or gravel. This deposit within the glacial sands formed the target of the former lignite mine "Robertshall". The lignite is heavily mixed with sand, which significantly reduces the quality of the deposit. This also explains the short useful life of the deposit between 1920 and 1922. (Bergamt Hannover, 1921)

According to the available information, groundwater is regularly present below the 17 m level, i.e., the strata to be drilled are presumably predominantly free of groundwater. (Bergamt Hannover, 1921)

2.3 Mining damage

Mining damage is damage to the earth's surface caused by mining activities, mostly to structures and real property. Underground mining of deposits gradually exposes the roof and causes it to collapse due to the lack of abutment. The previously existing physical equilibrium of the rock body is thus affected and movements occur in the subsurface. These application processes are noticeable up to the surface. (Fritzsche, 1962; Kratzsch H. , 2004; Kratzsch D. H., 1983)

A distinction is made between subsidence and surface caving. During mining at great depths of over 60 meters, the earth's surface gradually subsides. This process is referred to as subsidence. With subsidence, there are usually rock movements such as settling, strain or compression. At lower depths and near-surface mining, complete breakthrough of the overburden often occurs in the form of a surface caving. This is particularly favoured as a result of mining of thick seams. (Kratzsch H. , 2004; Bell, Stacey, & Genske, 2000)

The rock strata also have an influence on the effects at the surface. If brittle rock layers such as sandstone lie above the valuable mineral, these rock layers do not immediately collapse into the caving space. Depending on the structure of the rock, sudden rupture of fracture fissures may occur. (Buja, 2013)

In abandoned mining areas, there may also be mining damage as a result of groundwater alteration. When the dewatering systems are shut down, the mine water rises considerably. This can lead to swelling of earth layers. These become noticeable through upwelling at the surface. In addition, groundwater levels may rise. If the groundwater level drops significantly, usually due to artificial lowering of the same, this can lead to an increase in effective stresses. These eventually lead to subsidence of the ground surface. (Giesen, 2010; Kratzsch H. , 2004)

Mining damage does not necessarily have to be caused by underground mining. They also occur as a result of groundwater subsidence or horizontal earth movements in the area of influence of opencast mines. (Giesen, 2010; Kratzsch D. H., 1983)

Since both mining activities and the resulting damage occur more frequently in the German states of North Rhine-Westphalia and Saxony, a much larger data base is available for these states. A comparison of the frequency of occurrence of mining damage in the federal states is therefore hardly practicable. Furthermore, there is a lack of processed figures that could, for instance, provide statistics on the costs incurred as a result of mining damage.

2.3.1 Treatment of mining damage

In Germany, legal issues relating to mining damage are governed by the Federal Mining Act (Bundesberggesetz, BBergG) of August 13, 1980, §§110ff. The Federal Mining Act is the German federal law regulating mining law. It covers all mining law issues from exploration and extraction of a raw material to the closure of a mine or open pit. In the first section, it covers the adjustment measures for a new mining facility including the construction warnings. The second section addresses liability for mining damage and the mining damage compensation fund. The relationship between mining and public transportation facilities is addressed in the third section and surface observation in the fourth section. A detailed description of the content of the Federal Mining Act is not intended within the scope of this work. Instead, the development and the sections relevant for this thesis will be discussed in the following chapters.

Legally, the effects of the Robertshall mine discussed in this thesis are not considered mining damage. The detailed background is presented below.

2.3.2 Origin of the Federal Mining Act

The question of the legal regulations regarding mining damage emerged in the 19th century, particularly with the development of industrial coal mining. Most of the coal was mined in the lowlands, and the mining districts extended over a large area. The landowners demanded compensation from the miners for the damage caused to buildings or agricultural land. Up until then, the principle of free declaration applied, and later the principle of mining freedom: the finder was granted the right to dispose of the mineral resource free of charge upon application by the state, which reserved the right to technical and safety supervision (inspection principle 1865). In this context, the question of culpability arose in the case of mine damage despite the mining operator's compliance with the technical rules. (Kratzsch H. , 2004)

In the years 1830 to 1850, a regulation gradually emerged in the jurisdiction of the Prussian Supreme Tribunal. According to this, the mine owner must pay full monetary compensation for all damage caused by his mining operations to the property of others, even if he is not at fault. Furthermore, the landowner may sue the mine owner to stop mining, nor may the owner of the mine prevent construction activities at the surface. This regulation was written down in 1865 in the General Mining Law for the Prussian States (Allgemeines Berggesetz für die preußischen Staaten, ABG). (Kuehne & Trelease, 1984)

The legal process for settling mining claims has also changed since then. Instead of the indirect procedure via an arbitration commission, direct settlement between the parties involved has subsequently been established. Legal action for a declaratory action or suit for performance has since been taken only occasionally in serious or fundamental cases. (Kratzsch H. , 2004)

The Federal Mining Act has been in force since January 1, 1982. Compared with the previously applicable General Mining Act (ABG), it contains a number of changes in the section regarding mining damage. Accordingly, § 1 of the Act states that its purpose is also "to strengthen precautions against hazards to the life, health and property of third parties arising from mining activities and to improve their compensation for unavoidable damage". Previously, the purpose of the Act was to safeguard the supply of raw materials and the safety of operations and employees.

The addition of this third purpose also takes into account the site-specific nature of the deposit and the unavoidability of damage. Nevertheless, the prevention and minimization of damage is placed above all other objectives. Accordingly, the regulations on the operating plan procedure (§§ 55 ff.) create a precaution against dangers to life and health, as well as for the protection of material goods and the surface in the interest of personal safety and public transport. The landowner is obliged by the continuous control of the mining supervision (§§ 68 ff.) and adaptation and safety measures during the construction of a facility (§§ 110 ff.).

According to the old mining law, compensation for mining damage was limited to real property and its appurtenances. The amendment also includes damage to movable property and personal injury (strict liability). The introduction of a new presumption of liability for mining damage (§ 120) simplifies the burden of proof for the damaged party.

The Federal Mining Act has largely existed in its present form since then. The following chapter provides a more detailed description of this law.

2.3.3 Legal regulations regarding mining damage

As stated in the Federal Mining Act, the party causing the mining damage is liable to pay compensation in accordance with the rules of the German Civil Code (BGB). Liability for mining damage is a strict liability. Consequently, the person causing the damage must be liable, regardless of whether the damage was caused culpably or not (Lauerwald, 2000). Under § 120 BBergG (German Mining Act), a reverse onus applies to underground exploration or extraction within the framework of strict liability, i.e., the mining company must prove in case of doubt that no mining damage has occurred. (Kratzsch H. , 2004)

In the context of the investigation of mining relicts and their late effects, the term “old mine workings” is used. According to Meier (2001) the definition of the term “old mine workings” is determined on the one hand by legal aspects and on the other hand by geotechnical and mining damage aspects.

The Federal Mining Act does not contain the term “old mine workings”. Old mining facilities without owners or legal successors are only subject to mining supervision if they are adapted and reused as visitor mines or show facilities. The German federal states regulate the responsibilities for averting hazards from underground cavities and the associated long-term effects of mining within the framework of police law by means of laws or special ordinances. (Kratzsch H. , 2004)

For instance, in the Free State of Saxony, the Saxon Cavities Ordinance of February 20, 2012 (SächsGVBl. p. 191) regulates mining late effects. Mining late effects in the Free State of Thuringia are controlled by the Thuringian Old Mining and Underground Cavities Act.

These laws are based on state-specific ordinances on hazard prevention and ensuring public safety with varying contents. Legally, however, this is not a case of mining damage, as there is no longer a mining contractor. Therefore, there is no responsible party who can be held liable for the mine induced damage that occurred. Thus, the competence of the mining authority does not result from the BBergG, but from state-law rules of competence. The accountability is transferred to the federal states of Lower Saxony and Hamburg, respectively. The State Office for Mining and Geology of the two federal states (Landesamt für Bergbau, Energie und Geologie, LBEG) is therefore legally responsible for securing the underground mine workings.

From a legal point of view, "old mine workings" include facilities and their late effects that are attributable to mining exploration and extraction operations that are not subject to mining supervision under the Federal Mining Act. In many cases, historical mining be situated without an owner or legal successor. As a result, there is a lack of clear legal provisions, especially in the case of mining damage and their financial settlement. This often results in case-by-case considerations. (Meier, 2001; Kratzsch H. , 2004)

A special case of mining without owners or legal successors constitutes the nationalization and expropriation of mining operations in East Germany after 1945. The new mine owners were mostly nationally owned companies and did not enter into the legal succession of their predecessors. (Kratzsch H. , 2004)

From a geotechnical and perspective regarding mine damage, "old mine workings" describes operations whose effects are no longer subject to the laws of the active mining phase. The geotechnical definition is mainly of interest from a technical point of view. The specific mining methods and the development of the mine workings have a significant influence on the development of deformation and damage at the surface. Only their comprehensive knowledge allows to draw conclusions relevant to damage for an effective exploration and preservation. (Meier, 2001)

In the example presented here, the level of knowledge is limited. Therefore, sufficient information must first be collected through an investigation of the subsurface in order to initiate an appropriate securing measure.

3 Investigation of old mine workings

The first regulated securing and preservation measures of mining districts or parts of mine fields under today's views, took place in the second half of the 19th century. More and more, shafts were backfilled with waste rock piles or were properly sealed. In the 1950s, mining safety companies were established that were responsible for carrying out safety and safekeeping work as well as measures for reclamation. (Kratzsch H. , 2004)

According to Meier (2007), a distinction is made between securing and preservation of old mining-related structures and areas of influence. This is outlined briefly below and illustrated in Figure 2.

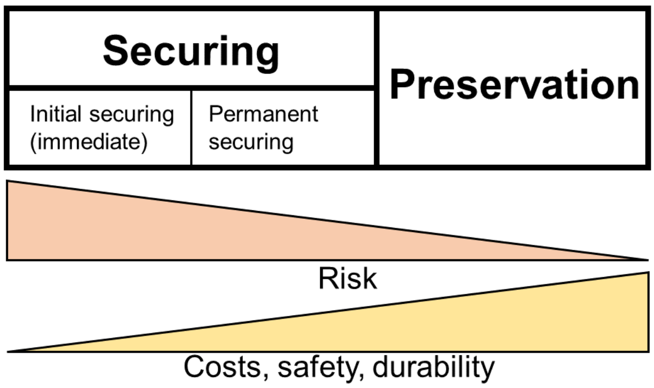


Figure 2 Securing and preservation following (Meier, 2007)

In general, the risk decreases with the expense of the measures. The term "*securing"* can be divided into two measures. The "*initial securing"* represents an "immediate measure". It is also referred to as temporary securing as its durability is very limited. Characteristics of initial securing are the local removal of the hazard (e.g., a barrier), monitoring measures (e.g., leveling, fissure monitors) or a temporary support structure.

"Permanent securing" refers to the totality of all surface and underground mining measures to avert hazards and increased risks. The durability of the measures is years, decades or longer.

In this process, the hazard or risk site of the old mining operation is not eliminated. The scope of the measures is determined by the geotechnical and surveying investigation as well as the hydrological evaluation of the risk situation. The subsequent use of the mining object is associated with permanent protection. Based on the local conditions, the effectiveness of the measures is maintained by monitoring or periodic maintenance.

If a mine object is permanently secured, it can become a custodial obstacle and lead to significant additional costs.

The term *“preservation"* is often used by mining authorities in the context of mining sectors in Central Germany, particularly in the case of mine closures. The synonym "restoration" was later used as an overarching term for securing and preservation. In lignite mining, preservation is applied in the deep mining sector and securing applied to work in the permeable opencast mines, including dumps.

Preservation is defined as the entirety of all surface and underground mining measures for the permanent prevention and elimination of hazards and increased risks. The measures vary considerably based on the current or planned utilization of the surface. If the utilization changes, so do the preservation measures and their requirements.

The installed preservation bodies represent structures within the mine workings. Consequently, they are also affected by weathering, rock pressure and aging processes. If changes in the rock mechanical and hydraulic properties of the subsurface are to be expected, the stability and functionality of the existing supports must be checked regularly. Geotechnical and surveying investigations must also be carried out prior to the implementation of any safeguards. Integration of exploration and safekeeping during the execution of mining operations has proven to be useful in the past, as it allows to react to changes.

In principle, a preservation includes long-term stable and persistent mining measures over a period of at least 100 years. Special structures, such as repositories for radioactive waste, require separate consideration and case-by-case examination and are not part of the explanation given here.

In the example of the Robertshall mine discussed as an example in this thesis, it involves the securing of old mine workings. In fact, the measures of backfilling of the cavities are carried out exclusively below the roads and properties. On the one hand, this is done due to economic reasons and, on the other hand, time constraints. The total area of the mine, and thus the area affected by possible mining damage on the surface, extends to approximately 25 ha. In the northern areas of the former mine, there are numerous localized fault pits on the surface. This suggests that the underlying surface layer has mostly collapsed and the mine has thus been backfilled. Consequently, there are no significant alterations to the subsurface and associated hazards expected in these areas. Furthermore, this area is used exclusively for forestry. An examination of the entire area is thus not economical, since the expenditure of time cannot justify the marginal increase in safety.

Due to the incomplete mine plans, only known and found cavities can be filled with building material and thus secured. This eliminates the aspect of securing the entire mine workings, as required by the preservation.

Furthermore, there is very little knowledge of the subsurface, as the area was only examined for exploration prior to mining by means of boreholes. The data collected during the backfilling operations also do not provide comprehensive information about the subsurface.

Additionally, the backfilling with sand is only durable for a limited period of time. In combination with the aspect that the backfilling was only limited to a certain area of the old mine workings, this case is referred to as permanent backfilling.

When exploring and locating unknown mining cavities, initially old maps and mine plans are consulted. These often show serious deficiencies with regard to completeness, positional accuracy and orientation. Furthermore, local coordinate systems were commonly used for old mine plans. (Randjbar & Schuscha, 2008)

In the case of "recent" old mining, historical aerial photographs and interviews with contemporary witnesses can be helpful. Sometimes, in former mining areas, the terrain morphology provides clues to mining activities. If the research in the files and the evaluation of the preliminary investigations have consolidated the suspicion of the existence of cavities close to the surface, further exploratory and investigative procedures can be applied. These can be divided into direct, indirect and special procedures and represent geotechnical and geophysical procedures (Randjbar & Schuscha, 2008; Meier, 2007; Tamáskovics, 2016):

- Direct methods (drilling, dynamic penetration for core sampling, clearing-out)
- Indirect methods (geophysical methods including geothermal methods)

- Special methods (tracer tests during water and weather movements, photo and television special operations)

Further, Randjbar (2008) recommends test measurements to determine an appropriate methodology. In many cases a combination of several different methods is useful. This results in an increased certainty in the interpretation of the results. The time and financial expenditure involved have an influence in the selection of the method.

Direct methods

Boreholes and dynamic penetration for core sampling are suitable as direct methods for exploration depths up to about 50 m (Meier, 2001). Boreholes provide depth-accurate prospecting with high vertical resolution of structures and allow sampling generally at the correct depth. However, this outcrop provides no information about the conditions adjacent to the borehole, and it is not uncommon for boreholes to be abandoned too early. Furthermore, drilling damages the subsurface and creates undesirable hydraulic pathways. (Ernstson, 2018)

The selection of the drilling method is determined by the geological and mining conditions. The local accessibility of the object and the task also have an impact on the selection. Based on the diverse technical potentials of boreholes, they are suitable for the spatial localization of cavities and shafts close to the surface. At the same time, a borehole provides information about the quantitative and qualitative properties of the overburden. A study by Meier (1999) showed that core drillings have an increased success rate compared to the other types of drilling methods. A total of 554 boreholes with a combined length of 6500 borehole meters were evaluated for this study. The highest success rate (63.9%) resulted from the detection of areal mining (room-and-pillar mining). A comparably low success rate (2.1%) was achieved in the search for drifts. The analysis of the effectiveness also made clear that a combination with other exploration methods leads to meaningful geotechnical data.

Indirect methods

Geophysical measurements examine the subsurface in a non-destructive process. Instead of punctual exploration by drilling, continuous surveying is possible and the data can be integrated over larger spaces. However, geophysical measurements provide inaccurate depth information and their vertical resolution is low. This is particularly the case with potential-methods. Results from geophysics often lead to ambiguities. However, these can be limited by the application of combined methods. In many localities in the near-surface exploration area, geophysical measurements can only be carried out to a very limited extent, and often not at all, due to a variety of interfering factors. (Ernstson, 2018)

Comparing indirect and direct methods is not appropriate considering their different methodological approach. Geophysics can be considered as a cost-effective substitute for drilling in relatively rare cases (Ernstson, 2018). Therefore, it may be reasonable for the investigation in terms of scope, cost and time to coordinate direct and indirect methods.

Ernstson (2018) recommends a preliminary geophysical survey campaign to reasonably place the boreholes according to the geophysical results. Skilled combinations allow geophysical profiles or monitoring networks to be connected to the boreholes for subsequent calibration of the evaluation.

The special methods will not be discussed further in the context of this thesis.

3.1 Direct Methods (Drilling)

Direct methods are used in the search for old mine workings, as described in chapter 3. The remaining drifts and cavities at the mine are believed to be at shallow depths. Therefore, this method is suitable for locating the mine workings being relatively inexpensive and not time intensive. For this reason, direct methods by means of drilling have been applied so far to locate the drifts of the Robertshall lignite mine which is the subject of this thesis. The advantage of this method is the possibility to backfill and secure the drift directly with material in case of a discovery. The procedure and the technical parameters are described in more detail below.

To secure such an area in the long term, drilling must be carried out at regular intervals. The spacing is determined by the width of the structures located in the underground. In the Robertshall example, a grid with a borehole spacing of approx. 2 m mut be drilled transversely to the expected drift, assuming the width of the drift to be also about 2 m. The results should thus provide information about the subsurface that covers as much area as possible. Since the area to be secured is large and this procedure is very time-consuming, the following procedure has been followed so far: Based on the old mine plans, strategic points were selected to serve as drilling sites. The location of these points is selected to allow several boreholes to be drilled with varying angles in different directions starting from there. The objective is to drill in the direction of suspected drifts. The directions and angles are calculated beforehand.

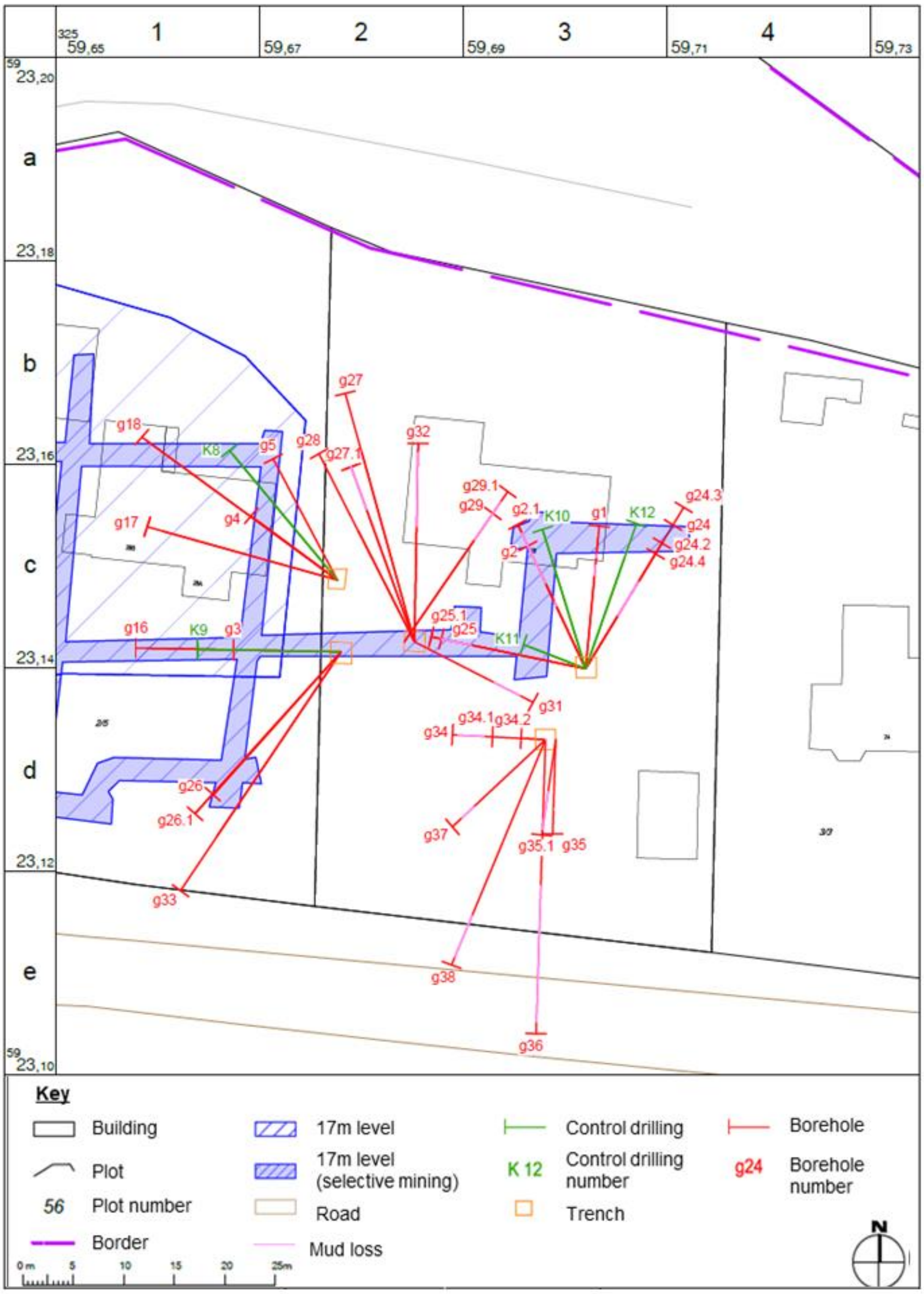


Figure 3 Example drilling plan

The positions of the drilling rig cannot be chosen randomly in an area characterized by residential areas and infrastructure elements. Locations must be chosen that are accessible to the drill rig and drilling crew. In addition, the locations should allow for some flexibility in case the drilling yields unexpected results. The drilling rig can be moved at short notice without having to plan a new starting point. In addition, since there are cables and pipelines in the subsurface, a trench must be created before drilling work begins. The trench is usually 1.5-2 meters in depth and prevents unknown cables and pipelines from being drilled into and damaged. Since the securing of the mine workings takes place below the properties and roads, drilling must inevitably be carried out in areas in which cables are located. In this case, exposing the lines is important for safety reasons for the drilling crew.

A fully hydraulic drilling rig is used, which allows the drilling process to be kept variable and the drilling pressure constant. As a safety measure, the boreholes are drilled at an inclination of 45 to 60 degrees to the horizon. This ensures that neither the drilling rig nor the operator is located above a possible cavity that could collapse during drilling.

The drilling method is circulation drilling. In this process, the drill cuttings are continuously conveyed with the aid of the circulation. Permanent control of the discharged cuttings allows conclusions to be drawn about the structure of the subsurface. These findings are documented in a drilling log. If a mud loss occurs during drilling, conclusions can be drawn about possible cavities in the course of the borehole. The boreholes are drilled with double casing to minimize the risk of mobilization of material in the subsurface by escaping drilling mud. The documented mud loss can only provide limited information about the size of the cavity. The drilling resistance also provides indirect information about the strata drilled through.

If voids are encountered, the boreholes are lined with a solid PVC pipe. The located drift section is then backfilled with a building material. It consists of a special binder, limestone powder and fly ash. The material is classified as Z0 (solid material for soil) according to table II.1.2-3 of the German Waste Management Association (LAGA), version dated November 5, 2004. The dry material is stored in a silo at the site and mixed with water on site for backfilling. It is then pumped into the borehole via a pump. Due to the low cover, the material is placed into the ground without additional pressure. After a sufficient setting time, control boreholes are drilled to determine whether the desired securing success has been achieved. If a control drilling indicated mud losses and thus cavities, the control borehole is backfilled in the same way as the exploration borehole. In this case it may be necessary to examine whether major changes have occurred in the subsurface and why the backfilling has not been successful.

3.2 Indirect Methods (Geophysics)

Geophysical measurements serve as an indirect method to investigate the subsurface. The following chapters present the applicability of geophysics in the exploration of old mine workings. For this purpose, first the principles of geophysics are explained and application examples from the localization of old mine structures are given before the individual methods are discussed in more detail. The methods described in chapters 3.2.3, 3.2.4, and 3.2.5 are the methods discussed in the scope of this thesis. A more detailed description of other possible methods would exceed the scope of this work.

3.2.1 Geophysics application in old mine workings

The following chapter presents the application type of geophysical methods for assessing the usability of endangered areas. The methods are evaluated in terms of their applicability and their relation to the hazard category of the area.

During geophysical investigations in mining, the working method requires significant changes in the physical properties of the medium. These changes are influenced in the rock mass, especially by the fracture system surrounding the cavity. A simplified representation of geophysical measurable zones of a mining cavity are shown in Figure 4.

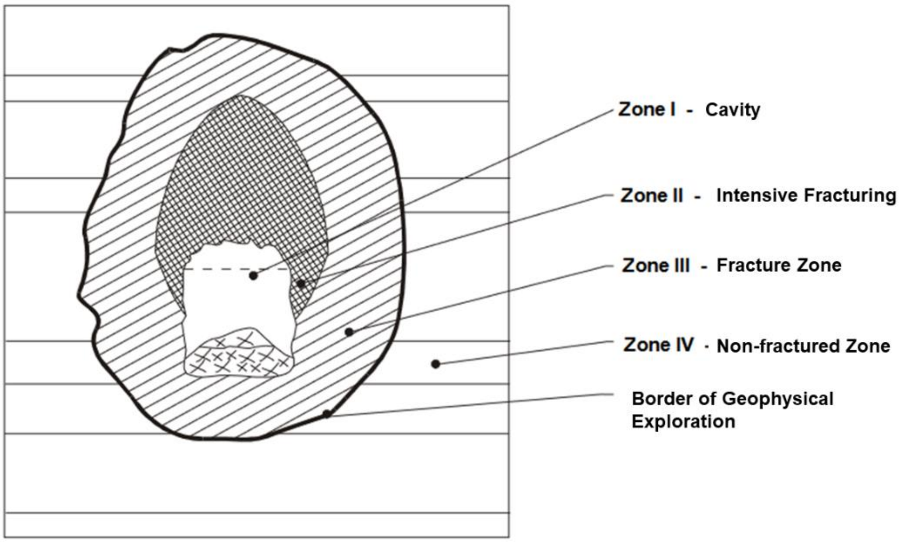


Figure 4 Geophysical model of a mining cavity (Marcak, 1999)

Zone 1 mostly represents a cavity that is often filled with water and falling rock fragments. In zone 2, intense fracturing develops, resulting in an upward displacement of the cavity. Zone 3 is an extraction-induced fracturing zone that develops as a result of rheological processes and as a function of weathering processes. Zone 4 represents an unaltered zone that has not yet been influenced by the cavity. The boundary of geophysical exploration is located between the latter two. In reality, this is not a clearly definable boundary, but rather a transitional phase. This is significantly related to the change in fracture intensity, which in turn influences the geophysical representation of this zone. The fracturing around the cavity usually results in density of the medium, through this a velocity reduction of the seismic waves and a change in the dielectric constant. This creates an anomalous effect in the geophysical field. (Marcak, 1999)

Whether a cavity or a loosened zone is present can only be determined to a limited extent without further investigation. When referring to a cavity in this paper, the possibility that it is a loosened zone is not excluded. For this reason, the term "cavity" will be used exclusively in the following.

3.2.2 Geophysics method testing

The detection of cavities in the subsurface is a task frequently approached to geophysics. A fundamental problem of cavity detection with geophysics is a physical issue. In all methods where the measured quantities are derived from a potential, it is essential that a cavity must not lie too deep in relation to its diameter. (Pilecki, 2003)

The aim of the first investigations is to find a geophysical method to map potential areas of cavities and voids in the area of the mine. The area of investigation extends along the Emmetal road, where the official mine plan shows a former underground drift. In order to verify the accuracy of the geophysical measurements, test profiles were constructed along drifts that had already been confirmed by drilling. This also serves to validate the measurement methods and provides information on how future measurement data can be interpreted. The location of the test profiles is shown in Figure 5 below.

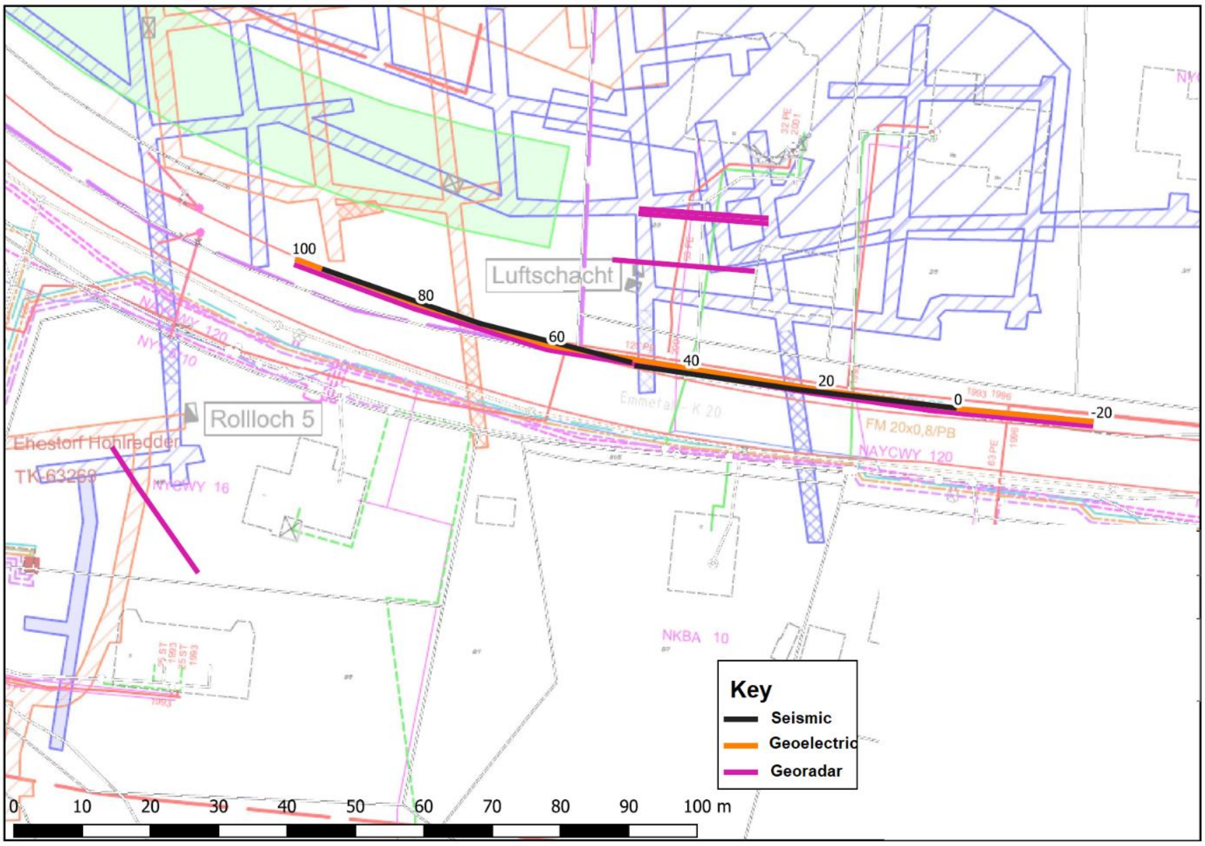


Figure 5 Test profile location

The main objective of the test measurement is to find a cost-efficient and effective geophysical method to reduce the number of drillings or to target the drillings. This is to be conducted exclusively in areas of the road and properties, as these are at increased risk of surface cave-ins. The measurement methods are applied in order to localize the cavities and subsequently secure them.

The selection of measurement methods is based on the cost per meter, the time required, and their depth range. The selected methods are geoelectrics, georadar and seismic and will be discussed in more detail in the following chapters.

3.2.3 2D Geoelectric

2D geoelectrics, or resistivity geoelectrics, is one of the active geophysical techniques that uses artificial fields. It is used to determine the distribution of resistivity in the subsurface. The method makes use of the properties of the rocks, which show different conductivities depending on the lithology and electrolyte content of the pore water. (Ernstson, 2018; Knödel, Krummel, & Lange, 1997; Loke, 2004)

For interpretation, Table 1 shows typical electrical resistivity values for some selected rocks and waters. It can be seen that moisture has a significant effect on resistivity values. Dry sands have very high electrical resistivity values. Dry areas of loosening or air-filled voids also have very high resistivity values.

Table 1 Specific electric resistivity for selected rocks and water (Knödel, Krummel, & Lange, 1997)

Material	**Value range [Ωm]**	
	Minimum	**Maximum**
Gravel	50 (waterlogged)	>1.000 (dry)
Sand	50 (waterlogged)	>1.000 (dry)
Silt	20	50
Loess loam	30	100
Clay (moist)	3	30
Clay (dry)		>1.000 (compact)
Sandstone	<50 (moist)	>10.000 (compact)
Limestone	100 (moist)	>10.000 (compact)
Argillaceous schist	50 (moist)	>10.000 (compact)
Water	10	300
Saltwater	0,25	

A direct current is injected into the subsurface via two grounded current electrodes A and B. A spatial potential field is generated with equipotential lines running perpendicular to the streamlines. The current lines are refracted at layer boundaries and at inclusions with changing conductivity contrasts. The distribution of resistivity in the subsurface can then be derived from the measurement of the potential profile at the earth's surface. (Johnson, Snow, & Clark, 2002; Knödel, Krummel, & Lange, 1997)

However, the resistivity cannot be determined directly by measuring current intensity I and current voltage V. Due to the high current density and immediate proximity of the electrodes, only the ground resistances would be measured. Therefore, a potential measurement between two probes M and N is measured. If the distances between these probes are varied, the electrical resistance can be derived for different depth ranges in the subsurface. At the electrodes A and B the current intensity is measured. An illustration of the principle is shown in Figure 6.

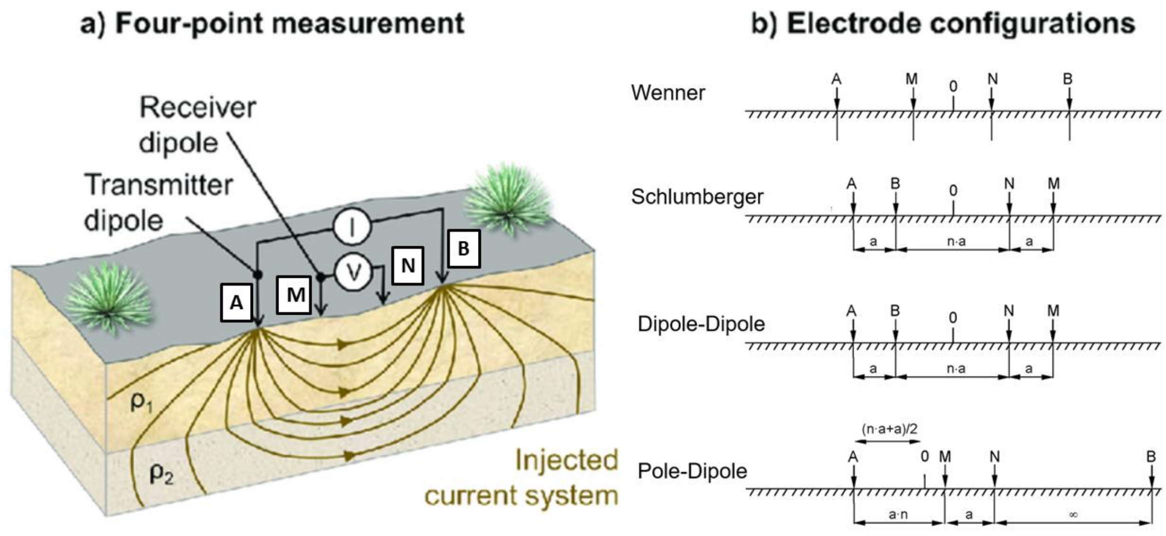


Figure 6 (a) Principle sketch of geoelectric resistance measurement (b) Common electrode configurations (Bücker, Lozano, & Ortega, 2017)

For this geophysical method, there are different ways to arrange the electrodes A and B, as well as the probes M and N. In general, a distinction is made between Wenner, Schlumberger, Dipole-Dipole and Pole-Dipole configurations. Differences between the configurations are found in the depth of investigation, resolution, sensitivity to technical disturbances and lateral inhomogeneities, as well as feasibility in the field. Both the Schlumberger and Wenner configurations were used for the test survey. The Wenner method is well suited for mapping conductivity changes over a larger area. The

Schlumberger method is used primarily for exploration of deeper structures. (Telford, Geldart, & Sheriff, 2010)

Multielectrode geoelectrics was applied for the test profile measurement. It is used to investigate complex geological conditions where application of one-dimensional sounding methods is unsuitable because the deviation from plane-parallel stratification is too large. The length of the profile, the desired depth of investigation and the desired resolution determine the number of electrodes and their spacing.

The electrode spacing a is constant. During the measurement, the distance increases with the factor n, so that mapping and sounding are combined. With increasing distance, the measurement depth increases and qualitatively shows the spatial distribution of the electrical resistance below the measurement profile. The measurement scheme is shown in Figure 7.

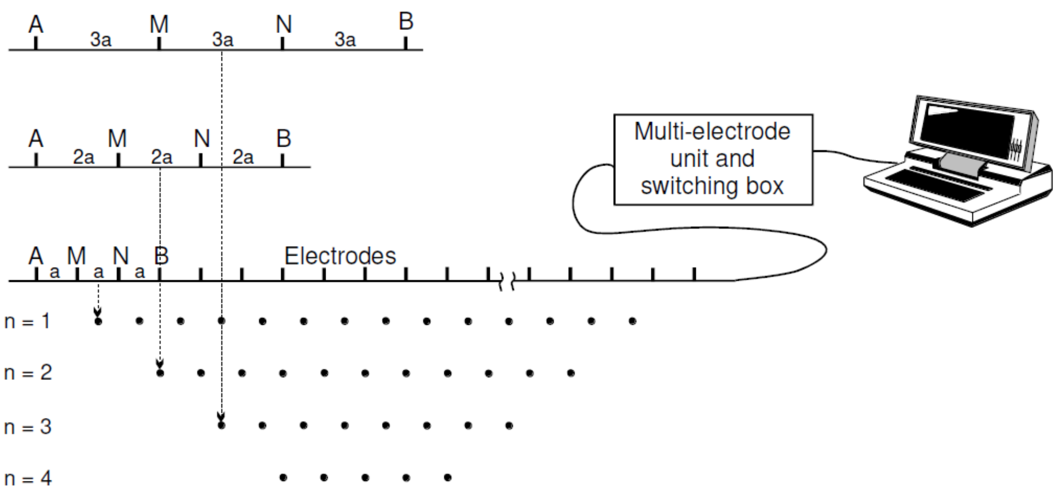


Figure 7 Measurement scheme of the geoelectric measurements (Knödel, Krummel, & Lange, 1997)

As part of the measurements on the test profiles, a geoelectric profile of 119 m was measured along the roadside. Table 2 shows a summary of the measurement parameters that were applied.

Table 2 Measuring parameters 2D-Geoelectric

Measuring device	Lippmann 4-point light 10 W
Measuring configuaration	Schlumberger, Wenner
Electrode distance	1 m
Number of profiles	2
Profile length	119 m
Penetration depth	Max. 22 m

3.2.4 Georadar

Georadar is an electromagnetic method. Short electromagnetic pulses are sent into the ground via an antenna, which are reflected at discontinuities. The discontinuities can be represented by material changes (layer boundaries) as well as by voids. Due to the comparatively low penetration depth, the method is mainly used in this measurement to detect loose zones that may have migrated to the surface (Knödel, Krummel, & Lange, 1997; Skolnik, 2008; Daniels, 2004)

The penetration depth depends on the working frequency of the antenna, as well as on the nature of the subsurface. The higher the frequency of the antenna, the greater the penetration depth and resolution. This means that smaller objects and thinner layers can also be detected. However, the higher frequency has a much lower penetration depth than the working method with lower frequencies. With regard to the properties of the soil, density and degree of moisture are decisive. In clayey, moist soils, the penetration depth is low, whereas in sandy, dry soils the penetration depth is high. The latter soil is present in the study area, which is why it was decided to carry out a test measurement using this method despite the low penetration depth of the georadar. Furthermore, the radargram is displayed during the measurement, so that initial evaluations and marking of suspicion points are already possible in the field. With this method, it is also possible to indicate not only the location but also the approximate depth of suspected suspicion points without the need for complex modelling. (Jol, 2008; Grasmück & Green, 1996; Knödel, Krummel, & Lange, 1997)

Table 3 contains the parameters used for the measurement.

Table 3 Measuring parameters Georadar

Recording system	SIR 3000
Frequency (antenna)	200 MHz (6 profiles)
Measuring length	450 ns (200 MHz)
Number of samples	512
Number of profiles	6
Total length of profiles	334 m

3.2.5 Seismic

Seismic uses the propagation of elastic waves in the subsurface. The basis is a targeted stimulation of elastic waves by seismic energy. This is induced by seismic sources such as falling weight, explosives, vibration. The seismic waves migrating through the subsurface are reflected, diffracted or scattered at interfaces such as a change in rock type, a fault surface or even anthropogenic emplacements. The recording of seismic waves returning from the subsurface at the earth's surface (seismic echo) is done by vibration transducers (geophones) placed along a projected profile at the earth's surface. Since the propagation velocity of seismic waves is material-specific, conclusions about the subsurface structure and material can be drawn by determining the velocity. The generation and propagation of an elastic wave by hammer impact and recording by geophones is shown schematically in Figure 8 and Figure 9 below. (Knödel, Krummel, & Lange, 1997; Berckhemer, 1997; Telford, Geldart, & Sheriff, 2010)

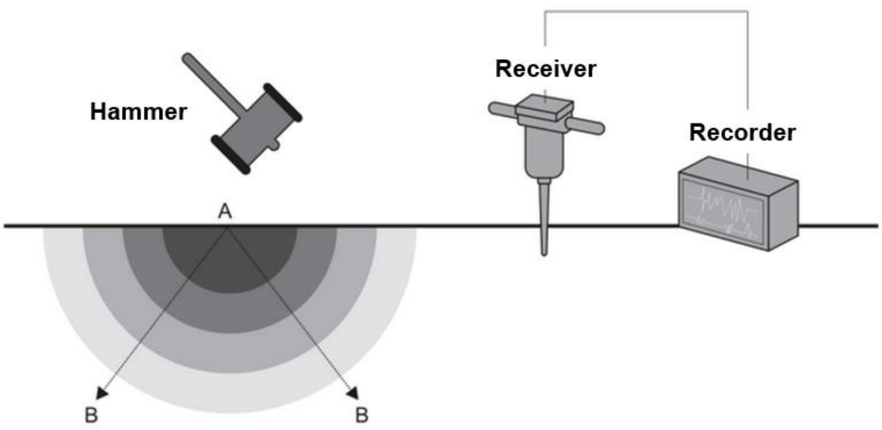


Figure 8 Generation of an elastic wave by hammer impact; gray shading: wave fronts; arrows from A to B: two exemplarily represented wave paths (Clauser, et al., 2006)

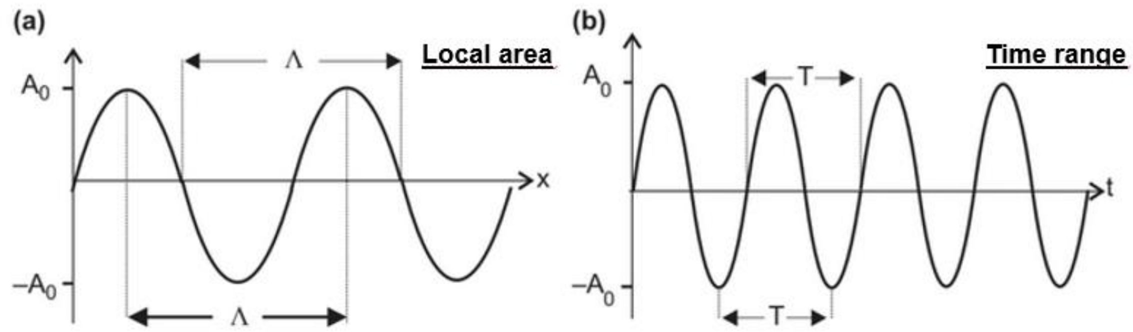


Figure 9 Deflection of a particle in space (a) and time (b) during the passage of a seismic wave (A: Wavelength; T: Period) (Clauser, et al., 2006)

During the stimulation of seismic waves, spatial waves, so-called compression waves (P-waves) and shear waves (S-waves), as well as surface waves are generated, which differ in their propagation characteristics. A distinction is made between refraction and reflection seismics.

Refraction seismics is based on the evaluation of refracted waves. Seismic waves hit an interface of two layers at a critical angle, travel along the interface (head wave) and reach the surface again. Due to the dense arrangement of the source and geophone positions, overlapping of the wave paths occurs. As a result, travel time curves are recorded, which can be represented in a model of the distribution of the P-wave velocity. Subsequently, statements can be made about the depth of interfaces.

Reflection seismics gives conclusions about the rock structure of the subsurface by measuring the refracted, diffracted and reflected waves.

The penetration depth of the measurement depends on the seismic properties of the subsurface, the display length, and the signal energy. In principle, penetration depths can be achieved that correspond to one third of the length of the profile. Tunnels and cavities in this depth range disturb the propagation of the seismic wave and produce characteristic patterns in the seismograms. The seismic signals are qualitatively evaluated. This procedure is repeated several times, each time the stimulation points and geophone position along the profile to be measured are offset by a certain amount. In this way, profiles of any length can be measured.

Two LS 24 land streamers with a total of 48 geophones, each spaced one meter apart, were used for the measurements of the streamer. The use of a land streamer eliminates the need for time-consuming technical modifications in the course of the profile and thus ensures rapid measurement progress. For this purpose, the land streamer is pulled as a whole into the next profile section after the measurement has been completed. Furthermore, a measurement on sealed surfaces such as streets or concrete places can be realized without significant damage to the floor. The land streamer on the test profile can be seen in Figure 10 below. The geophones are in direct contact with the ground. It must be ensured that there is no substance (e.g. leaves) between the geophones and the ground.

Figure 10 Land streamer on Emmetal road test profile

The entire profile length of 95 m was measured by first laying out the streamer from 0 - 47 m and then from 48 - 95 m. The source point distance is 4 m. The source point spacing was also 4 m. Both displays were shot completely through from the beginning

(- 4 m) to the end (99 m) of the total profile. The seismic energy was generated with a hand hammer. Table 4 lists the measurement parameters for the seismic measurements.

Table 4 Measuring parameters seismic measurement

Recording system	Geometrics Geode 24 (2 parts)
Geophone spacing	1 m
Active streamer	48 channels, 47 m
Record length	1 sec.
Sample interval	0,25 ms
Profile length	95 m
Stimulation point distance	4 m
Source	Hammer
Geophone	Vertical geophone (4,5 Hz), individual, on landstreamer
Data format	SEG-2

4 Evaluation of the test measurement

In this chapter, the results of the test measurements of all three geophysical methods are presented. For clarity, an additional summary is provided at the end of chapter 4.3 justifying the choice of method that will continue to be used. It should be noted that the measurements are evaluated qualitatively and the interpretation of geophysical measurements is made in a subjective approach.

4.1 Geoelectrics

The measurements were performed along the test profiles of the seismic as well as the georadar profiles. The results of the measurement are shown in Figure 11.

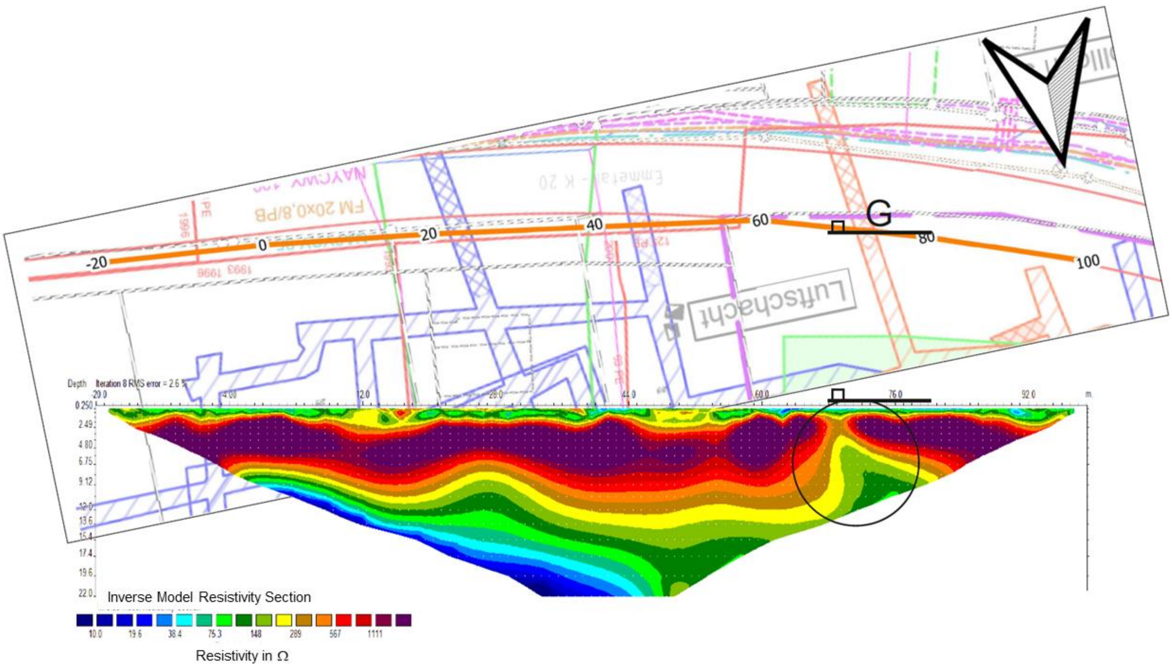


Figure 11 Geoelectric measurement

Overall, the resistivity values of the profile span a very wide range of values: the top 2 m are heterogeneous but relatively low resistivity overall. It is likely that the local differences in this uppermost layer are due to inhomogeneous refill material.

At depths of 2-2.5 m, a very distinct layer boundary toward very high resistivities is apparent. These resistivities above 1000 Ωm indicate a dry sand layer. The lower edge of this sand layer is mostly at about 8 m depth, but shows an anomaly at profile meter 70. The second layer appears to have a much lower thickness over a 5 m range.

Below the high-resistivity sand layer, especially at the beginning of the profile, a gradual transition to sometimes extremely low resistivities is apparent (ca. 10 Ωm).

The only anomaly of the resistivity distribution in the otherwise homogeneous, three-layer structure of the subsurface model is located at profile meter 70 and thus in the vicinity of the backfilled 13 m drift. Whether the anomaly ("G") is actually an indication of the drift location cannot be conclusively clarified with the help of this measurement, since the penetration depth at the edge of the profile is no longer large enough.

In the area of the other drifts that crossed the test profile, the resistance values do not show any abnormalities. It can be assumed that the geoelectrics in the depth range of 13 m or 17 m below ground level are not capable of resolving a cavity of the size of a drift. For an evaluation regarding the connection of the resistivity anomaly at profile meter 70 with the already backfilled drift, the area has to be evaluated by drilling. The clearly recognizable area of lowered specific electrical resistance values may have been caused either by a change in material or by increased moisture.

4.2 Georadar

The georadar evaluation program ReflexW 9.1 (Sandmeier Software, 2019) was used for the evaluation because it allows refined stemming data processing steps in addition to the common ones. Several data processing steps were tested on selected data sets and the following steps were performed on all data:

- Measurement geometry (profile length, direction of measurement).
- Static correction (adjusting the depth axis to the top of the terrain)
- Bandpass
- Amplification function
- Combination of radar data with GPS data

The measurements were carried out along the test profiles of the seismic as well as geoelectric measurements. Furthermore, one profile was measured on the property located south of the road, as well as two others located on the property north of the test profiles. Figure 12 and Figure 13 show the results of the measurements.

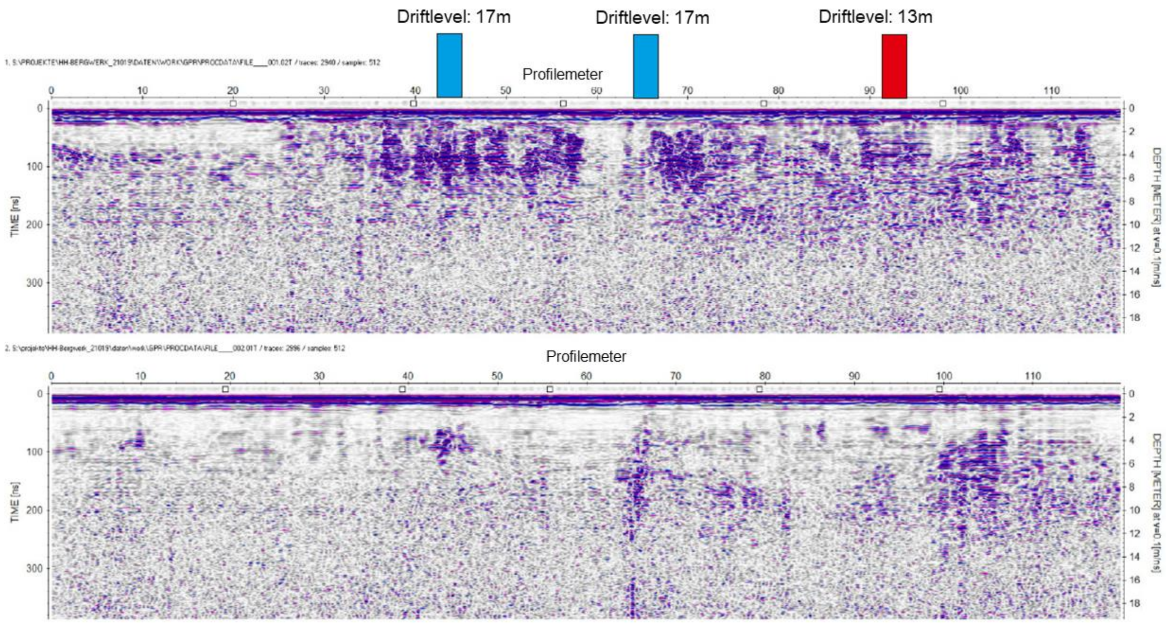


Figure 12 Georadar results Emmetal road test profile

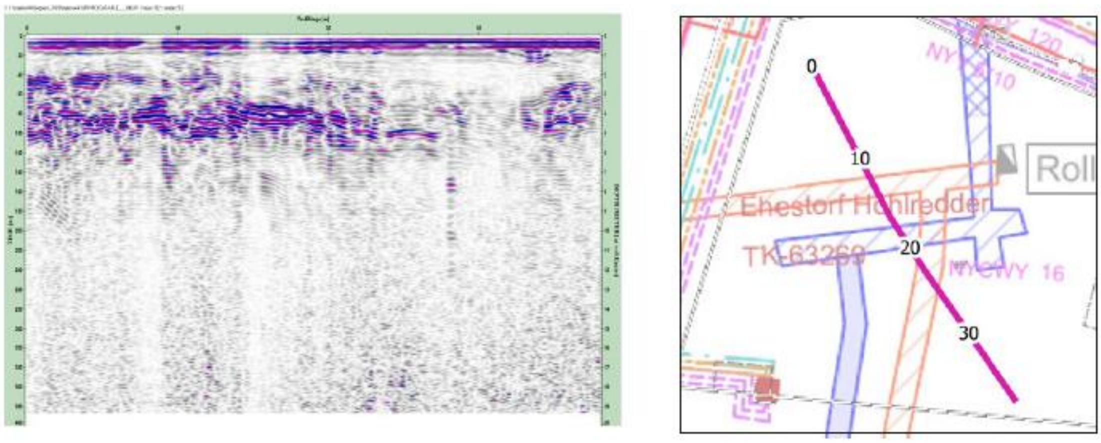


Figure 13 Georadar results Hohlredder test profile

The survey profiles are presented as 2D sections (radargrams), corrected for length and start time, and individually examined for noticeable reflection anomalies and structures.

The mapped drifts are located at 13 and 17 m depth. These depths are not reached by the georadar survey conducted here. Although possible instabilities can continue upwards in the subsurface and thus theoretically occur closer to the surface, this does not seem to be the case here. No correlating anomalous areas could be found in the area of the drifts. Even though there is a possibility that sinkholes or subsidence above the mine may show up in the radargrams, this could not be shown during the test measurements. Due to the lack of penetration depth, the radar measurements with a 200 MHz antenna, as they were carried out here, cannot be used for the questions concerning the stability of the underground and the detection of further drifts.

4.3 Seismic

The measurements were performed along the test profiles of the geoelectric as well as the georadar profiles. The result of the refraction seismics is shown in Figure 14.

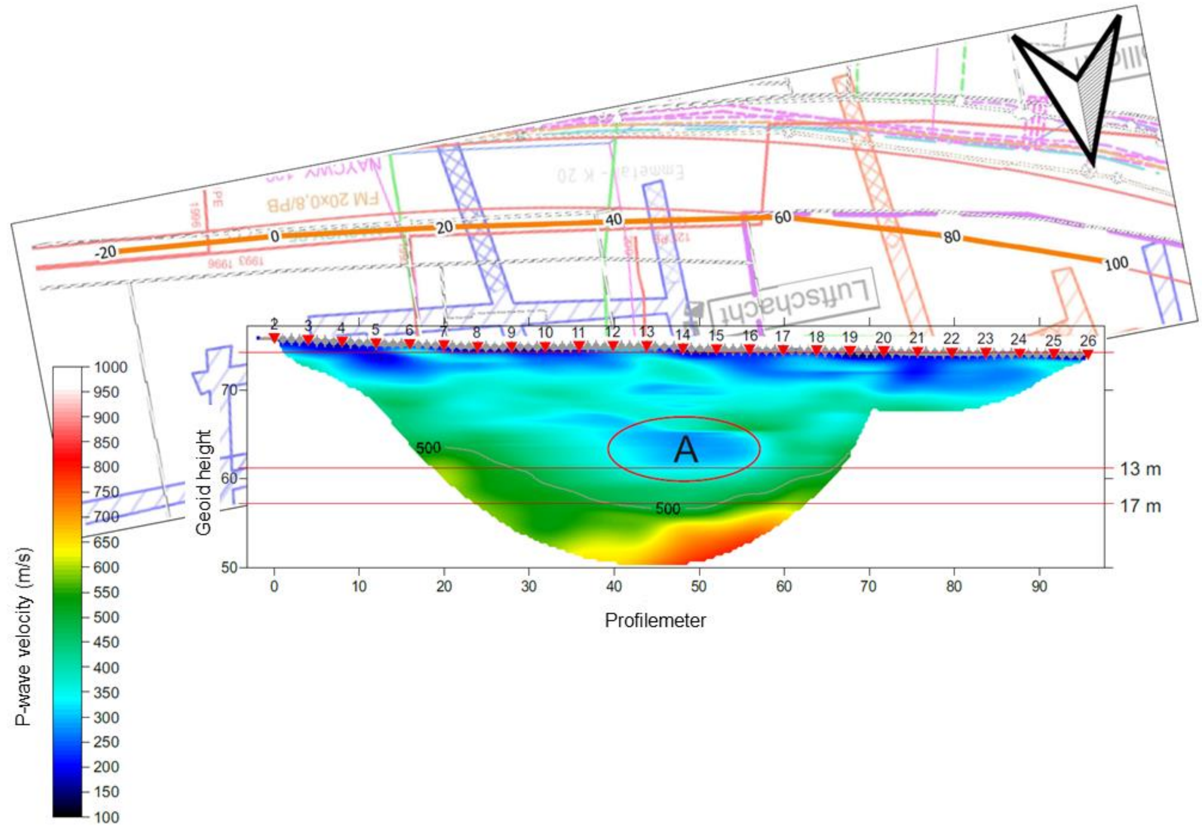


Figure 14 Results refraction seismic Emmetal road test profile

In general, slow velocities around 500 m/s are obtained. According to this, the surface layer is free of water. In the area shown there is no evidence of the drifts crossed by the profile. Refraction seismics is not suitable for resolving local small-scale elements. However, tomography can be used to image velocity variations in the subsurface. In the figure, area "A" is marked where the P-wave velocity is conspicuously low. Decreased velocities may be caused by a zone of loosening. In this area, the profile crosses a drift. Here, too, a more detailed investigation should be carried out, e.g., by means of drilling.

The seismic measurements show a complex wave field. From the seismic data there are indications of an inhomogeneously built up subsurface. The velocity variations may be due to material changes as well as variations in the density of a material's deposit. This could be due to the remaining lignite deposit confirmed by the drilling. The detected anomalies were mapped on a site plan and can be seen in Figure 15.

Figure 15 Anomaly location seismic test profile

Anomalies that are weaker are shown in purple. Suspicion points at the beginning or end of the profile are also categorized as weak because they cannot be adequately substantiated. Strong anomalies are shown in red.

Anomaly 1 is very clear and lies above a drift, as do anomalies 3 and 7. Anomaly 9 also lies over a drift, but it is at the western end of the profile and therefore cannot be adequately substantiated. Anomalies 2 and 4 are weakly pronounced.

Some anomalies are located in areas where a drift crosses the profile. However, there are other anomalies on the profile that show the same characteristic patterns in the seismogram and are not crossed by a drift. Clear anomalies 5 and 8 are not in the area of a drift, but they show the same characteristics. This area is suitable for verification of the process by exploratory drilling.

Nevertheless, it should be noted that the evaluation is qualitative and subjective. Therefore, it is possible that the marked anomalies have other causes and no evidence of cavities or drifts is found here. It is not possible to determine the depth position of the anomaly. The uncertainty of the positioning is about ±2 m.

4.4 Results of seismic measurement campaigns

Geoelectrics cannot verify any of the drifts crossing at 17 m depth. There is a noticeable change in resistivity values for one drift crossing at 13 m depth. However, since this anomaly is located above the suspected drift location and the testimony depth in this profile margin area does not extend to the suspected drift depth, this correlation cannot be conclusively evaluated without exploratory drilling.

The georadar measurements show penetration depths of 6 to 8 m. Although zones of weakness above the drifts may continue to this depth, the radargrams show no evidence thereof.

The seismic measurements were evaluated by refraction tomography on the one hand and qualitatively analysed for characteristic wavefield distortions on the other hand. The refraction tomography provides a depth distribution of P-wave velocities below the profile. Here, a zone of low velocities was localized overlying one of the previously known drifts. Lowered velocities indicate a loosened zone.

From the qualitative evaluation, small-scale suspected areas for voids and drifts are identified. The suspicion points are located above the known drifts as well as in areas where no mine workings are known. The reliability and positional accuracy of the evaluation can only be verified with exploratory drilling.

Seismic was selected as a suitable method for subsurface exploration. This method was the only one that reached the necessary depth to show the drifts as an anomaly. In addition, it was more reliable in detecting already known underground structures compared to the other measurement methods.

Measurements were carried out in a total of five campaigns between March and June 2021. Measurements were performed using the same equipment previously installed for the test profiles. The measurements were made using either the land streamer or the geophones were embedded in the ground along the profiles (see Figure 16 and Figure 17). The individual geophones placed in unpaved areas provide a better contact to the subsoil on uneven surfaces. The seismic energy was generated with a hand hammer. Measurements were taken with a maximum of 48 active channels. Profiles that were longer were measured in sections.

Figure 16 Setup of the measuring equipment (left) and Geophones inserted into the ground (right)

Figure 17 Streamer placement on sealed surface (left) connected single geophone (right)

During the geophysical measurements in the scope of this thesis, a total of 5000 m seismic profiles were measured. In the process, 43 suspicion points were interpreted and 36 were confirmed by means of drillings. It should be mentioned that at the time of writing this thesis a number of profiles could not yet be verified by drilling. Considering all verified measurements, the hit rate of the geophysics can be calculated to 83,72 %.

The results of the seismic measurements conducted are presented in Figure 18 which shows that the majority of the anomalies are located along the theoretical axis of the existing drifts. The cavities that were exclusively located by drilling technology followed the mining pattern of the existing mine plans. Thereby it suggests that the anomalies found follow a similar pattern. As a result, it leads to the assumption that the use of seismic has been effective. The verification of the anomalies found is done by drilling.

Furthermore, a summary of the anomalies shown in Figure 18 can be found in in the appendix. During the evaluation, the intensity of the anomalies has been categorized into weak and strong, as well as other categories such as areas with unclear signals. This categorization will be applied with regard to the amount of material backfilled. It is examined whether the tendency of the anomaly strength is related to the size of the supposedly found cavity.

The table is divided into campaign number, profile name and name of the measured anomaly. The name is classified as the sequential number on the measured profile (e.g. A1V1). The coordinates are given in UTM form. Subsequently, the anomaly is assigned a class from 1 to 3, where 1 (red) represents a strong anomaly, 2 (orange) a weak anomaly and 3 an area or unknown form.

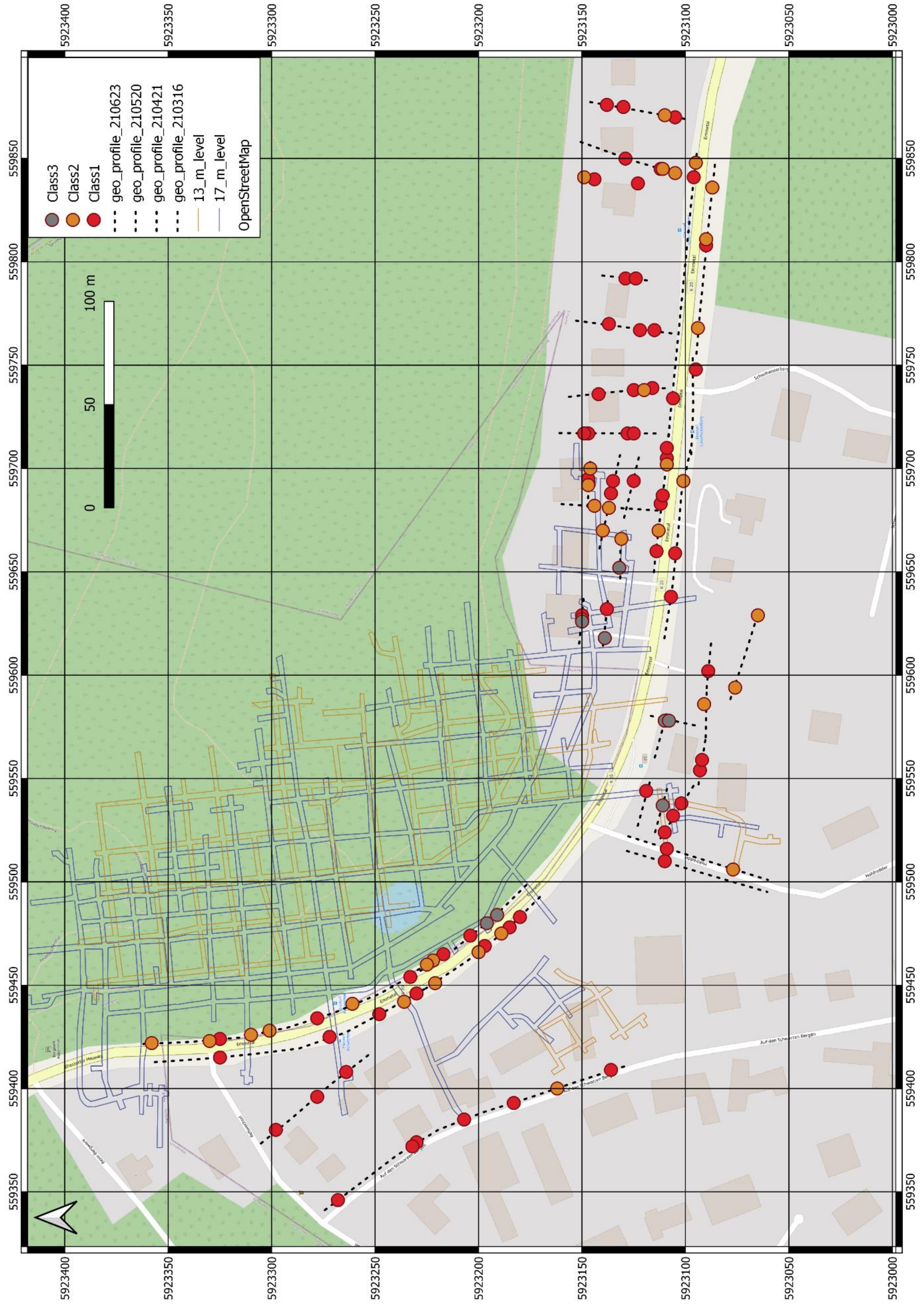


Figure 18 Locations of the measured anomalies

Second campaign

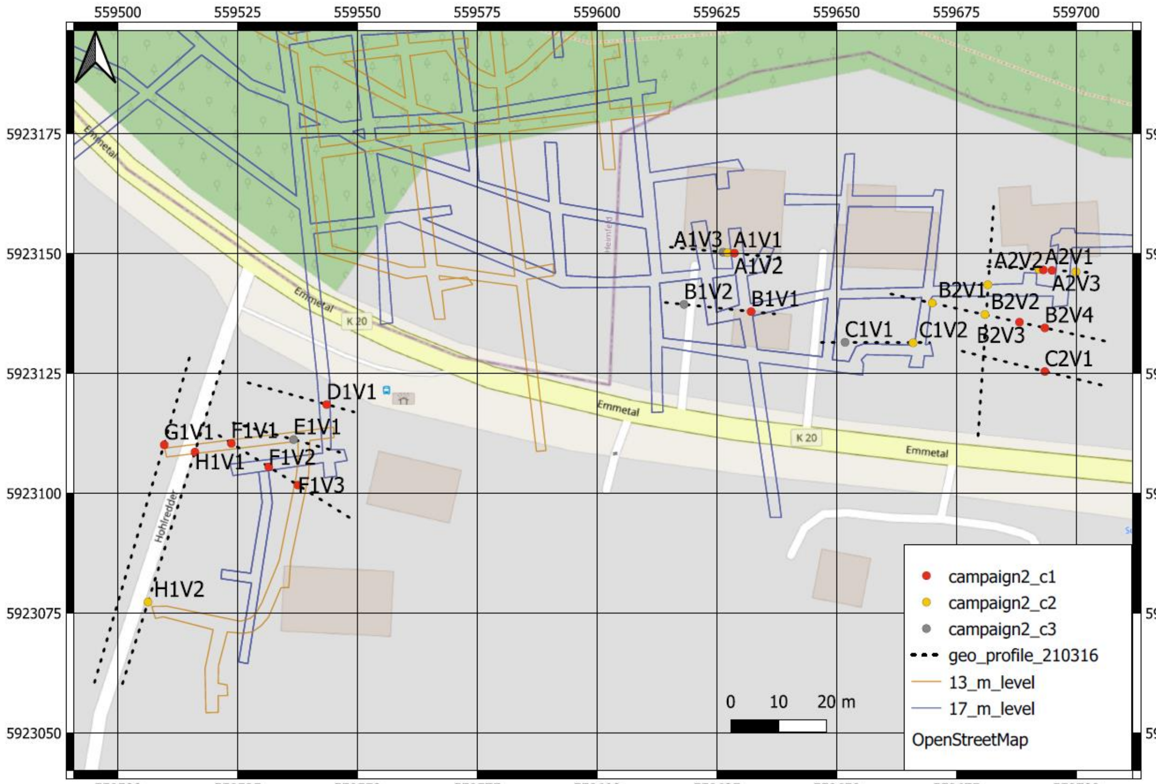


Figure 19 Second seismic measuring campaign

In the second measurement campaign, nine profiles with a total length of 433 m were measured and qualitatively evaluated. A total of 21 suspicion points were identified. The measurements of profiles B and C, which partly run parallel next to former drifts, show larger areas of the wave field disturbed. The evaluation indicates suspicion points of class 3, which can be represented as areas.

In profile B, suspicion point B2V2 is located directly in the area of a terrain step, which leads to distortions of the wave field. This suggests that this anomaly is not caused by a loosening of the subsurface. However, this anomaly can also only be observed at a certain distance from the source point and the geophone, which is typical for the investigated cavity anomalies. There is also the possibility of an overlap of both effects at this measurement point. However, the suspicion points B2V4, B2V3, B2V4 as well as C2V1 can be interpreted as extensions of the existing drifts. Their location at the border of the mapped mining area favours this assumption. These areas tended to be mined after the mine plans were made, so the latter is no longer accurate. Drilling conducted on this assumption yielded hits in the areas of the anomalies found, confirming the assumption. Profiles following these routes were therefore planned for the next measurement campaigns. The remaining anomalies found in profiles A, B and C correspond to the position of the former drifts. These were confirmed by drilling and subsequently backfilled.

The profiles measured in the area of the road "Hohlredder" do not show any unexpected measurement results. The anomalies found are exclusively in areas where the mine plans presented drifts.

The observed seismic velocities are very low throughout the study area of the second campaign. This indicates generally very loose subsurface conditions. The found suspicion points are located both over identified drifts and in areas where no drifts are known.

Third campaign

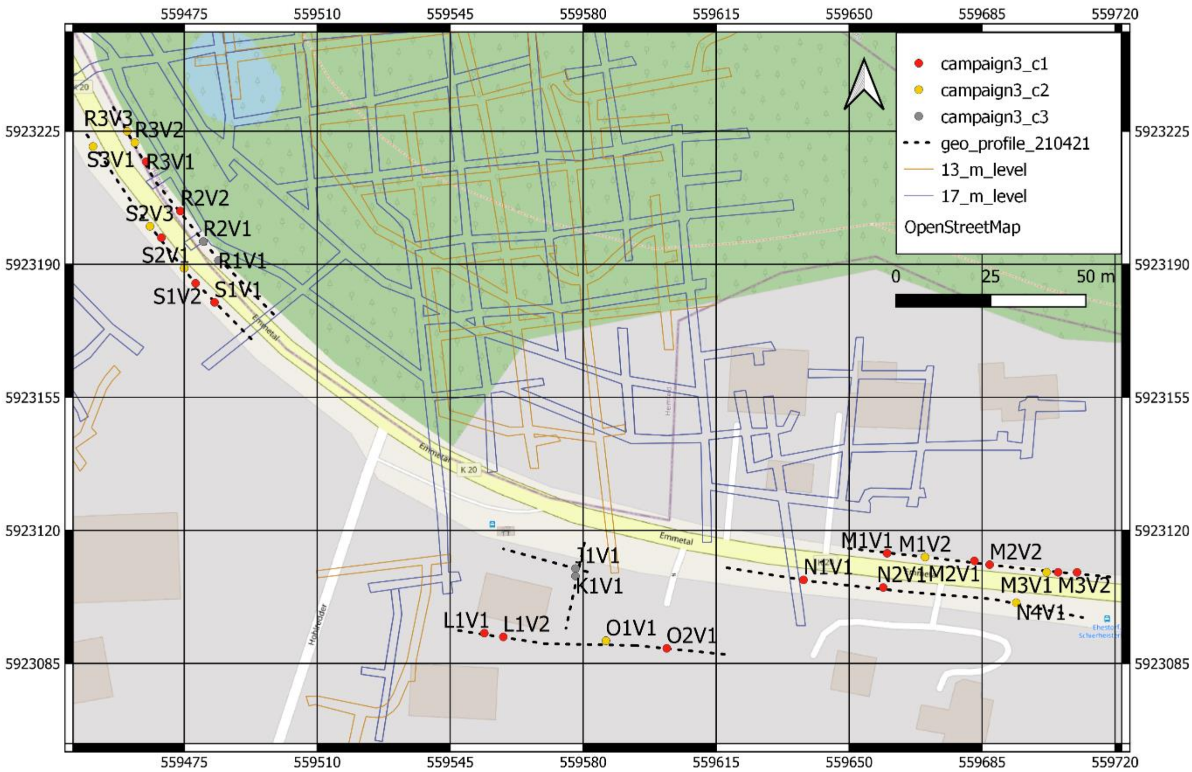


Figure 20 Third seismic measuring campaign

In the third measurement campaign, a total of 8 measurement profiles with a total length of 424 m were measured and qualitatively evaluated. A total of 28 suspected areas were identified.

Profiles M and N prepared for this measurement campaign run along the "Emmetal" road. The profiles were created parallel and as extensively to identify possible drifts that might intersect the road. Hereby all potential drifts that cross the road can be investigated. The results of measurement campaign 2 also indicate the presence of a drift that extends in a southwards direction. On profile M, this suspicion is initially confirmed in the form of two closely spaced anomalies. However, these are not repeated on the other side of the road in profile N. This suggests that a drift running in this direction is unlikely. Nevertheless, the possibility can only be excluded after an investigation by drilling. At the left end of profile M, anomaly M1V1 is located, which in conjunction with anomaly N2V1 could represent a line extension of the mining area. The same pattern is found at the eastern end of both profiles.

The results of the measurements of profiles K and J provide an increased suspicion of a drift below the intersection of both profiles. Measurements along profile J, as well as along profile K, demonstrate a clear anomaly in this area. The remaining anomalies found in profiles L and H must be verified by further measures for interpretation.

Profiles R and S were planned with the same objectives as profiles M and N. They are intended to provide information on possible drifts crossing below the road in order to identify potential danger zones. Parallel anomalies were found at three locations on both profiles. The missing connecting sections on the mine plan suggest the anomalies might represent the latter. Again, the assumption should be tested by drilling.

The observed seismic velocities are again very low throughout the study area of the third campaign. This indicates generally very loose subsurface conditions. The found suspicion points are located both over identified drifts and in areas where no drifts are known.

Fourth campaign

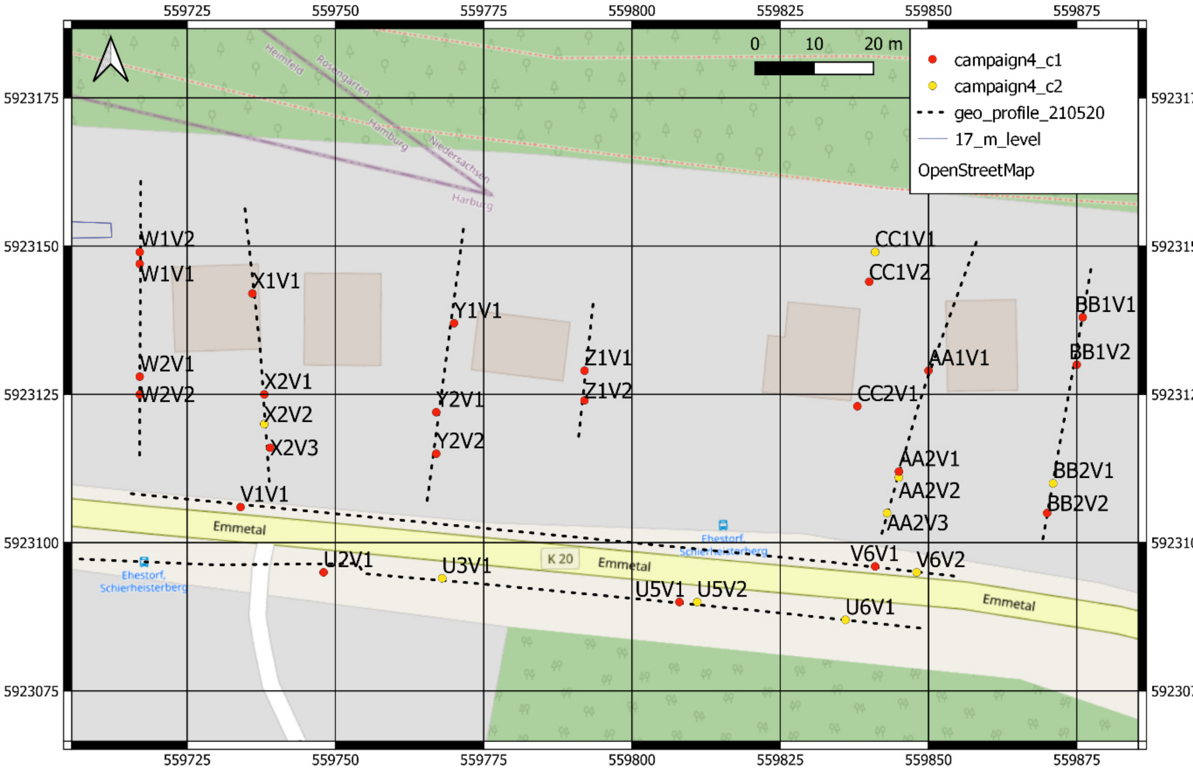


Figure 21 Fourth seismic measuring campaign

In the fourth measurement campaign, nine profiles with a total length of 591 m were measured and qualitatively evaluated. A total of 32 suspect areas were identified. Mine maps from the existing record (Bergamt Hannover, 1921) indicate an extension of the mine in eastern direction. The main purpose of this measuring campaign is to verify an extension in this area.

Profiles U and V along the road only indicate a few strong anomalies, which can also only be partially correlated. A verification of the anomalies V6V1 and V6V2 is reasonable, since they are within the immediate vicinity of other strong anomalies. However, it is still possible that the mine was not further developed towards the south. This assumption can only be verified by drilling.

The measurements on the profiles W, X, Y and Z imply a progression of the mine in an eastern direction. This can be demonstrated primarily by the parallel alignment of the strong anomalies W1V1, W1V2, X1V1, Y1V1, and Z1V1. Likewise, the anomalies W2V1, W2V2, X2V1, and Y2V1 extend within a straight line.

In general, it can be assumed that there is a high probability that mining activities were also present in this area.

Fifth campaign

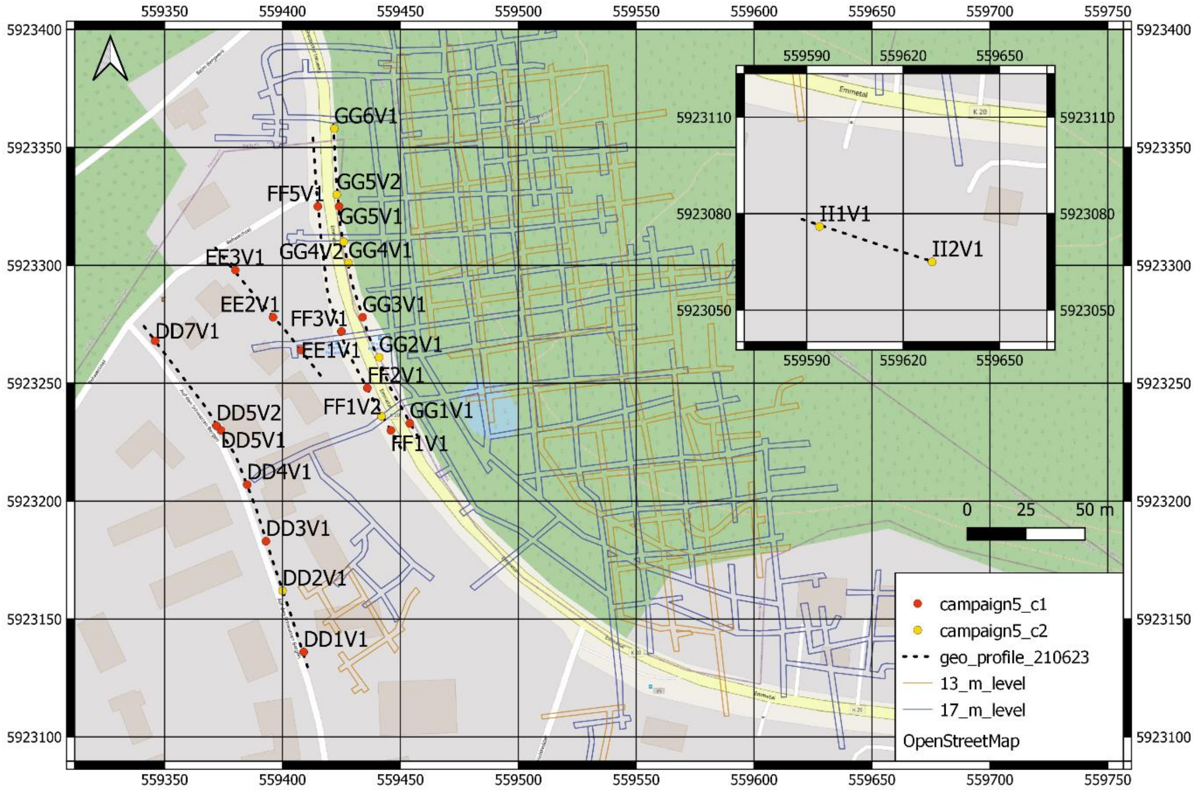


Figure 22 Fifth seismic measuring campaign

In the fifth measurement campaign, a total of five profiles with a total length of 569 m were measured and qualitatively evaluated. A total of 25 suspect areas were identified. This measurement took place in an area with high overlap. The overlap of the areas to be measured must not be greater than 30 m. Therefore, the measurements served on the one hand to find possible line extensions in western direction and on the other hand as a test whether the overlap above the cavities is too large for representative measurements. Test profile DD runs along a steeply rising road in a southerly direction. The theoretical overlay is between 21 and 37 meters.

The DD and EE profiles show only a few suspected areas, which do not always correspond to the location of drifts from the mine plan. Three suspicion points were measured on profile EE, all of which are located in an approximate extension of the routes from the mine plan. EE1V1 probably represents the known drift. Suspicion point DD4V4 represents the drift shown in the mine plan. DD1V1 shows with high probability the drift of the 13m level in spite of the high overlay of 36 m. A test by drilling could show if the measurements are successful despite the high overburden and if they can show the cavities representatively.

The same is true for profiles FF and GG, where the number of anomalies is higher. The measurements identify the already backfilled cavities in the area of the road only to a limited extent. The anomalies FF1V1 and GG1V1 are parallel to each other, but a few meters below the backfilled area. Similarly, FF3V1 and GG3V1 both lie a few meters above the backfilled drift. The backfilled drift west of “Chute 2” was not clearly detected during the measurement. Suspected points FF5V1 and GG5V1 above it are too far away from it for it to be a dislocation. It is more likely that they represent an extension of the drift east of them.

Profile II is located somewhat differently, because it was actually part of the 4th measurement campaign. Here only two weakly pronounced suspicion areas were marked.

4.5 Exploratory drilling to verify geophysical methods

In order to verify the suspicion points found, a direct exploration method must be used that can drill below the anomalies. As already explained in chapter 3.1, drillings are carried out to confirm the suspicion points. Only about half of the measured suspicion points were verified by drilling in the timeframe of this thesis. In total, 43 suspicion points were examined. Presented in the chapters below is a summary of the results of the drilling and the backfill quantities are put in context along the suspicion points that were detected during the geophysical measurements.

4.5.1 Loss of circulation

The mud drilling method is used for the exploration and securing of the former mine. The drilling fluid consists of water and transports the cuttings to the surface. For stabilization, the top section of the borehole is cased with a PVC pipe. In order to verify the detected anomalies, multiple suspicion points are approached from one drilling point. From this point, the boreholes are drilled in different directions with varying angles. The suspicion points do not provide accurate information about the depth of the cavity. For this reason, the borehole is always drilled to the 17 m level. If mud losses occur in the lower area of the borehole, the borehole is further extended until the mud loss is zero. Drilling logs are prepared to document the material type which is flushed out and the amount of mud loss. However, the details of the material type are not crucial to this work and will not be discussed. The percentage of mud loss is based on the operator's estimate and not on measurements. From the amount of mud loss, conclusions can be made about the locations of zones of loosening or cavities in the subsurface. It is only possible to estimate the size of the cavity, but not to give an exact figure.

A representation of mud losses in tabular form is unsuitable due to the amount of data and the allocation. However, the following example demonstrates the evaluation procedure. The remaining data in the form of tables and figures are part of the appendix. The boreholes were divided into areas; the results of the measurements on the property “Emmetal 26” serves as an example here. The evaluation of all boreholes was carried out respectively.

Table 5 assigns a backfill volume and mud loss to each borehole. The information on the mud loss is given per section per borehole. Start- and end points are given for this purpose. These are already calculated with the starting point on the surface and indicate the actual depth in mean sea level (MSL). It is evident that the individual sections often merge into each other or are very close to each other. Furthermore, the amount of mud loss is only an estimate by the drill rig operator. It is also noticeable that in many cases the mud loss amounts to zero or 100 percent. For this reason, an averaged value per borehole is used for the evaluation.

Table 5 Borehole parameters of the exploration area "Emmetal 26"

Borehole	**Volume** [L]	**Amount** [kg]	**GOK** [MSL]	**Mud loss**	**From** [MSL]	**To** [MSL]
g1	2910	2287	35,9	1	23,2	20,4
g2	150	118	35,9	0	-	-
g2.1	3910	3073	35,9	1	25,8	14,1
g24	140	110	35,9	0	-	-
g24.1	160	126	35,9	0	-	-
g24.2	180	141	35,9	1	27,7	23,5
g24.3	160	126	35,9	1	27,1	26,1
g24.4	140	110	35,9	1	25,2	23,0
g25	150	118	35,9	0	-	-
g25.1	1720	1352	36,3	1	20,8	16,8
g27	220	173	36	0	-	-
g27.1	200	173	36	0	-	-
g28	200	173	36	0	-	-
g29	210	165	36	0	-	-
g29.1	1110	872	36	1	18,1	11,6
g31	8730	6861	36	1	21,0	16,1
g32	12910	10147	36	1	19,8	9,5
g34	190	149	37,2	0	-	-
g34.1	210	165	37,2	0	-	-
g34.2	320	252	37,2	1	16,0	9,9
g35	220	173	37,2	1	16,4	15,9
g35.1	350	275	37,2	0,8	21,5	10,3
g36	300	236	37,2	1	22,0	8,0
g37	330	259	37,2	1	17,9	14,7
g38	280	220	37,2	1	18,4	14,0

A total of 25 holes have been drilled on the property, 15 of which have recorded mud loss. The designation of the borehole refers to the starting point. Subsequently, boreholes are drilled from the same starting point at different angles and respectively named .1, .2, .3, etc. It is noticeable that the mud loss is also 100% or zero except for borehole g35.1.

The following Figure 23 illustrates the results of the table. The mud loss is compared to the backfill volume. The highest backfill volumes are present in boreholes g31 and g32. The columns represent the backfill volume and the dots represent the mud loss height. The backfill quantities are addressed in more detail in chapter 4.5.2. An average mud loss of 89.64% occurred in 66.38% of the boreholes.

It is noticeable that an increased mud loss results in an increased backfill volume in almost all cases. A useful example are the boreholes g2 and g2.1. Both start at the same point at the surface and were drilled at different angles but in the same direction. Only g2.1 passes through a cavity and registers mud loss of 100%. During backfilling, material could only be placed in g2.1. With g2, only the borehole itself is backfilled.

On the other hand, boreholes g24 to g24.4. represent a counterexample. An increased mud loss was registered in three of the five boreholes, but only minimal amounts of material was backfilled. The reason for this may be the premature backfilling of borehole g1. This was backfilled before g24-g24.4 and could therefore have already secured this area. Boreholes g34.2, g35, g36, g37 and g38 are located in the area of the road that was backfilled during and after the end of operations, according to information of the mine records. Though, the mine plan does not mention any drifts in this area, it is assumed that mining took place beyond the documented mine plan. However, this provides an explanation for the backfill volume, but not for the mud loss in this area.

Figure 23 Correlation of mud loss and backfill volume

Figure 24 also shows the range in which mud loss occurred during drilling. The detected zones can be assigned to either the 13 or the 17 m level. The lower point of the mud loss area is of greater importance since loosened zones can migrate to the surface over the years.

The mud losses in the areas of the 17 m level are recorded at depths up to 27 meters. Also, the starting points of the mud loss lie very deep and partly clearly below the expected level. It is possible that the flush drilling has flushed out this area. Since the backfill volume does not correspond, another explanation is more likely. It is possible that the 17 m level does not apply to this area and mining took place in deeper levels.

The documented mud losses beyond this area are located at lower depths between 10 and 20 meters. These probably represent an extension of the 17 m level.

Figure 24 Mud loss range

As already explained, the boreholes constitute only linear information about the subsurface. They indicate only the area of a cavity. It is necessary to assign spatial values for these cavities. For this purpose, backfill volumes will be discussed in the next chapter.

4.5.2 Backfill quantities

The borehole represents only linear information about a spatial phenomenon. To obtain an understanding of the cavities of the subsurface, it is necessary to assign a volume to the linear data.

After a loss of circulation is detected and the borehole is encased with PVC-casing, material is placed in the cavity. Contrary to the mud loss, the quantity provides conclusions about the size of the cavity. For this purpose, a map was prepared, which provides information on the backfill quantity of the individual suspected points. The amount of backfill is never zero even if a cavity is not encountered, as the borehole must be backfilled.

The evaluation is made exemplarily on the basis of the date of the property “Emmetal 26” again. This area was investigated and evaluated during the second and third measurement campaign. Table 6 summarizes the suspicion points in this area and assigns them to a borehole. The class indicates how strong the anomaly was during the measurements, where 1 stands for strong and 2 for weak. Class 3 also exists, but was not confirmed during drilling on the property.

Table 6 Suspicion points assigned to borehole and backfill volume

Name	class	Borehole	Backfill volume [L]
A2V1	2	g2, g2.1	4060
A2V2	1	g2, g2.1	4060
A2V3	1	g2, g2.1	4060
A2V4	2	g2, g2.1	4060
B2V3	1	g34, g34.1, g34.2	1110
B2V4	1	g35	220
C2V1	1	g35	220
A2V5	1	g38	280
A2V6	1	g38	280
A3V1	2	g36	300
A3V2	1	g36	300
A3V3	1	g36	300
G4V1	2	g36	300

In this example, no correlation can be found between the strength of the anomaly at the suspicion points and the amount of backfill volume. This is due to the close proximity of the suspicion points to each other. This does not allow an exact delimitation of the findings to each other.

In total, a cavity was detected by mud loss in 36 of a total of 43 suspicion points, giving a hit rate of 83,72%. Of the 36 verified suspicion points, 23 were classified as strong anomalies and 13 as weak anomalies. All unverified suspicion points were anomalies of class 2 or lower. Thus, it can be concluded that class 1 anomalies have a 63.89 percent probability of being verified by drilling, class 2 has a 22.22 percent probability, and class 3 has a 13.89 percent probability.

Despite their low backfill volume, the suspicion points B2V3, B2V4 and C2V1 gave a decisive indication of a drift extension. Verification of the points provided evidence of this drift extension. A total of 1150 litres of backfill material was injected into that area. Based on these findings, an assumption of a mining area south of the road arose. This assumption was confirmed by drilling in December 2021.

It is apparent that there is a relationship between the strength of the anomaly and the amount of backfill. Weak anomalies were either not confirmed during drilling, or only small amounts of the construction material were placed.

During the backfilling process, mobilization of the subsoil cannot be excluded. Therefore, material can reach other nearby areas and already fill the cavity. The water content of the suspension is approx. 80% and can flush out parts of the sandy subsoil. Backfilling takes place without additional pressure, so the risk of mobilization is low, but not completely excluded.

Parts of the backfill may originate from a previous measure. Vice versa, this also serves as an explanation why in some cases less material than expected is placed. During the backfilling process there is also the possibility of mobilization of the subsoil.

5 Discussion of the results

In order to be able to answer the central question of the thesis, whether geophysics is a successful exploration method for old mining projects, the findings and problems are discussed in the following.

The data base on already performed investigations on this application example of geophysics is very limited. The selection of geophysical methods was based on a few application cases from the past as well as on advice from other companies. The insufficient data basis is mainly favoured by the fact that the implementation of similar projects is carried out by companies and there is no research topic involved.

A theoretical preselection limits the methods to seismic, geoelectric, and georadar. The deciding factor for the selection of these methods was the subsurface condition, which was very homogeneous due to the overlying sand layer. In addition, the formations searched for were located at depths of 13 and 17 m, respectively, which in turn directly ruled out some methods because their range would be too small. The cost of the measurements also factored into the pre-selection process.

The test measurements were carried out over an already known drift. This was used to evaluate the methods, as it could be examined whether the methods are able to map the route at all as expected. The aim of the test measurements was to find a suitable method for the further course of the work. For this purpose, all three measurements were made on the same profile on the grass strip along the “Emmetal” road.

Geoelectric measurements detected an inhomogeneous surface layer followed by a dry sand layer along the entire length of the test profile. This is interrupted at profile meter 70. With high probability this maps the underlying drift at a depth of about 13m. The depth of penetration is not sufficient to further verify the result. This method does not map any suspicion points in the area of the other drifts which the profile intersects. There is a gradual transition with partly very low resistivities below the already found sand layer which accounts for the penetration depth of the electromagnetic waves ending there.

The georadar measurements did not show any irregularities on the test profile. Therefore, the method was tested again on the property to the north, as well as on a property to the southwest. Similarly, below the test profiles on the properties there are already identified drifts. The georadar reached a maximum depth of investigation of approx. 8 m and can therefore only provide indications of the subsurface conditions above the possible cavities. Although it is possible that zones of loosening caused by the drifts could also be detected in the overlying strata, there are no indications to this effect.

The information density of the refraction seismic measurement is initially similar to that of the geoelectric measurement. It was already known before the measurement that small-scale cavities cannot be detected in the deeper depth range. However, an anomaly was found during the measurement in the area of the drift crossing below. For accurate measurement results the subsoil conditions must be as homogeneous as possible. The surface layers in the area investigated here consist exclusively of sand. In the area of the investigated cavities lignite was partially encountered. These conditions contribute significantly to a faster evaluation of the measurement results.

Nevertheless, it should be mentioned that the evaluation of the seismic measurements is subjective, and thus never free from errors. Furthermore, the evaluation only shows the position of the anomaly, but not the associated depth. However, for the objective of the securing, it is not necessary to image the subsurface in detail, but only to reliably detect zones of loosening. Therefore, seismic was selected as the geophysical method.

Furthermore, the economic efficiency of the method has to be considered. In this case the data basis is deficient. Prior to the implementation of the securing measures an assumption could already be made that the mine workings extended beyond the documented drifts. Also, the time required must always be taken into account for securing measures. Seismics is not a particularly time-consuming method and provides fast results. This is particularly important for short-term planning. In some cases, no cavities were encountered during drilling and rescheduling was necessary at short notice. Due to the fast availability and uncomplicated execution the project could be implemented without major delays, which can cause considerable additional costs.

Since the study area includes a residential area the surface characteristics vary. Contrary to geoelectrics, seismic measurements can be carried out on sealed surfaces as well as on soft grounds without any complications. Over the course of the work it became apparent that this saved time and therefore reduced expenses.

Seismic surveys were conducted in five measurement campaigns over the period from March to June 2021. A total of 110 suspicion points were found. These were transferred to plans and used for drilling scheduling. During drilling, as many suspicion points as possible were to be checked with one borehole due to time and cost constraints. At the same time, this made the evaluation more complicated, which will be discussed later.

A flush drilling method was used and the corresponding mud loss was documented. It amounts to between 0 and 100% during drilling and provides information about the areas in which a potential cavity is located. During the work, a total of 235 exploratory boreholes were drilled based on the geophysics measurement results. An average mud loss of 89.64% occurred in 66.38% of the boreholes. The average volume of backfill material amounts to 3,101.73 litres per borehole.

The evaluation of the data showed a clear correlation between mud loss and the subsequent backfill volume. This method is not sufficient to show the actual size of the void, since no total amount of loss is documented. Since the amount of mud loss was 100% in most cases, no correlation between the size and the backfill volume could be demonstrated. However, the mud loss gives information about the depth and location of the cavity and provides first indications about its size. In addition, there are some indications that the drilling activity mobilizes the sandy subsoil and slightly increase the size of the voids.

After drilling each borehole is secured and a water-cement mixture is injected through a PVC pipe. The backfill volumes were documented and evaluated to map the dimensions of the cavities. A disadvantage of this approach is that in retrospect it cannot be clearly assigned which backfill quantity belongs to which suspicion point. The map shows the volumes per borehole, but not the quantities per suspect point. This is due to the fact that often several boreholes were drilled in the area of a cluster of suspect points. However, the backfill quantities show a clear correlation to anomaly strength. Small amounts of backfill material were often placed at suspicion points with low anomaly strength. Boreholes planned with previous seismic measurements encounter a cavity 83.72 % of the time. This proves that seismic is a target-oriented measurement method to detect underground cavities.

The presentation of the results of the drillings with tables is not effective and is not able to represent the totality of the results. Within the scope of this work, a map was produced with the help of the software QGIS showing all detected anomalies of the measurements. While this served as a planning tool, it also provided evidence of a correlation between the detected anomaly density and the size of the cavity found. The density of suspicion points in the extended areas of the already documented drifts was noticeable. The measurements frequently indicated connecting drifts between structures. These two types, drift extensions and drift connections, have been detected by drilling in almost all cases.

The difficulty in evaluating the data is the specific allocation of a found cavity to a suspicion point. Whereas the geophysical survey collects data extensively, the boreholes only collect data on a point-by-point basis. This creates a lot of room for interpretation of the results. During the evaluation a cavity was assigned to a suspicion point if the borehole running below registered a mud loss. It is possible to use the mud loss data, because during the work a correlation between this and the backfill quantity has been proven. This correlation indicated that backfill material can be inserted into boreholes with mud loss. The mud loss data is the only information that provides accurate data on the depth of the supposed cavity. This allowed the backfill quantity to be additionally assigned to one of the two excavation levels.

In addition, the overall goal of properly securing the subsurface should not be ignored. The backfilling work is based solely on the plans based on the seismic measurements. After securing a total of 92 control boreholes were drilled, taking into account the necessary setting time and after completion of the drilling and backfilling work. This allowed to verify the reliability of the safety measures. In 27.17% of the control boreholes an inadequately secured zone was encountered. These zones were identified by flushing loss. Subsequently, backfill material was placed into these zones again. In the control drillings the average amount of backfill material required per well is approximately 1,423 litres. About 245 litres are required on average for backfilling the borehole itself. This results in an average quantity of 1,178 litres per rework. In the remaining cases (72.82%), the previously placed and cured backfill material was encountered. It can therefore be assumed that the desired securing success has been achieved and that no further movements of the ground surface are to be expected.

6 Conclusion

Within the scope of this work, geophysical measuring methods were investigated with regard to their applicability in securing measures in old mines. The former underground lignite mine “Robertshall”, which stopped production about 100 years ago, served as an application example. Initially, three geophysical measurement methods were evaluated on a test profile. With regard to the general suitability under the given conditions, seismics was found to be the optimum investigation method. Although georadar and geoelectrics provide a very good visualization of geological characteristics, it did not allow any statement with regard to the designation of the drifts on the test profile.

About half of the detected suspicion points could be verified by drilling during the course of the work. In total, a cavity was detected by mud loss in 36 of a total of 43 suspicion points, giving a hit rate of 83,72%. Of the 36 verified suspicion points, 23 were classified as strong anomalies and 13 as weak anomalies. All unverified suspicion points were anomalies of class 2 or lower. Thus, it can be concluded that class 1 anomalies have a 63.89 percent probability of being verified by drilling, class 2 has a 22.22 percent probability, and class 3 has a 13.89 percent probability.

The borehole constitutes of only linear information about a spatial phenomenon. To gain an understanding of the cavities, the backfill volume must be assigned to the linear data. The volume was correlated to the anomaly strength of the respective suspicion point. No reliable correlation between backfill quantities and anomaly strength could be established. One reason for this was the proximity of the suspicion points to each other, which made a clear assignment to a borehole difficult. Another reason could be the migration of backfill material in nearby boreholes.

After the evaluation of the data, it can be concluded that geophysics provide a cost and time advantage compared to conventional securing methods. Previous measurements mad it possible to avoid large-scale drilling campaigns and selectively verify assumptions about underground structures. In the example of the “Robertshall” mine, the securing of the subsurface with the help of the collected data geophysics was successful.

7 Bibliography

Bell, F. G., Stacey, T. R., & Genske, D. D. (2000). Mining subsidence and its effect on the environment: some differing examples. *Environmental Geology, 40*, S. 135-152.

Berckhemer, H. (1997). *Grundlagen der Geophysik.* Darmstadt: Wissenschaftliche Buchgesellschaft.

Bergamt Hannover. (1921). Acta betreffend Braunkohlebergwerk Robertshall - Betrieb.

Brassert, H. (1888). Allgemeines Berggesetz für die Preußischen Staaten vom 24. Juni 1865.

Bücker, M., Lozano, S., & Ortega, B. (Jun 2017). Geoelectrical and Electromagnetic Methods Applied to Paleolimnological Studies: Two Examples from Desiccated Lakes in the Basin of Mexico. *Bol. Soc. Geol. Mex [online]*, S. 279-298.

Buja, H. O. (2013). *Ingenieurhandbuch Bergbautechnik, Lagerstätten und Gewinnungstechnik.* Berlin: Beuth Verlag GmbH Berlin-Wien-Zürich.

Clauser, C., Arnold, J., Peching, R., Anferove, S., Anferov, V., & Blümich, B. (47 2006). Porosity and Permeability from Mobile NMR Core-Scanning. *Petrophysics*.

Daniels, D. (2004). Ground Penetrating Radar (2nd ed.). In Knoval. Institution of Engineering and Technology.

Ernstson, K. (2018). Geologische und geophysikalische Untersuchungen. In M. B. al, *Handbuch Oberflächennahe Geothermie* (S. 65-219). Springer-Verlag GmbH Deutschland.

Fritzsche, C. H. (1962). *Lehrbuch der Bergbaukunde.* Berlin/Göttingen/Heidelberg: Springer Verlag.

Giesen, S. (2010). *Bodenbewegungen infolge von Sümpfungsmaßnahmen für tiefe Tagebaue am Beispiel des Rheinischen Braunkohlenreviers.* Aachen: Rheinisch-Westfälische Technische Hochschule Aachen.

Grasmück, M., & Green, A. G. (1996). 3-D Georadar Mapping: Looking Into the Subsurface. *Environmental and Engineering Geoscience*, S. 195-200.

Hamburgisches Welt-Wirtschafts-Achiv (HWWA) (Ed.). (1949). Situation der westdeutschen Gummi-Industrie. *Wirtschaftsdienst*, S. Vol. 29, Iss. 2, pp. 48-50.

Hennigsen, D., & Katzung, G. (2006). *Einführung in die Geologie Deutschlands.* München: Spektrum Akademischer Verlag.

Hülsmann, K. H. (1 1992). Gesichtspunkte bei der Sicherung stillgelegter Tagesschächte. *Neue Bergbautechnik*, S. 3-8.

Hustrulid, W. (1982). *Underground mining methods handbook.* United States.

Johnson, W. J., Snow, R. E., & Clark, J. C. (2002). Surface Geophysical Methods for Detection of Underground Mine Workings. *Symposium on Geotechnical Methods for Mine Mapping Verifications.* Charleston, West Virginia.

Jol, H. (2008). *Ground Penetrating Radar - Theory and Applications.* Elsevier Science.

Knödel, K., Krummel, H., & Lange, G. (1997). *Handbuch zur Erkundung des Untergrunds von Deponien und Altlasten, Bd. 3: Geophysik.* Springer.

Kratzsch, D. H. (1983). *Mining Subsidence Engineering.* Heidelberg: Springer-Verlag Berlin.

Kratzsch, H. (2004). *Bergschadenkunde.* Bochum: Deutscher Markscheider-Verein e.V., Bochum 2004.

Kuehne, G., & Trelease, F. J. (Vol. 19, Iss. 2 1984). The New West German Mining Law. *Land & Water Law Review*, S. 371-394.

Lauerwald, U. (2000). *Die Bilanzierung und Prüfung von behebungspflichtigen und nicht behebungspflichtigen ökologischen Lasten.* Köln: Josef Eul Verlag.

Loke, D. M. (2004). *2-D and 3-D electrical imaging surveys.*

Marcak, H. (1999). Formation of sinkholes and other forms of deformation of discontinuous surfaces. *Mat. Symp. "Workshops '99"*, (S. 71-84).

Meier, G. (1999). Ingenieurgeologische Problemstellungen bei der Erkundung und Verwahrung von tagesnahen Hohlräumen und Altbergbau im mitteldeutschen Raum. *12. Nat. Tagung f. Ing-Geol.*, (S. 39-47). Halle.

Meier, G. (2001). Altbergbau in Deutschland: Umfänge Probleme Bearbeitung. *Altbergbau-Kolloquium* (S. 5-17). Freiberg: TU Bergakademie Freiberg.

Meier, G. (2001). Zur Effektivität von Bohraufschlüssen bei der Altbergbauerkundung. *13. Nat. Tagung f. Ing.-Geol.*, (S. 225-226). Karlsruhe.

Meier, G. (2004). Empfehlung "Geotechnisch-markscheiderische Untersuchung und Bewertung von Altbergbau" des Arbeitskreieses 4.6 der Fachsektion Ingenieurgeologie der DGGT e.V. *4. Altbergbau-Kolloquium* (S. 1-23). Essen: Verlag Glückauf.

Meier, G. (2007). Geotechnisch-markscheiderische Anforderungen an Sicherungen und Verwahrungen von Schächten im Altbergbau. *7. Altbergbau-Kolloquium* (S. 188-196). Freiberg: VGE Verlag GmbH.

Meyer-Abich, K.-M. (1982). *Energy Issues and Policies in the Federal Republic of Germany.* Frankfurt: Insitute Market and Plan, Department of Ecomonics, University of Frankfurt.

Ott, M. (1976). *Gefährdung der Tagesoberfläche durch Tagesbrüche in Braunkohlentiefbaubereichen des Bezirkes Halle.* Freiberg: Bergakademie Freiberg.

Peng, S. S. (2020). *Surface Subsidence Engineering - Theory and Practice.* Australia: CRC Press/Balkema.

Pilecki, Z. (2003). Die Anwendung geophysikalischer Methoden bei der Lösung von Altbergbau-Problemen. *3. Altbergbau-Kolloquium* (S. 1-10). Freiberg: VGE Verlag GmbH.

Prigge, H. (1956). Das Braunkohlebergwerk "Robertshall" bei Hamburg-Hausbruch. In *Harburger Jahrbuch.* Veröffentlichung des Helms-Museums Nr. 8.

Randjbar, B., & Schuscha, E. (4 2008). Ein Beitrag zu den bergschadenkundlichen Untersuchungen von Altbergbauen in Österreich. *BHM*, S. 133-137.

Skolnik, M. (2008). *Radar Handbook, Third Edition.* McGraw-Hill Professional.

Stefanko, R. (1983). *Coal mining technology: theory and practice.* United States.

Tamáskovics, N. (2016). Begschadenkunde, gestern, heute und morgen. *17. Geokinematischer Tag* (S. 284-295). Freiberg: Technische Universität Bergakademie Freiberg.

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (2010). *Applied Geophysics.* Cambridge: Cambridge University Press.

Walter, R. (1995). *Geologie von Mitteleuropa.* Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung.

8 Appendix

Appendix 1: Suspicion points and assigned boreholes

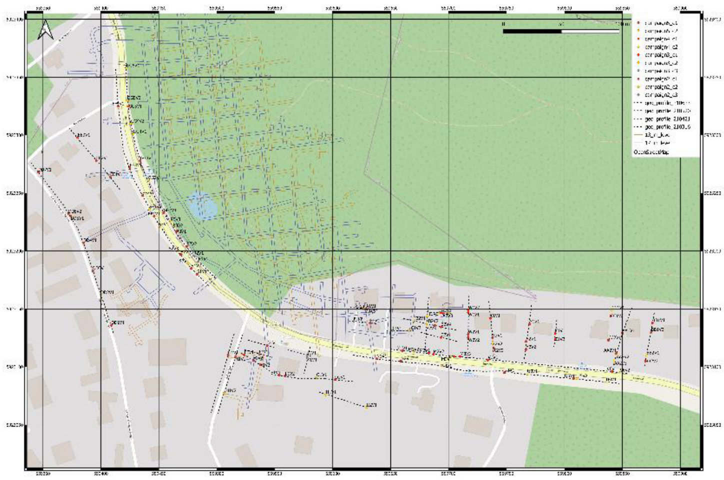
Campaign number	Name	local		UTM				Class	Confirmed by drilling	Borehole	Backfill volume [L]
		R1	**R2**	**X1**	**Y1**	**X2**	**Y2**		**y/n**		
2	A1V1	12		559627,3	5923150,2			2	y	g11	480
	A1V2	13,5		559628,7	5923150,1			1	y	g11	480
	A1V3	11		559626,3	5923150,3			3	y	g11	480
	A2V1	11		559692,3	5923146,7			2	y	g2	4060
	A2V2	12		559693,2	5923146,6			1	y	g2, g2.1	4060
	A2V3	13,8		559695	5923146,5			1	y	g2, g2.1	4060
	A2V4	19		559700	5923146,2			2	y	g2, g2.1	4060
	B1V1	18		559632,2	5923137,9			1	y	g21	2960
	B1V2	4	23	559618,2	5923139,4	559637,2	5923137,4	3	y	g12.1	370
	B2V1	9		559670	5923139,7			2	n	-	
	B2V2	20,5		559681	5923137,3			2	n	-	
	B2V3	28,5		559688,2	5923135,7			1	y	g34, g34.1, g34.2	1110
	B2V4	33,5		559693,5	5923134,5			1	y	g35	220
	C1V1	5	19	559651,8	5923131,5	559665,5	5923131,4	3	n	-	
	C1V2	19,5		559666	5923131,4			2	n	-	
	C2V1	18		559693,5	5923125,4			1	y	g35	220
	D1V1	17		559543,6	5923118,5			1	y	h5	220
	E1V1	13		559536,7	5923111,2			3	y	h9, h7, h8, h10, h6	22870
	F1V1	3		559523,7	5923110,4			1	y	h10	620
	F1V2	12		559531,5	5923105,5			1	y	h9, h8	16380
	F1V3	19		559537,6	5923101,7			1	y	h7, h12.1, h13	17980
	G1V1	19		559509,7	5923110,1			1	y	h2, h1.8, h21, h22	16460
	H1V1	20		559516,1	5923108,6			1	y	h2, h1.8, h21, h22	16460
	H1V2	53		559506,3	5923077,3			2	y	h16	190

	I1V1	23,5		559681,6	5923143,5			2	n	-	
3	M1V1	10		559659,7	5923114,2			1	y	g33	18600
	M1V2	20		559669,6	5923113,1			2	y	g33	18600
	M2V1	10,5		559682,9	5923111,5			1	y	g38	280
	M2V2	15		559687,4	5923111			1	y	g38	280
	M3V1	6		559702,3	5923109,3			2	y	g36	300
	M3V2	8,5		559704,7	5923109,1			1	y	g36	300
	M3V3	14		559710,2	5923108,6			1	y	g36	300
	N1V1	20		559637,5	5923107			1	y	vb36.3, vb27.2	1960
	N2V1	19		559659,3	5923104,5			1	y	g33	18600
	N4V1	6		559693,9	5923100,7			2	y	g36	300
	O1V1	15,5		559586,3	5923090,5			2	y	g39	9350
	O2V1	8,5		559602,2	5923088,9			1	y	g47	3420
	J1V1	3		559578,2	5923109,9			3	y	g43, g44	790
	K1V1	9		559578,4	5923107,9			3	y	g43, g44	790
	L1V1	7		559554,1	5923092,6			1	y	p1, p2, p2.1, p24, p25	39750
	L1V2	11,5		559558,6	5923092			1	y	p1, p2, p2.1	12460
	S1V1	14		559482,9	5923180,3			1	-		
	S1V2	21		559478	5923185,2			1	-		
	S2V1	3		559474,7	5923189			2	-		
	S2V2	13		559468,6	5923196,8			1	-		
	S2V3	17,5		559465,8	5923200,3			2	-		
	S3V1	16,5		559451,3	5923221,2			2	-		
	R1V1	20,5		559484,2	5923191,4			3	-		
	R2V1	4		559479,9	5923196,3			3	-		
	R2V2	14	18,5	559473,7	5923204	559470,9	5923207,5	1	-		
	R3V1	6	10	559464,5	5923216,9	559462,5	5923220,4	1	-		
	R3V2	12		559461,5	5923222,1			2	-		
	R3V3	15		559460,1	5923224,7			2	-		

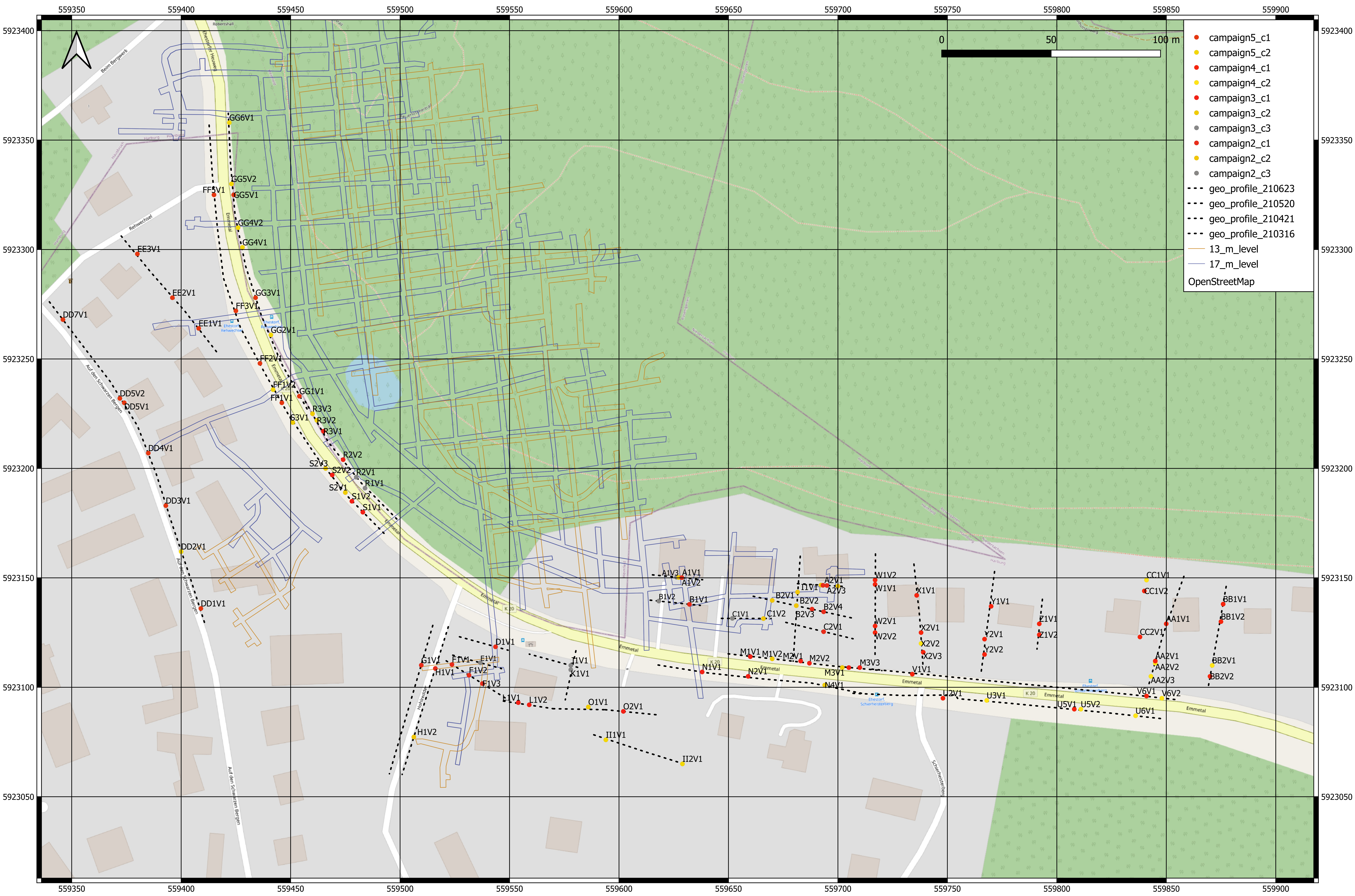
4	AA1V1	18		559850,2	5923128,5			1	-		
	AA2V1	12		559845,2	5923112,3			1	-		
	AA2V2	13	15	559844,9	5923111,3	559844,4	5923109,4	2	-		
	AA2V3	19,5		559843,2	5923105,1			2	-		
	BB1V1	8		559876	5923138,3			1	-		
	BB1V2	16,5		559874,5	5923129,9			1	-		
	BB2V1	14	16	559870,9	5923109,9	559870,6	5923108	2	-		
	BB2V2	19		559870,1	5923105			1	-		
	CC1V1	11		559840,7	5923148,6			2	-		
	CC1V2	16		559840,1	5923143,6			1	-		
	CC2V1	14		559837,7	5923122,8			1	-		
	U2V1	18		559747,8	5923095,2			1	-		
	U3V1	13		559767,6	5923093,7			2	-		
	U5V1	7		559808,2	5923089,8			1	-		
	U5V2	10	13	559811,2	5923089,5	559814,2	5923089,2	2	-		
	U6V1	11	14	559835,9	5923087	559838,9	5923086,7	2	-		
	V1V1	19		559734,4	5923106,4			1	-		
	V6V1	9		559841,4	5923095,8			1	-		
	V6V2	16		559848,4	5923095			2	-		
	W1V1	14		559717,1	5923147			1	-		
	W1V2	12		559717,1	5923149			1	-		
	W2V1	10		559717	5923128,1			1	-		
	W2V2	13		559717	5923125,1			1	-		
	X1V1	15		559736,3	5923141,5			1	-		
	X2V1	8		559737,9	5923124,7			1	-		
	X2V2	13		559738,2	5923119,7			2	-		
	X2V3	17		559738,5	5923115,8			1	-		
	Y1V1	16		559769,5	5923137,2			1	-		
	Y2V1	9		559767,4	5923121,5			1	-		

	Y2V2	16		559766,5	5923114,6			1	-		
	Z1V1	11		559792,3	5923129,3			1	-		
	Z1V2	16		559791,7	5923124,4			1	-		
5	DD1V1	6,5		559408,7	5923135,8			1	-		
	DD2V1	10,5		559400,1	5923162,2			2	-		
	DD3V1	9		559393,1	5923183,3			1	-		
	DD4V1	10		559385,1	5923206,6			1	-		
	DD5V1	12		559373,8	5923229,5			1	-		
	DD5V2	15	16	559372,3	5923232,1	559371,8	5923232,9	1	-		
	DD7V1	12	15	559346	5923268	559344,2	5923270,3	1	-		
	EE1V1	13		559408	5923263,8			1	-		
	EE2V1	8		559396,4	5923277,9			1	-		
	EE3V1	10	11	559379,7	5923297,5	559379,1	5923298,3	1	-		
	FF1V1	8		559446,2	5923229,5			1	-		
	FF1V2	16		559442,3	5923236,3			2	-		
	FF2V1	5		559436	5923247,6			1	-		
	FF3V1	8	10	559424,5	5923271,8	559423,9	5923273,7	1	-		
	FF5V1	14	17	559415,2	5923324,5	559414,9	5923327,4	1	-		
	GG1V1	7	10	559454,1	5923233,2	559452,6	5923235,8	1	-		
	GG2V1	14		559440,5	5923260,7			2	-		
	GG3V1	8,5		559434,1	5923277,8			1	-		
	GG4V1	9		559427,6	5923301,2			2	-		
	GG4V2	18		559425,8	5923309,9			2	-		
	GG5V1	9	10	559423,8	5923324,6	559423,8	5923325,6	1	-		
	GG5V2	14		559423,4	5923329,6			2	-		
	GG6V1	19	20	559421,7	5923358,3	559421,7	5923359,3	2	-		
	II1V1	6		559594,2	5923076,4			2	n		
	II2V1	19		559629,1	5923065,1			2	n		

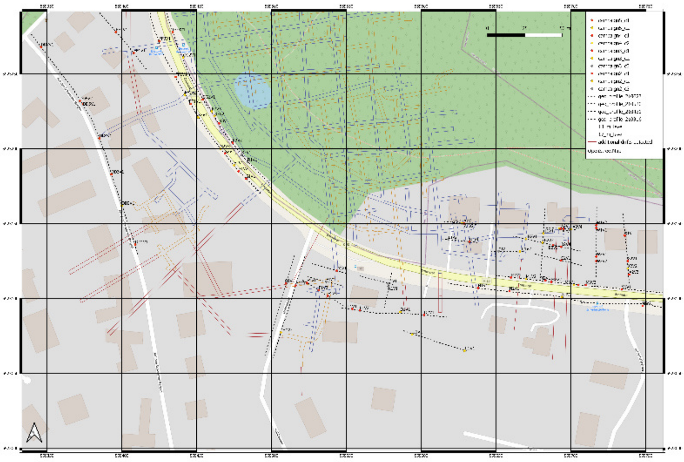
Appendix 2: Map presentation of all detected anomalies



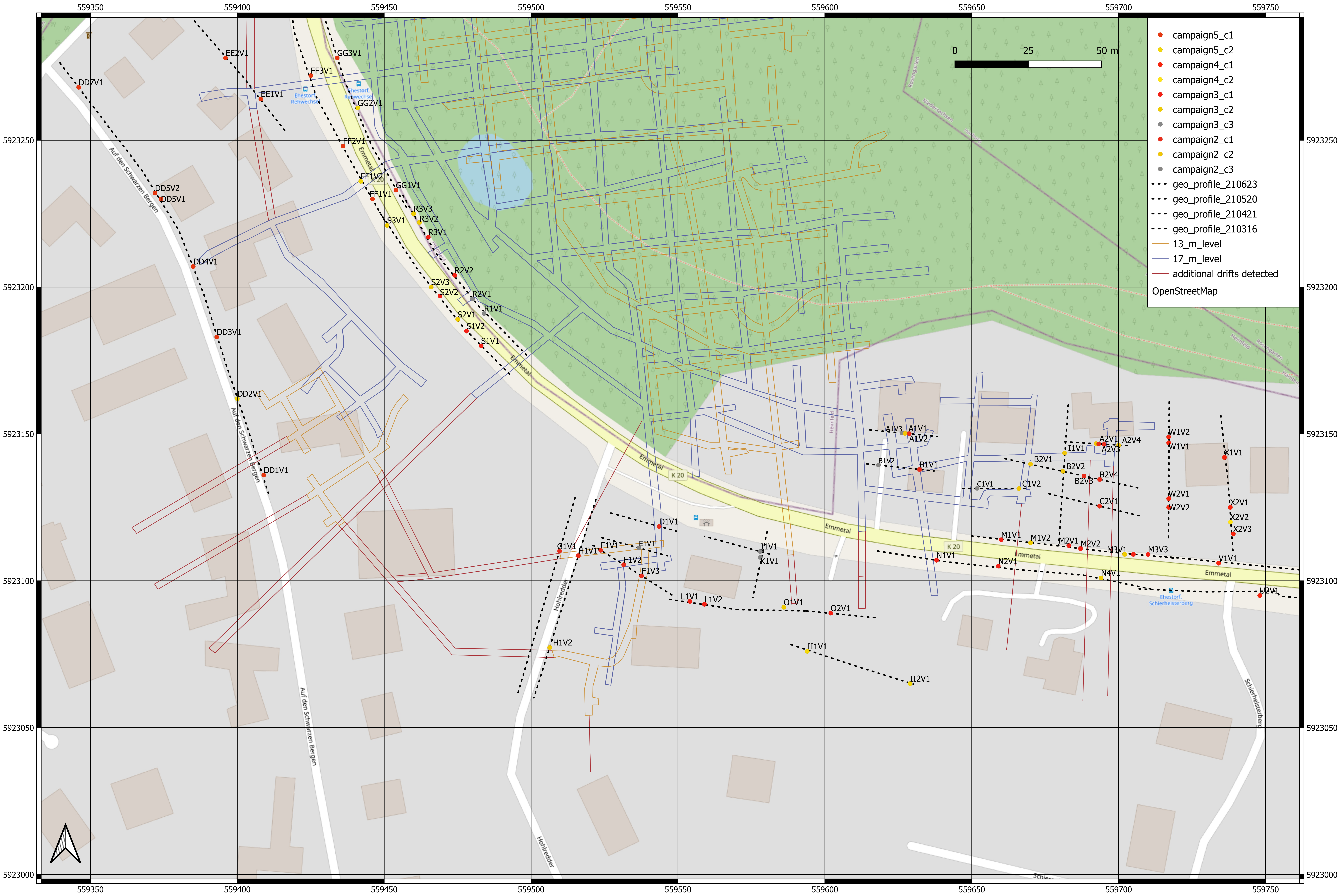
(see back)


559350
559400
559450
559500
559550
559600
559650
559700
559750
559800
559850
559900
5923400
5923350
5923300
5923250
5923200
5923150
5923100
5923050
0
50
100 m
campaign5_c1
campaign5_c2
campaign4_c1
campaign4_c2
campaign3_c1
campaign3_c2
campaign3_c3
campaign2_c1
campaign2_c2
campaign2_c3
geo_profile_210623
geo_profile_210520
geo_profile_210421
geo_profile_210316
13_m_level
17_m_level
OpenStreetMap
GG6V1
GG5V2
GG5V1
FF5V1
GG4V2
GG4V1
EE3V1
EE2V1
GG3V1
FF3V1
EE1V1
GG2V1
DD7V1
FF2V1
FF1V2
FF1V1
GG1V1
DD5V2
DD5V1
R3V3
S3V1
R3V2
R3V1
DD4V1
R2V2
S2V3
S2V2
R2V1
R1V1
S2V1
S1V2
S1V1
DD3V1
DD2V1
DD1V1
A1V3
A1V1
A1V2
B1V2
B1V1
I1V1
A2V1
A2V3
B2V1
B2V2
B2V3
B2V4
C1V1
C1V2
C2V1
W1V2
W1V1
X1V1
W2V1
W2V2
X2V1
X2V2
X2V3
Y1V1
Y2V1
Y2V2
Z1V1
Z1V2
CC1V1
CC1V2
CC2V1
AA1V1
AA2V1
AA2V2
AA2V3
BB1V1
BB1V2
BB2V1
BB2V2
D1V1
G1V1
E1V1
H1V1
F1V2
F1V3
J1V1
K1V1
L1V1
L1V2
O1V1
O2V1
H1V2
II1V1
II2V1
M1V1
M1V2
M2V1
M2V2
M3V3
M3V1
N1V1
N2V1
N4V1
V1V1
U2V1
U3V1
U5V1
U5V2
U6V1
V6V1
V6V2
Emmetal
Ehestorfer Heuweg
Beim Bergwerk
Rehwechsel
Auf den Schwarzen Bergen
Schierhesterberg
K 20

Appendix 3: Map presentation of additional proven drifts



(see back)

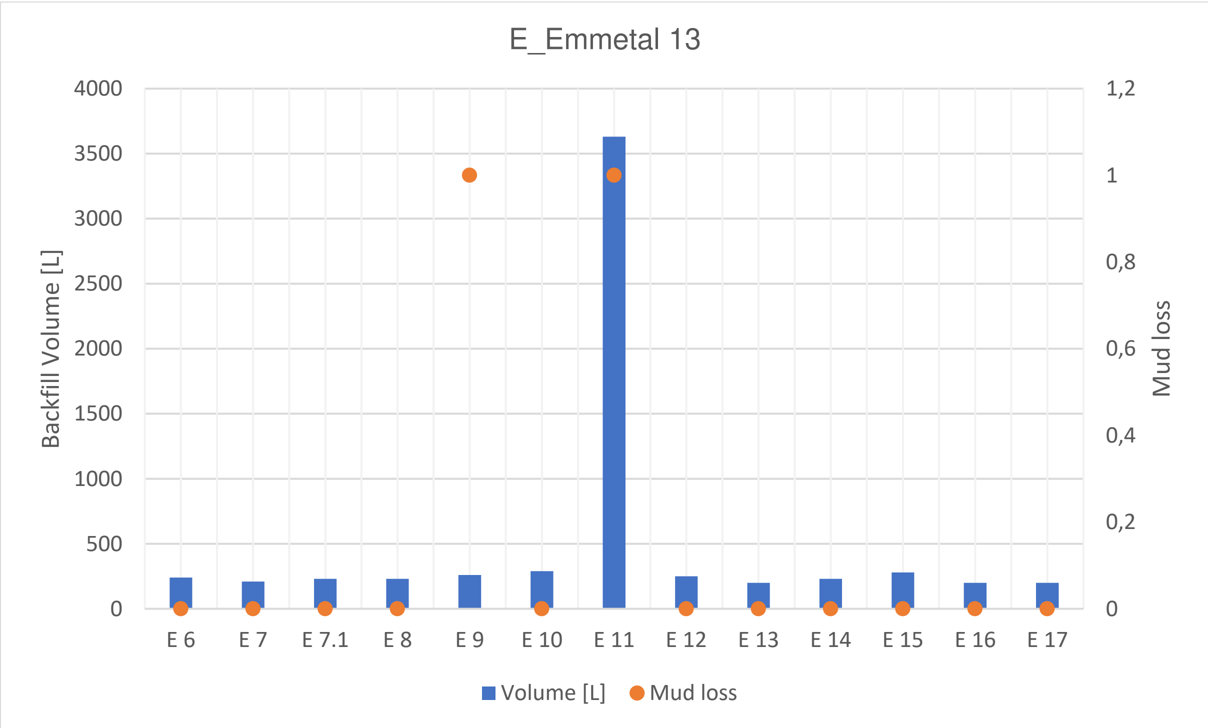


559350
559400
559450
559500
559550
559600
559650
559700
559750
5923250
5923200
5923150
5923100
5923050
5923000
0
25
50 m
campaign5_c1
campaign5_c2
campaign4_c1
campaign4_c2
campaign3_c1
campaign3_c2
campaign3_c3
campaign2_c1
campaign2_c2
campaign2_c3
geo_profile_210623
geo_profile_210520
geo_profile_210421
geo_profile_210316
13_m_level
17_m_level
additional drifts detected
OpenStreetMap
EE2V1
EE1V1
GG3V1
FF3V1
GG2V1
FF2V1
DD7V1
DD5V2
DD5V1
FF1V2
FF1V1
GG1V1
R3V3
R3V2
R3V1
S3V1
DD4V1
R2V2
S2V3
S2V2
R2V1
R1V1
S2V1
S1V2
S1V1
DD3V1
DD2V1
DD1V1
A1V3
A1V1
A1V2
B1V2
B1V1
C1V1
C1V2
B2V1
B2V2
B2V3
B2V4
I1V1
A2V1
A2V3
A2V4
W1V2
W1V1
X1V1
C2V1
W2V1
W2V2
X2V1
X2V2
X2V3
D1V1
G1V1
H1V1
F1V1
E1V1
F1V2
F1V3
J1V1
K1V1
M1V1
M1V2
M2V1
M2V2
M3V1
M3V3
N1V1
N2V1
N4V1
Y1V1
Y2V1
L1V1
L1V2
O1V1
O2V1
H1V2
II1V1
II2V1
Auf den Schwarzen Bergen
Emmetal
Hohlredder
K 20
Ehestorf, Rehwechsel
Ehestorf, Schierheisterberg
Schierheisterberg

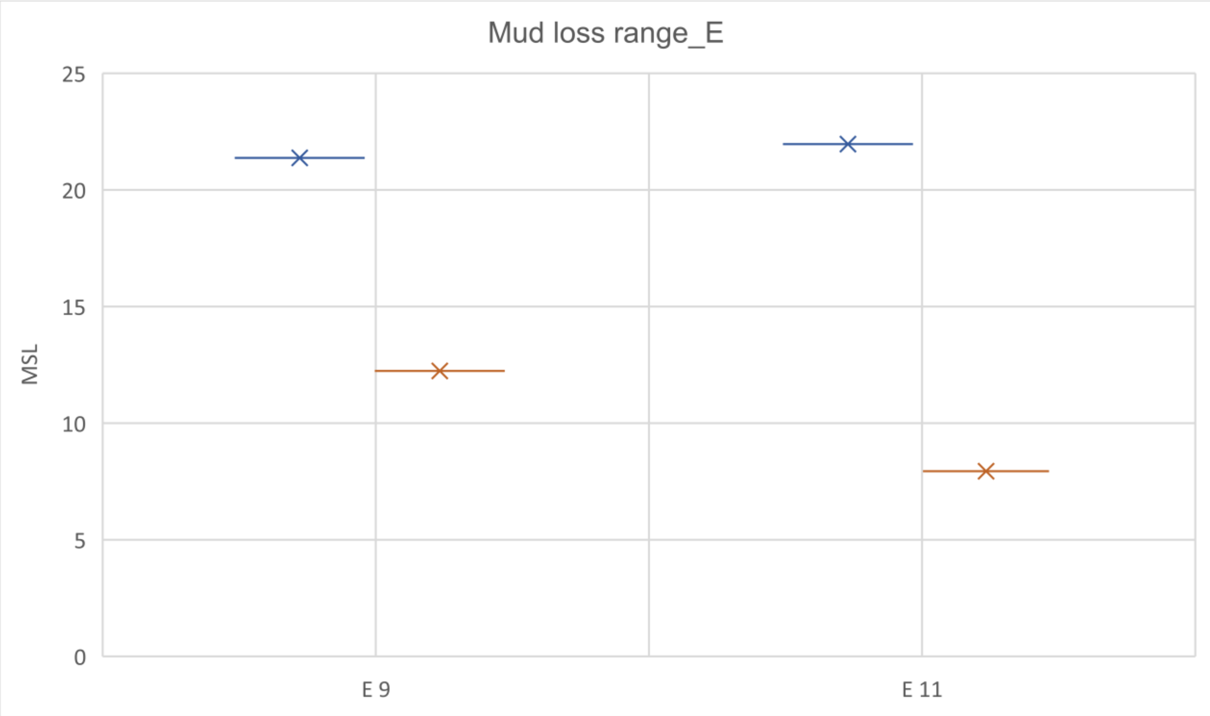
Appendix 4.1: Boreholes E

Borehole	Volume [L]	Amount [kg]	MSL	Mud loss	From [MSL]	To [MSL]
E 6	240	188	44	0		
E 7	210	165	44	0		
E 7.1	230	180	44	0		
E 8	230	180	44	0		
E 9	260	204	44	1	21,2	12,2
E 10	290	227	44	0		
E 11	3630	2853	44	1	21,9	7,9
E 12	250	196	44	0		
E 13	200	157	44	0		
E 14	230	180	44	0		
E 15	280	220	44	0		
E 16	200	157	37	0		
E 17	200	157	37	0		

Appendix 4.2: Backfill Volumes and Mud loss



Appendix 4.3: Mud loss

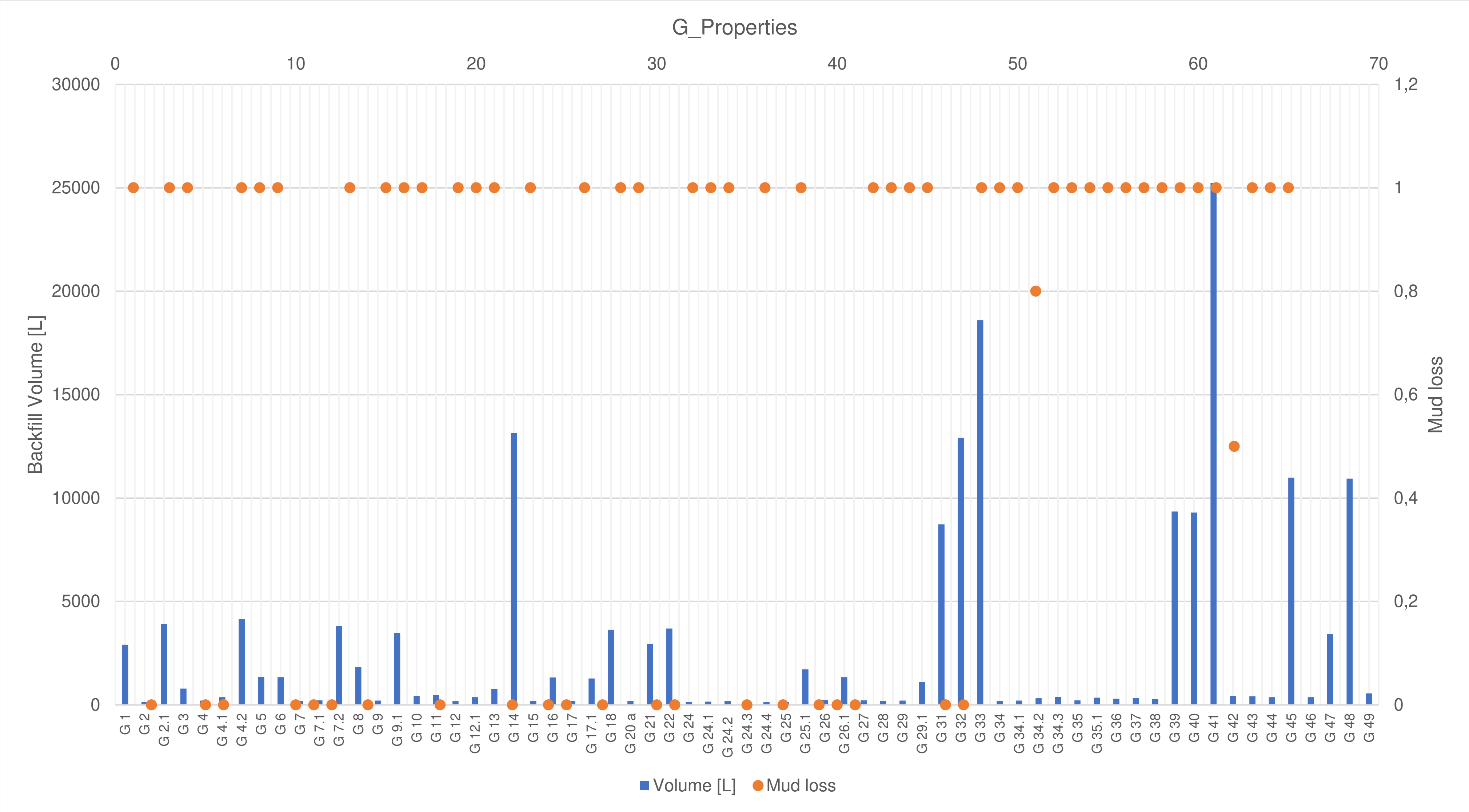


Appendix 5.1: Boreholes G

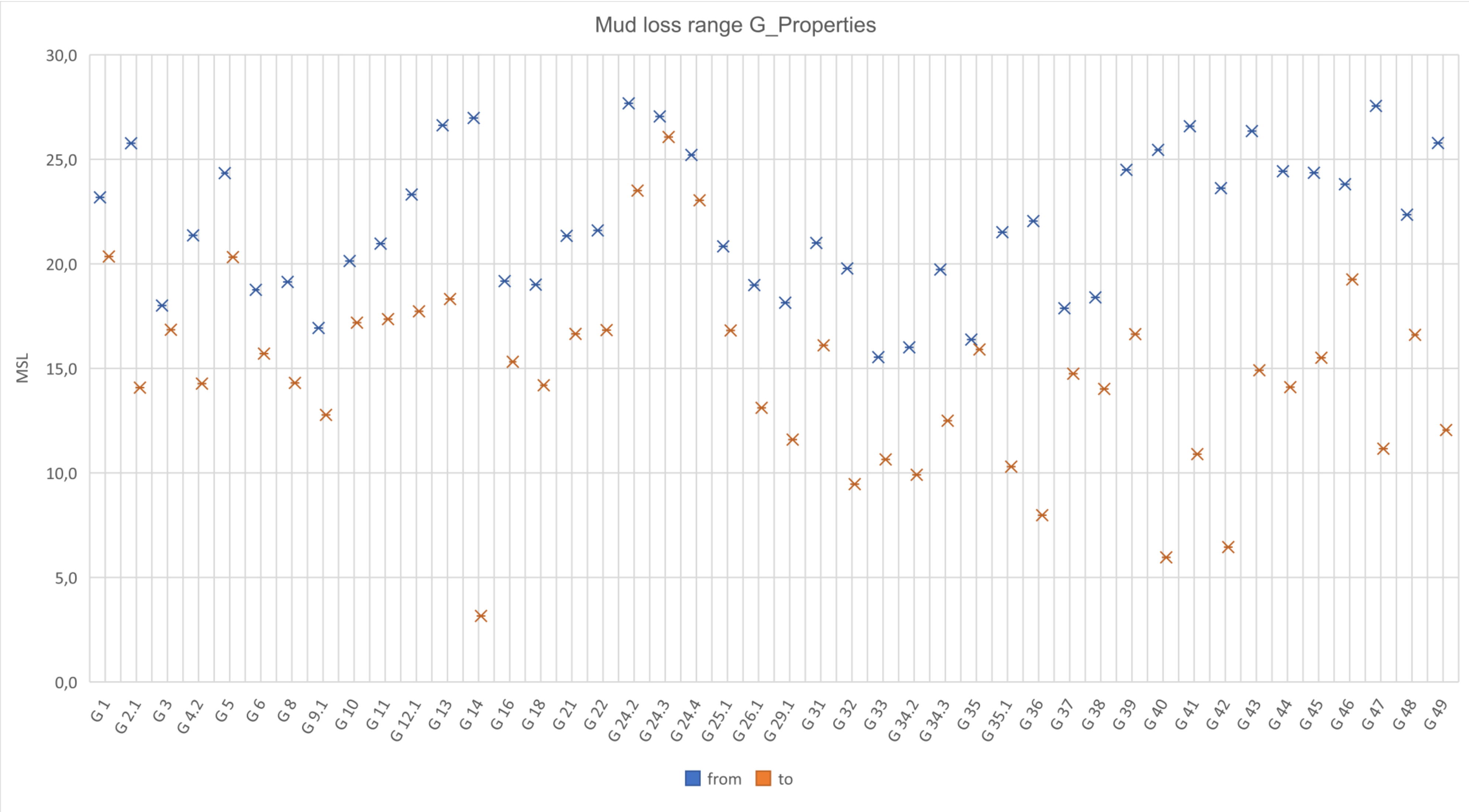
Borehole	Volume [L]	Amount [kg]	MSL	Mud loss	From [MSL]	To [MSL]
G 1	2910	2287	35,88	1	23,2	21,8
				1	20,8	20,4
G 2	150	118	35,88	0		
G 2.1	3910	3073	35,88	1	25,8	25,1
				1	22,1	14,1
G 3	790	621	36,34	1	18,0	16,8
G 4	210	165	36,55	0		
G 4.1	370	291	36,55	0		
G 4.2	4150	3262	36,55	1	21,4	14,3
G 5	1350	1061	36,55	1	24,3	20,3
G 6	1340	1053	34,78	1	18,8	15,7
G 7	190	149	34,78	0		
G 7.1	220	173	34,78	0		
G 7.2	3810	2994	34,78	0		
G 8	1830	1438	34,78	1	19,1	14,3
G 9	210	165	35,13	0		
G 9.1	3480	2735	35,13	1	16,9	12,8
G 10	430	338	35,13	1	20,1	17,2
G 11	480	377	35,13	1	21,0	17,4
G 12	180	141	36,06	0		
G 12.1	370	291	36,06	1	23,3	17,7
G 13	770	605	36,06	1	26,6	26,1
				1	23,0	18,3
G 14	13150	10335	36,06	1	27,0	3,2
G 15	190	149		0		
G 16	1330	1045	36,34	1	19,2	15,3
G 17	190	149	36,55	0		
G 17.1	1280	1006	36,55	0		
G 18	3630	2853	35,13	1	19,0	14,2
G 20 a	190	149	35,13	0		
G 21	2960	2326	36,06	1	21,3	16,6
G 22	3690	2900	35,88	1	21,6	16,8
G 24	140	110	35,88	0		
G 24.1	160	126	35,88	0		
G 24.2	180	141	35,88	1	27,7	23,5
G 24.3	160	126	35,88	1	27,1	26,1
G 24.4	140	110	35,88	1	25,2	23,0
G 25	150	118	35,88	0		
G 25.1	1720	1352	36,34	1	20,8	16,8
G 26	230	181	36,34	0		
G 26.1	1340	1053	36	1	19,0	13,1
G 27	220	173	36	0		
G 28	200	173	36	0		

G 29	210	165	36	0		
G 29.1	1110	872	36	1	18,1	11,6
G 31	8730	6861	36	1	21,0	16,1
G 32	12910	10147	36	1	19,8	9,5
G 33	18600	14620	36,34	1	15,5	15,2
				0,5	15,2	14,0
				0,8	14,0	10,6
G 34	190	149	37,20	0		
G 34.1	210	165	37,20	0		
G 34.2	320	252	37,20	1	16,0	9,9
G 34.3	390	307	37,20	1	19,7	12,5
G 35	220	173	37,20	1	16,4	15,9
G 35.1	350	275	37,20	0,8	21,5	19,9
				1	19,9	10,3
G 36	300	236	37,20	1	22,0	8,0
G 37	330	259	37,20	1	17,9	14,7
G 38	280	220	37,20	1	18,4	14,0
G 39	9350	7350	35,66	1	24,5	16,6
G 40	9300	7310	35,66	1	25,4	6,0
G 41	25230	19831	35,66	1	26,6	25,2
				1	19,6	10,9
G 42	440	346	35,66	1	23,6	6,4
G 43	420	330	35,66	1	26,3	14,9
G 44	370	291	35,66	1	24,4	14,1
G 45	10990	8638	37,44	1	24,4	15,5
G 46	370	291	37,44	0,5	23,8	19,3
G 47	3420	2688	37,44	1	27,6	26,1
				0,5	26,1	22,2
				1	22,2	21,3
				0,5	21,3	20,2
				0,8	20,2	19,5
				1	19,5	16,0
				0,5	16,0	14,4
				1	14,4	13,1
				0,5	13,1	11,2
G 48	10940	8598,98	38,82	1	22,4	20,8
				0,8	20,8	16,6
G 49	560	440,16	38,82	1	25,8	25,4
				0,8	21,1	12,1

Appendix 5.2: Backfill Volumes and Mud loss G



Appendix 5.3: Mus loss range G

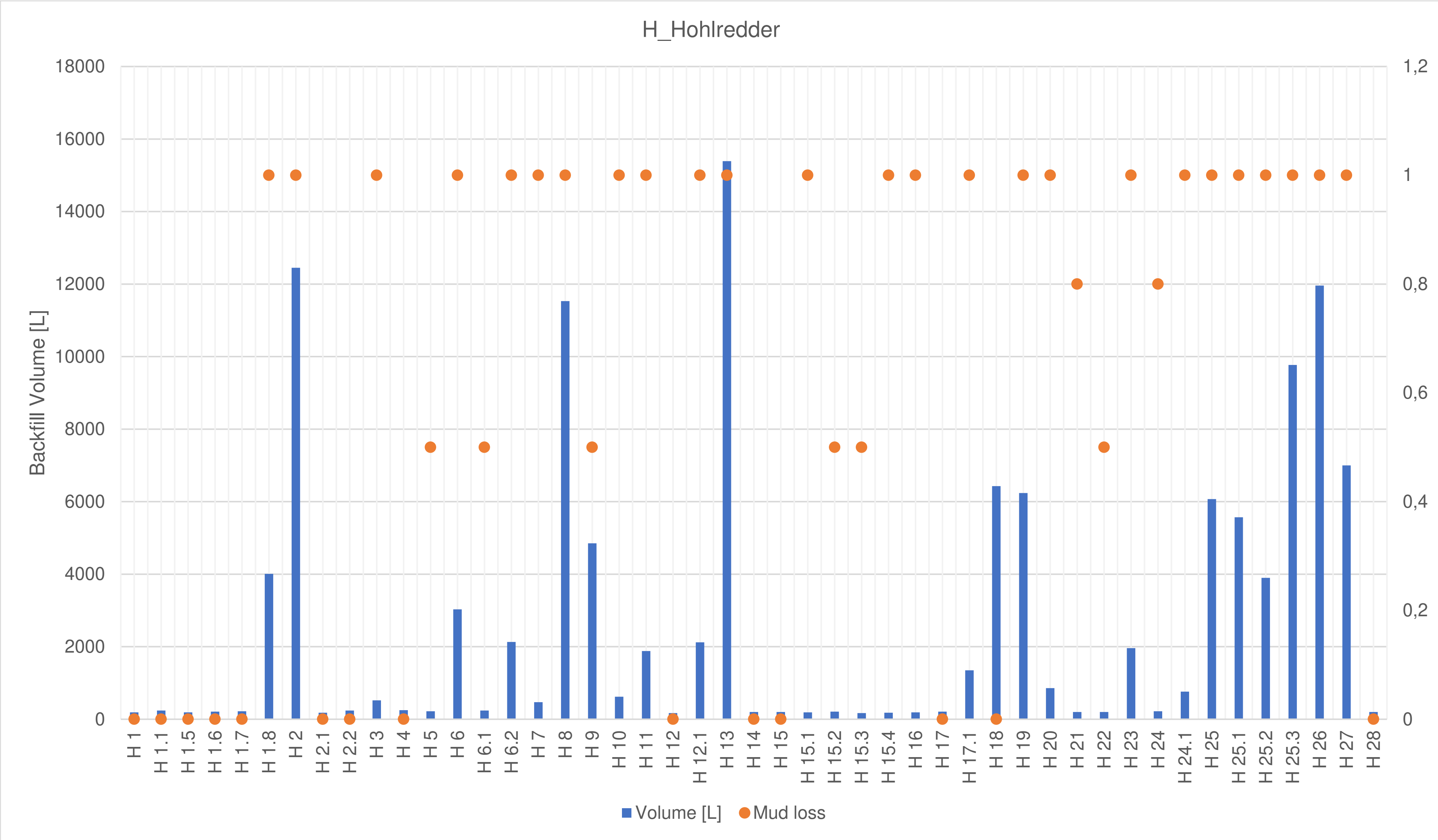


Appendix 6.1: Boreholes H

Borehole	**Volume [L]**	**Amount [kg]**	**MSL**	**Mud loss**	**From [MSL]**	**To [MSL]**
H 1	190	149	35,64	0		
H 1.1	240	189	35,64	0		
H 1.5	190	149	35,64	0		
H 1.6	210	165	35,64	0		
H 1.7	220	173	35,64	0		
H 1.8	4010	3151	35,64	1	21,83	17,5
H 2	12450	9785	35,64	1	24,56	22,53
				1	22,25	18,87
H 2.1	180	141	35,64	0		
H 2.2	240	189	35,64	0		
H 3	520	409	35,04	1	24,44	24,00
				1	22,90	5,275
H 4	250	197	35,04	0		
H 5	220	173	35,04	0,5	23,76	22,40
H 6	3030	2382	35,04	1	20,61	7,785
H 6.1	240	189	35,04	0,5	29,19	17,09
H 6.2	2130	1674	35,04	1	18,18	7,58
H 7	470	369	35,04	1	28,36	24,43
				0,5	24,43	24,05
				1	24,05	21,03
H 8	11530	9062	35,04	1	26,29	22,95
				0,5	22,05	20,38
				0,1	20,38	6,63
H 9	4850	3812	35,04	0,5	24,93	24,33
				1	24,33	22,87
				0,8	17,47	15,84
				1	15,84	11,64
H 10	620	487	35,04	1	25,46	20,38
H 11	1880	1478	35,04	1	24,04	22,51
				1	20,10	15,50
				0,5	15,50	11,04
H 12	170	134	36,91	0		
H 12.1	2120	1666	36,91	1	22,61	19,34
H 13	15390	12096	36,91	1	24,95	19,68
H 14			36,96			
H 15	200	157	36,96	0		
H 15.1	190	149	36,96	1	26,45	26,17
H 15.2	210	165	36,96	0,5	25,32	24,51
H 15.3	170	134	36,96	0,5	26,26	25,44
H 15.4	180	141	36,96	1	27,21	25,99
				0,5	25,99	25,67
				1	25,67	24,35
				0,5	24,35	23,45

H 16	190	149	36,96	1	23,14	21,18
				1	19,22	18,10
				0,5	18,10	16,14
H 17	210	165	38,40	0		
H 17.1	1350	1061	38,40	1	28,53	18,85
				0,5	18,85	18,01
H 18	6430	5054	38,40	0		
H 19	6240	4905	38,40	1	19,83	11,54
H 20	860	676	38,40	1	25,65	20,48
H 21			35,64	0,8	24,15	23,83
				1	23,83	23,50
				0,4	22,53	21,08
H 22			35,64	0,5	21,64	19,11
				0,8	19,11	15,69
H 23	1960	1541	36,91	1	17,44	11,66
H 24	220	173	35,04	0,8	23,18	21,88
H 24.1	760	597	35,04	1	22,24	21,65
				0,5	21,65	21,25
				0,3	13,61	13,12
H 25	6070	4771	35,84	1	19,49	9,64
H 25.1	5570	4378	35,84	1	20,92	7,53
H 25.2	3900	3066	35,84	1	21,92	12,22
H 25.3	9770	7679	35,84	1	25,14	13,40
H 26	11960	9400	35,84	1	22,03	7,84
H 27	7000	5502	35,84	1	23,06	8,66
H 28			36,91			

Appendix 6.2: Backfill Volumes and Mud loss

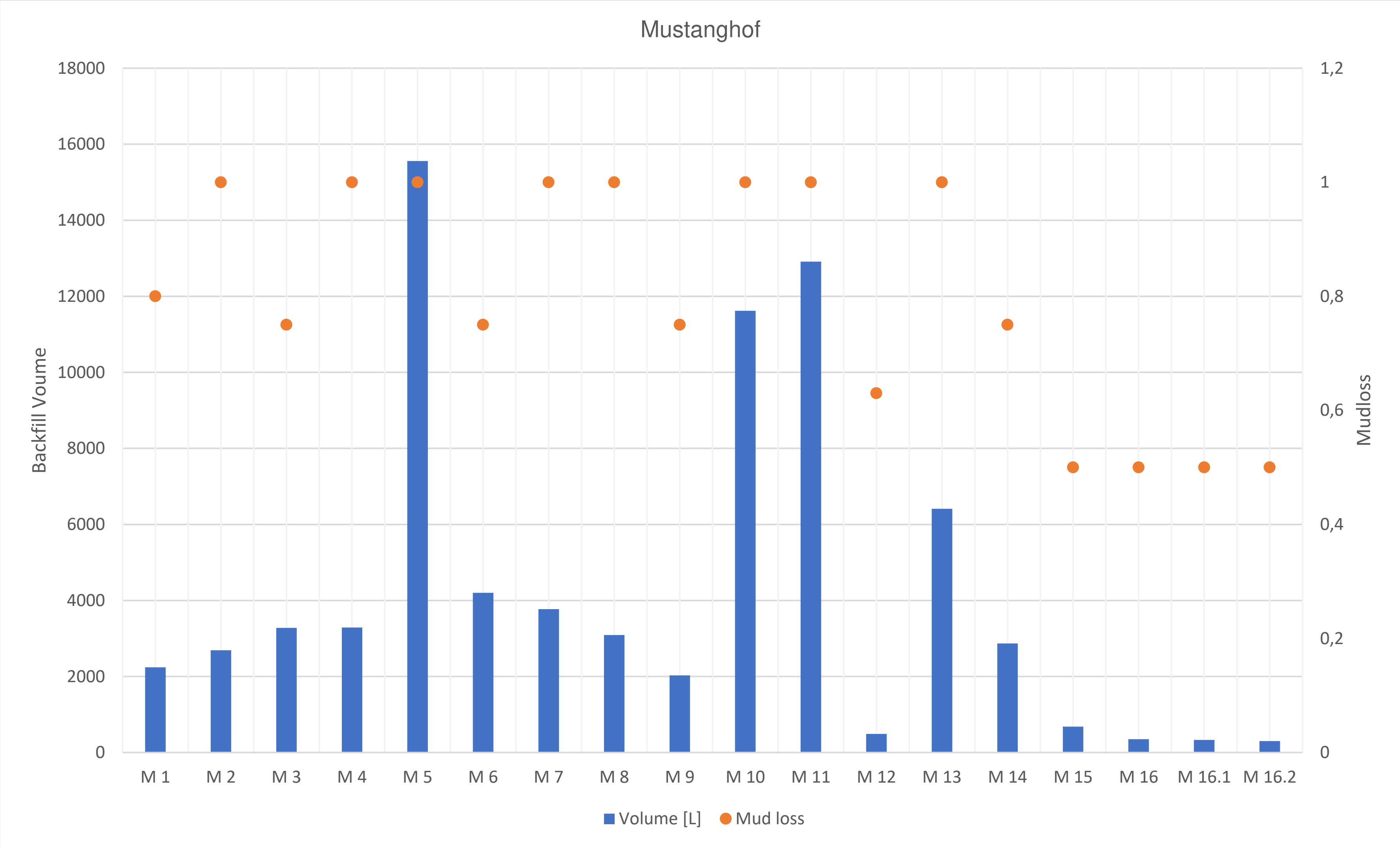


Appendix 6.3: Mud loss

Appendix 7.1: Boreholes M

Borehole	Volume [L]	Amount [kg]	MSL	Mud loss	From [MSL]	To [MSL]
M 1	2240	1761	40,872	1	24,792	24,122
				0,5	23,292	19,292
				1	18,002	6,002
M 2	2690	2114	40,872	1	23,372	22,802
				1	19,162	7,962
M 3	3280	2579	40,872	0,5	21,802	16,382
				1	16,382	4,402
M 4	3290	2585	41,771	1	22,811	12,381
M 5	15560	16380	41,771	1	25,651	13,341
M 6	4200	3301	41,771	0,5	24,261	21,351
				1	21,351	11,001
M 7	3770	2963	41,771	1	27,771	26,571
				1	25,881	18,371
M 8	3090	2429	41,771	1	21,701	8,011
M 9	2030	1596	41,771	0,5	22,471	16,171
				1	16,171	4,781
M 10	11620	9133	41,771	1	25,151	20,841
M 11	12910	10148	41,771	1	25,061	16,311
M 12	490	385	41,771	0,5	24,841	24,151
				0,5	22,221	20,291
				1	20,291	19,611
				0,5	19,611	16,681
M 13	6410	5038	41,771	1	22,081	16,081
M 14	2870	2256	41,771	0,5	28,391	26,931
				1	26,931	17,581
M 15	680	534	40,872	0,5	17,802	12,802
M 16	350	275	40,872	0,5	18,592	13,532
M 16.1	330	259	40,872	0,5	22,022	13,952
M 16.2	300	236	40,872	0,5	19,492	14,172

Appendix 7.2: Backfill Volumes and Mud loss

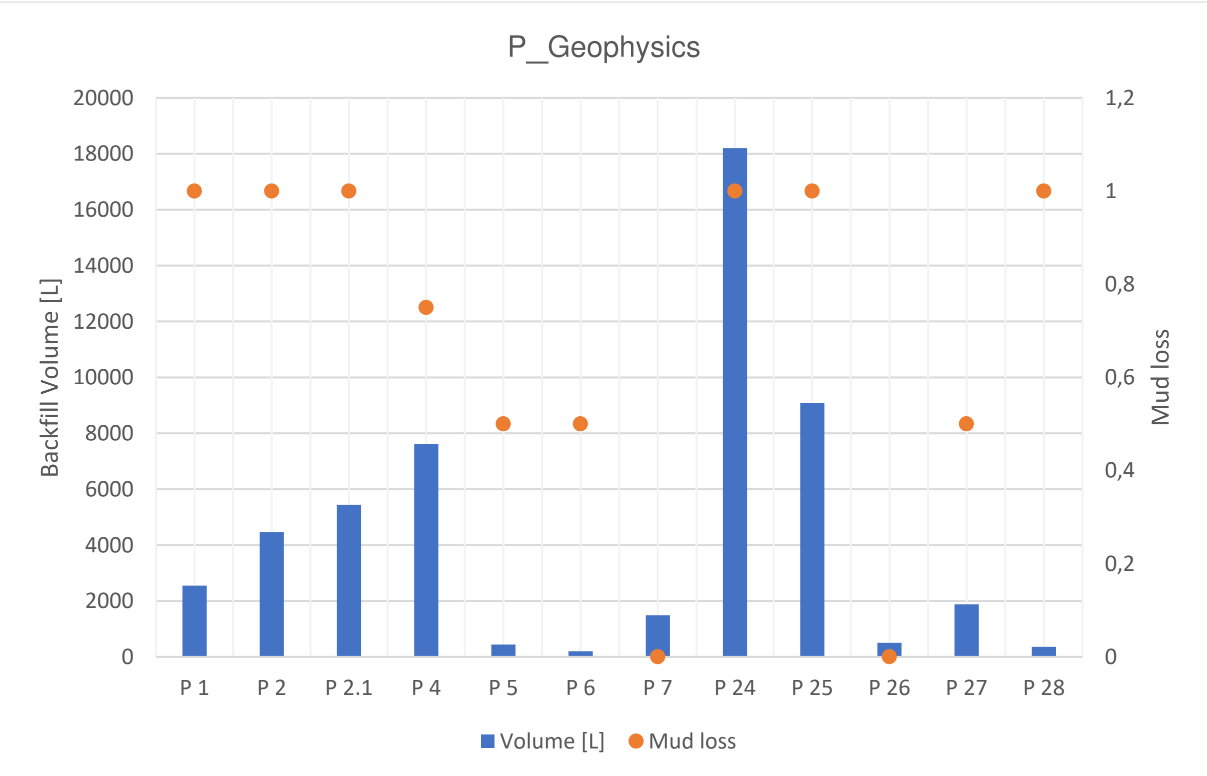


Appendix 7.3: Mud loss

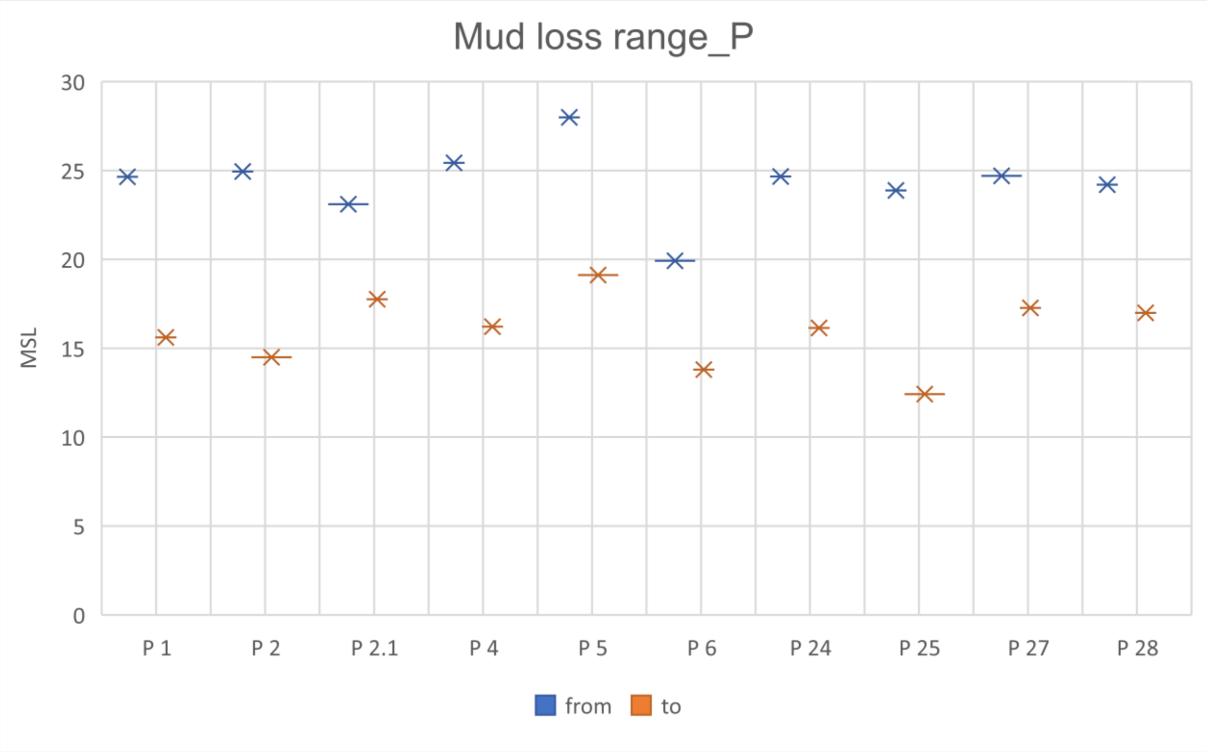
Appendix 8.1: Boreholes P

Borehole	**Volume [L]**	**Amount [kg]**	**MSL**	**Mud loss**	**From [MSL]**	**To [MSL]**
P 1	2550	2004	36	1	25	16
P 2	4470	3513	36	1	25	14
P 2.1	5440	4276	36	1	23	18
P 4	7620	5989	37	1	25	25
				1	25	19
				1	19	18
				1	18	16
P 5	440	346	37	1	28	19
P 6	200	157	35	1	20	14
P 7	1490	1171	35	0		
P 24	18200	14305	36	1	25	16
P 25	9090	7145	36	1	24	12
P 26	500	393	36	0		
P 27	1880	1478	36	1	25	17
P 28	360	283	36	1	24	23
				1	18	17

Appendix 8.2: Backfill Volumes and Mud loss



Appendix 8.3: Mud loss

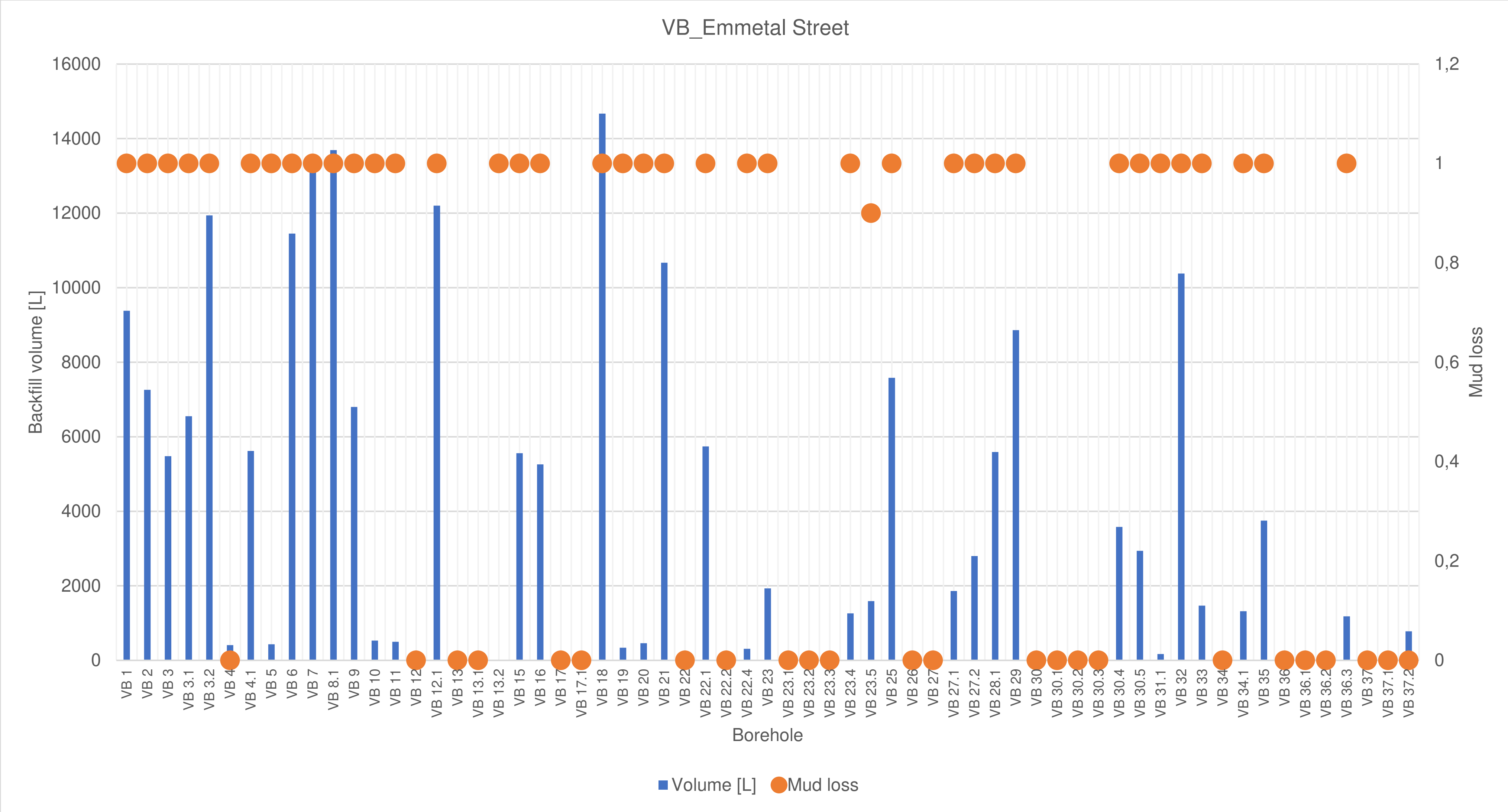


Appendix 9.1: Boreholes VB

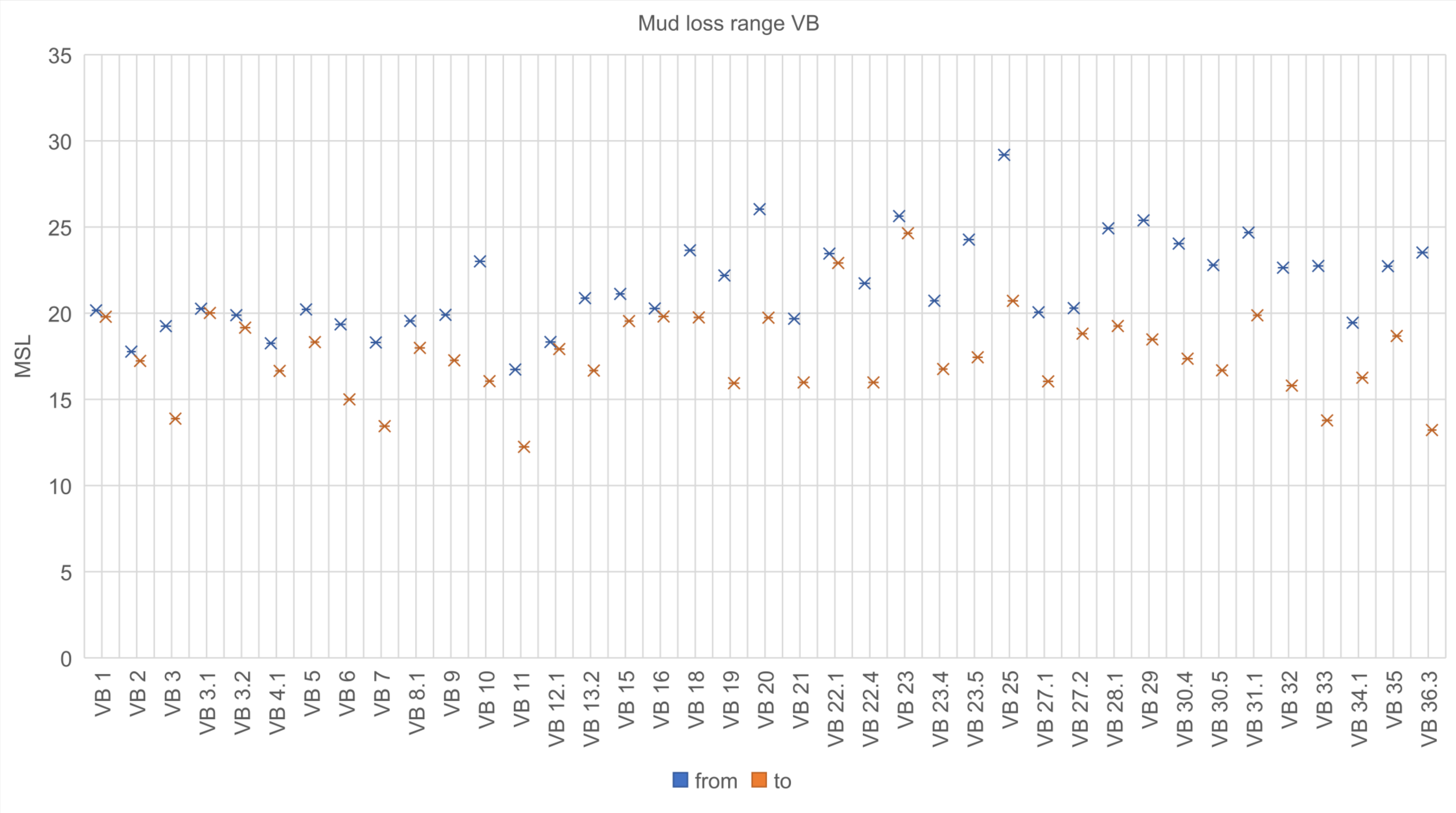
Borehole	Volume [L]	Amount [kg]	Mud loss	MSL	From [MSL]	To [MSL]
VB 1	9380	7373	1	31	20	20
VB 2	7260	5706	1	31	18	17
VB 3	5480	4307	1	31	19	14
VB 3.1	6550	5148	1	31	20	20
VB 3.2	11940	9385	1	31	20	19
VB 4	410	322	0	31		
VB 4.1	5620	4417	1	31	18	17
VB 5	430	338	1	32	20	18
VB 6	11450	9000	1	32	19	15
VB 7	13260	10422	1	32	18	17
			1		14	13
VB 8.1	13690	10760	1	32	20	18
VB 9	6800	5344	1	32	20	17
VB 10	530	417	1	32	23	21
			1		19	16
VB 11	500	393	1	32	17	15
			1		14	14
			1		14	12
VB 12	190	149	0	32		
VB 12.1	12200	9589	1	32	18	18
VB 13	210	173	0	33		
VB 13.1	220	173	0	33		
VB 13.2	0	0	1	32	21	20
			1		17	17
VB 15	5560	4370	1	33	21	20
VB 16	5260	4134	1	33	20	20
VB 17	200	157	0	33		
VB 17.1	220	173	0	33		
VB 18	14670	11530	1	33	24	20
VB 19	340	267	1	33	22	16
VB 20	460	362	1	33	26	20
VB 21	10670	8387	1	34	20	16
VB 22	190	149	0	34		
VB 22.1	5740	4511	1	34	23	23
VB 22.2	180	141	0	34		
VB 22.4	310	244	1	34	22	16
VB 23	1930	1517	1	34	26	25
VB 23.1	230	181	0	34		
VB 23.2	200	157	0	34		
VB 23.3	220	173	0	34		
VB 23.4	1260	990	1	34	21	17
VB 23.5	1590	1250	1	34	24	23

			1		23	17
VB 25	7580	5958	1	34	29	21
VB 26	150	118	0	34		
VB 27	180	141	0	34		
VB 27.1	1860	1462	1	34	20	16
VB 27.2	2800	2201	1	34	20	19
VB 28.1	5590	4393	1	34	25	19
VB 29	8860	6964	1	34	25	18
VB 30	150	118	0	35		
VB 30.1	160	126	0	35		
VB 30.2	190	149	0	35		
VB 30.3	180	141	0	35		
VB 30.4	3580	2814	1	35	24	17
VB 30.5	2940	2311	1	35	23	17
VB 31.1	170	134	1	35	25	20
VB 32	10380	8159	1	35	23	16
VB 33	1470	1155	1	35	23	14
VB 34	180	141	0	35		
VB 34.1	1320	1038	1	35	19	16
VB 35	3750	2948	1	35	23	19
VB 36	170	134	0	35		
VB 36.1	190	149	0	35		
VB 36.2	180	141	0	35		
VB 36.3	1180	927	1	35	24	13
VB 37	170	134	0	35		
VB 37.1	180	141	0	35		
VB 37.2	780	613	0	35		

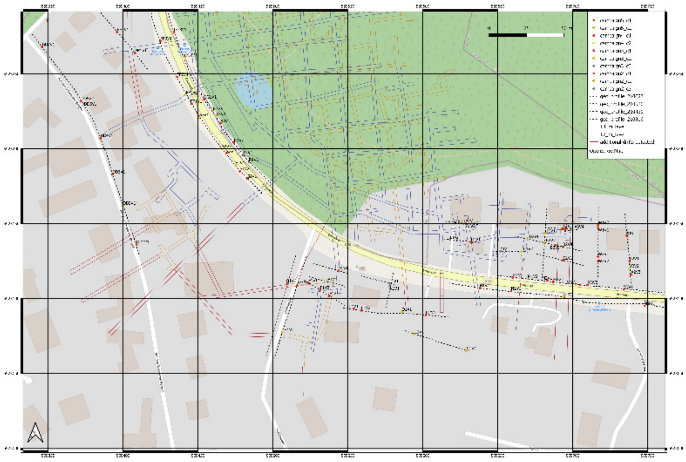
Appendix 9.2: Backfill Volumes and Mud loss



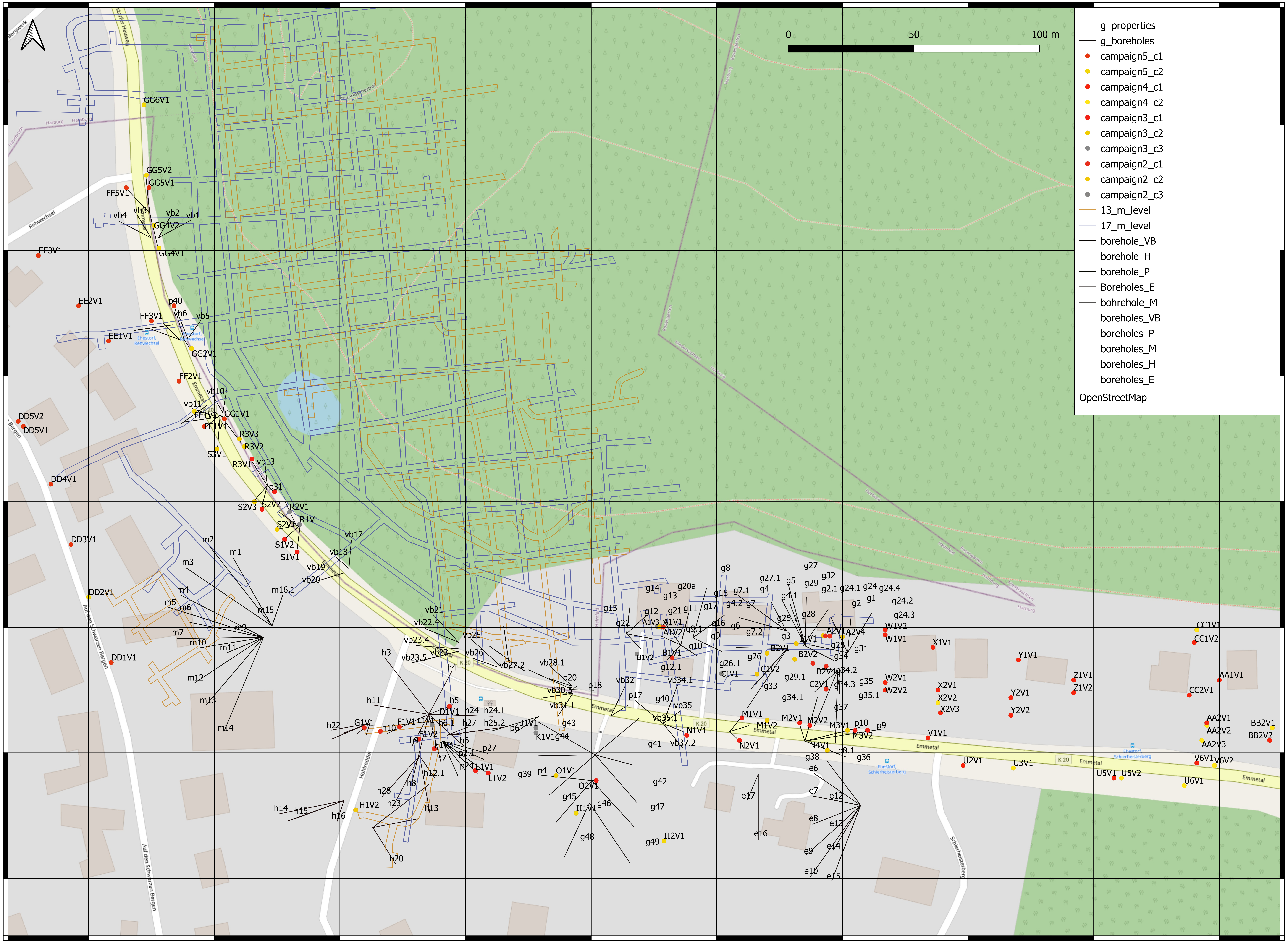
Appendix 9.3: Mud loss



Appendix 10: Map presentation of boreholes



(see back)


0 50 100 m
g_properties
g_boreholes
campaign5_c1
campaign5_c2
campaign4_c1
campaign4_c2
campaign3_c1
campaign3_c2
campaign3_c3
campaign2_c1
campaign2_c2
campaign2_c3
13_m_level
17_m_level
borehole_VB
borehole_H
borehole_P
Boreholes_E
bohrehole_M
boreholes_VB
boreholes_P
boreholes_M
boreholes_H
boreholes_E
OpenStreetMap
559400 559450 559500 559550 559600 559650 559700 559750 559800 559850
5923350 5923300 5923250 5923200 5923150 5923100 5923050