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# Resource and Reserve Classification of a Solwara 1 type Deposit at an Arctic Mid Ocean Ridge

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# Abstract

As land-based deposits become depleted, deep-sea deposits with a high concentration of economic elements become a new focus for exploitation. Comparing deep-sea mining activities with their land-based counterparts can help to understand and prevent problems in deep-sea mining. A 3D geometric model based on the data for the Solwara 1 deposit, a seafloor massive sulfide deposit in the Bismarck Sea, has been created using the modeling software Leapfrog Geo, the model is shown in Figure 1. This model has been further refined and qualimetric constraints put on it to check its economic viability. With a cut-off grade of 2.6% the resource estimate resulted in 834 kt indicated and 1299 kt inferred ore with an average copper equivalent grade of 7%. Since the resource estimate has only indicated and inferred ore the reserve can only be classified as probable. Depending on the mining system used this results in 417 kt to 584 kt probable ore reserve. It is also largely unknown what environmental effects deep-sea mining has. Further research of the Solwara 1 deposit to increase geological knowledge and the effects of deep-sea mining on the environment must be taken before mining activities should begin.

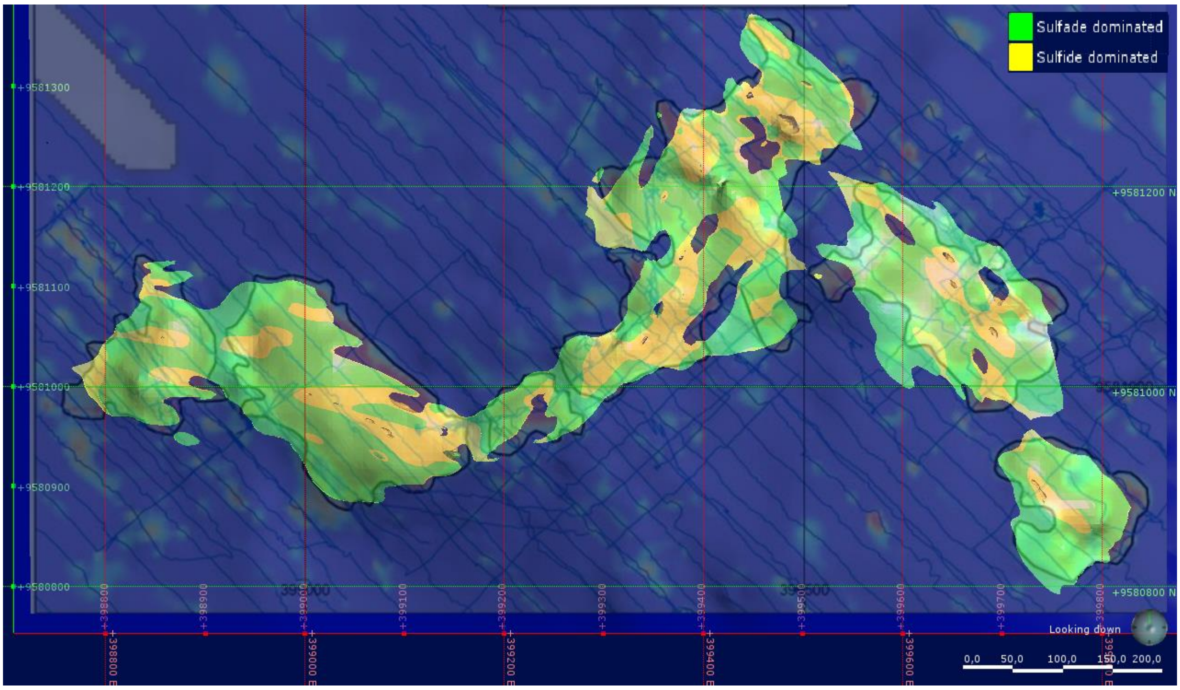


**Figure 1: Top down view of the geometric model with outlines of electromagnetic map**

# Acknowledgements

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# Abbreviations

| | |
|---|---|
| **Ag** | Silver |
| **Au** | Gold |
| **Cu** | Copper |
| **CuEq** | Copper Equivalent |
| $F_{H_{m0}}$ | Cumulative distribution function of the significant wave height |
| **$H_S$ / $H_{m0}$** | Significant Wave Height |
| **g** | gram |
| **k** | kilo |
| **PNG** | Papua New Guinea |
| **ppm** | parts per million |
| **SMS** | Seafloor Massive Sulfide |
| **t** | ton |

# 1. Introduction

## 1.1 Importance of Natural Resources for Modern Society

Natural resources are the foundation of our civilization. Population growth and the rising standards of living, all over the world, results in the need for new resource deposits to provide the materials needed for new constructions, cars, cell phones, etc. While recycling and development of new materials to substitute is important, it will not be the only solution. As we continue the exploitation of land based mineral deposits we will have fewer and fewer minerals available to us. This leads to an increase of value of the resource, which makes lower grade deposits profitable to mine. This increases the overall footprint of mining activities, which causes more environmental harm. Investing into new technology, to cheaply and cleanly extract new deposits, is an important step to ensure sustainable resource management. That will enable future generations to meet their needs with the resources available. In the past 10 years, increased exploration efforts did not result in many more successful mining operations. New deposits are being found at greater depth or in remote areas (Meinert, Robinson and Nassar, 2016). Exploration of the deep-sea has led to the discovery of various mineral deposits on the seafloor. Among those are seafloor massive sulfide (SMS) deposits, like the Solwara 1 deposit, which can be a source of valuable economic elements.

## 1.2 Introduction to the Deep-Sea and Deep-Sea Mining

The ocean covers 71% of Earth's surface. Most of it is deeper than 200m and belongs to the deep-sea, which is unexplored by humans. It is suspected that a vast amount of mineral resources can be found there (Scott, 2001). The deep-sea is a unique ecosystem of our planet. It is an extreme environment. The temperature is between 0-3°C but can reach 400°C near hydrothermal vents. There is no sunlight and the pressure is immense (Birney *et al.*, 2006). Even though the conditions are so extreme, live thrives there and we can find biodiverse communities (Van den Hove and Moreau, 2007). The main mineral resources of the deep-sea are manganese nodules and crusts and SMS deposits which contain copper (Cu), silver (Ag), gold (Au), zinc, and lead (Scott, 2001). These deposits have economic potential and the desire to mine them led to the development of new technologies for deep-sea mining. These advances have the potential of being cheaper than traditional mining (Birney *et al.*, 2006). This is because the minerals are closer to the ocean floor surface, resulting in less waste rock, and have a higher grade than traditional mines on land. Ocean mining is not a completely new field. Since the 1990s diamonds are already being recovered off the shore of  Africa to a depth of about 100m (Scott, 2001). In the 1960 first attempts on deep-sea mining have been made with little success due to technological limitations and lower resource prices (Glasby, 2000). Today private companies, like Nautilus Minerals or Neptune Minerals, and different countries, including China, Korea, Japan, The United States of America, and Norway, are looking to exploit deep-sea mineral deposits.

## 1.3 Goal of this Thesis and Methods used

The purpose of this thesis is to give necessary background information on deep-sea mining, deep-sea ore deposits and how they are formed. I will give an overview of the current state of deep-sea mining and compare it to land based mining in terms of environmental impact, accessibility, and quality. To do that I will look at the Solwara 1 project of Nautilus Minerals and the resource estimate for Solwara 1 by Blue Mining. I will create a 3D geometric and qualimetric model of the Solwara 1 deposit and perform a resource estimation on it. I will check how the Norwegian Sea will influence the potential mining activities. Each topic touched upon, in this thesis, contains a vast amount of information. Because of that, I am limited to providing an overview of these topics. When calculating and comparing my results with established reports, I will use the same processing parameters, losses, and royalties that Nautilus Minerals used. Feasibility studies for deep-sea mining in Norwegian territory have already been done. These can provide further insight into the cost for a Norwegian deep-sea mining project.

Land-based mining is a complex but well understood topic, it can be used as a starting point for comparison with deep-sea mining. It shares many similar topics such as legal, social, economic, and environmental issues. A 3D geometric model of the Solwara 1 deposit can be created using a modeling software such as Leapfrog Geo. Leapfrog Geo is a software for implicit 3D geological modelling developed by the company ARANZ Geo. It is capable to create a 3D model from data such as drillholes, surfaces, and points. This cuts the time consuming manual work and allows the model to be easily updated, when new data becomes available. Filters can be applied to the model so that certain criteria can be highlighted. Block models can be created from the initial model. On the model qualimetric constraints, like the grade of the ore, can be applied to be able to classify the deposit.

The thesis starts with a literature review in Chapter 2. This will provide necessary background information on the formation of SMS deposits, the company Nautilus Minerals, how land-based mining is done today and what challenges it faces, the current state of exploration in Norway, social and legal issues and what influence the ocean will have. Chapter 3 will summarize the theory of implicit modeling, resource and reserve classification and assessing which mining method should be used. In Chapter 4 I will present the material and data used in this Thesis. Detail on how the 3D model was created, what parameters were used to qualify the geometric model, and what was used to perform a resource and reserve estimate are given in Chapter 5. Chapter 6 lists the results from the geometric and qualimetric modeling. In Chapter 7 I will provide a discussion of the results, a comparison of land-based to deep-sea mining, a comparison of the results to other, and a discussion on which criteria are important for assessing deep-sea mining methods. In Chapter 8 I will have concluding remarks and suggestions for further work.

# 2. Background Information

## 2.1 Land-Based Mining

### 2.1.1 Operation of Land-Based Mines

Mining has been done since the prehistoric time. Even though the techniques employed today vary greatly from earlier times. The general goal, of getting economic minerals out of the ground for further processing, remains the same. To show commonalities and differences of deep-sea mining a quick overview of traditional land-based mining is given here. Modern mining can be divided into five stages: prospecting, exploration, development, exploitation, and reclamation. Prospecting and exploration are done before the main mining endeavor and can be combined into one step. Development and exploitation usually happen at the same time (Hartman and Mutmansky, 2002).

Prospecting, the search for a new ore deposit, is the first and most difficult step in a new mining endeavor. When prospecting a geologist needs knowledge about the genesis of the area to determine where mineral deposits might be found (Johansson *et al.*, 2008). Deposits can be located below the surface, so direct and indirect detection methods are used. Direct methods include visual examination of the deposit site and can be augmented with aerial photographs and the study of geological maps. Indirect search uses geophysics to look for magnetic, electrical, gravitational, or seismic anomalies (Hartman and Mutmansky, 2002).

Exploration tries to accurately determine the size and value of the deposit. The techniques employed are similar but more precise than the ones used in prospecting, sometimes it is difficult to draw a line where prospecting ends and exploration begins and the two stages merge together (Hartman and Mutmansky, 2002). During exploration the geologist systematically examines the deposit to determine its true size. Samples are obtained via drilling and then analyzed and evaluated to calculate the grade of the deposit. The overarching goal is to become certain if the orebody is economically viable for mining (Johansson *et al.*, 2008). Mining costs, mineral recovery rates and environmental costs are calculated. The final step is to classify the deposit as a resource or reserve and determine if the evaluation stops here or the project progresses to the development stage (Hartman and Mutmansky, 2002).

The third stage is development. During this stage the ore deposit is prepared for mining. The ore is accessed, either by removing the overburden, the waste rock on top of the ore deposit, or by excavating a shaft to the ore. This will create a pit mine or an underground mine respectively. In preparation of the mining endeavor, a company must get the necessary permits and usually an environmental impact statement. After that, infrastructure, such as power, mineral transportation, mineral processing, waste areas, offices, and other facilities need to be taken care of, before mining can begin. Since development and exploitation usually occur at the same time this stage can last for decades. Because of that, the development plan can and will change during the live time of the mine, as new technologies become available, the market changes, and more information about the orebody becomes available.(Hartman and Mutmansky, 2002).

Exploitation is the fourth stage of mining, during which the actual recovery of minerals in large quantities is done. Depending on the location of the orebody, mining will either be done on the surface or underground (Johansson *et al.*, 2008).

The final step is reclamation, in the past this was not considered beforehand but a topic addressed after the mining operation was done. In many countries no mining will be allowed without consideration of the aftermath and the environment (Hustrulid, Kuchta and Martin, 2013). The mining company must make sure that the area around the mine is safe, mine shaft must be sealed and no longer needed infrastructure removed. During reclamation, the land surface, water quality, and waste areas need to be restored so that no long term environmental pollution can occur. Proper planning beforehand and planning a mine with subsequent development in mind can minimize certain issues (Hartman and Mutmansky, 2002).

Due to the long-term nature of mining, proper care must be taken after mining activities stops. Reclamation now includes actions such as removal of chemicals and toxic waste, removal of structures and roads, capping of tailings, removal of sediment control structures and restoring drainage ways. Long-term observation and maintenance must be planned for, when calculating reclamation cost (Chevrel and Cottard, 2000).

### 2.1.2 Social and Environmental Impact of Land-Based Mines

The major impact from mining on the environment comes from a few key sources. Those are waste rock disposal, tailings, leaches, and mine water. Waste rock is made of soil and rock which must be removed to access the ore body. It can be used in construction projects or to backfill areas where the mining operation has concluded. The waste rock is usually disposed in piles near the mine. Tailings are waste solids remaining after processing of the ore. It is a slurry of water and solid particles, which is disposed of in tailings ponds or tailings dams on site.

Leaching is a refinement process in which economic elements are extracted by letting a leaching solution percolate through the ore. After the leaching is done the spent ore must cleaned to prevent environmental damage (Chevrel and Cottard, 2000). Mining only affects a small area, tailings and waste rock deposits are the true cause of pollution. The nature of the waste rock determines the nature of the pollution. For example, when it contains sulfides and comes in contact with oxygen and water acid mine drainage results (Salomons, 1995).

Acid mine drainage is one of the most serious environmental threats to the water supply. When sulfides are exposed to air and water, they can react and form sulfuric acid (Salomons, 1995), which can mobilize heavy metals and other harmful elements (Septoff, 2005). A relative small shift in pH can cause a big increase or decrease in the metal concentration in a solution (Salomons, 1995). When not properly taken care of this can contaminate streams, rivers, lakes, or the groundwater (Septoff, 2005). This can lead to build-up of toxic sediments, change in pH levels, degradation of habitats, and contamination of human water supplies. When a mine is below the ground water level, ground water will infiltrate the mine. This water must be dealt with, as mentioned above if handled improperly it can cause the contamination of surface water. Water infiltrating the mine can cause the groundwater lever to drop which can have an impact on nearby wells, wetlands, and plants (Chevrel and Cottard, 2000).

Erosion of waste rock or discharge of tailings can introduce metal particulates and sediments into the aquatic eco system (Salomons, 1995). Mining sites cover a large area with large quantities of exposed material. This can lead to an increase in sediments in nearby rivers and lakes. These can cause local problems such as toxic effects in fish, but also alter the river downstream where the sediments settle (Chevrel and Cottard, 2000).

Mined out shafts can collapse and cause sinkholes or subsidence on the surface (Hartman and Mutmansky, 2002). The maintenance of physical stability of mines and their waste is important since failure can endanger humans and the environment (Chevrel and Cottard, 2000). Mining can have a big impact on the human community and environment around the mining site. Since a big part of mining today is in remote areas, populated by indigenous people, it will have a bigger socio-cultural impact. Remote areas do not have the infrastructure to accommodate mining ventures regarding power, labor force, service industry, and road access for transportation (Chevrel and Cottard, 2000). The impact of mining on a community can be classified into direct, indirect, induced, and cumulative impacts. Direct Impacts come from a specific action due to the mining effort. Indirect impacts are alterations because of direct impacts. Induced impacts are several times removed from the main project. Cumulative impacts are the result of a combination of several different projects in the area (Joyce and MacFarlane, 2001). There are many examples where changes brought by mining have a positive and a negative impact, so it is impossible to draw a broad conclusion on the socio-cultural effect of mining (Chevrel and Cottard, 2000).

## 2.2 Deep-Sea Mining of Seafloor Massive Sulfide Deposits

### 2.2.1 Current State of Technology

Like stated in Chapter 1.2 the idea of deep-sea mining has been around since the 1960. Low metal prices and a tendency to mine lower grade land-based deposits have so far stopped commercial mining of deep-sea deposits (Kotlinski, 2001). At the time of writing Nautilus Minerals plans to start the first commercial mining operation in 2019 at the Solwara 1 deposit (Lipton, 2018). How viable deep-sea deposits are going to be, is a matter of their concentration, their magnitude, and the cost of extraction. How efficient deep-sea mining is, depends on the mining and lifting system used (Sharma, 2017). Since on site staff is impossible in the deep-sea, unmanned vehicles will be used. These will either be remotely controlled or have to be able to make autonomous decisions (Jasiobedzki and Jakola, accessed 2018, Liu *et al.*, 2016). Jasiobedzki and Jakola (accessed 2018) see these problems for deep-sea mining vehicles:

- "*Low situational awareness of the operators due to restricted camera views, unnatural illumination conditions, lack of 3D perception and non-visual sensory perception.*
- *Potentially poor visibility underwater especially when close to active mining areas.*
- *The need for real time and wide bandwidth of communication links to the surface transmitting images and telemetry.*
- *Complexity of the teleoperation tasks that need to be performed, e.g., navigation of a Remotely Operated Vehicle (ROV), which is performed in all six degrees of freedom; operation of mining tools during precise mining.*
- *The presence of long tethers connecting to the surface (directly or indirectly).*
- *The lack of accurate, detailed, and current maps of the seabed at the mining worksite.*
- *The need to maintain a positioning system infrastructure enabling accurate localization.*
- *The need for underwater infrastructure in support of the mining operations and craft.*

- *The cost of retrieving craft due to failure, operator error or for maintenance.*"

Some of the challenges could be solved by adapting technology used in space exploration, since they face similar problems (Jasiobedzki and Jakola, accessed 2018).

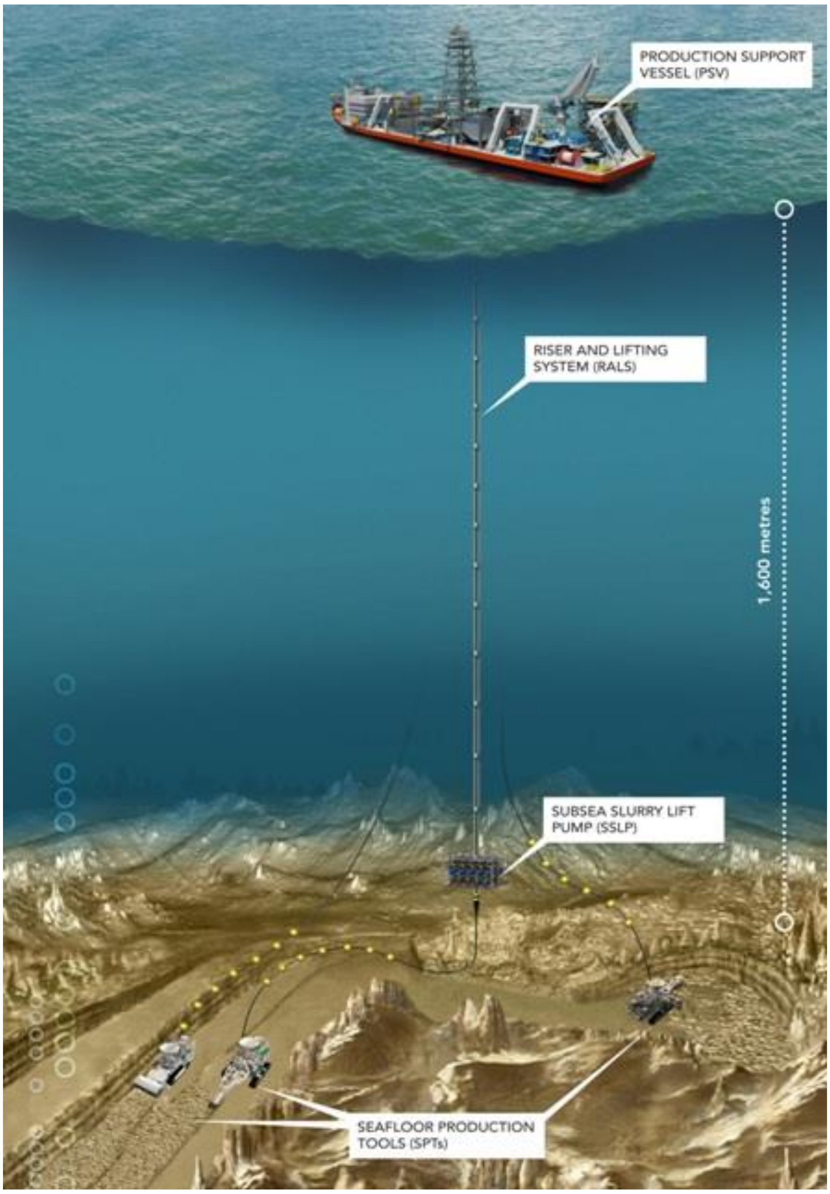


**Figure 2: Overview of Nautilus Minerals mining system showing the seafloor production tools, the subsea lifter system, and the production support vessel (Nautilus, accessed 2018)**

Nautilus Minerals is developing a mining system for their Solwara 1 project shown in Figure 2. Their system consists of a production support vessel, a riser and lifting system and the seafloor production tools. The seafloor production tools will be three separate remote operated vehicles, the auxiliary cutter, the bulk cutter, and the collection machine. The auxiliary cutter will be used to prepare the seafloor for the other vehicles, it will flatten rough terrain to create a more even surface. The bulk cutter is the main mining vehicle, it will run on the ground prepared by the auxiliary cutter. The collection machine will pump a slurry of seawater and the mined material to the riser and lifting system, which is a pumping station suspended under the support vessel by a steel pipe. At the production support vessel, the slurry will be dewatered and stored until the mined material can be transferred to a transport vessel. The seawater from the slurry will be pumped back down to the seafloor (Yu and Espinasse, 2009, Nautilus, accessed 2018, Liu *et al.*, 2016).

Another system is developed by Neptune minerals, a US company also interested in mining the western pacific. Their mining system consist of a mining vessel a grabber mining tool, a remotely operated vehicle, a subsea rock sizer and a lifter system. The grab is lowered from the mining vessel and used to prepare the seafloor for the cutting vehicle. After that the main job of the grabber will be to feed cut material into the subsea rock sizer. The system is developed for operation in areas with higher wave height. The lifter system has buoyancy elements, so it is not affected by the vessels motions but can be decoupled if the weather is too rough. It is designed to work and remain connected during storm events (Yu and Espinasse, 2009).

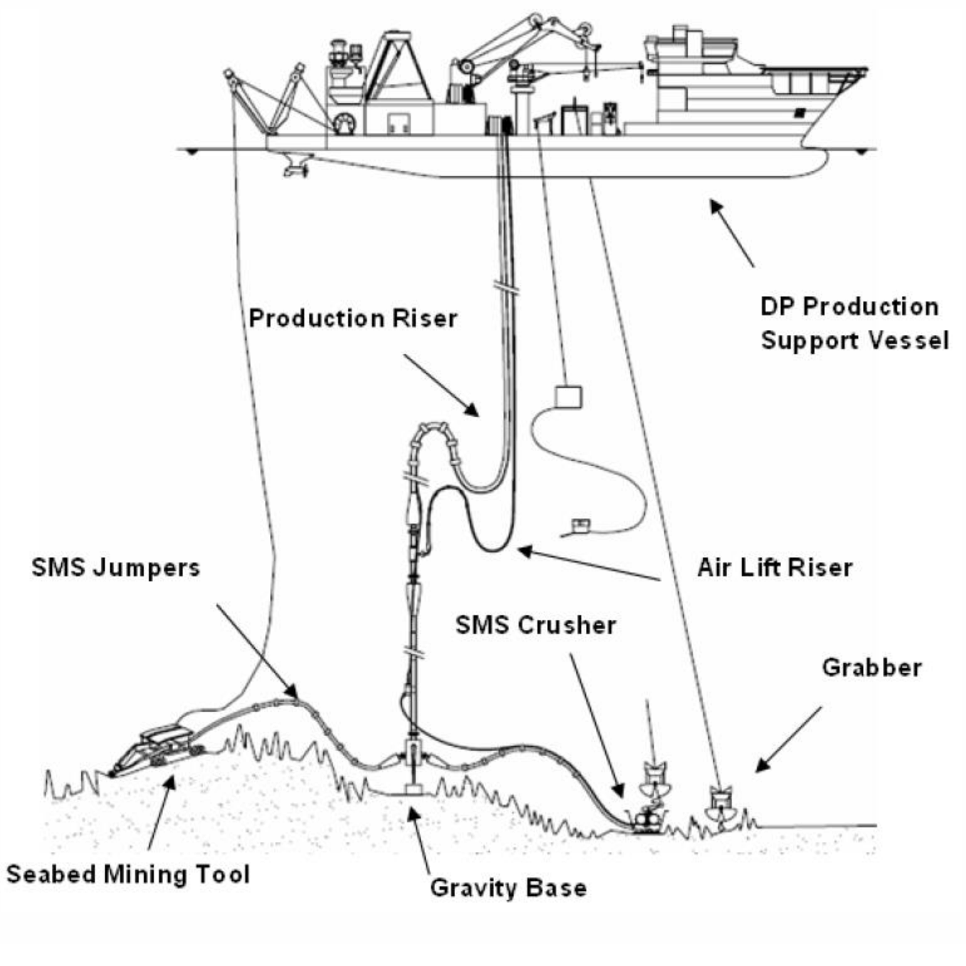


**Figure 3: Mining system developed by Neptune Minerals (Yu and Espinasse, 2009)**

BAUER maschinen GmbH is developing a vertical mining system. On land trench cutters are used for foundation work, but the technology could be adapted to work in a deep-sea setting as seen in Figure 4. A trench cutter is made up of a heavy steel frame with cutting wheel drums at the bottom. It would be lowered from the mining ship at the sea surface but can stand securely on the seafloor. A trench cutter was already used to mine diamonds at a depth of 165m in 1994 (Spagnoli *et al.*, 2016). BAUER plans to use a discontinuous ore transportation system. The ore is sucked up from the crusher and deposited into a container at the top of the mining system. Once this container is full it can be detached from the mining system and lifted to the support vessel. This system would decrease the energy needed from around 700 kW, to run the pump, to about 400 kW, to run the winch. BAUER plans to use a closed system where a cutting fluid is used to transport the ore from the cutter to the storage unit. This cutting fluid can then be recycled at the support vessel and reused. This would prevent sediment plumes which are an environmental hazard (Weixler, 2018)

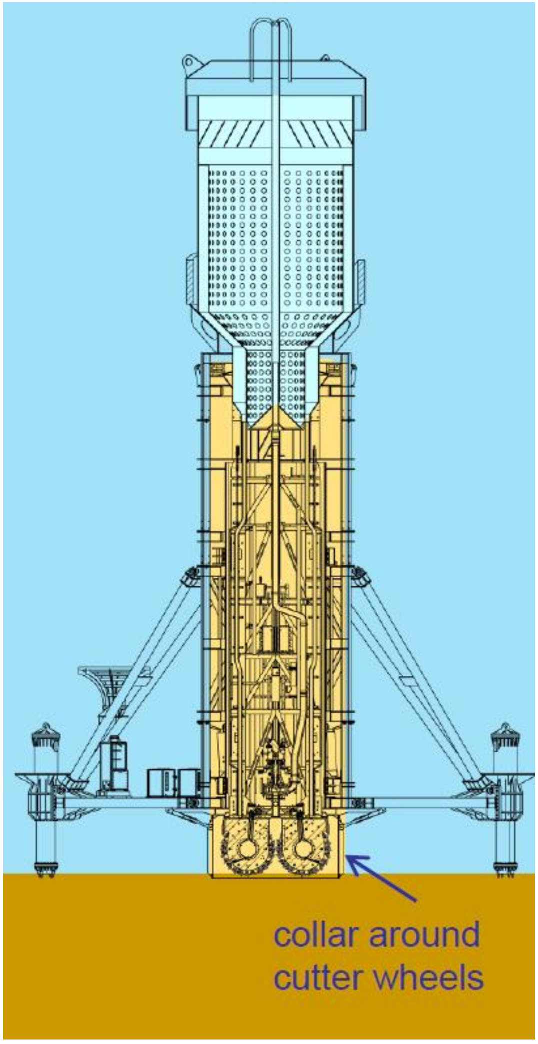


**Figure 4: BAUER trench cutter (Spagnoli *et al.*, 2016)**

India is working on a system to mine manganese nodules in the Central Indian Ocean Basin, they plan to use remotely controlled vehicles to collect the nodules and a flexible riser system to bring them to the surface. Tests have been carried out at 500m water depth. The challenge is to bring the system to 6000m water depth where the nodules are (Sharma, 2017). China is developing mining solutions for manganese nodules and SMS deposits. In 2001 they successfully tested a design in a lake with artificial nodules (Liu, Yang and Han, 2010, Liu *et al.*, 2016).

### 2.2.2 Social and Environmental Impact of Deep-Sea Mining

It is difficult to predict what effects deep-sea mining will have on the environment since it is a new endeavor. We lack the necessary tools and frameworks to monitor and assess changes in the deep-sea environment (Santos *et al.*, 2018, Durden *et al.*, 2017). Santos *et al.* (2018) propose these questions that should be answered before any large-scale mining operation can begin:

- "*how deep-sea biological communities change in time and space and how they disperse*
- *how resilient to disturbances these biological communities are and which are their recovery times*
- *which features, conditions, species should be considered to define a conservation legal status for deep-sea communities*
- *which innovative technologies and tools are key to increase scientific knowledge and to avoid/mitigate the deep-sea mining derived impacts*"

The remote nature and extreme environment make direct observation difficult, so laboratory experiments are an important tool to gather the necessary data. The problem with these experiments is that fauna endemic to the vent site should be used, which can be difficult to obtain. Since deep-sea species are specially adapted to deal with the extreme conditions of their environment the use of shallow water counterparts to the deep-sea species may not be representative enough. Depending on the experiment, the laboratory environment could also not include all the other effects deep-sea mining has (Santos *et al.*, 2018). According to Halfar and Fujita (2007) and Santos *et al.* (2018) and Weaver, Billett and Van Dover (2018) environmental effects of deep-sea mining include:

- sediment plumes, both near the ocean floor and in the water column which can affect filter feeder
- toxic elements released during mining
- noise and light pollution which can harm exposed animals

- additional sedimentation
- alteration in the pathways the hydrothermal fluid uses to reach the surface
- mixing of nutrient rich deep-water with surface-water
- impact on the behavior of other species

There is a unique ecosystem at active hydrothermal vents. Extremophiles who can survive at high pressure and temperature use the chemicals in the vent fluid to create energy (Rosenbaum, 2011, Van Dover, 2004). Most active hydrothermal vents have a large population of big and small invertebrates, who live in symbiosis with aerobic chemoautotrophic bacteria. They have evolved to tolerate concentrations of sulfides and metals, that would be toxic to most other animals. Most of these animals are new or unknown to science. The diversity at each individual hydrothermal site is rather low, with a few dominant species per site. Between different hydrothermal sites the diversity is high and each site hosts different dominant species (Van Dover, 2004, Niner *et al.*, 2018). Van Dover (2004) lists these negative impacts as a worst-case scenario:

- "*Loss of sulphide habitat*
- *Degradation of sulphide habitat quality*
- *Modification of fluid flux regimes*
- *Local, regional, or global extinction of endemic or rare taxa*
- *Decreased diversity (at all levels: genetic, species, phylogenetic, habitat, etc.)*
- *Decreased seafloor primary production*
- *Modification of trophic interactions*
- *Exposure of surrounding seafloor habitats (non-sulphide) to sediment and heavy metal deposition*
- *Effects of scaling-up*
- *Continued ignorance about what is not known*"

Creating and implementing an environmental management framework can only benefit deep-sea mining in the future. The framework would help make environmental protection decisions during the planning stage of the project. This would make planning cheaper and easier since the developing company would know what issues they must address, creating a fair and uniform playing field. It would make it easier to assess the direct and cumulative impacts of various mining projects and strengthen protection of the sea. The framework should be used at all stages of the lifecycle of the deep-sea mine and include all available data on the environment of the project area (Durden *et al.*, 2017).

## 2.3 How Seafloor Massive Sulfide Deposits are formed

SMS deposits from on extension zones along mid ocean ridges or on sites of active subsea volcanism. As seen in Figure 5, cold, alkaline, oxidizing, and metal deficient sea water infiltrates the basaltic crust and the upper mantle. There it becomes hot, up to 400°C, acidic, reducing, and leaches economic elements from the rock. As the hydrothermal fluid rises, it alters the host rock, dissolving and depositing new minerals as it travels towards the surface. When the fluid comes into contact with the cold seawater, minerals precipitate from the hydrothermal fluid. The minerals form chimneys over the venting site which are called black smokers. These chimneys consist of a mixture of barite ($BaSO_4$), anhydrite ($CaSO_4$), pyrrhotite (FeS), pyrite ($FeS_2$), chalcopyrite ($CuFeS_2$), and sphalerite ((Zn, Fe) S) (Robb, 2004) (Rosenbaum, 2011).

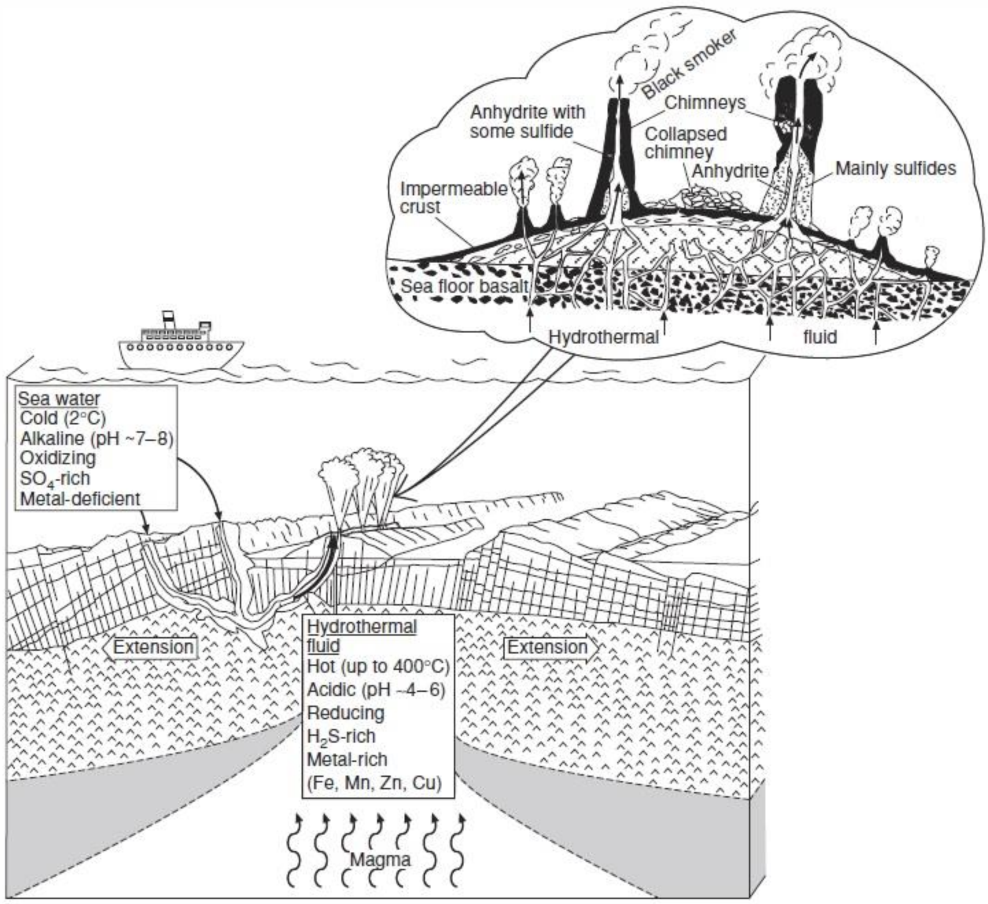


**Figure 5: Concept for fluid circulation at a mid-oceanic ridge, cross section of a chimney site with black smokers in various stages of development. (Robb, 2004)**

Beneath the black smokers there is a lens of sulfide ore containing mainly pyrite, chalcopyrite, and sphalerite. As seen in Figure 5 this lens is crisscrossed with cracks and fissures along which the hydrothermal fluid flows on its way up. (Robb, 2004). SMS deposits have a metal zonation pattern which extents vertical and lateral, Fe to Fe-Cu to Cu-Pb-Zn to Pb-Zn-Ba. This zonation is a result of the evolution of the fluid and growth of the SMS deposit over time. As seen in Figure 6, at lower temperatures the solubility of economic elements is quite poor resulting in a mound that mainly consists of barite and anhydrite. As the temperature increases the solubility rises, first Zn, Pb, and some Au become soluble enough to form sphalerite and galena deposits. At even higher temperatures Cu is transported as a chloride complex and chalcopyrite will start to be precipitated at the base of the SMS mound. At this stage, the higher temperatures cause the earlier formed minerals to dissolve and reprecipitate further away from the center. Sulfate reducing bacteria may also play an important role in the formation of SMS deposits. Not all SMS deposits will have this shape, since the properties of the fluid dictate it as they rise through the rock (Robb, 2004).

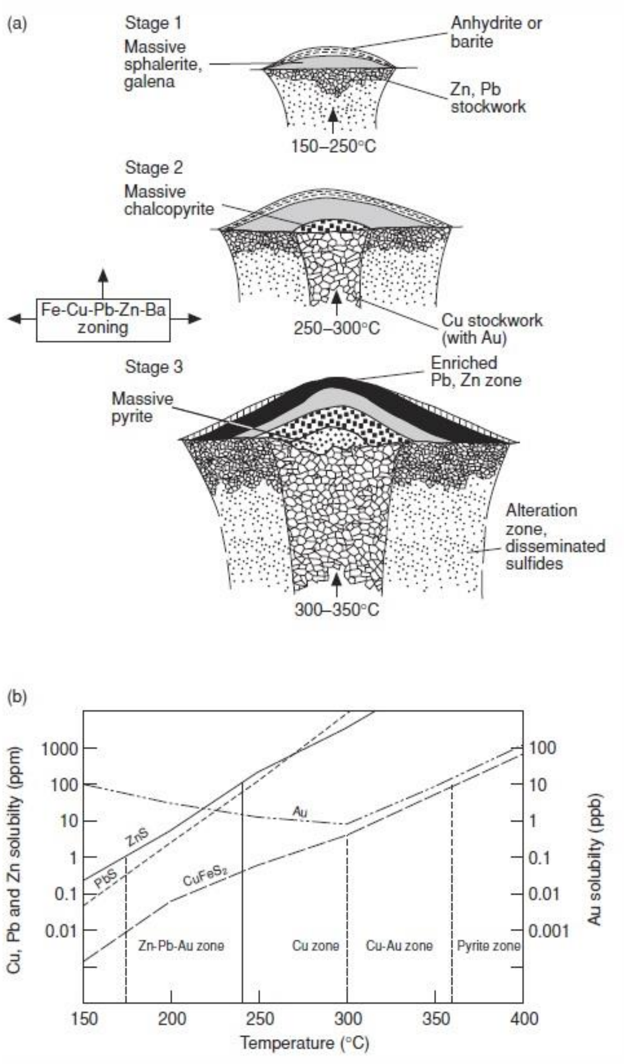


**Figure 6: a) Model detailing the growth of a SMS deposit over time and the evolution of the fluid resulting in a characteristic zonation pattern. b) Temperature vs solubility of economic elements pH=4; 1 M NaCl, $aH_2S$=0.001 ,$SO_4/H_2S$=0.01 (Robb, 2004)**

## 2.4 Overview of the Company Nautilus Minerals and their Projects

### 2.4.1 Overview of the Company

Nautilus Minerals is a Canadian company with the goal to explore and mine the already mentioned SMS deposits. For that purpose, they develop a new mining system based on technology from the offshore oil and gas industry and dredging and mining industry. Among other projects they are working on exploration and exploitation of the Solwara 1 deposit and have acquired a mining lease and an environmental permit from the Papua New Guinean (PNG) government for this site. An overview of the mining system used by Nautilus Minerals can be found in Chapter 2.2.1. Besides the project in PNG Nautilus Minerals is also conducting deep-sea exploration off the coast of Tonga. They started in 2008 and have discovered 19 promising sites that are ready for further investigation in the future (Nautilus, accessed 2018). Nautilus minerals was also involved with deep-sea exploration in Fiji, the Solomon Islands, New Zealand and Vanuatu (Jankowski, 2011).

### 2.4.2 The Solwara 1 Project

In 1985 the research vessel RV Moana Wave discovered the SMS deposits off the coast, of PNG, in the Bismarck Sea (Nautilus, accessed 2018). Its location is inside the Exclusive Economic Zone of PNG (Yu and Espinasse, 2009). Solwara 1 was found by the Australian Commonwealth Scientific and Industrial Research Organization in 1996. The Solwara 1 deposit is found at a depth of around 1600m. The average copper grade is 7% which is an order of magnitude higher than the average for land-based mines. The average gold grade is 6g/t but grades of 20g/t were found (Nautilus, accessed 2018). The resource estimate for Solwara 1 by Lipton (2018) is 1030 kt indicated ore and 1357 kt inferred ore as seen in Table 1. Indicated and inferred are terms used in resource classification explained in chapter 3.3. Table 2 shows the resource estimate performed by Rahn (2016), the estimate was done without a cut-off and results in total tonnage of 2112 kt. Figure 7 shows how with increasing cut-off the tonnage above the cut-off decreases, while the average grade increases. At a cut-off of 2.6% about 800 kt of ore remain, with an average grade of about 6%. The outline of Solwara 1 can be seen in the electromagnetic map of the deposit shown in Figure 8. The location of the chimneys, seen Figure 9, can be used together with the electromagnetic map to give a general shape of the deposit. Table 3 shows the return period for the wave height at the Solwara 1 location.

**Table 1: Mineral Resource estimate for Solwara 1; edited from Lipton (2018)**

| **Class** | **Domain** | **Tons (kt)** |
|---|---|---|
| **Indicated** | Sulfide dominant | **1030** |
| **Inferred** | Sulfide dominant | 1330 |
| | Sediment | 27 |
| | Total Inferred | **1357** |

**Table 2: Resource estimate of Solwara 1; edited from Rahn (2016)**

| | **Tonnage [kt]** |
|---|---|
| **Ore Zone** | 1349 |
| **Sediments** | 763 |
| **Total** | 2112 |

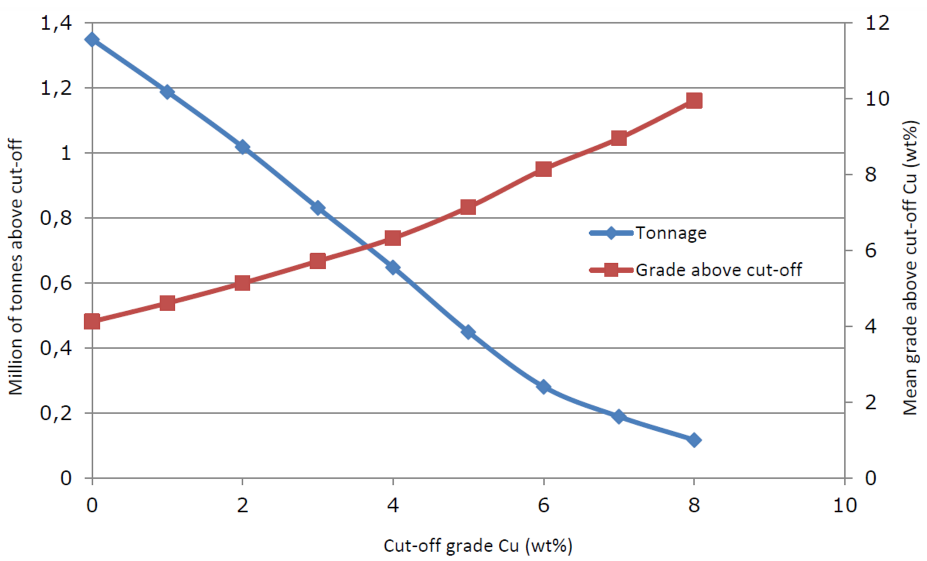


**Figure 7: Cut-off vs tonnes above cut-off; From Rahn (2016)**

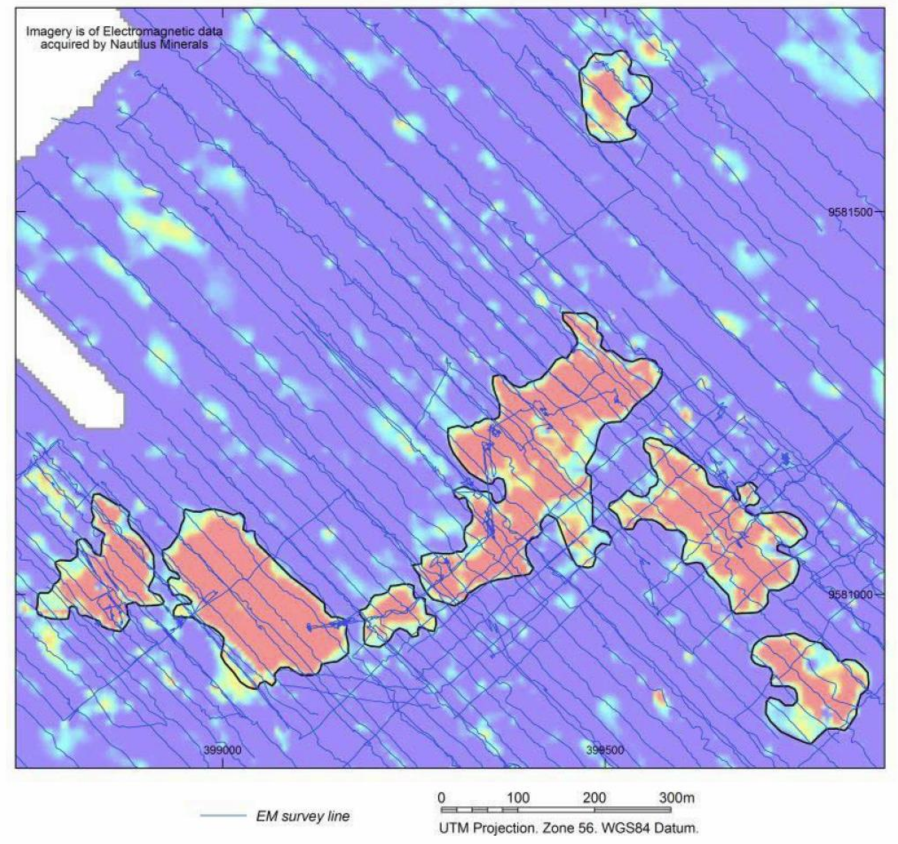


**Figure 8: Electromagnetic map of Solwara 1 (Lipton, 2012)**

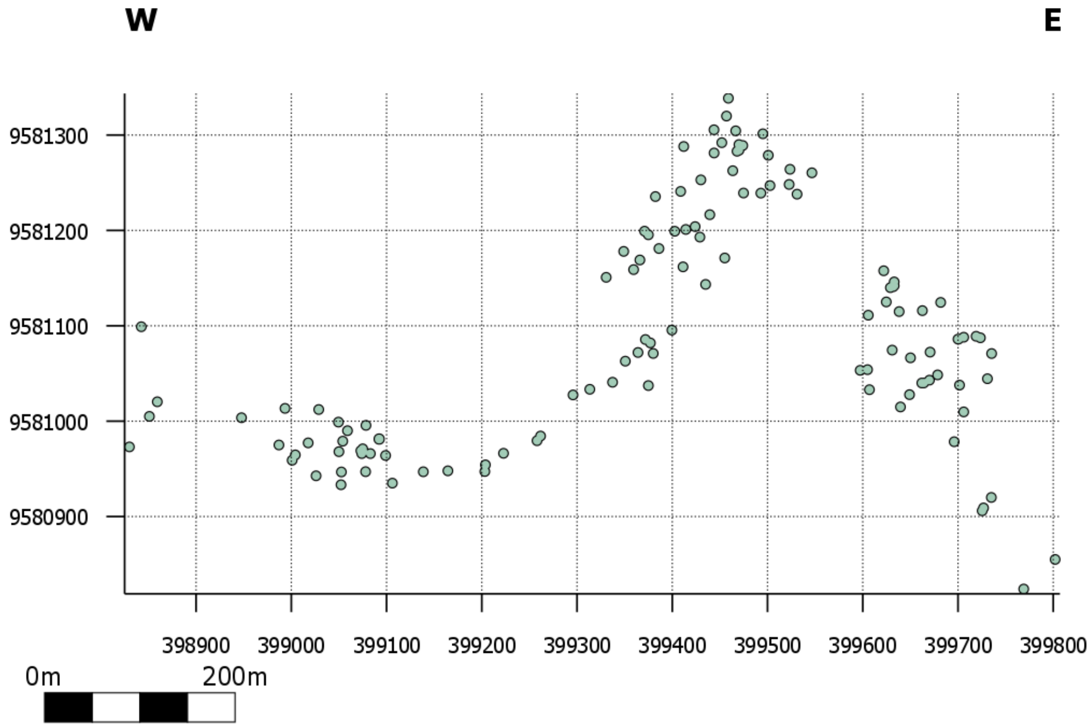


**Figure 9: Visualization of Chimney locations of Solwara 1**

**Table 3: Ocean data from Solwara 1 modified from Lipton (2012)**

| Annual non-cyclonic conditions | Return period (years) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **5** | **10** | **25** | **50** | **100** |
| **Significant wave height [m]** | 3.08 | 3.50 | 4.02 | 4.40 | 4.89 | 5.25 | 5.61 |
| **Spectral peak wave period [s]** | 8.90 | 9.25 | 8.95 | 9.37 | 9.84 | 10.2 | 10.5 |
| **Maximum single wave height [m]** | 5.73 | 6.50 | 7.48 | 8.19 | 9.10 | 9.77 | 10.4 |

### 2.4.3 Governmental and Social License for Solwara 1

The government granted Nautilus the mining lease for Solwara 1 in January 2011 and the environmental permit was granted in December 2009 (Nautilus, accessed 2018). At the end of 2017 non-governmental organizations and coastal communities of PNG launched a law suit against Nautilus to gain more insight into the environmental, health, and economic impacts of the Solwara 1 project. They claim that the environmental impact statement published by Nautilus has insufficient information (Natalie, 2017). It is difficult for Nautilus to obtain and hold a social license because of the remote location of the mine. Even if one group would grant such a license they are not the only ones who claim to be affected and other stakeholders might disagree. The framework for such a problem set in place by the PNG government is meant to deal with land-based operations and is insufficient to address the specific needs of deep-sea mining (Filer and Gabriel, 2017). Rosenbaum (2011) argues that Nautilus does not have a social license to operate until they performed social and economic impact studies which show the impact of deep-sea mining on:

- "*Marine ecosystems and fisheries resources of local, national, and regional economic importance*
- *Local society and culture; and*
- *Human health including the bioaccumulation of metals and other toxicants – including dietary intake studies for communities eating fish caught in the Bismarck Sea, the monitoring of metals associated with the Solwara 1 deposit and an assessment of which communities are likely to be exposed to dietary contamination (which relates to market sales of seafood as well as proximity of communities to points of pollution).*"

## 2.5 Current State of Exploration in Norway

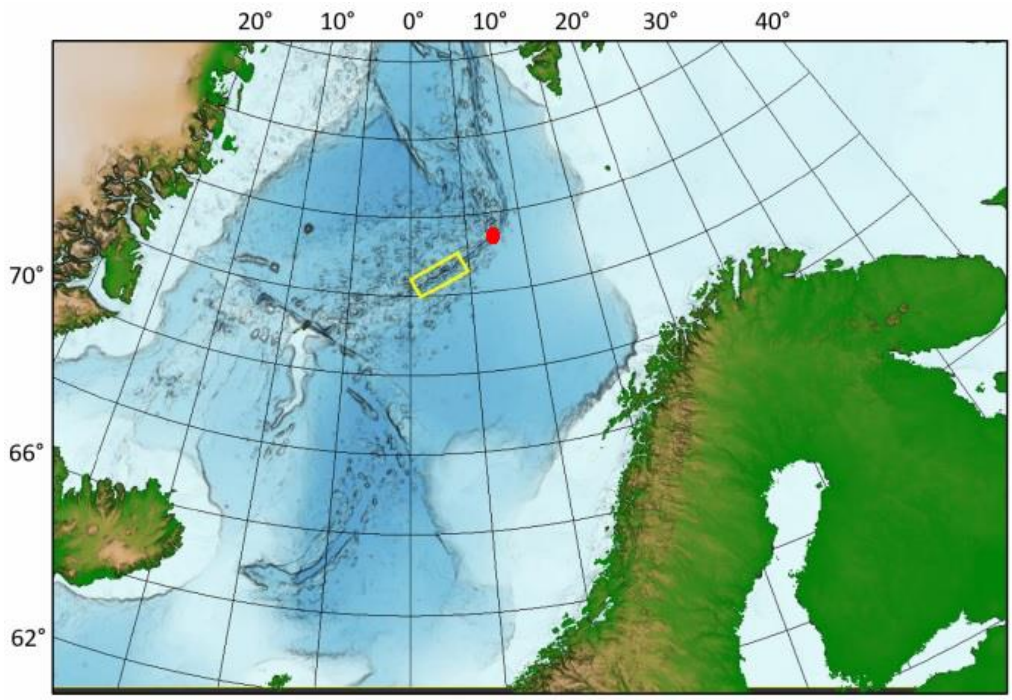


**Figure 10: Location of Mohn’s Ridge (yellow rectangle) and Loki’s Castle (red dot); modified from Norwegian-Petroleum-Directorate (2018)**

The Norwegian Petroleum Directorate wants to map deep sea mineral resources of the Norwegian continental shelf. For that they offered a bidding contract for companies to collect data and sample on SMS deposits of the Mohn’s Spreading Ridge (Figure 10) in the Norwegian Sea between a depth of 2000 and 3300 meters. The duration should be about one month in the summer of 2018. (Norwegian-Petroleum-Directorate, 2018). Currently MarMine investigates several areas along the AMOR in the Norwegian Sea (Figure 11). Several water and rock samples have been taken and the sites have been geologically mapped (Ludvigsen *et al.*, 2016). Loki’s Castle, an active vent site, is located at 73°30′N and 8°E. It is an active vent site on the top of an Axial Volcanic Ridge (Pedersen *et al.*, 2010). Mohn’s Treasure lies south-west of Loki’s Castle and is believed to be an inactive site. Two more sites are located south of Loki’s Castle and west of Mohn’s Treasure, which have been chosen based on assumptions from other hydrothermal vents (Ludvigsen *et al.*, 2016).

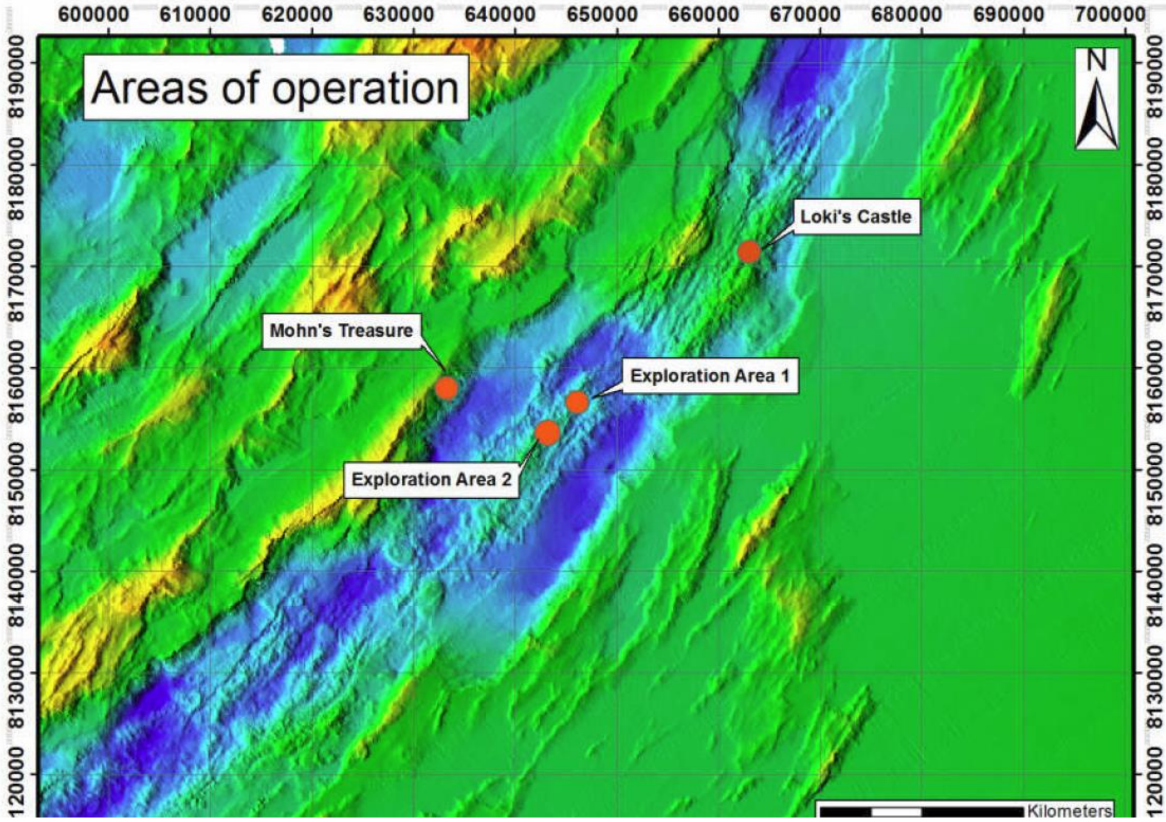


**Figure 11: Exploration Areas of MarMine (Ludvigsen *et al.*, 2016)**

## 2.6 Jurisdictional Issues of Deep-Sea Mining

### 2.6.1 Governmental License

Each country sets its own laws to regulate deep-sea mining for minerals within their exclusive economic zone. The International Marine Minerals Society published a voluntary code describing principals and operation guidelines to form a framework that should help companies make responsible decisions when preforming deep-sea mining. The code aims to set high standards for deep-sea mining operations to protect the environment and hopes that companies adhere to it, when the countries laws do not provide enough environmental protection (IMMS, 2011, Verlaan, 2011). In international waters companies must apply to the International Seabed Authority for exploration rights. The number of application has increased dramatically in the past couple of years compared to the decades before (ISA, accessed 2018, Durden *et al.*, 2017). Mining endeavors in international waters will be more complicated since the deep-sea is a Common Heritage of Mankind and may only be exploited to the benefit of mankind as a whole (UN, 1982).

### 2.6.2 Social License to Operate

The term "Social License" was first used by Jim Cooney in 1997. He used it to describe risk management that was focused on the local community level instead of the governmental level. It is the unofficial equivalent to a "governmental permit" on a more local level, which would help the mine to remain operational. Cooney foresaw that in a globalized world a mining company must maintain both a good standing with the government in the country they operate in and with the local stakeholders who are affected by the mining operation. Since its first inception the term has had different definitions due to its intended vagueness (Cooney, 2017). A social license refers to the acceptance of stakeholders to an operation that affects them. It used to be limited to mining but can now be used in a wider context. The stakeholders are not limited to the local population, they can be NGOs or other parties (Boutilier, 2017, Boutilier and Thomson, 2011). Since stakeholders can stop a project or cause increased cost it is beneficial for the company to have them approve of the project. It is important to note that a social license is more about perception than it is about objective facts. The stakeholders who 'grant' a social license are, in most cases, not professionals with an unbiased view (Boutilier, 2017). Boutilier and Thomson (2011) have a list of four factors which indicate if a social license will be granted. Table 4 shows that each one of the four factors is not enough to grant a social license but a combination of them is necessary, they build upon each other. If a stakeholder has institutionalized trust (factor 3) he will also have factors 1 and 2. If a stakeholder does not believe the company has economic legitimacy he will also not believe it has any of the other factors. And if factor 2a or 2b are not met factor 3 will also not be met (Boutilier and Thomson, 2011).

**Table 4: Four factors that indicate how likely it is if a social license will be granted; Retrieved from Boutilier and Thomson (2011)**

| Level & Label | Description | Role in Determining SLO Levels as Described in Thomson & Boutilier Pyramid Model |
|---|---|---|
| **1. Economic legitimacy** | *The perception that the project/company offers a benefit to the perceiver.* | *If lacking, most stakeholders will withhold or withdraw the* [Social License to Operate] *SLO. If present, many will grant an acceptance level of SLO.* |

| | | |
|---|---|---|
| **2a. Socio-political legitimacy** | *The perception that the project/company contributes to the well-being of the region, respects the local way of life, meets expectations about its role in society, and acts according to stakeholders' views of fairness.* | *If lacking, approval level of SLO is less likely. If both this and interactional trust (2a & 2b) are lacking, approval level is rarely granted by any stakeholder.* |
| **2b. Interactional trust** | *The perception that the company and its management listens, responds, keeps promises, engages in mutual dialogue, and exhibits reciprocity in its interactions.* | *If lacking, approval level of SLO is less likely. If both this and socio-political legitimacy (2a & 2b) are lacking, approval level is rarely granted.* |
| **3. Institutionalized trust** | *The perception that relations between the stakeholders' institutions (e.g., the community's representative organizations) and the project/company are based on an enduring regard for each other's interests.* | *If lacking, psychological identification is unlikely. If lacking but both socio-political legitimacy and interactional trust are present (2a & 2b), most stakeholders will grant approval level of SLO.* |

## 2.7 Relevant Ocean Mechanics for Deep-Sea Mining in the Norwegian Sea

The Norwegian Sea lies north east of the coast of Norway. It is located between the Barents Sea to the north west, the Greenland Sea to the east, the Atlantic Ocean to the south east, and the North Sea to the south. Due to the Gulf stream the Norwegian Sea is year-round ice free. Because of its warmer water "polar lows" can form over the Norwegian Sea. Polar lows are short lived storm events in the polar regions. They develop when cold artic air flows over ocean areas with a relative high surface temperature. Such conditions result in strong convection and wind forces of hurricane strength with heavy rain or snowfall (Føre *et al.*, 2011, Kolstad, 2006).

Waves of too much height can cause damage, if the mining equipment remains attached to the ship. A way to measure the waves in a sea state is the significant wave height $H_S$. It is defined as the average height of the highest 1/3 of all waves in a the sea state (Manual, 1984). When calculated from a wave spectrum the significant wave height is called $H_{m0}$. The cumulative distribution function for each month can be estimated with:

$$F_{H_{m0}}(H_{mo}) = \frac{n_{H_{m0}}}{n+1}$$

$n$ is the total number of observations and $n_{H_{m0}}$ is the number of observations less or equal to $H_{m0}$. Another factor is the return period. It estimates the wave height which will be exceeded once during the return period. It can be calculated with the help of a Weibull Plot. A Weibull plot uses a special scale to fit Weibull distributed data in a linear fashion (see Appendix A) (Nelson, 2005).

# 3. Theory

## 3.1 Generation of a 3D Geometric Model to define the Shape of Deposits

Explicit modelling works similar to engineers drawing a building plan. Known points are directly connected to create surfaces (ARANZ, accessed 2018). 3D models are created by viewing and connecting the drillhole data in a series of 2D sections an example for that can be seen in Figure 12. Several of these 2D sections are then joined together to create a 3D model, this can be seen Figure 13. Drawing and constructing the wireframe models is very time consuming. During this process it is up to the geologist to ensure that the boundaries of lithological units are respected and other local features are integrated into the model (Cowan and Beatson, 2003).

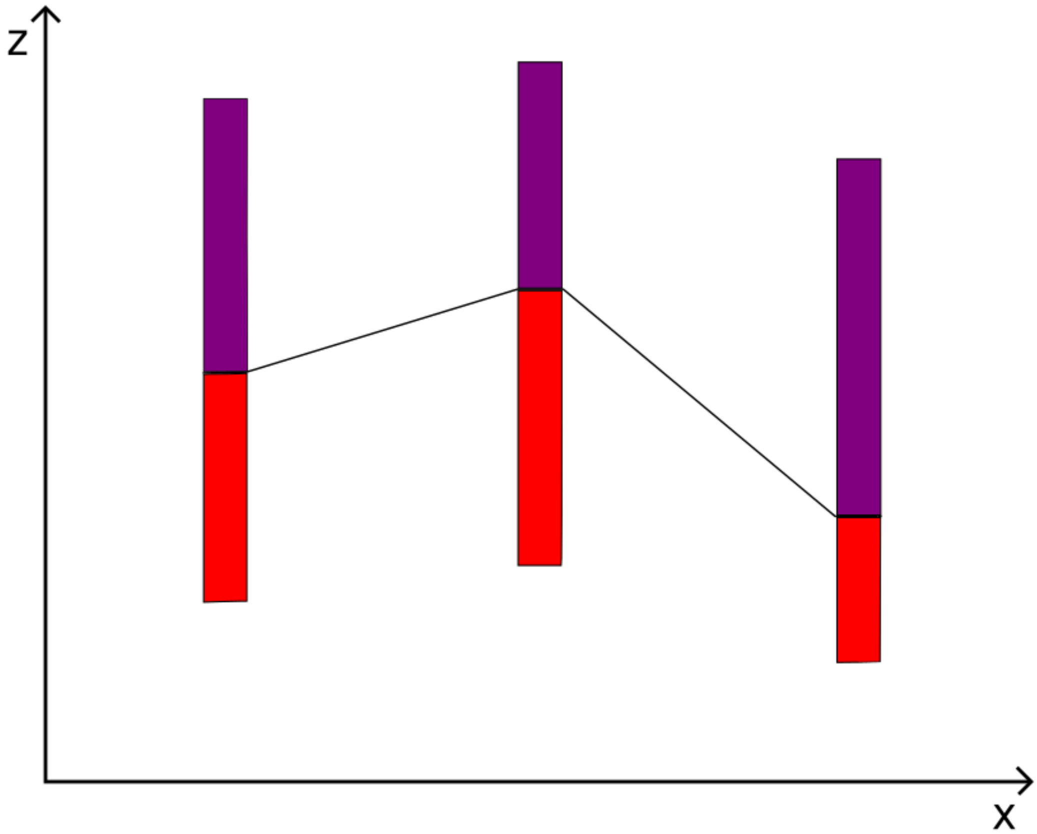


**Figure 12: Example for connecting drillholes in explicit modeling to create a 2D section**

Geology does not come in straight lines like buildings, there are many unknowns, and the model might need to change when more data becomes available. This is not always possible with explicit modelling (ARANZ, accessed 2018, Lane, accessed 2018). Most of the time it is only possible to make one model beforehand because creating multiple different models to compare with each other would be to time intensive and therefore too costly (Cowan and Beatson, 2003). Implicit modelling uses mathematical algorithms and interpolates the shape of the deposit form the drillhole data. It requires very little in terms of direct input from the user (Cowan and Beatson, 2003). This makes it faster and more flexible to later alterations. It also gives more consistent results since no unwanted gaps or spaces will appear. In explicit modelling sections are generated independent and then put together, while in implicit modelling everything can be considered together, and new data can be used to keep the model updated (Lane, accessed 2018). Implicit modelling allows for greater complexity and for multiple models to be created in a short amount of time. This leads to better understanding and decreased risk since a multitude of solutions can be considered (Hollenbeck and Melker, accessed 2018).

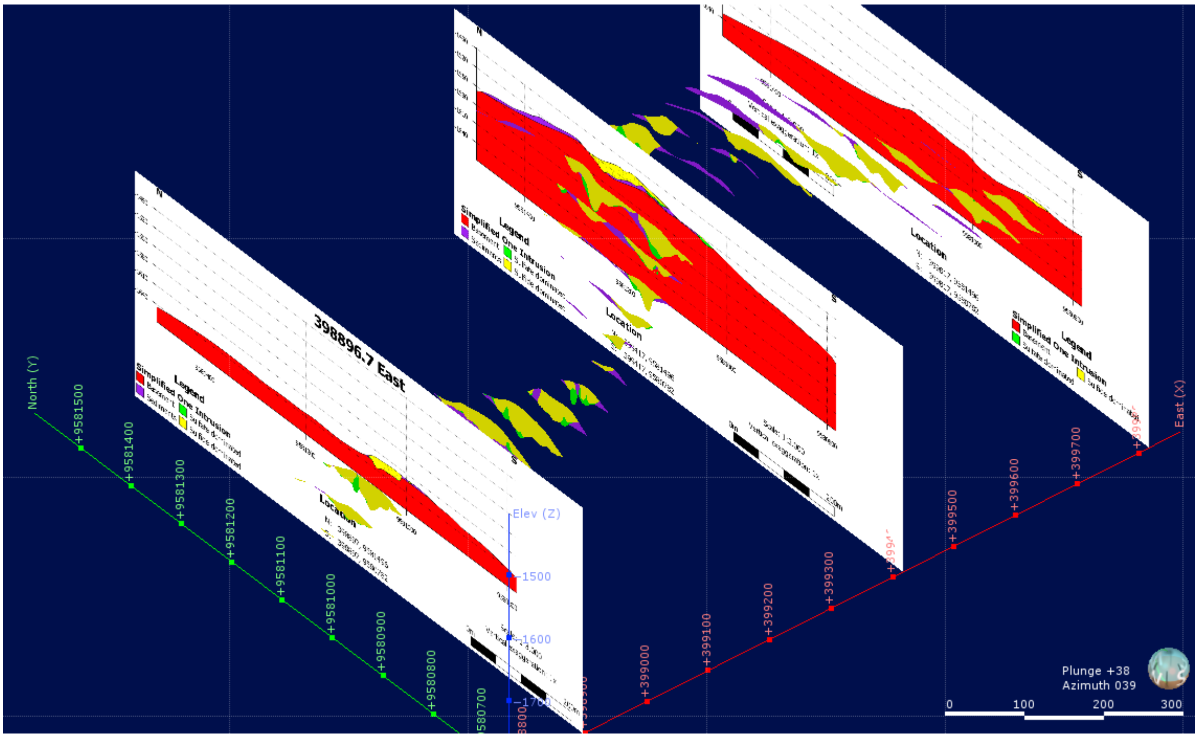


**Figure 13: Example for explicit modelling showing a series of 2D sections stacked after each other**

## 3.2 Generation of a 3D Qualimetric Model to quantify the Ore Variations

Qualimetry is the process of assessing the quality of any product, or process. It then allows to filter for certain quality parameters, which means there a certain constrains put upon the product, or process (Nazarov and Krushnyak, 2006). For the qualimetric model of this thesis the important parameter would be the copper equivalent (CuEq) value. We then can apply a cut off and disregard any value below the cut-off, so only the economic relevant data is left. Geostatistics is an important tool for a wide variety of scientific fields. It is, for example, used in geology, geography, atmospheric, environmental, and epidemiological science. It contains a variety of probabilistic tools which are used to work with, understand, and model data which has a spatial variation. Within geostatistics kriging refers to liner regression techniques, the term was used by Georges Matheron in 1963 and named after Daniel Kriege (Gething, 2010, Chilès and Delfiner, 2012). The advantage over other geostatistical methods is that it takes into account that there is spatial variance of the interpolated value. Which can be described by a variogram (Akin and Siemes, 1988). The key parameters of a variogram are sill, range, and nugget as seen in Figure 14. The range is the maximum distance at which the sample points influence each other after this distance the samples don't have a statistical influence on each other. At the range the variogram has its sill value. The sill is the value where the variogram levels off. In theory a variogram should be zero at the origin. If it is not zero at the origin then this difference is called the nugget (Bohling, 2005). A variogram can also be used in resource and reserve classification (Benndorf, 2015), which is discussed in chapter 3.3.

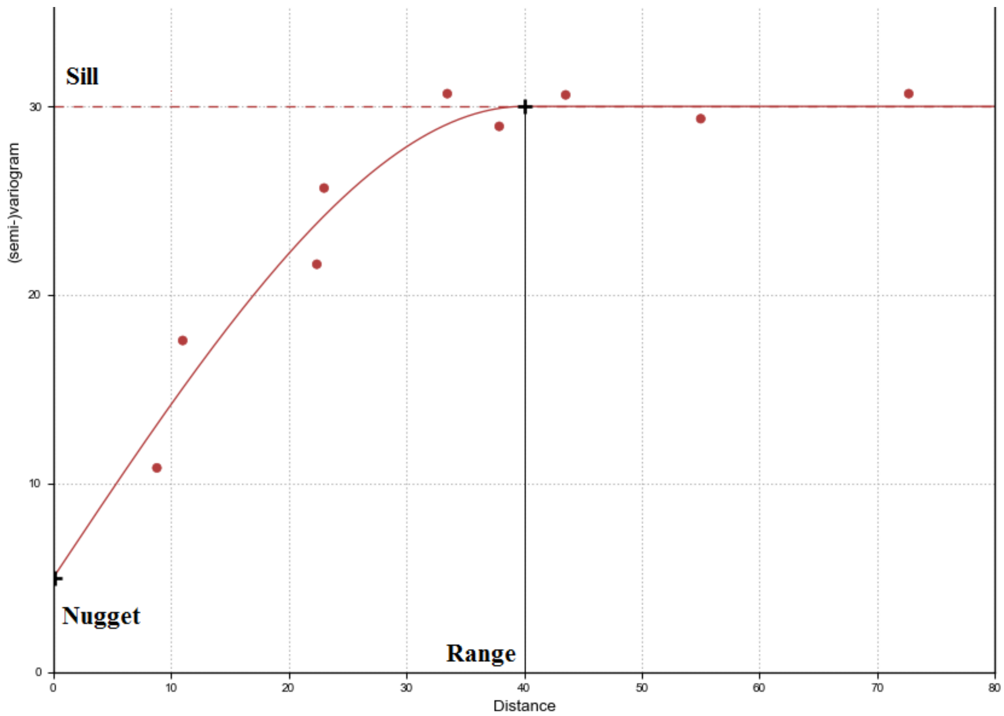


**Figure 14: General shape of a variogram and the key parameters used to describe the spatial structures: Nugget, Range, and Sill**

## 3.3 Resource and Reserve Classification of a Deposit

There are many codes which give guidelines to classify resources and reserves, the Joint Ore Reserves Committee (JORC) Code, the Pan-European Reserves & Resources Reporting Committee (PERC) Code, The South African Code for the Reporting of Exploration Results, Minerals Resources and Mineral Reserves (SAMREC) Code, and the Securities and Exchange Commission (SEC) Industry Guide 7, are a few examples. While different in their wording they all use the same general idea. An ore deposit is either viable for mining and is classified as a reserve or it is not viable for mining and classified as a resource. A resource may later become viable for mining and gets reclassified. They also differentiate the amount of knowledge gathered about the deposit normally called “inferred”, “indicated”, and “measured”. Inferred resources have the least amount of confidence, it is based on extrapolated data, and limited evidence and sampling, there is enough to imply the presence of the deposit but not verify the grade or continuity.

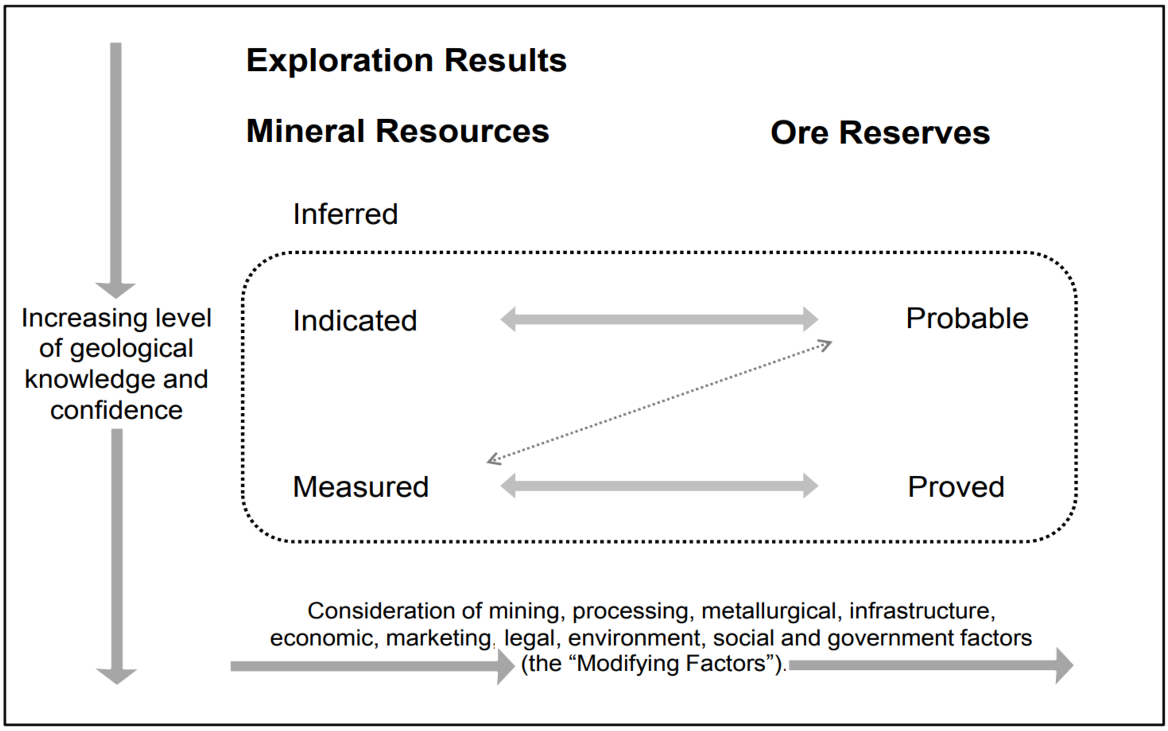


**Figure 15: JORC Code showing the relation between exploration results mineral resources and ore reserves and detailing how increasing knowledge and modifying factors determine for the results (JORC, 2012)**

It can be expected that further investigation would make an inferred resource become an indicated resource. Indicated resources have enough information on quantity, grade, shape, and physical characteristics and the confidence in the information is high enough to allow the modifying factors to be applied and determine if the resource can be classified as probable reserve or not, but more exploration must be done to be sure of the viability of the deposit. Measured resources have a higher level of knowledge and a high confidence in that information than indicated resources. Modifying factors can be applied to try to convert the resource into a proved reserve. When converting from a resource to a reserve many modifying factors, as seen in Figure 15, determine if the ore deposit is viable for mining or not. These factors have a wide range of possible origins, from economic, to geological, to social, environmental, and political. Possible economic considerations are cost of establishing a mine with the necessary infrastructure, the price and demand of the potential ore. The other issues include, what stance does the local population have on the project, how will the environment be affected by the mining, what is the cut-off grade for the ore. Another factor is if the deposit contains more than one economically interesting metal, in such a case a metal equivalent is used. Using a calculation formula all metals, but one, are converted into the one metal remaining (JORC, 2012, SAMREC, 2016, SEC, 1992, PERC, 2015).

The cut-off grade is determined by the ore operating cost, which is the operation cost of the mine per ton of ore, and the revenue of the mined metal per gram (Pittuck, 2015). Net Smelter Return is the revenue generated from a mineral product after deducting all the cost that is not related to the mining process (Goldie and Tredger, 1991). It can be used an alternative to the metal equivalent explained in chapter 3.3. Often metal equivalent calculation ignores different treatment cost and losses in the refinement process and is only done once at an initial pricing level for the metal. Net Smelter Return can give a more flexible and accurate revenue estimate. (Goldie and Tredger, 1991).

These codes are all deliberately vague in their wording because no two deposits are the same and experience is needed to decide which methods to use and when enough data has been collected to have enough knowledge and high enough confidence to classify the deposit. The most obvious factor for gathering data is the drillhole spacing. More drillholes means more data and more confidence in the data. But drilling more also increases the cost for the company exploring the deposit. Most companies want the most information with the least cost, the drillholes must be set up in such a way that the confidence in continuity and grade is high enough without costing too much. The maximal viable drillhole spacing depends on the deposit and how complex it is and the level of risk that the person doing the exploration is willing to accept.

Benndorf (2015) suggest that a variogram can be used to aid in resource classification. As seen in Figure 16 about half the range it is measured and from that point until the range of the variogram is indicated, everything past the range is inferred. These are just suggestions and they should be adapted to fit the current case.

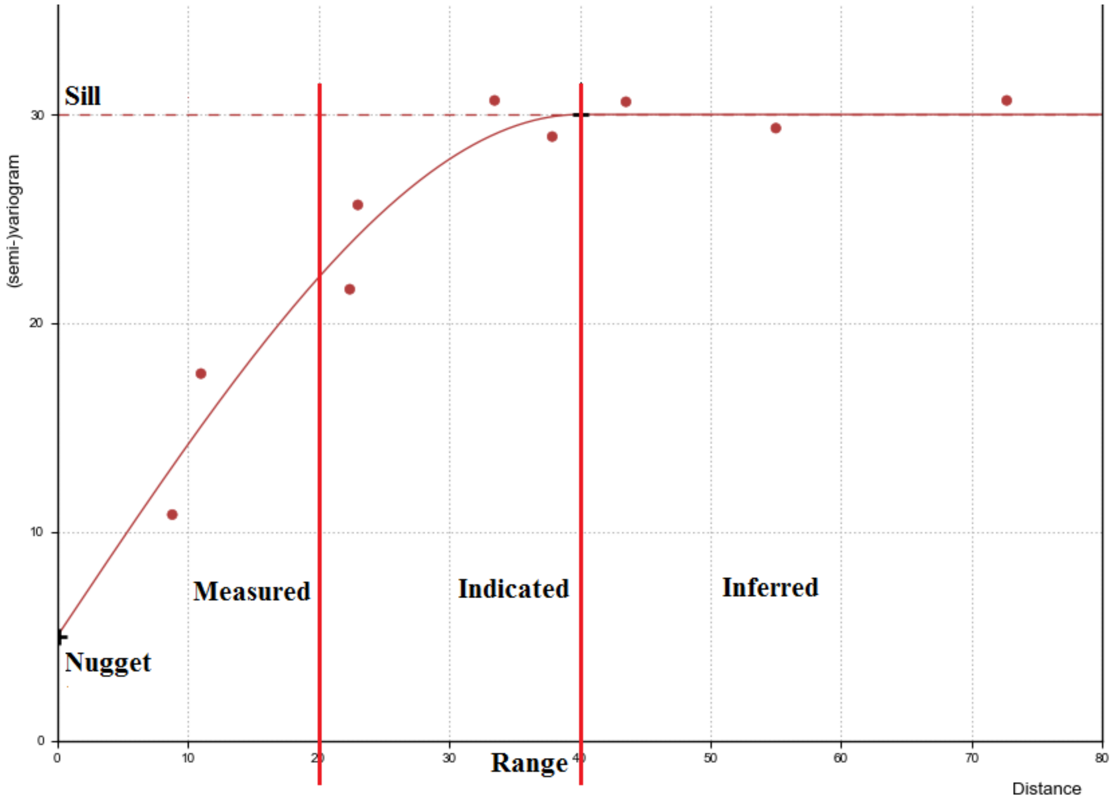


**Figure 16: Example for a variogram used to classify a resource based on sample distance; modified from Benndorf (2015)**

Choosing the right mining method is critical for the success of a mine. A deposit has limiting factors and characteristics that make some mining methods more applicable than others (Bitarafan, 2004, Singhal, 1995). There are different approaches to selecting the right mining method, such as the numerical approach, where every factor gets a weighted value. These values give a characteristic an unfavorable, neutral, or favorable rating for a given method. They can also eliminate a method outright (Singhal, 1995). Assessing the mining site in such a way is a difficult task, which increases with complexity of the mining site.

In practice to be able to define a reserve additional studies must be performed. Each study will be more detailed than the one before since more data is gathered and analyzed. First is the Preliminary Economic Assessment or scoping study. After that Preliminary Feasibility study and lastly the Feasibility Study is performed. In addition an environmental impact assessment needs to be performed (Jackson, 2014, Rupprecht, 2004). Scoping studies are a first assessment of the deposit. They are carried out early and give a rough financial estimate, they are accurate to 30-50%. Scoping studies are an important tool to determine if a project should be further developed or not. Often, they use known costs of similar projects to perform their calculations. Care must be taken during a scoping study since the decision whether the project continues or stops relies on the result of the study. A scoping study looks at the mineral deposit and its grade. With that data a rough estimate on the value of the deposit can be calculated. Part of the resource might not become a reserve, but this is of no concern during the scoping study since it has to work with little information (Rupprecht, 2004).

The next step is a prefeasibility study, this is done once a minerals resource has been defined. Prefeasibility studies are accurate to 15 to 30% on the cost. Rupprecht (2004) has a list of topics a prefeasibility study must cover:

- *Location and description of the project*
- *Regional and local geology*
- *Mineral resource estimate and model*
- *Reserve conversion*
- *Preliminary studies completed on geotechnical, environmental and infrastructure requirements*
- *Mine design based on a resource model, best alternatives selected from a range of alternatives*
- *Mine sections and level plans*
- *Mining method(s) and extraction sequence*
- *Ore handling*
- *Bench scale metallurgical tests and preliminary process design completed*
- *Process plant*
- *Mill flow sheet*
- *Pre-production construction schedule*
- *Production schedule*
- *Capital and operating cost estimate*
- *Preliminary financial evaluation and risk analysis.*

Lastly the full feasibility study is there to show that the project is economically and technically viable. It should be 10-15% accurate for the cost. A full feasibility study is used to ensure financing and provides a budget for the project. Rupprecht (2004) says a full feasibility study should include these points:

- *Ore reserves as per standard definition (i.e. SAMREC, JORC, etc.)*
- *Scale of the project*
- *Construction budget and schedule for the project*
- *Cost estimate for operating and capital*
- *Contingency; there are many approaches to the inclusion of a contingency. The contingency may be an estimate of costs that will arise subsequent to the study or it may be a hedge against improper or incomplete estimates*
- *Market estimates; the most significant variable in a feasibility study is often commodity price and currency exchange rate*
- *Cash flow study; an appropriate discount rate should be agreed by all concerned and used to calculate the NPV*
- *Risk and sensitivity analysis; risk and sensitivity analysis are commonly used to assess the upside and downside potential of the project.*

The environmental impact assessment ensures that the mine has a small negative environmental and social impact. Its job is to identify environmental problems and find solutions for them. It can be the most time consuming and costly study when developing a mine and starting it early in the development process is critical (Rupprecht, 2004).

# 4. Material used in this thesis

In this thesis drillhole data from Solwara 1 is used to create a 3D model of the deposit in Leapfrog Geo. Figure 8 shows the electromagnetic map used to define the general shape of the deposit. Figure 9 is a visualization of the chimney location of Solwara 1, it was used to determine where the feeder channels should be. The data set can be found in the Blue Mining report by Rahn (2016) and the reports for Nautilus Minerals: Lipton (2008), Lipton (2012), and Lipton (2018). The average grade for silver, gold, and copper are 18.53 ppm, 3.39 ppm, and 4.1% respectively more information can be found in Table 5. There is also data for lead and zinc available, but since the concentrations are very low they were omitted in this thesis. Figure 17, Figure 18, Figure 19 show the histograms for each element. Figure 20 shows the location of the drillholes for Solwara 1.

**Table 5: Statistical data for Solwara 1**

| | **Ag [ppm]** | **Au [ppm]** | **Cu [%]** |
|---|---|---|---|
| **Count** | 1085 | 1151 | 1171 |
| **Length** | 771.85 | 823.56 | 839.85 |
| **Mean** | 18.53 | 3.39 | 4.10 |
| **SD** | 37.33 | 5.20 | 5.34 |
| **CV** | 2.01 | 1.54 | 1.30 |
| **Variance** | 1393.88 | 27.07 | 28.49 |
| **Minimum** | 0 | 0 | 0 |
| **Q1** | 1 | 0.3 | 0.1 |
| **Q2** | 7 | 1.9 | 2 |
| **Q3** | 20 | 4.4 | 6 |
| **Maximum** | 556 | 89.5 | 37.7 |

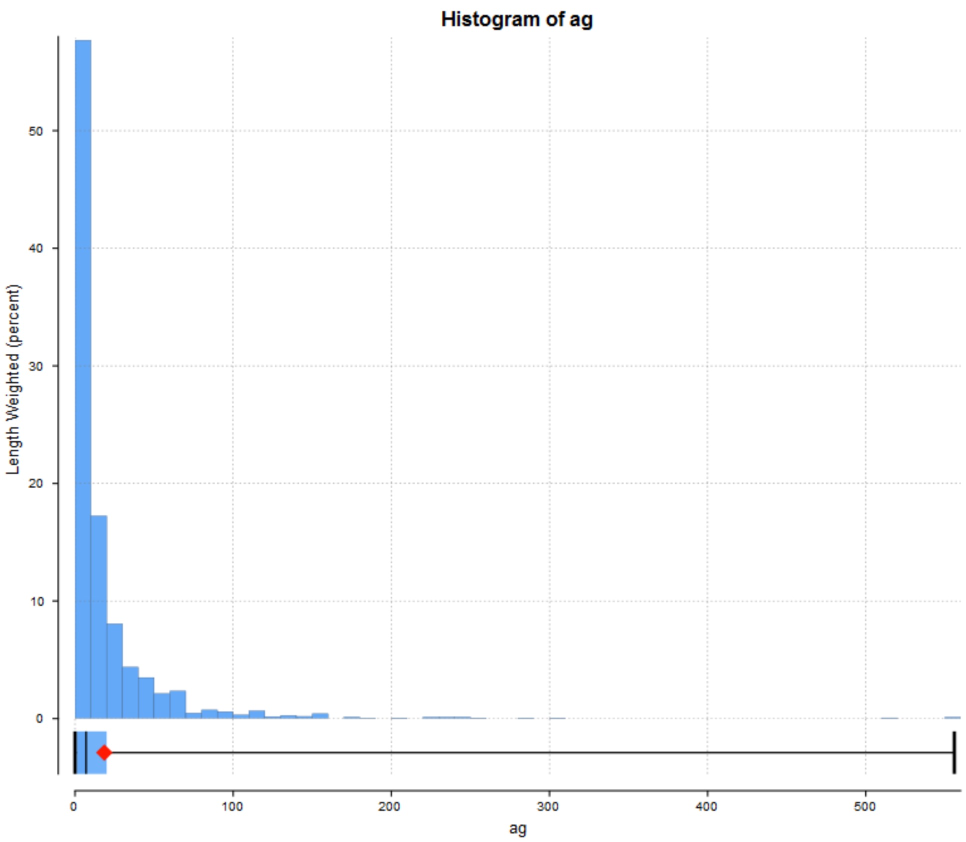


**Figure 17: Histogram of Ag [ppm]**

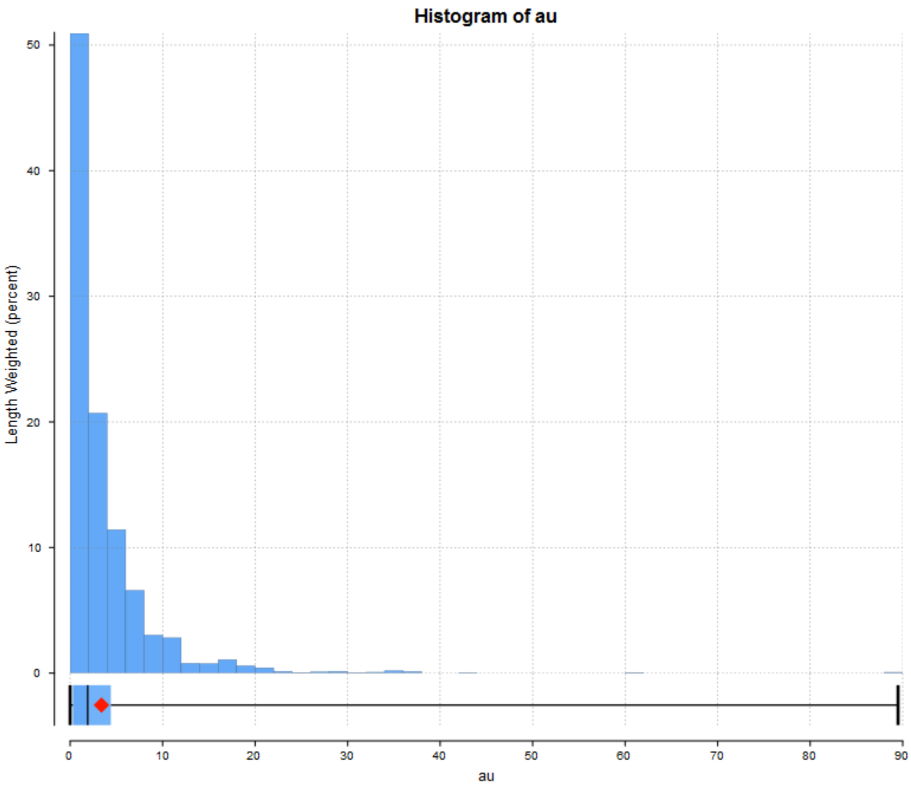


**Figure 18: Histogram of Au [ppm]**

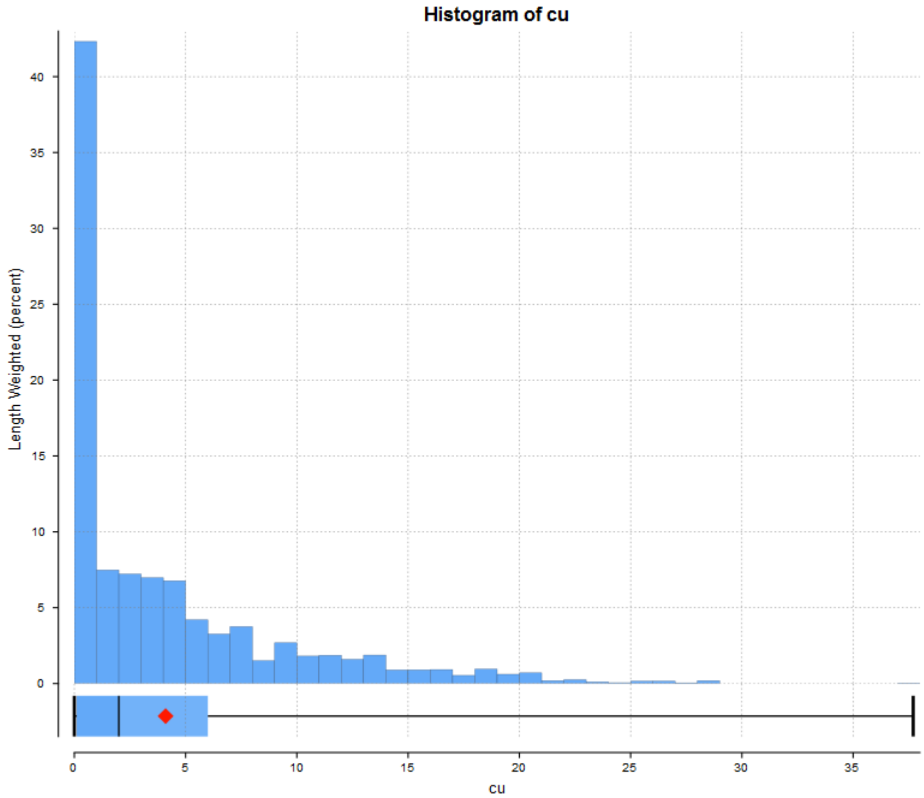


**Figure 19: Histogram of Cu [%]**

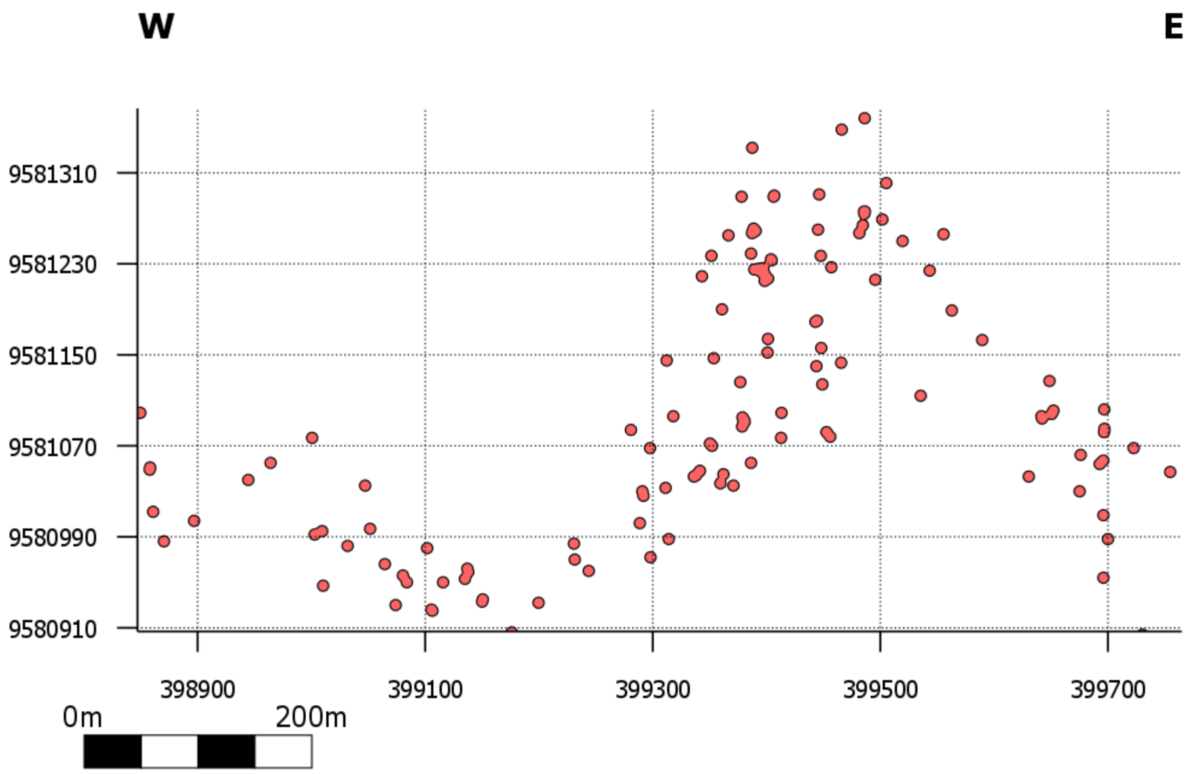


**Figure 20: Locations of the drillholes for Solwara 1**

Table 6 shows the lithology of the Solwara 1 deposit. The colors indicate the simplified grouping used in this thesis: Sediments, Sulfate dominated, Sulfide dominated, Basement.

| **Table 6: Lithological units of Solwara 1; Text from Lipton (2018)** | | |
|---|---|---|
| *"Mud-silt-sand-gravel* | *SS* | *Unconsolidated to weakly consolidated sediments. Grain-size, 'cohesive muds' and sulfide clasts to be noted during detailed logging.* |
| *Cemented sediment* | *SC* | *Any sedimentary material that has been cemented by fine-grained/cryptocrystalline sulfide or sulfate minerals and/or amorphous opaline silica. May contain filled or open worm burrows and gastropod shell-fragments replaced by sulfides.* |
| *Sparry precipitate* | *PT* | *Precipitate of sulfate crystals, often with bladed barite, found within or at the base of the sediment units. Crystal size is generally larger than within the cemented sediments with bladed barite visible to the naked-eye and fractured surfaces on the rock having a "sparry" appearance. Does not contain any sedimentary features or relict clasts.* |
| *Conduit-bearing Facies* | *CF* | *Similar appearance to the internal texture seen in surface chimney samples. Zoning of sulfides around open conduits is a key diagnostic feature. Any other indication of open channel-ways (including open vugs with visible coatings of euhedral sulfides) also suggests chimney building processes at work. Chimney structures can be identified from the detailed bathymetry, and drillholes proximal to these are likely to intersect Conduit-bearing facies under any cover sediments. Conduit-bearing facies are usually found at the top of sulfide dominated mineralisation but their root-zone of feeder channel-ways may extend to depth in drill core.* |
| *Sulfide dominant rock* | *RI* | *Sulfide dominated. Total sulfide percent is generally greater than the sum of anhydrite+clay. Sulfides are dominated by pyrite; sulfates are dominated by anhydrite but may include barite. Analogous to Massive Sulfide in VHMS deposits.* |
| *Sulfate dominant rock* | *RA* | *Sulfate dominated. Sulfates are dominated by anhydrite but may include barite.; sulfides are dominated by pyrite but may include chalcopyrite. Generally, found in a 'footwall' position below the main mineralised zone but may also occur lateral to the root-zone of chimneys.* |

| | | |
|---|---|---|
| *Clay dominant rock* | *RC* | *Clay dominated. Sulfates are dominated by anhydrite but may include barite; sulfides are dominated by pyrite but may include chalcopyrite. Generally, found in a 'footwall' position below the main mineralised zone but may also occur lateral to the root-zone of chimneys* |
| *Volcaniclastic breccia* | *VB* | *Matrix-poor volcaniclastic breccia with close-packed clasts of the massive volcanic material. May be strongly altered but retains textural evidence of a volcanic precursor lithology.* |
| *Massive volcanic* | *VC* | *Matrix-poor volcaniclastic breccia with close-packed clasts of the massive volcanic material. May be strongly altered but retains textural evidence of a volcanic precursor lithology.* |
| *Core loss* | *xL* | |
| *Void* | *xV* | *Natural void interpreted from drillers data/comments and supported by evidence in core."* |

# 5. Methods

## 5.1 Leapfrog 3D modelling

Leapfrog Geo is a software for 3D implicit modeling. The 3D model of the Solwara 1 deposit was created as followed:

- Import bathymetric data and drillholes into the program.
- Create a topography from the bathymetric data and ensure that the drillholes lie on the topography.
- Create a geological model with a deposit boundary between basement and sediments.
- Create a sulfide and sulfate intrusion. A SMS deposit is not a true intrusion but a hydrothermal alteration of the host rock. In the modeling software treating it as an intrusion is the best way of modeling the deposit.
- Use the magnetic map to create a structural trend and apply it to the deposit.
- Create a polyline feeder system based on the location of chimneys on the ocean floor to limit and shape the deposit.
- Create interpolants for distance to the drillholes and the copper equivalent values.
- Make sure the variograms are correct and apply the cut-off.
- Create combined models which combine distance to drillholes and copper equivalent values to create the resource estimate.
- Create a block model from the combined models.
- The block model can be evaluated to get the tonnage of the ore available

## 5.2 Metal equivalent calculation

Lipton (2012) performed a resource estimate and a copper equivalency calculation. The cut-off value given by Lipton (2012) is 2.6% CuEq. The formula for the copper equivalency is:

$$"CuEq = Cu \cdot CuRec + \left[\frac{Au \cdot AuRec \cdot AuPrice}{CuPrice}\right] + \left[\frac{Ag \cdot AgRec \cdot AgPrice}{CuPrice}\right]$$

*Cu = %Cu*

*CuPrice = Cu price ($/t)*

*Cu Rec= Recovery of Cu (after adjusting for metallurgical transport and royalty losses)*

*Au = Au (g/t)*

*AuPrice = Au price ($/g)*

*Au Rec= Recovery of Au (after adjusting for metallurgical transport and royalty losses)*

*Ag = AG (g/t)*

*AgPrice = Ag price ($/g)"*

*Ag Rec= Recovery of Ag (after adjusting for metallurgical transport and royalty losses)*

Losses can be estimated as followed: 3% loss during transport and processing, 2.25% losses of metal produced as royalties to PNG. Metallurgical recovers are 91.5% for copper 45% for gold and 50% for silver (Lipton, 2012). Later in the report they use this formula:

*"CuEq = 0.915*Cu + 0.254*Au + 0.00598*Ag"*

When performing the copper equivalence calculation it was unclear which values were used by Lipton (2012). For example, the value of 0.915 refers to the metallurgical recovery for copper but ignores losses during transport and royalties. Because of this the copper equivalent calculation by Hansen (2012) is used in this thesis, since it is clearer in its application. Because the equivalence calculation includes different recovery rates for each metal it avoids a problem this method has compared to Net Smelter Return and is suitable to use. Table 7 shows the recovery values and metal prices used for the copper equivalency calculation.

$$CuEq = \frac{(Cu \cdot CuRec \cdot CuPrice + Au \cdot AuRec \cdot AuPrice \cdot Ag \cdot AgRec \cdot AgPrice)}{CuPrice}$$

(Hansen, 2012)

**Table 7: Recovery values calculated from the losses, royalties and recovery values provided by Lipton (2012). Metal prices by InvestmentMine (2018)**

| | Cu | Au | Ag |
|---|---|---|---|
| **Price** | 50.72 €/1% | 35.4 €/g | 0.48 €/g |
| **Recovery** | 0.87 | 0.43 | 0.47 |

## 5.3 Resource and Reserve classification for Solwara 1

The range of the copper variogram is 35m and the resource estimate by Lipton (2012) uses only indicated and inferred. This means there is still much information to be gained about the Solwara 1 deposit. Based on the range of the variogram 0-10m will be used as indicated and 10m+ as inferred to perform the resource estimate. A reserve estimate is more difficult since much more information is needed to perform such a task. The Preliminary Economic Assessment by Lipton (2018) is just the first of three studies which are needed before a reserve classification can be done. Certain issues such as metallurgical recovery, royalties, and legal issues have already been addressed for Solwara 1 but need to be investigated further. This thesis will assume that any issue needed for a reserve classification has been addressed so that a reserve classification can be performed. Jackson (2014) suggest that generally between 40-80% of a resource can be converted to a reserve, this is for land-based resources. In a deep-sea mining setting no such general estimate exists but for the calculation performed it will be assumed that the numbers are the same.

# 6. Results

## 6.1 Ocean Mechanics in the Norwegian Sea

The meteorological data for the Norwegian Sea is provided by Reistad *et al.* (2011). Table 8 shows the average significant wave height, standard deviation, and the cumulative probability for each month, at a location near Loki's Castle. The significant wave height is lowest in July with 1.4m and highest in January with 3.6m. The average significant wave heights are plotted in Figure 21. The values are calculated from the data from 2005-2015. Table 9 shows the single highest wave height for different return periods. The wave height for a return period of 5 years is 12.3m.

**Table 8: Average significant wave height, standard deviation, and comulative probability percentile for the location NORA10 7361N 0815E**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Okt | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean $H_S$ [m] | 3.6 | 3.5 | 3.1 | 2.5 | 2.0 | 1.5 | 1.4 | 1.5 | 2.2 | 2.9 | 3.0 | 3.3 |
| Std. dev. | 1.6 | 1.6 | 1.5 | 1.2 | 1.0 | 0.7 | 0.6 | 0.7 | 1.0 | 1.4 | 1.3 | 1.5 |
| Mean $T_P$ [s] | 10.8 | 10.3 | 9.9 | 9.0 | 8.4 | 7.6 | 7.8 | 7.7 | 8.9 | 9.7 | 9.9 | 10.4 |

**Table 9: Return period for single highest wave for the location NORA10 7361N 0815E**

| Return Period | 1 | 5 | 10 | 25 | 50 | 100 |
|---|---|---|---|---|---|---|
| H [m] | 10.8 | 12.3 | 12.8 | 13.5 | 14 | 14.6 |

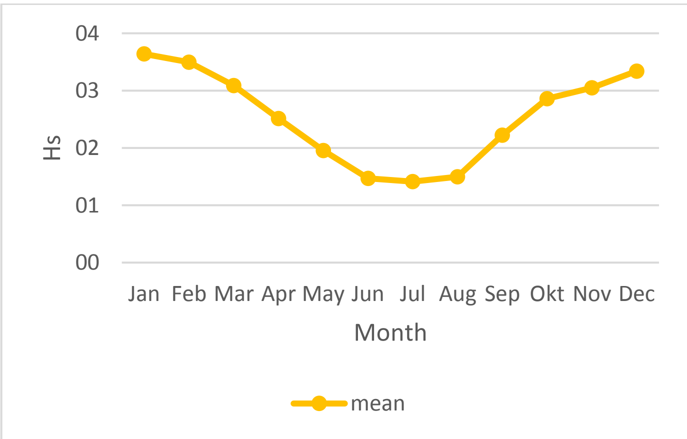


**Figure 21: Cumulative probability per month for NORA10 7361N 0815E**

## 6.2 Geometry of the model

The model was created with the Solwara 1 data. The shape of the model seen in Figure 22 matches the outline of the electromagnetic map. Figure 23 show the location of the cross sections shown in Figure 24 and Figure 25.

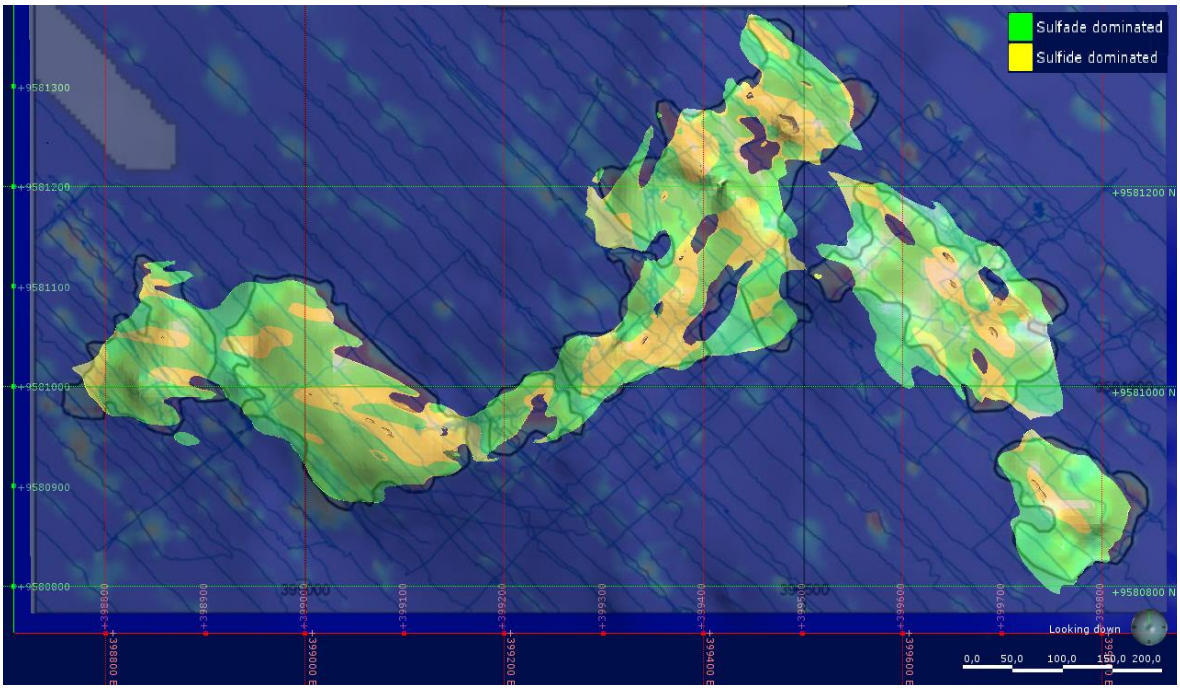


**Figure 22: Top down view of the geometric model with outlines of electromagnetic map**

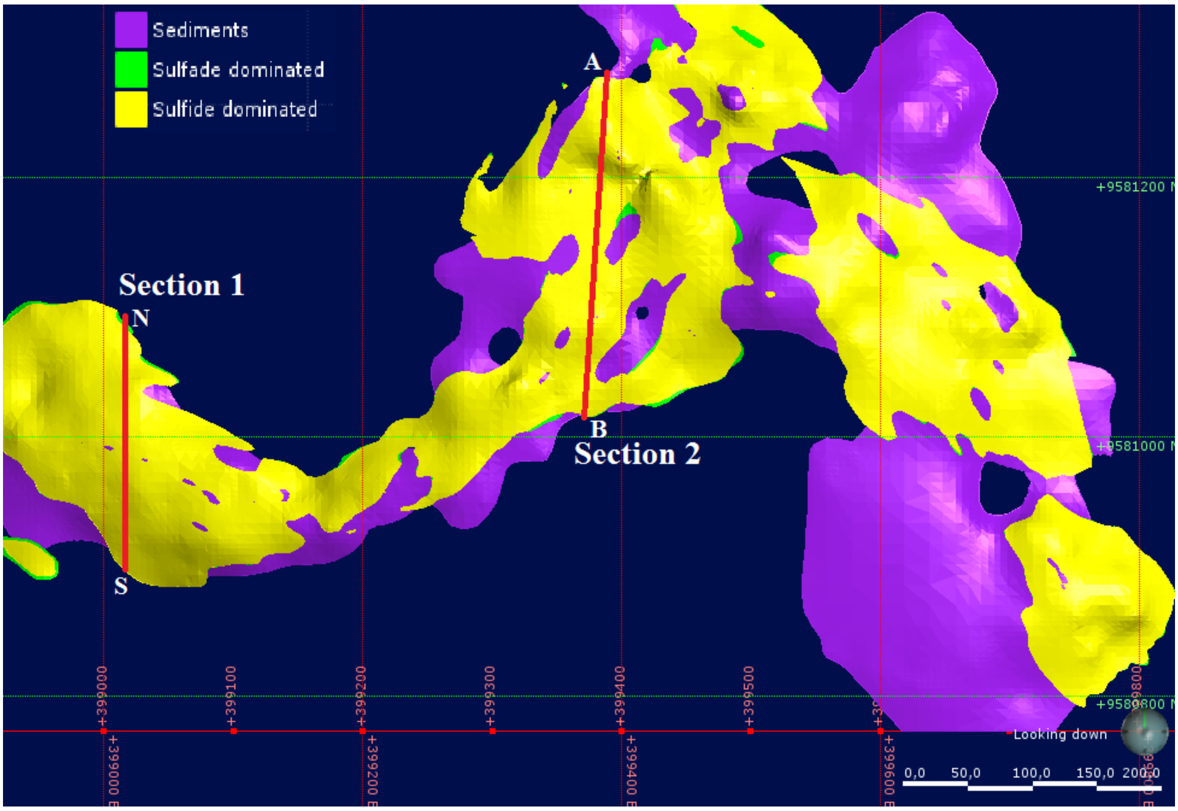


**Figure 23: Location of cross sections**

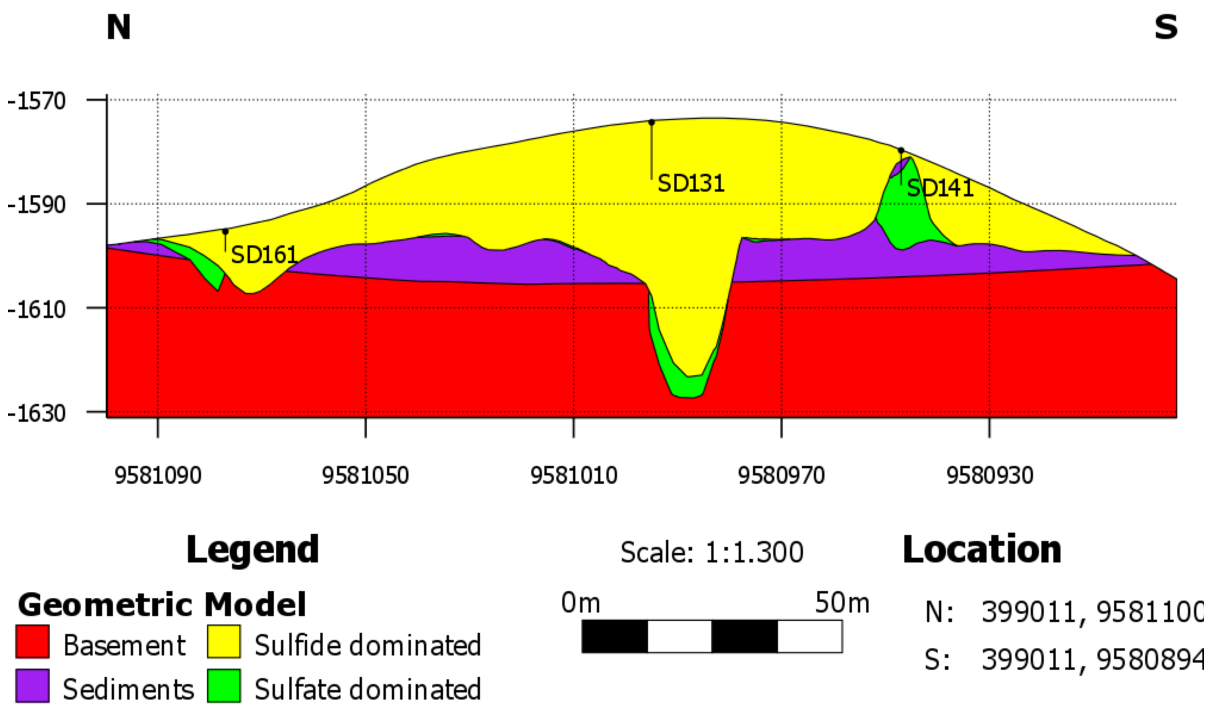


**Figure 24: Cross section 1 showing a feeder channel below drillhole SD131**

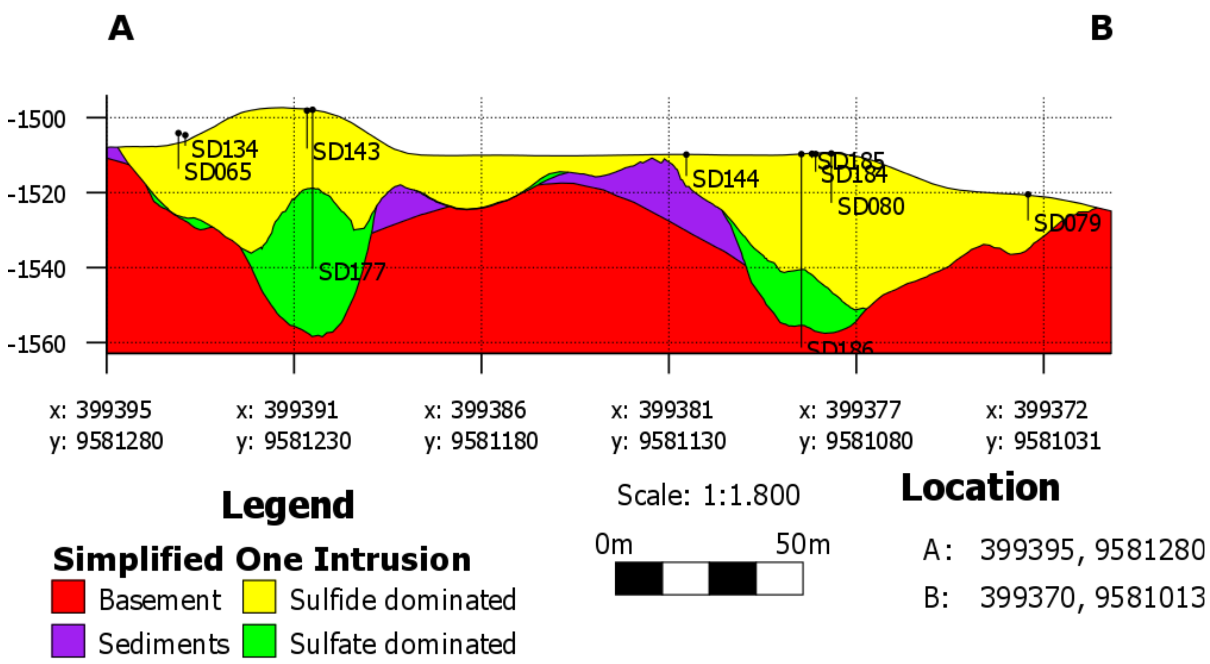


**Figure 25: Cross section 2 showing two exceptionally deep drillholes**

## 6.3 Qualimetric model

Table 10 shows the important factors for the qualimetric model. The block size is 10m*10m*0.5m, which is a reasonable block size for mining purposes. Mining systems presented in this thesis will remove material in layers about 0.5m thick. The 10m width and depth ensures that the block model remains easy to calculate. The mean copper equivalent concentration above the cut-off is 7.0% for the sulfides and 6.3% for the sediments. The maximum copper grade is at 35.7% and the minimum at 0% for the sulfides and at 9.6% and 0% for the sediments. Figure 27 and Figure 28 show again cross section 1 and 2 with the block model. For visual clarity the blocks in the cross sections are 1m high instead of the 0.5m used in the evaluation of the model.

**Table 10: Statistics of Copper Equivalent**

| **Sulfides** | **> 2.6% cut-off** | **<2.6% cut-off** |
|---|---|---|
| Block Count | 11981 | 25012 |
| Mean | 7.4 | 0.3 |
| Min | 2.6 | 0.0 |
| Q1 | 4.7 | 0.0 |
| Median | 6.7 | 0.0 |
| Q2 | 9.1 | 0.1 |
| Max | 35.7 | 2.6 |
| Std. dev. | 3.5 | 0.6 |
| Coeff. Var. | 0.5 | 2.2 |
| Var | 12.5 | 0.3 |
| **Sediments** | **> 2.6% cut-off** | **<2.6% cut-off** |
| Block Count | 1499 | 11324 |
| Mean | 6.5 | 0.1 |
| Min | 2.6 | 0.0 |
| Q1 | 4.2 | 0.0 |
| Median | 5.8 | 0.0 |
| Q2 | 7.6 | 0.0 |
| Max | 21.7 | 2.6 |
| Std. dev. | 3.5 | 0.3 |
| Coeff. Var. | 0.5 | 5.4 |
| Var | 12.1 | 0.1 |

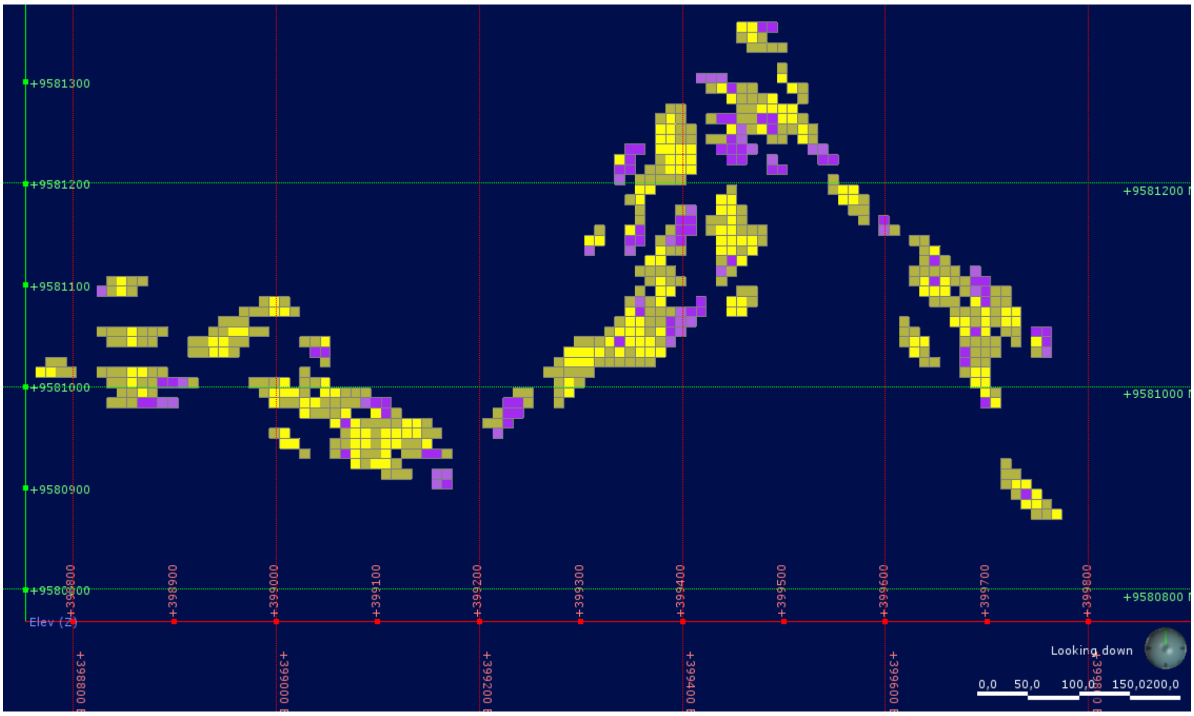


Figure 26: Block model top down view

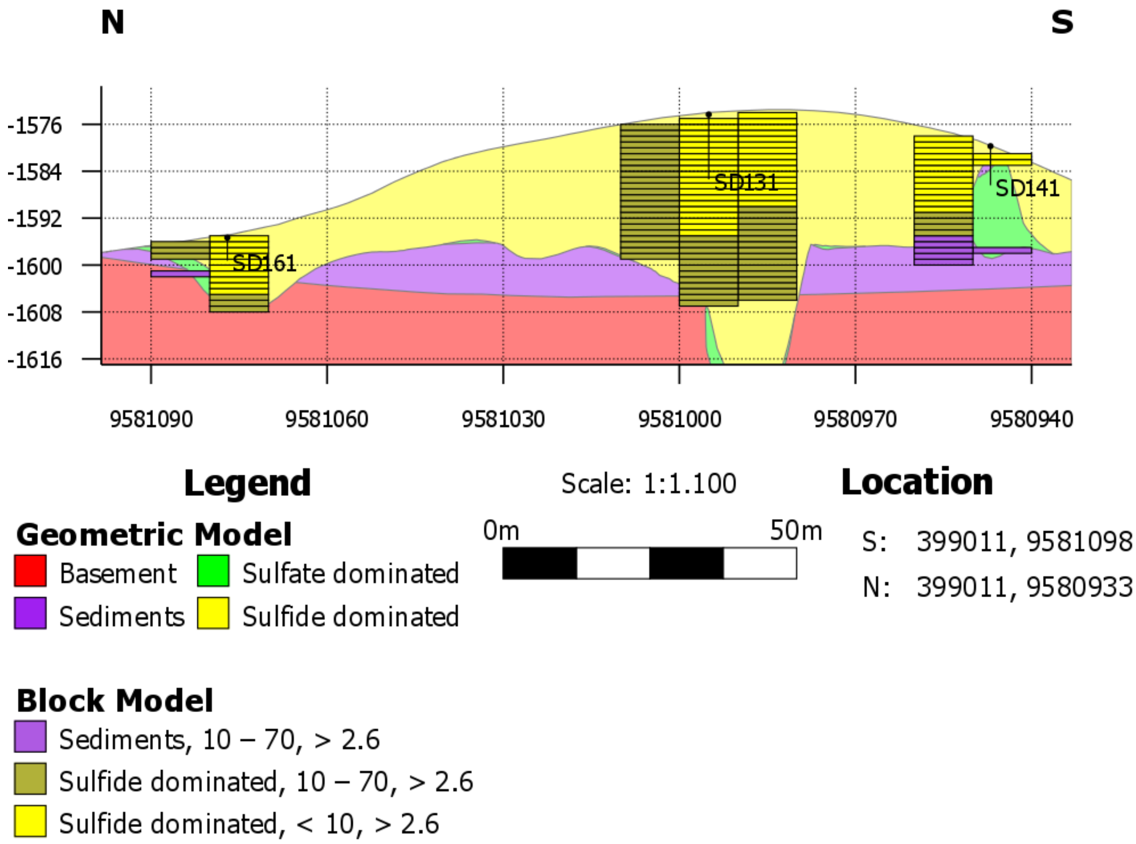


Figure 27: Cross section 1 with the block model

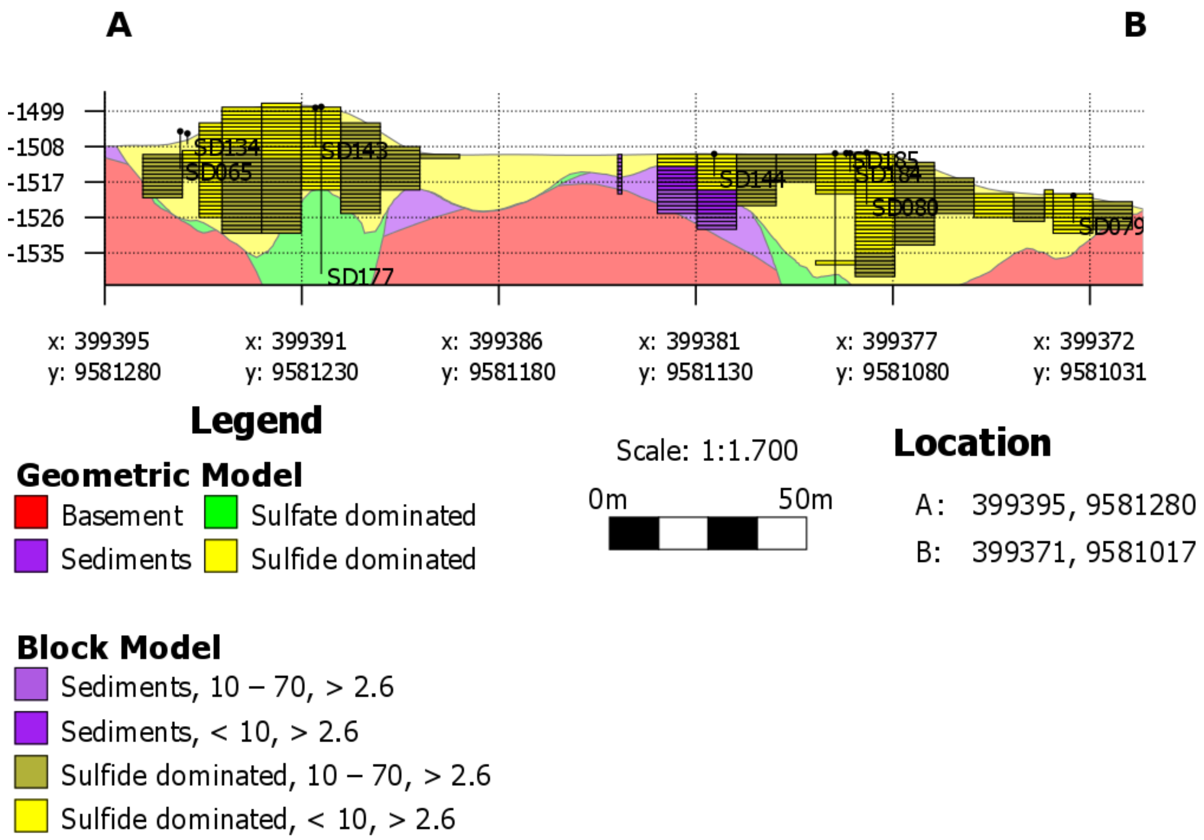


**Figure 28: Cross section 2 with the block model**

## 6.4 Resource estimate

**Table 11: Resource estimate**

| | mass indicated [kt] | mass inferred [kt] |
|---|---|---|
| **Sulfides** | 766 | 1232 |
| **Sediments** | 68 | 67 |
| **Total** | **834** | **1299** |

The average bulk density was calculated for each lithology from the densities found in the nautilus repot (Lipton, 2018). For sulfides it is 3.14 t/m³ and for sediments it is 1.75t/m³. This results in a total indicated mass of 834 kt and a total inferred mass of 1299 kt as seen in Table 11. Figure 26 shows the final block model for copper equivalency.

# 7. Discussion

## 7.1 Comparison of Deep-Sea Mining to Land-Based Mining

The five stages of mine development can still apply for deep-sea mining. First a deposit needs to be found and identified. Then more in-depth study must be performed to determine size and value. Unlike mining on land these steps need to be performed remotely. Development consists of adapting the mining technology to the situation on the site. The sea-bed and ocean mechanics must be analyzed and the mining equipment modified appropriately. After that, the mining operation can begin. There is no infrastructure needed, but expensive equipment, like the support vessel and remote operated vehicles. Right now, reclamation will probably only consist of monitoring of the site to see how the deep-sea reacts. A deep-sea mining site will be similar to a pit mine on land. The valuable minerals are at the ocean floor with a thin layer of sediment above them. Because of that there is less waste rock in deep-sea mining than in a pit mine. A deep-sea mine of an SMS deposit, will have a smaller footprint than a similar mine on land. The reason for this is that the concentration of economic elements, in SMS deposits, is higher by an order of magnitude. For comparison the Aitik copper mine in Sweden has an average copper concentration of 0.38% (Wanhainen, Kontturi and Martinsson, 2003) while the average for the Solwara 1 drillholes is 4.81% and the average above the cut-off is 8.86%. During the mining operation workers will monitor and perform the mining remotely. Since they are far removed from the mine, deep-sea mining is safer for the workers. Personal will need special training since remote operation is more difficult. Visibility is limited underwater, and further limited because of sediment plumes created by the mining activity. We do not yet know how the deep-sea communities behave and change over time. While we understand how a mine will affect animals and plants on land, we do not know what ultimate effect a deep-sea mining operation will have. Problems stemming from deep-sea mining will not affect us directly. They will be indirect or induced problems, meaning they will be one or more steps removed from the mining operation, since humans do not directly interact with the deep-sea. An environmental problem in the deep-sea could later affect parts of the ocean we interact with and cause long term problems. It is difficult to predict such problems and experiments are limited to laboratory work where not all aspects of the deep-sea can be simulated. When mining active vent sites, a unique ecosystem will be destroyed. We do not know how long such a community takes to recover, or if it will recover at all. Sediment plumes are the equivalence to dust for a surface mine. Since water is more viscos than air, tiny particles will stay in suspension much longer and travel further before settling down. This will cause added sedimentation around the mining site, which can affect marine lifeforms, and introduce more heavy metals and other trace elements to the food chain. Noise behaves differently in the ocean than it does on land. A deep-sea mining activity will create noise pollution which is already detrimental for marine life forms.

## 7.2 Differences between Norway and Papua New Guinea

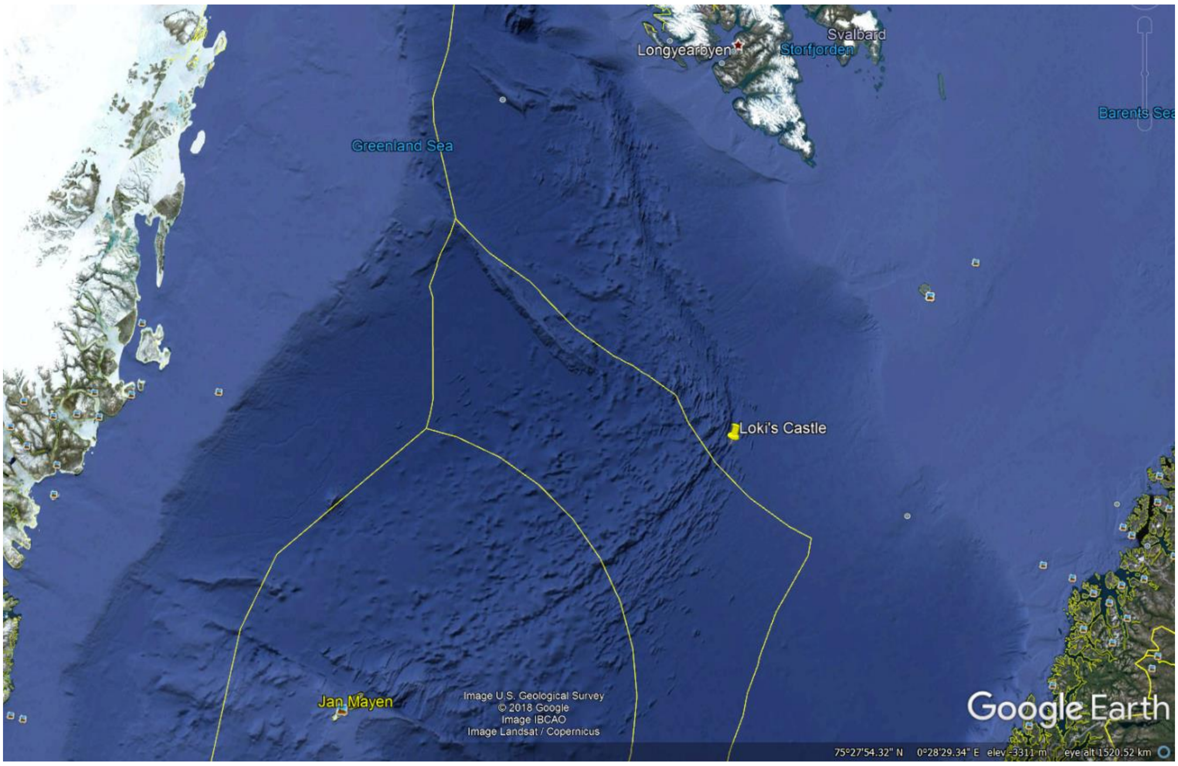


**Figure 29: Location of Loki's Castle with simplified maritime boarders; (Google-Earth, 2018) boarders by Price (2006)**

The wave height at the Norwegian site is higher than in the Bismarck Sea. In the Bismarck Sea the maximum wave height with a return period for 5 years is 7.48m compared to 12.3m for the Norwegian Sea. Further wave heights of Solwara 1 can be found in Table 3. Because of that precautions for the riser system must be taken. The movement because of the wave heights can cause damage to a rigid riser system or the support vessel. A flexible riser system with a "S"-bend at the top that allows for the wave induced up and down could prevent that. The greater water depth at the Norwegian site must also be considered. The deposits lie at a depth of 2000-3000m. A continuous delivery system could become too expensive because of the length and the amount of booster pumps needed along the way to keep the flow strong enough.

The power consumption of the pumps must be taken into account when designing such a system. A discontinuous system could be a more affordable alternative. The mining equipment itself must be adjusted for the increased pressure experienced at such a depth. Another key part are the Polar lows which can occur in the Norwegian Sea. During these storm events the mining activity must be stopped, and a continuous riser would need to be decoupled from the support vessel to avoid damage. Such a maneuver is currently only possible with a flexible riser system. The Norwegian government has given out contracts for further exploration of the Norwegian sites, since they are not very well explored. Once this is done further differences and adjustments to the mining system can be made. Loki's castle lies within the Svalbard's fisheries protection zone as can be seen in Figure 29 and Figure 30 (teal colored area). It is part of the Norwegian extended continental shelf but lies outside of Norway's exclusive economic zone. So far it is assumed that it falls within Norwegian authority. The first commercial endeavor will set a precedent for this case. Both in Norway and PNG environmental and fishery groups see deep-sea mining as a potential problem for the marine ecosystem and the fish stock on which a lot of people rely.


**Figure 30: Norwegian maritime boundaries (Kartverket, 2018)**

## 7.3 Development of Deep-Sea Mining Methods for the Norwegian Sea

The mining solutions mentioned in chapter 2.2.1 are only some of the systems currently in development. The system proposed by Nautilus is very ambitious, it has three separate vehicles which work depended on each other. A complex system with many individual parts is susceptible to breakdowns. But if enough material and terrain is prepared the breakdown of one machine might not cause the production to stop for a prolonged period. They use a rigid riser system which is easier to set up and maintain while currently having the drawback that it cannot be detached from the mining vessel. This is not a big problem since the Bismarck Sea is rather calm. The system proposed by Neptune is simpler as it uses a grabber and a mining vehicle. The grabber acts as both preparation and collection machine while the vehicle does the bulk cutting. Sizing the rock on the seafloor will bring its own challenges. At great depth the pressure changes how much energy is needed to crush a rock. The sizer will have a greater need for power. On the other hand uniformly sized rock pieces are easier to transport to the surface and will reduce stress on the riser system. Neptune uses a flexible riser system which is designed to withstand storm events and higher waves. Because of this they can mine even in a rougher sea-state. If the weather conditions become too harsh to continue mining, they can detach the riser system and pick it back up once weather conditions improved. The system by BAUER uses only established technology which they want to adapt to deep-sea operation. Trench cutters are used in building projects and shallow water mining. Their discontinuous transport system would be cheaper to run in deeper settings where more pump strength is required to pump the ore slurry to the surface. Their system is also designed to be abandoned if weather conditions are too harsh for mining and can be retrieved later. The trench cutter is designed to reduce sediment plumes which makes it more environmental friendly than the other system.

Overall the decision for a deep-sea mining systems will depend on many factors such as the resource mined, the ocean mechanics on the surface, the topography of the seafloor, the depth of the resource, and environmental concerns. Due to the unknowns and lack of practical experience in deep-sea mining it is difficult to foretell which factors will play the most important role. Since deep-sea mining concerns many stakeholders their opinion of the mining method will shape and influence the overall decision. Economic, political, social, and environmental issues must be considered if an informed decision is to be made. Currently different stakeholders all over the world are in the process of developing and testing new mining systems for various forms of deep-sea mining. Once these prototypes are done they have to be upscaled to work under various conditions including the sea state (ice, high waves), the weather (rain, wind, storm), and the deep-sea environment (pressure, temperature, currents, topography, sediment plumes).

## 7.4 Resource estimations and Reserve classification

As can be seen in the cross sections, Figure 24 and Figure 25, the drillholes are usually not very deep and most of the time do not penetrate the SMS deposit. This leads to a lack of information on how deep the deposit extends. The resource estimate of this thesis is 834 kt indicated ore and 1299 kt inferred ore. The result of the Blue Mining Report by Rahn (2016) is a total of 2112 kt ore at a 0% cut-off or indication if it is indicated or inferred. The result in the report for Nautilus Minerals by Lipton (2018) is 1030 kt indicated ore and 1357 kt inferred ore. Overall all three estimates are close to each other. Rahn (2016) provided a diagram (Figure 7) which shows the relation between cut-off, recoverable ore tonnage and ore grade. According to this figure the tonnage decreases from 1349 kt to around 800 kt when a 2.6% cut-off is applied. The average copper grade of this thesis is 6.8% (see Appendix B). The blue mining report lists an average grade for copper of 4.12% while the Nautilus report lists an average grade for copper of 7.2%. In the Sediment zone this thesis has 5.9 % copper, the Blue mining reported has 3.87% copper, and Nautilus has 4.1% copper. The differences in the estimations and grade can be attributed to the experience of the creator and different programs and techniques used to create and evaluate the model.

When classifying the Solwara 1 deposit as a reserve all aspects of the deposit and its environment must be considered. In a Norwegian setting the mining site is far away from the Norwegian main land, so power supply will be an issue and a system with lower power requirements is preferable. The cost for the mining equipment itself needs to be considered, currently there is no established mining system, so development and production of new systems is very expensive, which again favors a system which relies on modified established technology. Environmental friendly and sustainable development is an important part of Norwegian politics, in which again BAUER has provided for the problem of sediment plumes. An endeavor where the question of the environmental impact remains unknown will not be allowed. Assuming that between 40% and 80% of the resource will become a reserve the reserve in the Solwara 1 deposit is between 334 kt and 667 kt probable ore. Since the mining system proposed by Nautilus minerals has the most steps, first levelling the ground with the auxiliary cutter, then mining the ore with the bulk cutter and then collecting it with the collection machine, it will lose the most material along the way. The mobility of the vehicles might also limit which parts of the deposit can be accessed. This mining system was designed for shallower waters with a calmer sea. The overall reserve can be estimated to be around 50% of the resource, resulting in 417 kt ore. The Neptune mining system is designed for a rougher sea. Depending on its strength the grabber can also reach and mine parts of the deposit which are harder to reach for a remote operated vehicle. The subsea sizer system will create a substantial amount of sediment plumes. The reserve can be estimated to be around 60% of the resource, resulting in 500 kt of ore reserve. The system proposed by BAUER can reach most of the deposit. Its discontinuous transport system has the least power requirements. It is also designed for greater water depth and rougher weather. The reserve can be estimated to be 70% or more, resulting in 584 kt probable ore reserve. Overall the system proposed by BAUER seems to be the most viable for a Norwegian mining site, since the waves in the Norwegian Sea can be quite high which limits a continuous riser system. The great water depth is another argument for using a discontinuous system to save cost. Furthermore, their system minimizes sediment plumes which are considered an environmental problem.

# 8. Conclusion and Further work

Even though the setting in Norway is different and brings its own unique challenges, a Solwara 1 type deposit could be mined there. A common figure in the deep-sea mining industry is 2000 kt ore production per year, this would make the current reserve too small to mine. Further exploration of the ore field is necessary to convert the inferred resource to indicated or measured resources so that they can be classified as a reserve. Even though the idea for deep-sea mining has been around for some time, commercial deep-sea mining is a new and interesting field. With modern technology, it promises easy access to ore deposits which contain a high concentration of economic elements. Since these elements become depleted on land we must find a way to satisfy our demand for them. Our way of life and the change away from fossil fuels depends on these elements and accessing deposits with a high concentration can help satisfy our needs.

However deep-sea mining is not without its critics. A big problem is how little we know about the deep-sea ecosystem. We do not understand how different parts of the deep-sea interact with each other or with the shallower parts of the ocean. Because of that the environmental impact of deep-sea mining is difficult to predict. This causes pushback from NGOs and local population, who see a danger to their livelihood. Sustainable management of the deep-sea resources is important to maintain this unique environment and minimize long term environmental impacts.

The development of deep-sea mining methods has progressed rapidly in the recent past. Different deep-sea deposits have different requirements, so several specialized systems will emerge. Nautilus Minerals wants to start the deep-sea exploitation of the Solwara 1 deposit in 2019 and with that begin a new area of mineral mining. Other companies and countries are working to develop their own mining solutions and begin exploitation of other deep-sea deposits. Each country must regulate deep-sea mining within its authority before allowing such projects, to minimize environmental impact. The international deep-sea is a Common Heritage of Mankind, so it will require some effort to change the laws for exploitation. Resource classification criteria will have to evolve to encompass the new challenges deep-sea mining brings with it.

It is important that we understand the deep-sea better. Further research into deep-sea deposits and the marine communities around them is important. That will allow us to better assess and mitigate potential environmental problems created by deep-sea mining and help us preserve this unique ecosystem.

Once the required drillhole data is available for the sites of Norwegian interest a resource estimation can be made and after that a comparison between Solwara 1 and Norwegian sites could give more insight in the viability and differences of these SMS deposits.

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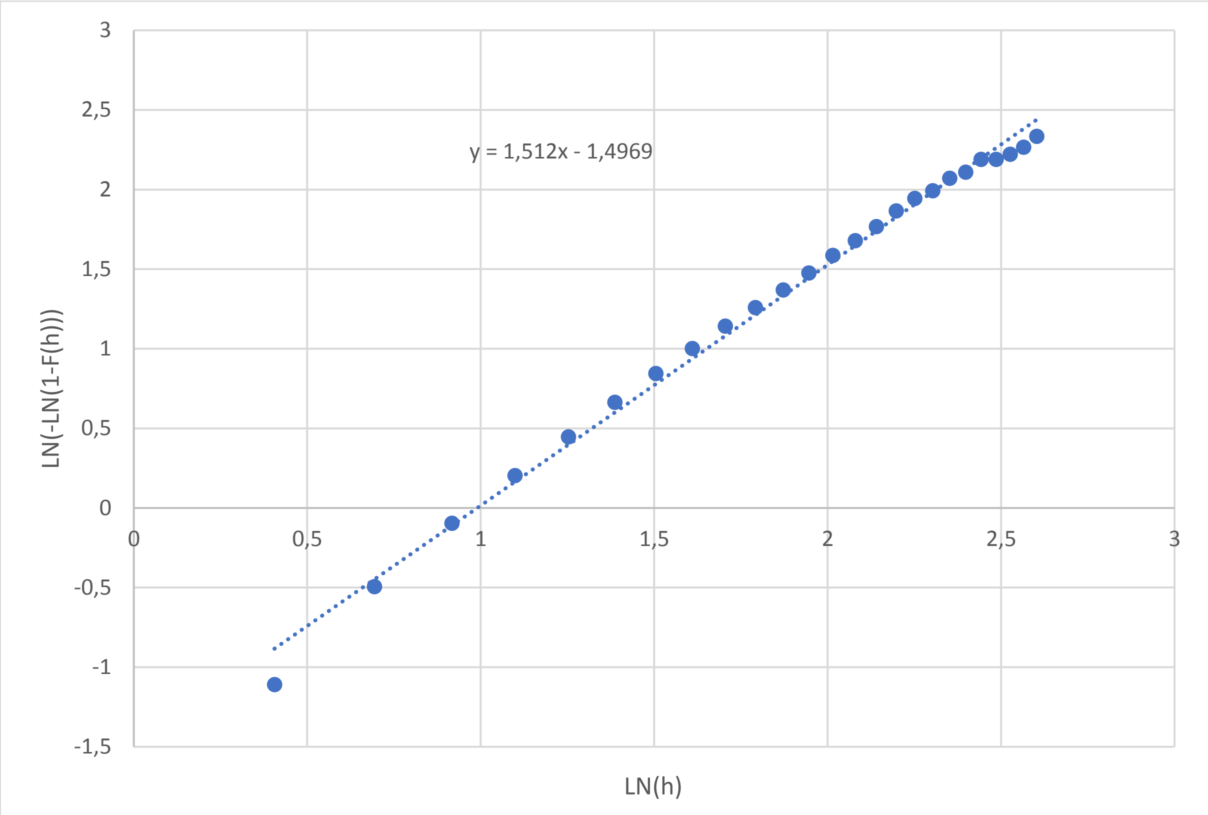
# Appendix

## A) Weibull Distribution

A Weibull distribution plots the ***LN(-LN(1-F(h))) vs LN(h)*** where ***h*** is the wave height and ***F(h)*** is the empirical cumulative distribution function. Then a best fit line is plotted through the points. The values in this function graph can be used to calculate the significant wave height which is expected to be exceeded once in a given return period.

| Upper Limit h | n | Sum (n) | F(h) | LN(h) | LN(-LN(1-F(h))) |
|---|---|---|---|---|---|
| 0.5 | 94 | 94 | 0.003065 | -0.693147 | -5.786015121 |
| 1 | 2961 | 3055 | 0.099628 | 0 | -2.254294848 |
| 1.5 | 5572 | 8627 | 0.28134 | 0.405465 | -1.107552728 |
| 2 | 5376 | 14003 | 0.456659 | 0.693147 | -0.494265717 |
| 2.5 | 4300 | 18303 | 0.596889 | 0.916291 | -0.095913091 |
| 3 | 3376 | 21679 | 0.706985 | 1.098612 | 0.205006308 |
| 3.5 | 2578 | 24257 | 0.791058 | 1.252763 | 0.448331849 |
| 4 | 2011 | 26268 | 0.85664 | 1.386294 | 0.663921383 |
| 4.5 | 1403 | 27671 | 0.902394 | 1.504077 | 0.844499563 |
| 5 | 983 | 28654 | 0.934451 | 1.609438 | 1.00245177 |
| 5.5 | 674 | 29328 | 0.956431 | 1.704748 | 1.14212163 |
| 6 | 430 | 29758 | 0.970454 | 1.791759 | 1.258973728 |
| 6.5 | 305 | 30063 | 0.9804 | 1.871802 | 1.369211698 |
| 7 | 216 | 30279 | 0.987445 | 1.94591 | 1.47650092 |
| 7.5 | 155 | 30434 | 0.992499 | 2.014903 | 1.587757644 |
| 8 | 86 | 30520 | 0.995304 | 2.079442 | 1.679156365 |
| 8.5 | 56 | 30576 | 0.99713 | 2.140066 | 1.767041104 |
| 9 | 40 | 30616 | 0.998435 | 2.197225 | 1.865574145 |
| 9.5 | 20 | 30636 | 0.999087 | 2.251292 | 1.945715858 |
| 10 | 8 | 30644 | 0.999348 | 2.302585 | 1.992672726 |
| 10.5 | 9 | 30653 | 0.999641 | 2.351375 | 2.071024888 |
| 11 | 3 | 30656 | 0.999739 | 2.397895 | 2.110383254 |
| 11.5 | 4 | 30660 | 0.99987 | 2.442347 | 2.191044436 |
| 12 | 0 | 30660 | 0.99987 | 2.484907 | 2.191044436 |
| 12.5 | 1 | 30661 | 0.999902 | 2.525729 | 2.222700874 |
| 13 | 1 | 30662 | 0.999935 | 2.564949 | 2.265682224 |
| 13.5 | 1 | 30663 | 0.999967 | 2.60269 | 2.335134042 |




## B) Copper concentration of Solwara 1

| Cu >2.6% | Block Count | Mean | Std. dev. | Coeff. var. | Vari-ance | Mini-mum | L. quar-tile | Me-dian | U. quar-tile | Maxi-mum |
|---|---|---|---|---|---|---|---|---|---|---|
| Sulfide dominated | 12715 | 6.8 | 3.5 | 0.5 | 12.2 | 0.0 | 4.1 | 6.3 | 8.9 | 37.7 |
| Sediments | 832 | 5.9 | 3.0 | 0.5 | 9.3 | 0.2 | 3.7 | 5.2 | 6.8 | 18.4 |