Ref. Ares(2021)3597407 - 01/06/2021

ROBOMINERS

ROBOMINERS DELIVERABLE D2.2

CONCEPTUAL MINING STRATEGIES AND REPORT ON STUDIES OF BOTTLENECKS AND OTHER LIMITING FACTORS

Summary:

This document is the accompanying documentation of deliverable D2.2. It identifies potentially useful mining strategies and describe their geometry, with particular attention to the feasibility of robotic mining and transport. Both conventional and new bio-inspired options are considered. It also discusses the set of factors which may lead to 'pathological' situations - geometric and other problems for robotic mining using either conventional or bio-inspired mining strategies.

Authors:

Stephen Henley, RCI
Eva Hartai, UNIM
Tobias Pinkse, KUTEC
Asko Ristolainen, TalTech
Michael Berner, MUL
Giorgia Stasi, RBINS
Mike McLoughlin, RCI
Tim Rhodes, RCI
Hilco van Moerkerk, RCI
Colin Morrish, RCI
Mark Howson, RCI
.....

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement nº 820971.

Title:	CONCEPTUAL MINING STRATEGIES AND REPORT ON STUDIES OF BOTTLENECKS AND OTHER LIMITING FACTORS		
Lead beneficiary:	RCI		
Other beneficiaries:	UNIM, GeoZS, RBINS, GEOM, TAU, TalTech, LPRC,MUL, ASSIM		
Due date:	M24		
Nature:	Public		
Diffusion:	all Partners		
Status:	Working Document		
Document code:			
Revision history	*Author*	*Delivery date*	*Summary of changes and comments*
Version 01	SH	2020/05/26	Initial version of the document / accepting reviews
Version 02			
Final version			

Approval status				
	Name	Function	Date	Signature
Deliverable responsible	Stephen Henley / RCI	WPL	2021/05/26	
WP leader	Stephen Henley / RCI	WPL	2021/05/26	
Reviewer	Vitor Correia / EFG		2021/05/25	
Reviewer	Nelson Cristo / ASSIMAGRA		2021/05/23	
Project Coordinator	Claudio Rossi / UPM	PM	27.05.2021	

This document reflects only the author's view and the European Commission is not responsible for any use that may be made of the information it contains.

Diffusion List		
Partner name	Name	e-mail
All partners	-	ROBOMINERS_all@autolistas.upm.es

TABLE OF CONTENTS

Executive Summary

The purpose of D2.2 is to identify potentially useful mining strategies and describe their geometry, with particular attention to the feasibility of robotic mining and transport. Both conventional and new bio-inspired options are considered. After the introduction to this deliverable in Section 2, Section 3 introduces the concepts of underground mining layouts by presenting examples of real mines, selected from those described in more detail in D5.1.

Section 4 identifies some of the more commonly used underground mining strategies, while section 5 examines the range of transport options and highlights those that are most appropriate for a robotic mining system. In section 6, the range of bio-inspiration possibilities is outlined, while section 7 identifies the options for use of backfill which will be needed to minimise surface waste dumping, and which may or may not be compatible with mine geometries produced by particular mining strategies.

Section 8 discusses the set of factors which may lead to pathological situations - geometric and other problems for robotic mining using either conventional or bio-inspired mining strategies. These are situations that may arise from the underlying geometry of particular mining methods or from the interaction between the mining method and mechanical or other constraints of robotic systems. Where these identified problems are related to the geology, they are discussed in more detail in D5.2.

1. INTRODUCTION

This deliverable documents tasks 2.1 and 2.6 as described in the Grant Agreement.

Development of non-traditional mining strategies and mine layouts must first take into consideration the wide variety of conventional mining strategies. There are too many for a complete description here, but key features of the main categories will be summarised. The mining strategy and associated mine designs are of course dependent upon the geology and geometry of the mineral deposit itself as well as the physical and chemical rock properties. These properties themselves, as controls on mining, will be discussed in detail in deliverable D5.2.

Potential non-traditional mining strategies are discussed next. These are based upon bio-inspired ideas, especially feeding patterns as best seen in a wide range of trace fossils. Depending on the deposit geometry these may lead to two-dimensional or three-dimensional layouts. A versatile mining strategy recently developed by the IPKON Institute in Moscow, is known as "honeycomb mining". Although inspired by the structure of a honeycomb, this is a very flexible method that can be used for efficient mineral extraction from a wide variety of different deposit geometries and lends itself to robotic operation.

Complex mine layouts may lead to situations in which mining becomes inefficient or impossible. This deliverable also discusses some of the problems which may occur, and restrictions on mine layouts that may be unsuitable for robotic operations. Solutions to such problems can include the use of alternative mine designs, or more intelligent use of data - which may include additional data obtained by longhole drilling, or real-time geophysical data capture and modelling.

Situations are considered in which autonomous robotic decision-making must be supplemented by operator intervention, such as at the end of a local orebody within a series of disconnected mineralised areas, or where an ore deposit is intersected by a fault or a dyke or other igneous intrusion. In conventional mining, such situations are very commonly encountered, and usually require detailed understanding of the geological history and structure of the mineral deposit to predict whether and where an extension of the orebody might be. Simple cases include faulted tabular deposits (seams or veins) where the direction and amount of the fault throw need to be estimated accurately. Slightly more complex cases include separate 'en echelon' lenticular ore bodies, which are typical of many epithermal gold-silver deposits, where the structure of the whole deposit must be understood to determine the direction and distance in which to seek the next lenticular orebody.

Encoding of such geological knowledge in an artificial intelligence decision-making system is a non-trivial task, and fitting an optimal robotic mining strategy to uncertain and incomplete geological knowledge will require either the development of considerable on-board intelligence or some real-time interaction with the geologists and mining engineers, with management of robot operation from a control room at the surface.

The mineralogical and chemical information will be obtained from instruments on the mining robot by analysing the working face and/or the slurry as mined. Slurry analyses can be related directly to face analyses and absolute spatial coordinates by measurement of the slurry flowrate through the robot's "digestive system" that will support real-time selective mining. Such matters are discussed in deliverables D6.6 and D6.7.

2. MINING STRATEGIES AND POSSIBLE GEOMETRIES

Conventional mining strategies (sections 3 and 4 below) generally fit regular geometric extraction layouts to ore deposits, whether these are of regular or irregular form. The ROBOMINERS project seeks solutions which are bio-inspired, and typical layouts are irregular in form, based for example on feeding patterns of burrowing animals. However, it is likely that neither approach is optimal.

Unlike biological systems, the mining geologist and engineer will have at least some information on the global form of a deposit and the distribution of minerals within it. This information is conventionally represented as a block model or a triangulated wireframe model, but in each case the underlying information is a 3D function which estimates grades and other values at every point in the three-dimensional volume of the deposit.

There are many ways in which a mining strategy may be framed, usually as an optimisation problem. A mining company will often wish to maximise net present value. This could lead to a strategy that prioritises early extraction of high-grade ore, though such an approach would often be modified to include simultaneous extraction of lower grade material in order to keep a constant grade for optimal recovery by the chosen mineral processing technology. An alternative approach might be to minimise the costs of infrastructure development; this could lead to early mining of the most accessible parts of the deposit. Yet another approach could be to maximise total mineral recovery. This would lead to deliberate extraction of low-grade material for blending with high-grade ore to produce resultant mill feed close to the economic cut-off grade.

ROBOMINERS allows implementation of any of these strategies – and one more: maximisation of mineral grade extracted at all times. This would be achieved by an ore following method, with mining at any time of the highest grade of ore which is currently accessible. This could be modified by a cost constraint so that time and energy costs of re-positioning of the miner robot are combined with the accessible mineral grades and input to a decision function algorithm.

2.1.1. Feeding patterns.

There is an important distinction between biological feeding patterns and mine layouts inspired by them. In the biological pattern, the final destination of the 'mined' product is the animal itself. In a mine, the product must be delivered to the ground surface, either as raw ore or a concentrate, to be processed into a product suitable for the market.

This means that there is more geometric freedom for a biological feeding pattern because an animal can store the "mined product" internally and then everything else is excreted and can be used as backfill. In a mine, normally the product must be delivered elsewhere - for further processing, perhaps - as soon as possible after mining, so there are priorities to keep delivery pathways open and as short as possible. This thus rules out some geometries such as continuous spirals where backfill cannot be done and the delivery pathway becomes steadily longer during mining.

<u>Shape-shifting robots</u>
The closest analogue to an animal, to allow maximum flexibility of feeding pattern or mining strategy, would be for the robot to process the mined material internally, excrete the waste, and store a concentrate within its own body - which would increase in volume, growing as required. The robot

would in effect be a flexible self-lengthening sausage. At some point it would need to return to an unloading point to transfer the concentrate to the surface. This still rules out ever-lengthening spiral designs.

Fixed geometry robots

If a robot is defined to have fixed geometry, then it will need either to:

(a) transfer all mined material using transport robots or reconfigurable conveyor systems to a mineral processing service (either a robot or transfer to surface)

or

(b) (b) be followed closely by a mobile mineral processing module which separates waste from mineral concentrate. The waste can then be left as backfill with minimal or no further transport. The concentrate would have to be transported to surface, using transport robots or a continuous mechanical, pneumatic or hydraulic transport system.

2.1.2. Possible or impossible layouts

Spiral or other simple geometric feeding patterns are possible for animals but not for robot miners because of two factors:

(1) animals need no umbilical connection for control or power supply. Insects or worms gain their power directly from the food they consume while burrowing. There is no geometric or topological constraint on the feeding pattern. For mining robots, continuous spirals or other simple linear patterns are impracticable because of ever-increasing lengths of umbilical and distances for ore transport.

(2) for burrowing animals there is no space problem. In soil, sea-bottom sediment, or other soft substrates, material consumed is the same volume as material defecated. In mining hard (or soft) rock, the volume of fragmented material after extraction is always larger than the volume of in-situ rock.

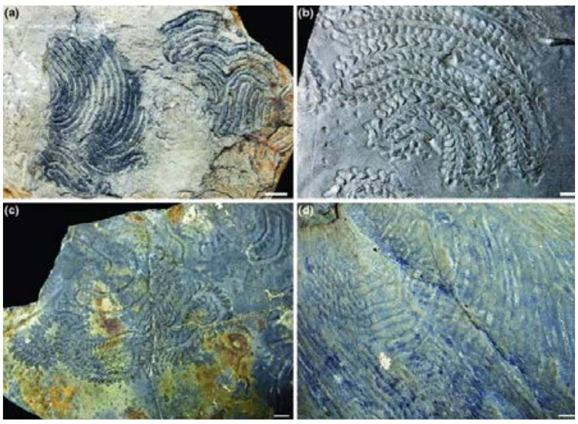

Figure 2.1 Some impossible or impractical layouts

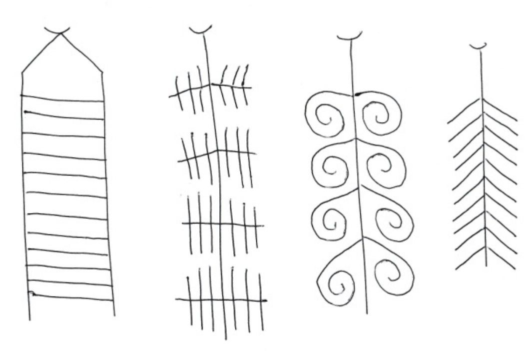

Figure 2.2 Some possible layouts
(plan views of workings in a flat-lying seam, from a shaft at top of each diagram)

What separates the impossible from the possible is that the possible layouts all allow a short maximum umbilical length between the robot and either the mine entrance or the nearest point in a main drive. Spirals are possible, on condition that they are short.

3. MINING SCENARIOS FOR ROBOMINERS

The ROBOMINERS project aims to develop a mining technology which can be applied where traditional mining is ineffective or hindered by serious obstacles. Firstly, the method must minimize the surface impacts of the ore exploitation, allowing mining activity in protected environments. Secondly, limited land use, facilities, energy demands, material transport and re-deposition must render the method more cost-effective than traditional mining, lowering the volume of the orebody necessary for economic operation. Thirdly, as the exploitation is done by robots, ore bodies in zones of the lithosphere which are dangerous or inaccessible for human miners can also be reached by the technology, also allowing the economic viability of some mines sites that are, nowadays unviable, with current technology.

Considering the possibilities and the potential advantages of the technology to traditional mining, the following geological and mining scenarios were set up:

- Operating and abandoned mines with known remaining unfeasible resources;
- Ultra depth;
- Small deposits uneconomic for traditional mining.

These scenarios were discussed in detail in Deliverable 5.1, titled “Review Document Giving Scope and Examples of Deposit Types of Interest” (Hartai et al., 2020). Some of the examples discussed in D5.1 are reviewed here, with emphasis on the mining strategy and the geometry of their exploitation methods.

3.1. Operating and abandoned mines with known remaining unfeasible resources

In Europe, there are numerous ore deposits where operations were stopped because remaining resources could not be exploited economically anymore. In such cases, application of the ROBOMINERS technology can be based on existing geological knowledge and technical facilities. A special advantageous case is when the ROBOMINERS technology can be coupled to an adjacent, operating traditional mine, supplying ores of alternative quality.

3.1.1. Example for the scenario: Neves-Corvo

The ca. 230 km long Iberian Pyrite Belt (IPB) extends in E-W strike through Southern Spain into Portugal. The most abundant metals produced from the IPB are copper, lead, zinc, silver and gold. Neves-Corvo is a Cu-Zn ore deposit located in the western, Portuguese part of IPB. It is a volcano-sedimentary massive sulphide (VMS) deposit, formed in subsiding basins of an extensional tectonic regime from the Late Devonian to the Carboniferous. Ores are hosted by rhyolite dominated volcanic, volcaniclastic and sedimentary complex.

Typical ore bodies of the deposit are lenses of polymetallic Cu-Pb-Zn massive sulphides (chalcopyrite, pyrite, galena, sphalerite) with additional Sn (cassiterite) mineralisation that formed at or near the seafloor. Ore minerals are intergrown, often replacing each other formed by a multistage hydrothermal process, resulting in complex textures and structures. The shape of the ore bodies was also influenced by gravity-driven mass transport processes and subsequent low-angle thrusting and asymmetric detachment folding. The geology of the deposit is summarised in detail in the reports of the H2020 project CHPM2030, as Neves-Corvo was a pilot site of the project (Ramalho et al. 2017, 2019).

The mine is operated by Somincor, a subsidiary of Lundin Mining. Primary targets of the operation are several massive sulphide ore lenses linked by zones of thin discontinuous mineralisations in a shallow NE dipping zone. Seven major massive sulphide bodies are located at Neves, Corvo, Graça, Zambujal, Lombador, Semblana and Monte Branco. Geometry of the ore lenses is well known from mining and exploration *(Figure 3.1)*. They are relatively flat, extensive in two dimensions (600-1200 m × 500-700 m) and their thickness varies from 50 to 90 m. The lenses are accompanied by stockwork zones in the footwall host rocks, mostly rich in copper as well as the bottom part of the lenses. Over that, there are zones rich in tin and zinc, while the top of the massive sulphide lenses is low grade ore or barren pyrite *(Figure 3.2)*.

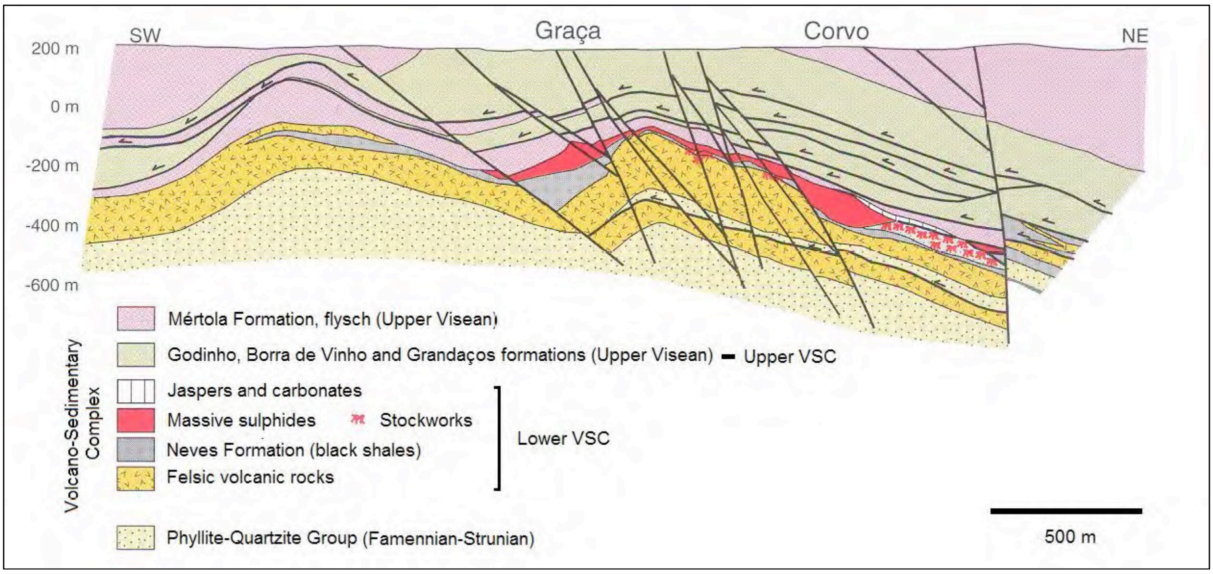

Figure 3.1: Neves-Corvo general geological section, adapted from Relvas et al., 2006 (Ramalho et al. 2017).

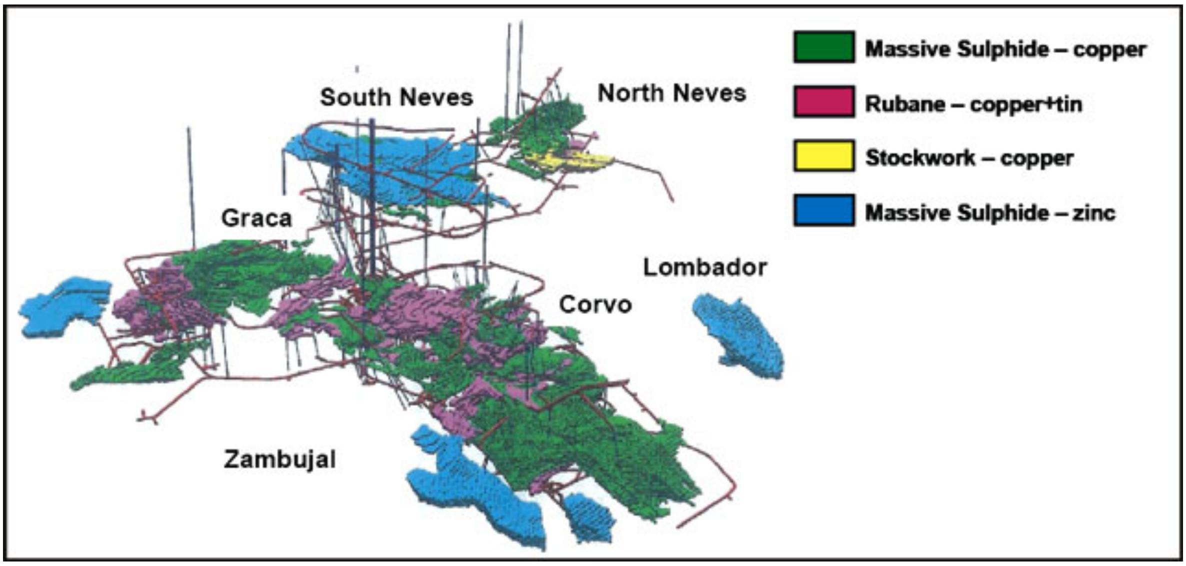

Figure 3.2: 3D model of the ore bodies (isometric view to NW) published by Somincor. Source: https://www.sec.gov/Archives/edgar/data/1377085/000120445908001113/p20.jpg

ROBOMINERS technology could allow economic exploitation of the thin mineralised bodies between the major lenses, which are relatively well-explored between Corvo, Zambujal, and Semblana deposits. ROBOMINERS automated stopes could be developed and serviced from the existing and operational underground haulage, hoisting, ventilation and energy supply systems. The extracted product could be blended with the traditionally mined products at a suitable point of the processing flowsheet in on-site ore processing facilities.

3.1.1.1. The adopted mining methods in Neves-Corvo and possible application of ROBOMINERS technology

During the 25 years of continuous mining in the Neves-Corvo mine, various mining methods have been developed and tested. Geology and geotechnical considerations and the geometry of the deposit resulted in modifications in the mining methods. In the currently active mining regions, drift and fill as well as bench and fill mining are being utilized. Although the massive sulphide deposits are characterized as generally regular and predictable, the geometry of the high-grade zinc and copper zones within the deposits can be overly complex. Therefore, the mining methods should be adapted to the present conditions.

A drift and fill method is implemented in the areas where the mineral deposit thickness is less than 10m. Drift-and-fill stopes at Neves-Corvo are normally accessed from a footwall ramp with footwall access drives driven along the orebody strike at 20m vertical intervals. Access crosscuts are driven down from the footwall access drives into the orebody. A horizontal slice is subsequently mined using drifts developed either longitudinally or transversely in sequence. Standard drift dimensions are 5.0 m x 5.0 m, with the sidewalls often being slashed before backfilling. Following completion of a drift it is tightly backfilled with hydraulic sand fill or Paste fill before the drift alongside is mined. When a complete 5 m high orebody slice is mined and filled, the back of the access drive is “slashed” down, and mining recommences on the level above *(Figure 3.3).*

In the areas with sufficient thickness (more than 20 m in vertical thickness) and continuity, the bench and fill mining method is applied instead. This method is more productive with less operating costs compared to drift and fill mining.

Bench-and-fill stopes are also accessed from a footwall ramp, with footwall drives driven along strike in waste at 20m vertical intervals. According to Figure 3.4, upper and lower access crosscuts are driven across the orebody to the hanging-wall contact. Adjacent stopes are extracted in sequence. Initially, the so-called primary stopes are extracted up to 120m long. The stopes are normally mined in an up-dip direction. The primary stopes are normally filled with cement paste fill and subsequently tightly filled with hydraulic sand fill. After the backfill process for each of the bench-and-fill stope is finished, the back of the former drilling level is slashed out to establish a new mucking level for the next stope above.

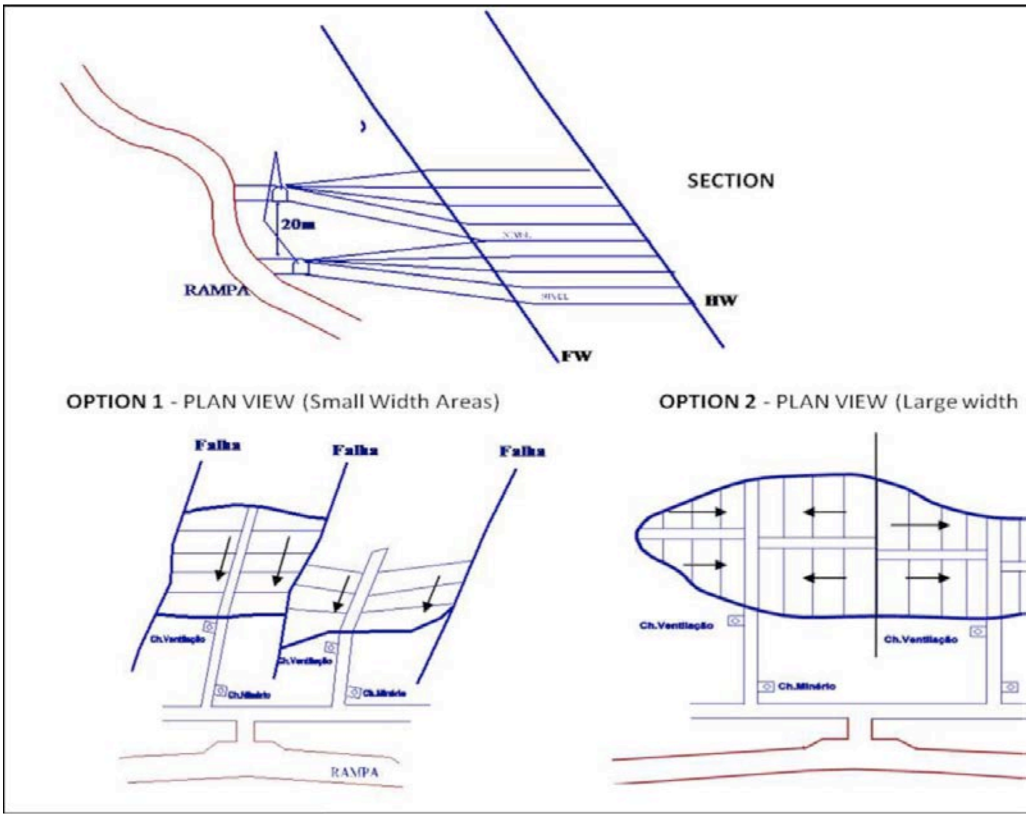

Figure 3.3: The typical drift and fill mining method used at Nerves-Corvo **(Wardell Armstrong International 2017)**.

Both bench-and-fill and drift-and-fill methods are closely related to the generic cut-and-fill, whose geometry is described in section 4.2 below.

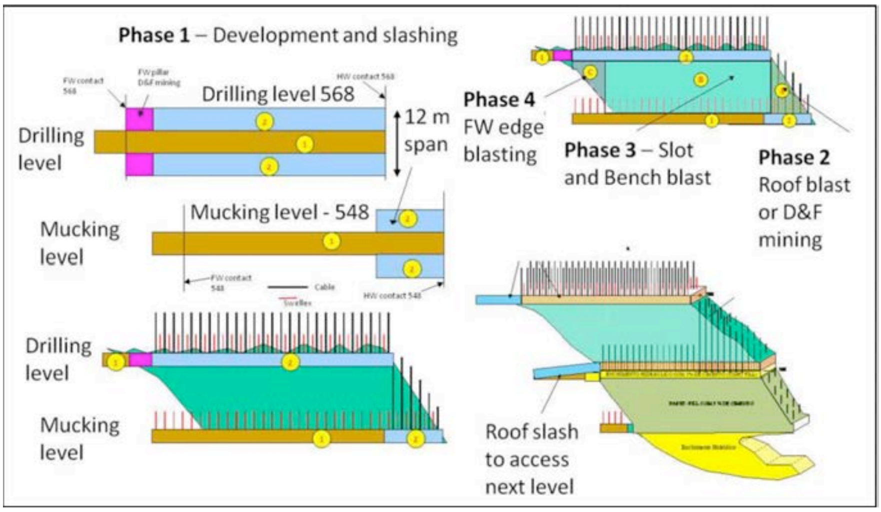

Figure 3.4 : The typical bench and fill mining method used at Nerves-Corvo **(Wardell Armstrong International 2017)**.

In order to take advantage of the high strength massive sulphide zinc ore and reduce the costs with the similar recovery rates of the Bench-and-Fill mining method, an optimised Bench-and-Fill mining method was developed and introduced. This method is bottom-up with transverse stopes being accessed from footwall ramps and crosscuts. Initial extraction of the primary stopes is followed by backfilling and extraction of secondary stopes between the already mined and backfilled primary stopes. The primary and secondary stopes are of 15m width and 20m height with a variable length depending on the width of the orebody. After the primary and secondary stopes are extracted, the operations in the next level above can be commenced *(Figure 3.5).*

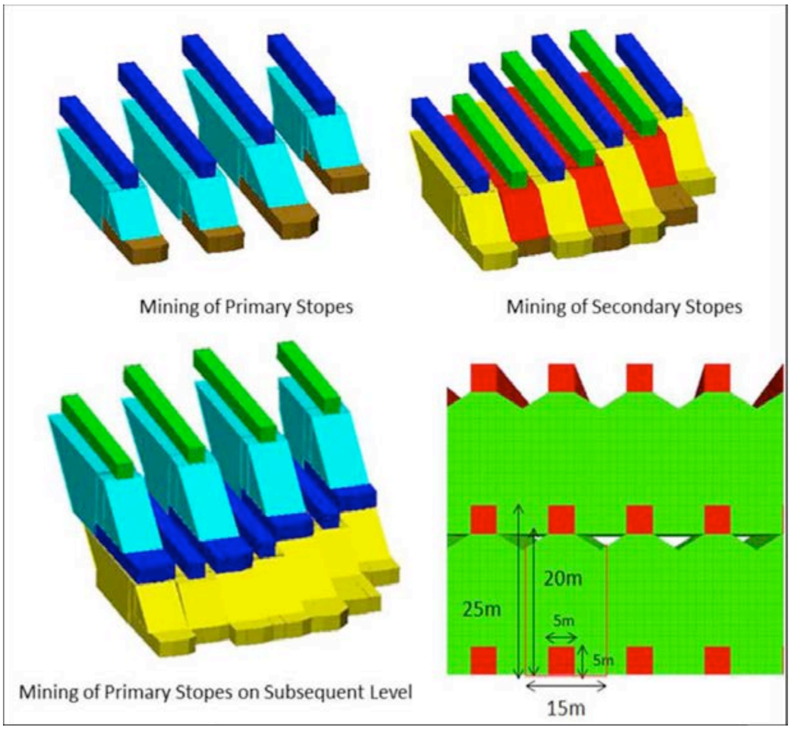

Figure 3.5 : The current optimized bench and fill mining method at Nerves-Corvo **(Wardell Armstrong International 2017)**.

The other variations applied in the mine are Mini bench-and-fill (MBF) and the sill pillar mining method. The MBF mining method is a hybrid method which can provide higher productivity compared to the drift and fill mining when the orebody thickness is between 10-15 m. The sill pillar mining method was also developed to extract the ore remaining in sill pillars between up-dip mining panels (Wardell Armstrong International 2017).

As mentioned above, there are some zones connecting the already developed deposits, which would entail high operating costs for extraction and extraction would not be economic with the traditional mining methods explained *(Figure 3.6).* These deposits could be rather small with less economic application of methods such as Mini Bench-and-fill mining or drift and fill mining method. This opens new opportunities for the application of ROBOMINERS technology, which can start operation from pre-existing infrastructures and the already developed mining regions.

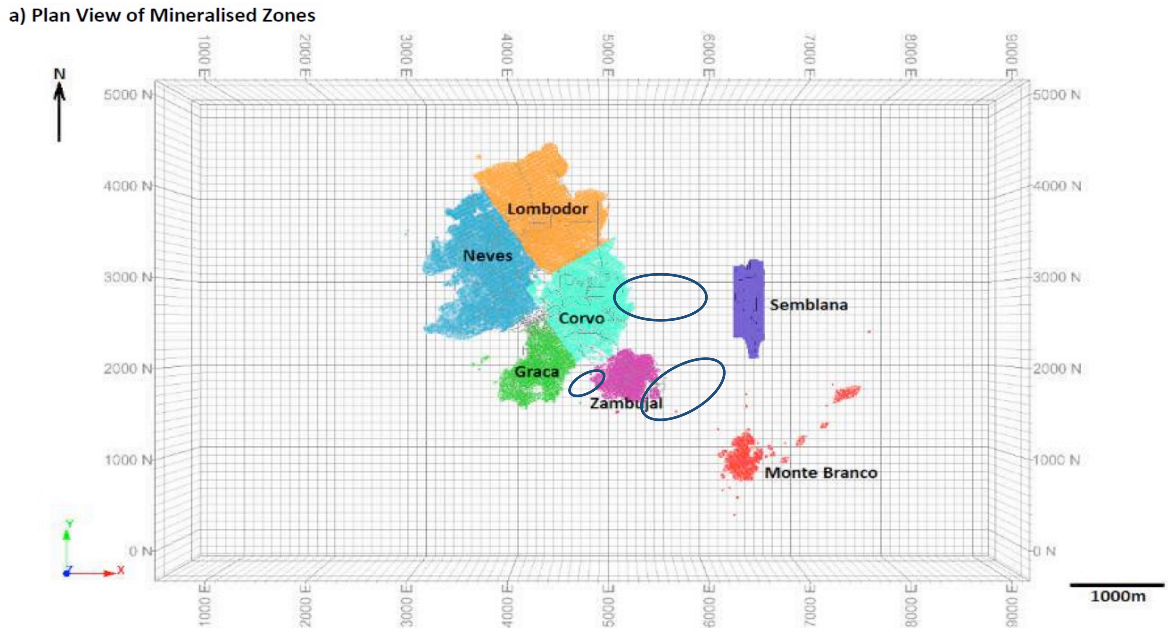

Figure 3.6: The zones lying between previously developed mining regions for application of ROBOMINERS technology (blue circles) **(Wardell Armstrong International 2017)**.

3.2. Ultra-depth

Ore bodies are considered to be 'ultra-deep' when situated below the level of traditional mining, ca. 2.5 km. However, depth limits of mining depend on several factors, including geothermal gradient, rock mechanical properties and fluid transport conditions. In the EU, the deepest operating mine is about 1400 metres deep (Pyhäsalmi in Finland), so practically every deposit below that level can be regarded as fitting to the ultra-depth scenario.

Exploration data of deep level ore bodies are extremely limited or lacking as these were not potential targets of the mining, and extrapolation from near-surface geological models is not straightforward. Even if there is an indication of the existence of such ore bodies, reaching the accuracy of knowledge on geometry and quality appropriate for initiating the mining requires significant additional exploration work in general. In the case of specific deposit types, however, geometry and position of a probable continuation can be predicted; for example a stratiform deposit known in the basement at the shallow edges of a basin may also be found in tectonically subsided inner parts within the same succession.

3.2.1. Example for the scenario: Kupferschiefer, Fore-Sudetic Monocline

The Central European Basin System developed in the end of the Variscan (Hercynian) orogenic period extending from Silesia (Poland) in the east to England in the west. The Permian succession of the sea filling the basins contains a formation comprising dominantly bituminous marly shale, which is known as a horizon enriched in several metals, mainly base metals, named Kupferschiefer (copper shale) after its German outcrops with deposits mined in the medieval age already. The horizon lies on white and red coloured, barren sandstone, and is covered by Zechstein limestone or dolomite *(Figure 3.7).* The main metals are Cu, Pb and Zn in small grained (20–200 µm) sulphide minerals, but V, Mo, U, Ag, As, Sb, Hg, Bi, Se, Cd, Tl, Au, Re and PGE are also enriched. The magnitude of the original sediment hosted stratiform enrichment is some 100 ppm in general, but local secondary ore-forming processes extending the mineralisation also to the underlying and overlying formations produced higher grade disseminated and replacement style deposits. Although these deposits are of various size and quality, the formation itself is persistent and continuous with a thickness of 0.3–4 m across the continent.

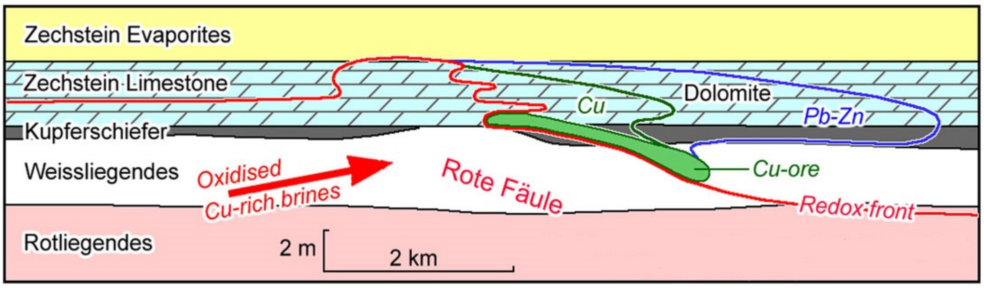

Figure 3.7: Schematic cross section (exaggerated vertically) of the Kupferschiefer mineralisation showing the relationship between secondary geochemical processes, metal zoning and ore formation Source: Borg et al. 2012.

Ongoing tectonic processes positioned the Kupferschiefer horizon to various levels. Outcropping deposits are exhausted mostly. Currently, there are operating mines producing copper and silver ores in Upper Silesia, Poland: Rudna, Sieroszowice, Polkowice, Lubin-Małomice, Głogów Głęboki-Przemysłowy and Radwanice-Gaworzyce, situated around the Fore-Sudetic Monocline *(Figure 3.8)*. The mined levels are between 900 and 1400 metres, but a considerable part of the known resources lie deeper. Beds of the Fore-Sudetic Monocline dip towards NE at a slight angle of 1–6 degrees, and the occurrence of the succession was confirmed also beneath the Polish Lowlands in the North, in 2000–4000 m depth. That's true also for other regions: the deepest crosscut of the horizon was reached under the North Sea at ca. 4000 m in hydrocarbon exploration wells.

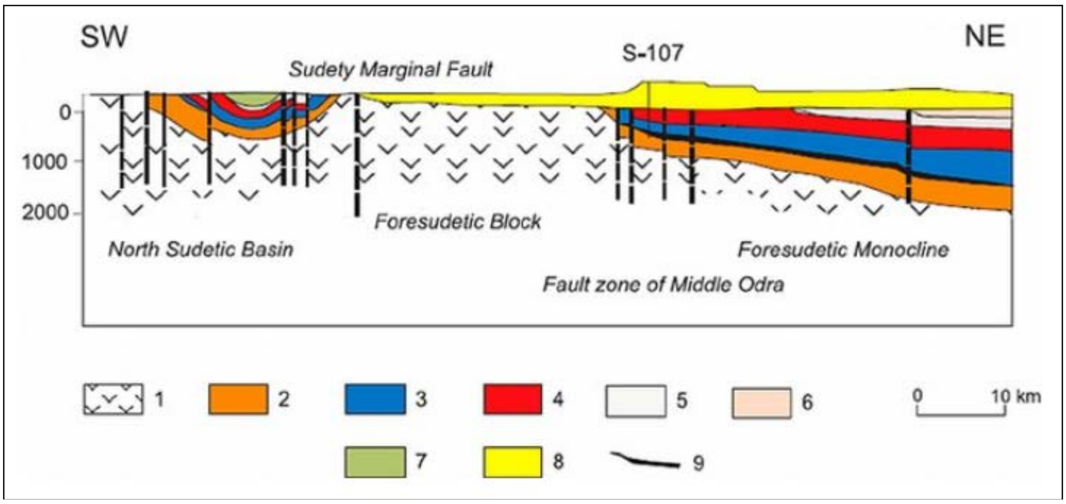

Figure 3.8: A geological cross-section across the North Sudetic Basin (the old copper ore basin area), Fore-Sudetic Block and the Fore-Sudetic Monocline (the LGOM Copper Ore Basin). 1: Crystalline basement, 2: Rotliegendes, 3: Zechstein, 4: Bunter Sandstone, 5: Muschelkalk, 6: Keuper, 7: Upper Chalk, 8: Cenozoic formation, 9: ore deposit. Source: Bauer et al., 2015.

Total thickness of copper-bearing layers in the Fore-Sudetic Monocline area commonly varies from 1 to 7m (3-4 m in average), with a maximum of 17 m. The thickness of the most enriched shale layer with 5–11wt% Cu content) is generally 0.4–0.6 m, max. 1.7 m. Detailed data on the explored ultra-deep sections of the ore deposit are not public (or only partly available) but considering the distribution of the known ore bodies, the potential resources of copper and silver ores are very large. Application of ROBOMINERS technology could extend the mining economically toward these ultra--deep levels.

3.2.1.1. The adopted mining methods in adjacent mines and possible application of ROBOMINERS technology

The first adopted exploitation method in the copper mines of the region began in 1967 with a longwall mining system (see section 4.1.6 below). The extracted regions were either caved behind or filled with dry backfill. However, this mining system was not efficient. The relatively low dip angle of the orebody and its thickness also enabled application of a room-and-pillar mining system with rockbolt support in the year after (*Figure 3.9* – and see section 4.1.5). Many years of experience proved the efficiency and economically justifiable performance of the new mining system. Underground haulage of the extracted minerals was conducted by means of self-propelled machines, instead of chain conveyors and scrapers applied in the former longwall mining system. The first version of this system was introduced by dividing the extracted region into large pillars. Subsequent extraction of the pillars reduced the sizes of remaining pillars. The first implementation of the room-and-pillar system was done in Lubin mine. However, initial stability issues such as rock falls in the roof led to modernisation of the system (Janowski et al., 2007).

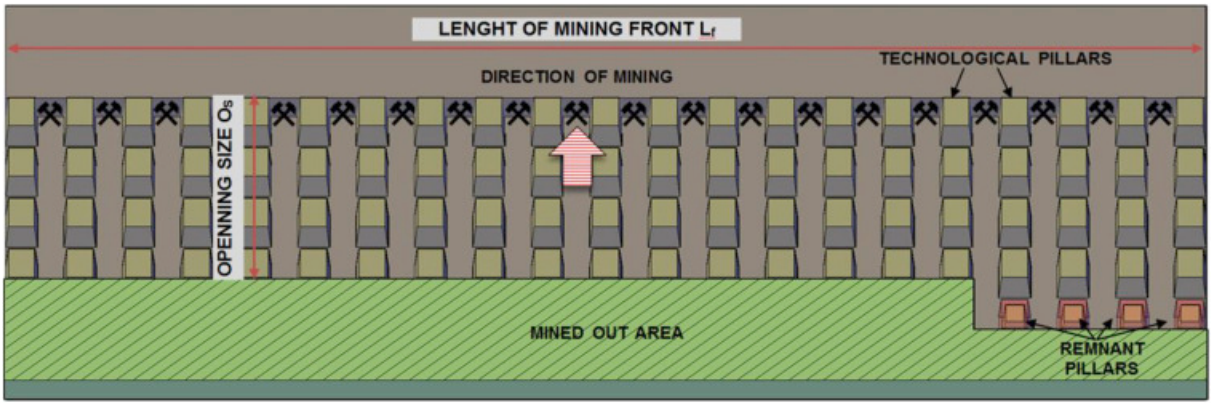

Figure 3.9: A sketch of the mining method used in KGHM copper mines (Fuławka et al. 2018).

The strength of rock is quite variable in different regions; however, investigations show a moderate to high compressive strength in the latest working areas (Polkowize mine with average UCS=80-160 MPa – Rudna and Lubin mine with an average UCS of 60 MPa).

The following mining operations are required for a traditional room-and-pillar mining system: drilling blastholes, loading and blasting the explosives, haulage of extracted ore and installation of rockbolt if needed. The modern mining operations in room-and-pillar systems are largely facilitated in terms of efficiency and safety due to extensive mechanisation by self-propelled machines such as drill rigs, haulage trucks, loaders, roof bolters and blasting machinery *(Figure 3.10).*

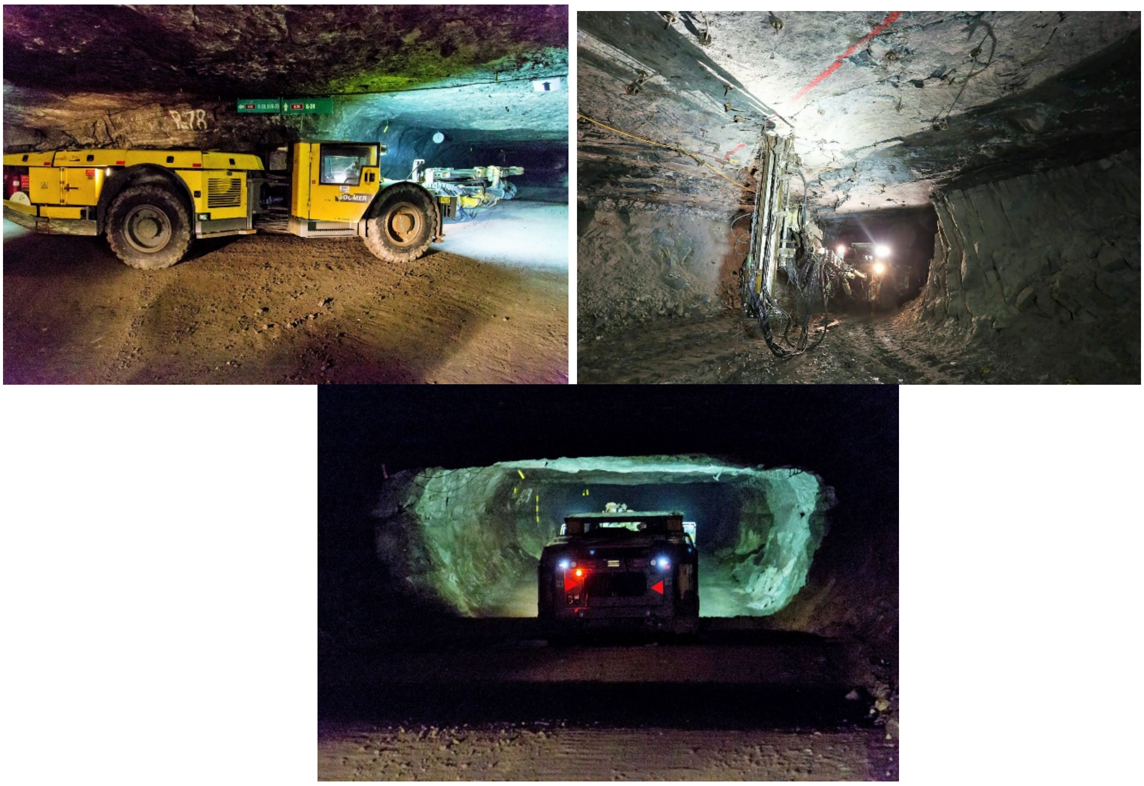

Figure 3.10: The use of machinery in Rudna mine (KGHM).

The relatively deep mining conditions (up to approx. 1200m depth) and the hard brittle rocks in the mining regions has led to mining hazards. The induced seismicity as a result of overstressing of the rock mass is regarded as the most evident consequence. The stiff rock mass contributes to the accumulation of strain energy, which in turn triggers strong tremors. The strongest mining tremors with energy of 10 e^{6} J are regarded as small earthquakes and often associated with rockburst, which endangers working environments and could lead to harsh accidents *(Figure 3.11)*.

Figure 3.11: Examples of damage resulting from rockbursts.

In case such accidents are predicted with the increasing depth of the mines, adaptations to the mining system (pillar design) might be necessary. In addition, the use of backfill and destressing by the so-called group blasting are considered. The KGHM company adopts typical relieve (destress) blasting and the group blasting to release some of the induced energy. The most common blasting method is group blasting which is based on the simultaneous detonation of a large number of working faces. Implementation of this approach maximises the seismic effect and destresses the area with additional dynamic impact. Besides, relaxation in the rock mass is expected to take place by taking away the support of roof over an extensive area and exceeding the strength of overlaying layers.

Expanding the active mining regions to deeper recently explored areas requires more robust mining strategies. Ultra-deep mining (>2.5 km) is mainly experienced in gold mines of South Africa. The so-called sequential grid mining has replaced longwall mining in many deep mines of South Africa. This mining method is designed based on Control of Energy Release Rate. The general aspects are:

- Control of mining span (by stabilising pillars)
- Control of effective stope width
  - Physical control
  - Backfill
  - Partial extraction
- Control of mining sequence and mining geometry

Besides, modifications in the support systems with higher energy-absorbing properties are necessary. High support resistance pre-stressed elongates are successfully applied in deep South African mines.
In spite of all the aforementioned measures, there are still many risks associated with deep mining, which cannot be avoided as long as working personnel are involved in underground mining operations. Thus, automated mining is obviously an important step towards increasing safety in such conditions and enabling the extraction of deep orebodies. Existing mining access routes could be a great advantage in providing for ROBOMINERS operations to extract ore deposits. The same mining principles should also be adopted for ROBOMINERS to provide them with a safe working environment.

3.3. Small deposits uneconomic for traditional mining

Widely distributed forms of mineralisation are veins crosscutting the host rock. Vein fillings can display high concentrations of useful metals, but mostly in relatively small volumes embedded in barren host rock. In the ancient hand-working mining tradition such veins were ideal targets, so a large number of vein-type deposits were explored and mined. But the current industrial, mechanised mining requires larger volumes to be cost-effective, rendering easily accessible, large-tonnage, lower-grade deposits economic and vein-like bodies uneconomic.

Consequently, there are innumerable deposits in Europe, which were abandoned, or never mined because of the development of the mining technology. However, if the investment and operational costs could be significantly reduced, maybe by applying the ROBOMINERS technology, the deposits supplying small volumes of high-grade ores or ores of special composition would become viable.

3.3.1. Example for the scenario: United Downs project, Cornwall

Cornwall in South-west England is famous as a traditional mining region producing tin, copper, tungsten ores and some additional mineral resources. The mining declined and remaining mines were closed at the end of the 20th century, but still there are significant registered resources, and exploration activity – aimed partly on reopening abandoned mines – did not cease. Cornish Metals (formerly Strongbow Exploration) holds mineral rights in the region including the United Downs area, located approximately

8 km east of South Crofty Mine *(Figure 3.12)* in the Gwennap mining district, within the richest copper-producing region in the world in the 18th and early 19th centuries.

In April 2020, Cornish Metals reported the discovery of a new zone of high-grade copper-tin mineralisation located in a previously unmined area between the historic United Mine and Consolidated Mines at United Downs *(Figure 3.13)*. It is a 'semi-massive' sulphide deposit that has been intersected in a drillhole at around 100 m depth with grades of 7.46% Cu and 1.19% Sn over a drilled interval of 14.7 metres. The crosscut was oblique; therefore, the true thickness must be much less than this length. The main mineralised structures in the nearby mines trend ENE and dip steeply to the north. Exploration is continuing, and although recent results indicate that it is very likely this deposit will be shown to have reserves that are economic using conventional mining methods, the style of the deposit is nonetheless typical of very many that are otherwise assumed to be sub-economic.

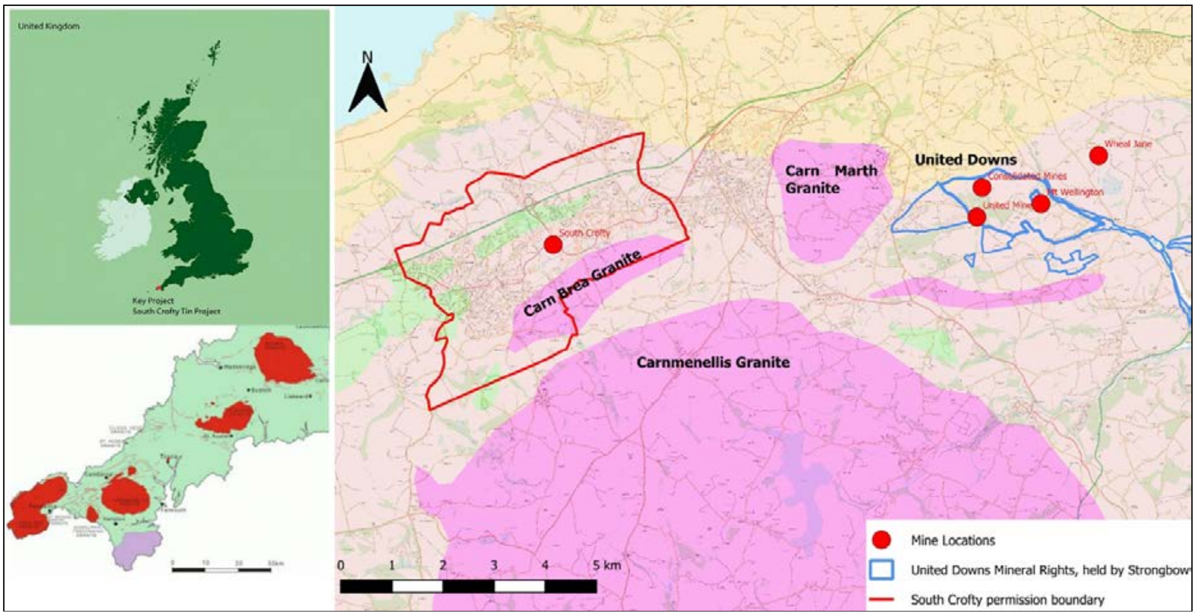

Figure 3.12: Location of the United Downs copper-tin project.
Source: https://www.cornishmetals.com/projects/uk/united-downs/

If this is a tabular vein similar to other lodes of the area, we can expect a zonation. At the nearby South Crofty Mine, copper-tin-zinc-tungsten mineralisation hosted within Devonian metasediments and upper levels of a granite batholith, are vein infill deposits. These pass into tin mineralisation at depth as the mineralised veins pass into the underlying granitic host rock, which was encountered at United Downs between 300 and 600 m and again at 700 m, vertical depth. Even if so, it probably will prove to be too small for modern conventional mechanised mining. However, it would be ideally suitable for robotic extraction by the ROBOMINERS technology, using ore-following methods. Dewatering, a common demand in the mines of Cornwall causing environmental problems could be also avoided.

3.3.1.1. The adopted mining methods for narrow vein deposits adjacent to United Downs and possible application of ROBOMINERS

There are several factors that need to be considered for a proper selection of mining method for a narrow vein deposit. The vein geometry and the rock mechanical properties of the vein (deposit) and the hosting rock constitute the main factors. Due to the variability of geometry in narrow-vein deposits, the adaptability of the mining method is of crucial importance. Besides, the mining method should enable minimal dilution. In cases where the minimum stope width is smaller than the vein width, some dilution must be expected. Above all, efficient and safe mining requires careful geomechanical investigations to provide the stability of stopes and development openings. These are discussed further in deliverable D5.2.

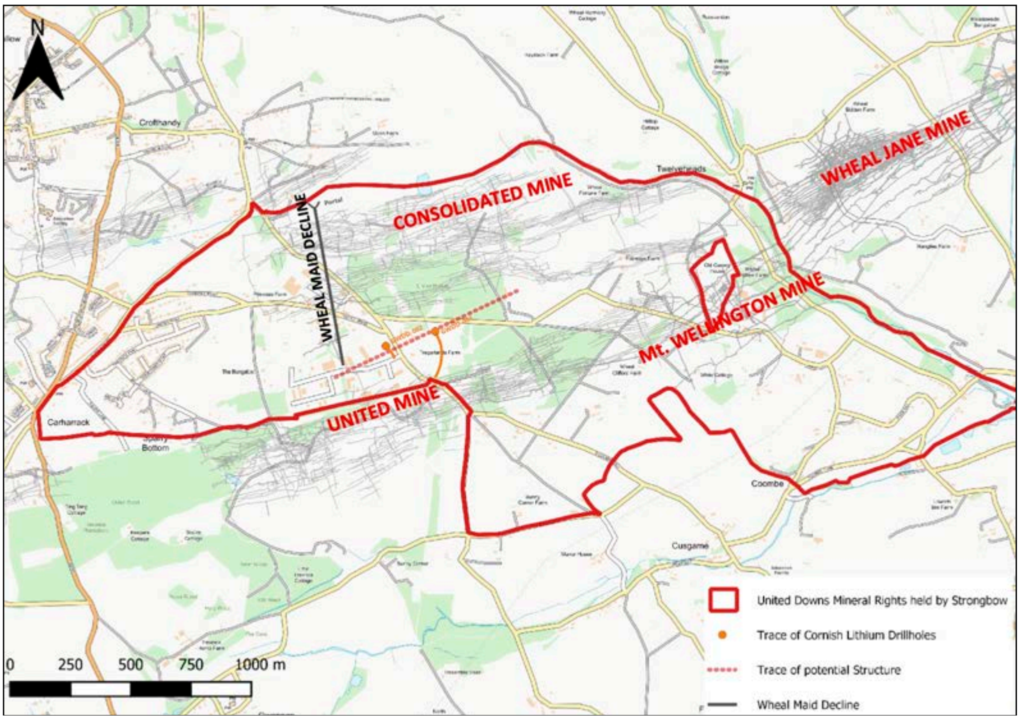

Figure 3.13: United Downs area showing location of the Wheal Maid decline and likely orientation of the newly discovered deposit. Source: https://www.cornishmetals.com/projects/uk/united-downs/

Historically, the most common mining method in Cornwall was one or other form of open stoping, using pillars or timber supports as necessary. The mining methods implemented for Wheal Jane mine, exploited during the mid-to-late 20th century, as one of the adjacent mines to the explored deposit was a combination of shrinkage, open and sub-level stoping (*Figure 3.14*). In the steeply dipping regions, shrinkage stoping method was initially being applied. The method is based on piling the mined material inside the stope, which provides a support for the sidewalls and a platform for later mining sequences. The main advantage of the method is that geologists and controlling personnel are enabled to distinguish between mining regions based on the high or low grade deposits. However, they are not cost-effective compared to sublevel stoping and a large amount of mined ore which is piled cannot be extracted over a long period of time. Besides, high dilution of material can be expected where weak side walls exist.

The sublevel stoping (longhole-based) method is commonly applied in areas with wider and more continuous steeply dipping veins, where the sidewall rocks are strong. The method was initially applied in Cornwall at Wheal Jane in 1979 and at South Crofty in 1982 (*Figure 3.15*).

The method can produce large volumes of ore quickly. The main disadvantage is that changing of the vein characteristics cannot be easily predicted, unless strong geological and geomechanical data are available.

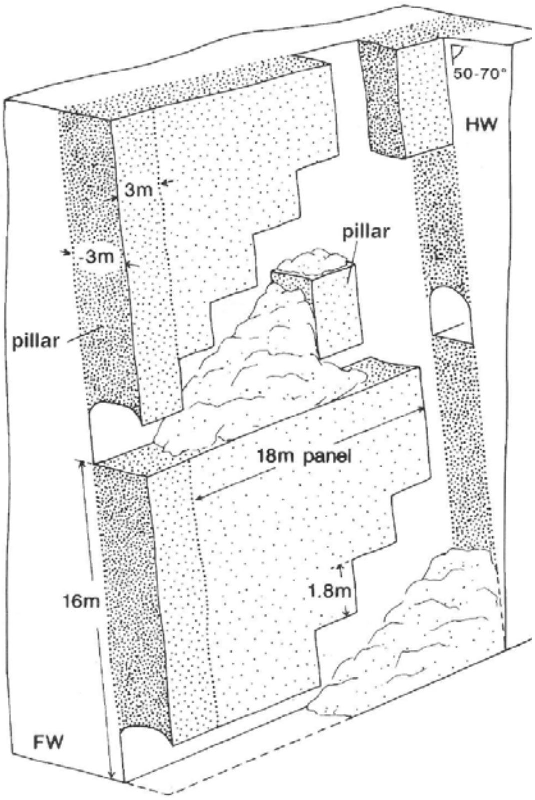

Figure 3.**14**: Schematic block diagram showing semi-shrinkage stoping at Wheal Jane mine **(Dominy et al. 1998)**.

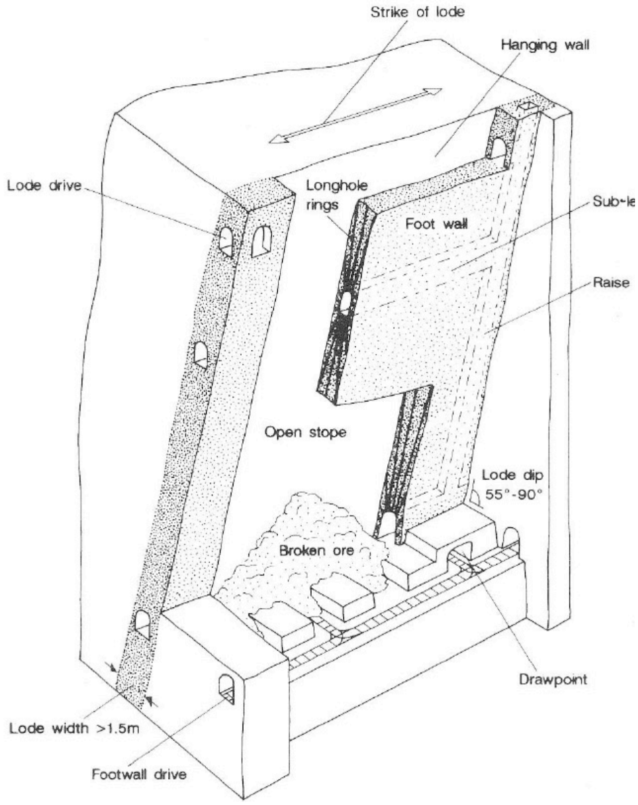

Figure 3.**15**: Schematic block diagram showing sub-level stoping at South Crofty mine **(Dominy et al. 1998)**.

An inherent disadvantage of sublevel stoping is possible dilution from the wall and roof rocks. This could happen where the ore boundaries are irregular or the hosting rock is unstable. To decrease such negative impacts, over-breaking of the rock must be avoided by efficient blasting. Besides, where necessary application of rock and cable bolts should be considered as a method of supporting the hanging wall. Introduction of backfill into the stopes is another supporting method that can be applied. As for Wheal Jane mine, supporting pillars were being left in random positions depending upon the local ground conditions and mineralisation. In general, sublevel stoping mines enjoy from a safer extraction environment mainly because they are non-entry methods.

Another method which was used for a short while in Wheal Jane mine is the Cut-and-fill stoping method. It is applicable to narrow or wide orebodies where the sidewalls are weak, and a high recovery and selectivity required. It enables an entry method of extraction.

Since there are many unknown parameters regarding the shape, extent and the mineralisation of the new explored mineral deposit (United Downs) ROBOMINERS technology can be of high advantage for this possibly small ore deposit. This technology can be applied without the necessity of dewatering the nearby closed mines. It can begin exploration and extraction from the pre-mined regions. In addition, ROBOMINERS are specifically efficient mining tools, as they can minimise dilution during extraction, which is quite common in stoping of narrow veins *(Figure 3.16)*. The high flexibility of the ROBOMINERS concepts can be very beneficial in avoiding the extraction of unwanted low grade surrounding rocks (Dominy et al. 1998).

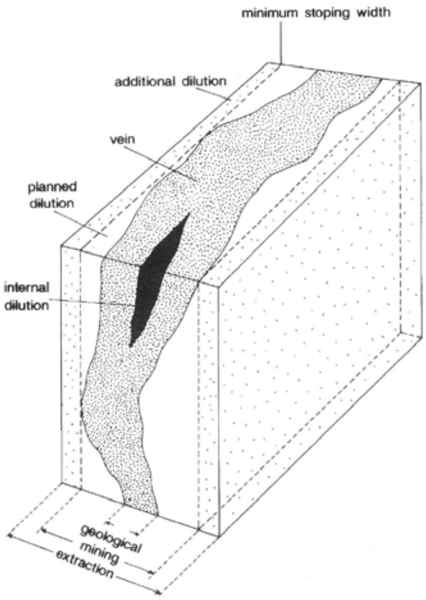

Figure 3.16: The unwanted dilution in a systematic extraction of open stopes (Dominy et al. 1998).

4. CONVENTIONAL UNDERGROUND MINING METHODS

There are many different types of mine layout that are used, depending on the deposit geometry, rock strength, and distribution of the required minerals within the deposit. Some methods allow selective mining, while others are bulk extraction methods (Table 4.1). Illustrations of some of these are adapted from 911metallurgist[1], Harraz (2010) and Western Mining Corporation Ltd (1979).

Table 4.1 Common underground mining methods.

Selective mining is possible	Unselective (bulk) mining
Open stoping Shrinkage stoping Room-and-pillar Longwall mining Cut-and-fill	Block caving Sub-level caving Vertical crater retreat

Depending on the rock strength, artificial support may or may not be required for safe operation, to keep mine openings accessible. For caving methods, by definition, support is not required as controlled or uncontrolled subsidence of a volume of rock is an integral part of the mining method. In those methods, such as shrinkage stoping or longwall mining, where artificial support is required only as long as needed to keep the working face open, the supports (such as hydraulic or wooden props) are either removed or allowed to be crushed under the lithostatic pressure when access is no longer required.

Several different mining methods are referred to as "stoping". Stoping is the process of extracting the desired ore or other mineral from an underground mine, leaving behind an open space known as a stope. In principle it is a selective method as it is the removal of the orebody from the surrounding rock. Stoping is used when the surrounding rock is sufficiently strong not to cave into the stope, although in many cases artificial support is also provided or the stope is back-filled with waste rock.

Stoping is very commonly used for the extraction of narrow vein mineral deposits (*Figure 4.1*), traditionally using manual or semi-mechanised methods.

[1] https://www.911metallurgist.com/mining-method-comparison/

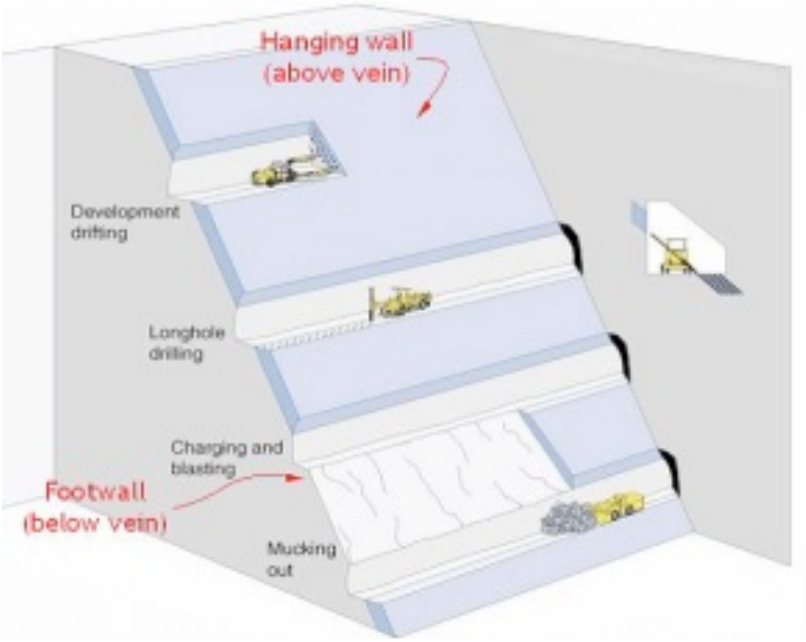

Figure 4.1 (after Harraz, 2010): Conventional stoping methods for narrow vein deposits.

For gently dipping (sub-horizontal) tabular deposits, the most common methods used are variants of room-and-pillar or longwall mining.

4.1. Open stoping

This is a method used when the surrounding rock is sufficiently strong that openings need minimal artificial support, provided that sufficient pillars are retained to prevent catastrophic collapse of the mine workings. There are three main forms: underhand, overhand, and combined.

4.1.1. Underhand stoping

Underhand stoping (*Figure 4.2*) is the working of an ore deposit (or individual panels) from the top downwards. Like shrinkage stoping, underhand stoping is most suitable for steeply dipping orebodies. Ore must be lifted from the working face to a transport level above.

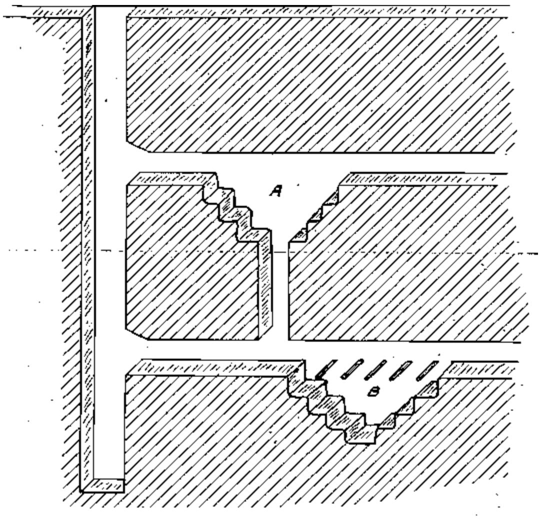

Figure 4.2 (after 911metallurgist.com): Underhand stoping.

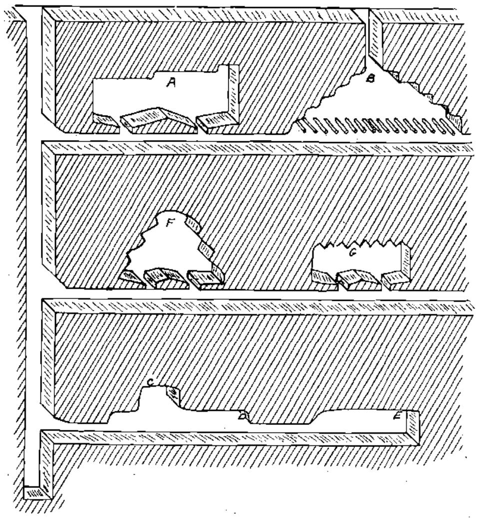

Figure 4.3 (after 911metallurgist.com): Overhand stoping.

4.1.2. Overhand stoping

In overhand stoping (*Figure 4.3*), the deposit (or individual panels) is worked from the bottom upward, the reverse of underhand stoping. With the advent of rockblasting and power drills, it became the predominant direction of stoping.

4.1.3. Combination stoping

This may be a simple combination of underhand and overhand stoping (Figure 4.4), or in less steeply inclined deposits may be a form of room-and-pillar mining, and sometimes referred to as 'breast stoping'.

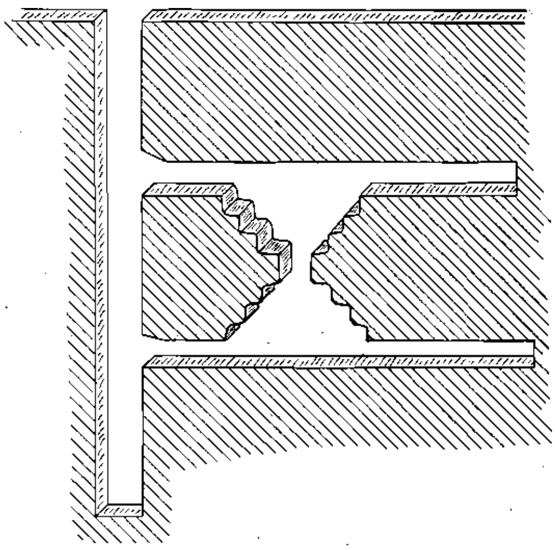

Figure 4.4 (after 911metallurgist.com): Combination stoping.

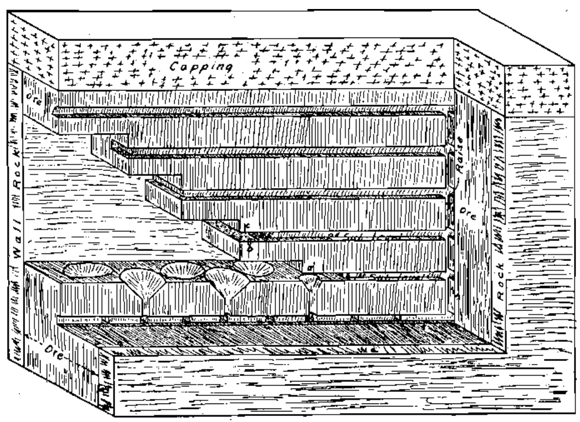

Figure 4.5 (after 911metallurgist.com): Sub-Level stoping.

4.1.4. Shrinkage stoping

This is a method (*Figures 4.6, 4.7*) used in many small mines for steeply dipping and narrow-vein ore deposits. Working upwards from a haulage level, ore is blasted and broken material accumulates below the working face to drop through chutes (ore passes) into the haulage level to be removed by wagon or conveyor belt. Before it is removed, the broken ore acts as a platform on which miners stand to drill blast holes upwards. The broken ore helps to support the surrounding rock. When the top of the stoped panel is reached, all remaining broken ore can be removed from the stope, which may then be backfilled or left empty. The method is more suited to manual than mechanised mining.

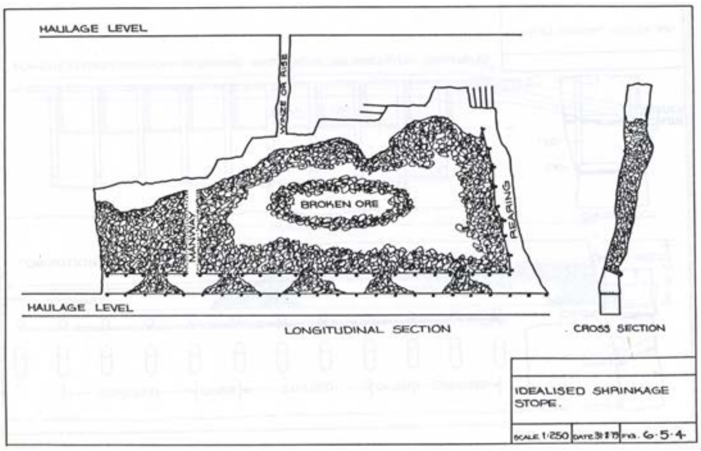

Figure 4.6 (after Western Mining, 1979): Shrinkage stoping.

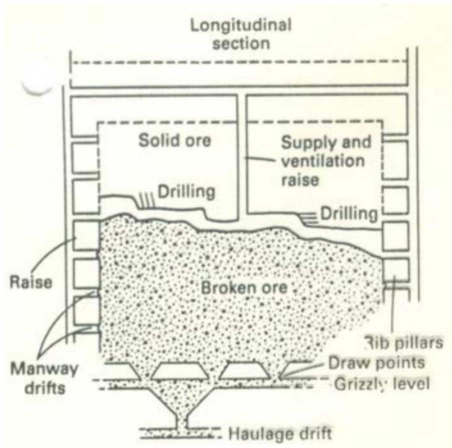

Figure 4.7 (after Harraz, 2010): Shrinkage stoping.

4.1.5. Room and Pillar Mining

This tends to be used for relatively thick tabular deposits of minerals such as salt, gypsum, or bauxite or in underground quarrying of marble, slate, or limestone, as well as in Bushveld-style reef deposits of chromite or platinum ores.

In this method (Figure 4.8), normally used for near-horizontal tabular deposits, minerals are extracted from a rectilinear grid of tunnels, leaving pillars between them to support the hanging-wall (roof). Once the whole deposit has been mined, it is common practice then to 'rob' the pillars, starting at the farthest point, allowing the rocks above to collapse into the mined opening, though clearly this can have serious environmental consequences especially if there are any surface structures above the mine, or watercourses which could then flood the workings through the overlying broken rock.

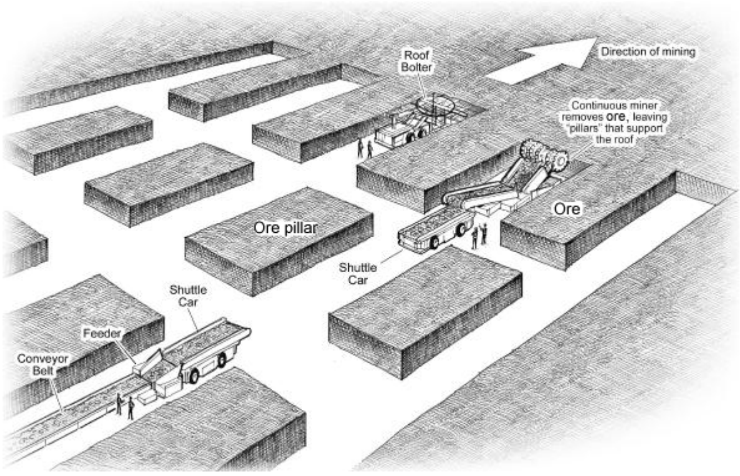

Figure 4.8 (adapted from Harraz, 2010): Room and pillar mining.

4.1.6. Longwall mining

This is most often associated with coal mines (Figure 4.9) but can be used for many other stratiform minerals such as potash or other evaporates, usually when seams are relatively thin, and large excavation equipment cannot be used.

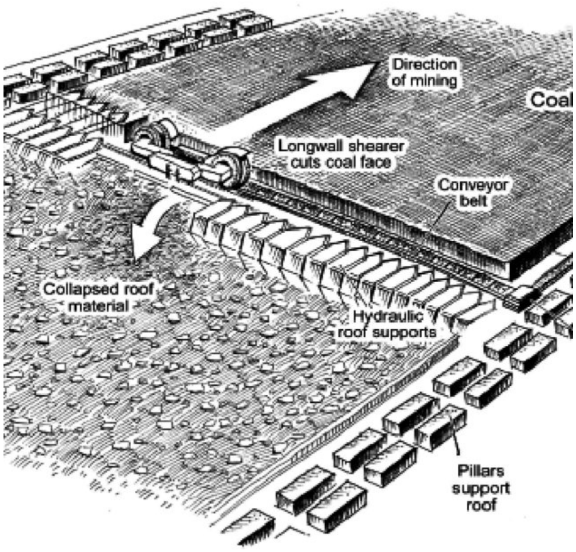

Figure 4.9 (from Victaulic Ltd): Longwall mining.

4.2. Cut and fill stoping

This is a very commonly used mining method (*Figure 4.10*), particularly for vein deposits. It is so widely used because, although expensive, it allows selective mining, maximising ore recovery and minimising dilution by waste. It is a preferred method for mining steeply dipping mineral deposits, especially if they have irregular ore zones and patchy mineralisation. It is a 'bottom up' method, with ore mined in horizontal slices, advancing upwards. When a slice is fully mined, the opening is backfilled to provide support for the walls on each side. The fill material can be rock waste or tailings with or without cement and provides a working platform for equipment when mining the next higher slice. Drift-and-fill and bench-and-fill are closely related variants of cut-and-fill.

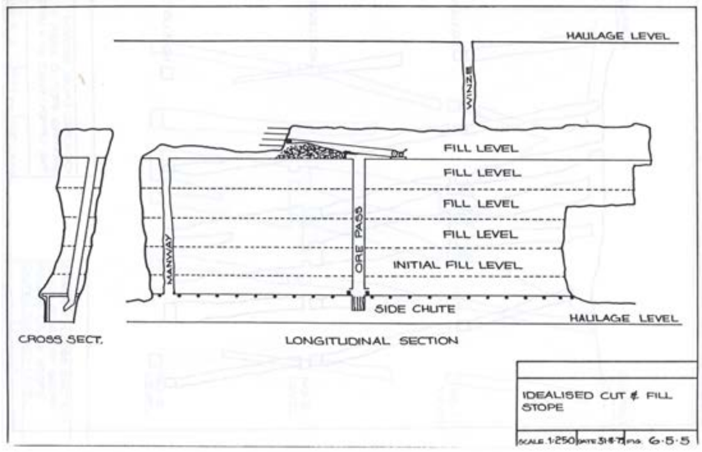

Figure 4.10 (after Western Mining, 1979): Cut and fill stoping.

4.3. Block caving

There are several variants of block caving, but the common factor is that a large volume of ground is broken above a haulage drift (*Figures 4.11, 4.12*), and fragmented ore is extracted through a chute or ore-pass into wagons or on to a conveyor belt for transport out of the mine. The mined block of ore is usually fragmented by longhole drilling and blasting. This method is suitable principally for massive deposits with simple internal geometry (i.e., little or no internal waste partings or 'horses'). The usual design of block cave operations, with a fan of long upward drillholes, with explosive charges to break the ore, is not easily adaptable for robotic mining. For operations in a flooded mine environment, it is also not clear whether block caving would in general be viable, since the relative densities of ore and water may not allow for smooth flow of ore fragments. Even in a dry environment, a frequently encountered problem is blockage of the ore pass by over-sized boulders which require manual attention - drilling and blasting to break them and clear the blockage.

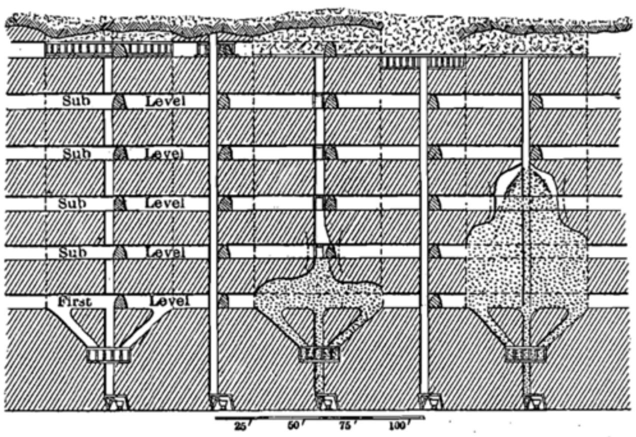

Figure 4.11 (after 911metallurgist.com): Block caving.

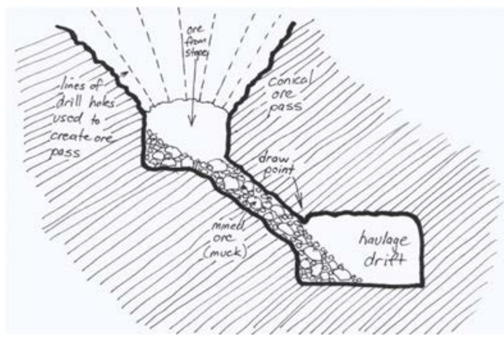

Figure 4.12: Block caving elevation view showing ore transfer via an ore-pass to a haulage level.

4.4. Sub level caving

Mining is conducted in sublevel caving from the top down. Sublevel caving is depicted in Figure 4.13. The ore in the stope is fragmented from rings that are drilled and blasted in fan formation above each sublevel retreating from the hanging wall to the foot wall. The blasted ore is withdrawn. As it is being withdrawn, the country rock from the hanging wall fails. This failed country rock falls on top of the broken ore. The broken muck is recovered. Care is taken during the recovery to minimise the amount of country rock recovered with the ore.

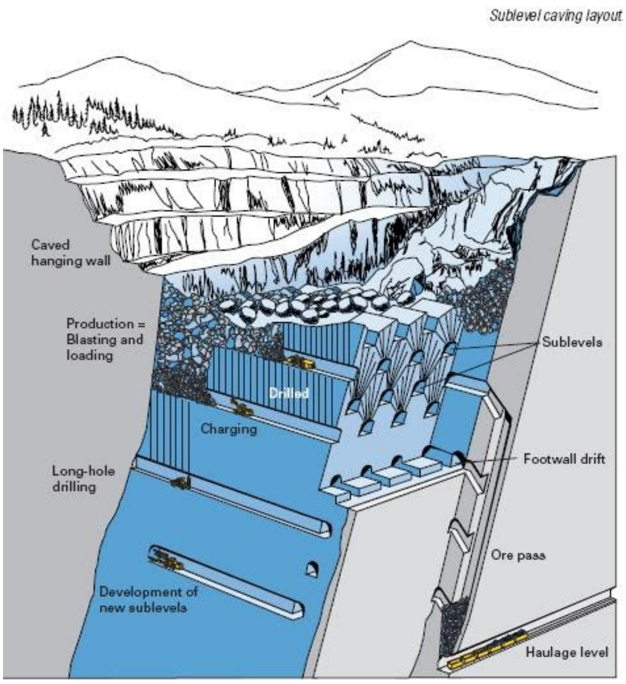

Figure 4.13: Sublevel caving.

Development for sublevel caving includes ensuring access to the stope and ore pass in the footwall of the stope. This mining method requires levels to be developed at fairly close vertical increments from which the vertical rings are drilled. Access to these levels could be through a vertical excavation or a ramp that vertically spirals by the stope.

In addition to conducting drilling operation from these levels, they would provide access to the ore pass in the footwall of the stope.

Sublevel caving is suitable for steeply dipping orebodies. The orebody rock would be reasonably competent. It would therefore not fail with the country rock as the ore previously blasted is withdrawn. The country rock from the overlying footwall and wall rocks would enclose the orebody rock. It would also naturally fail into the void left as the ore is extracted.

This mining method requires an orebody with a high intrinsic value. Dilution could conceivably exceed 20% due to country rock which is barren mixing with the ore as it is being recovered. Much development must be conducted, with many sublevels being excavated with the drilling and blasting required to generate the mobile granular ore within the caving medium.

A geomechanical concern may be as mining progresses downwards, these stresses may increase in the lower abutments.

4.5. Alimak raise mining

Mining is conducted in Alimak Raise Mining from the bottom up. Longitudinal and transverse section of the stope mined by Alimak raise mining of 2339 No. 17 stope in Dome Mine (Timmins, Ontario, Canada) in shown in Figure 4.14.

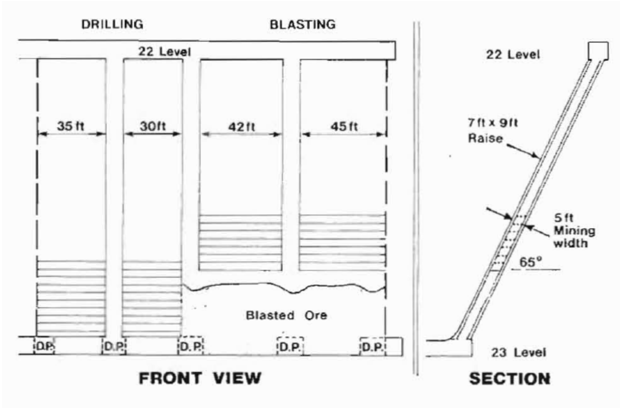

Figure 4.14: Longitudinal and transverse sections of 2339 No. 17 stope (Robertson, Vehkala, & Kerr, 1990, p. Figure 2).

Holes are drilled horizontally from drill raises driven from the 23 Level to the 22 Level along the stope dip. The drill raises measures 2.15 metres by 2.75 metres. One drill raise was developed 35 feet (10.7 metres) from the left side of the depicted stope. The other drill raise was drilled 45 feet (13.7 metres) from the right side of the depicted stope. The drill raises measures 2.15 metres by 2.75 metres.

An inspection raise is driven between the two drill raises. This will be 30 feet (9.2 metres) from the left drill raise and 42 feet (12.8 metres) from the right drill raise. This inspection raise is used to monitor the accuracy of the drilling and to provide a free face for blasting. The inspection raise was 1.83 metres by 1.83 metres.

An isometric section of the same stope being mined by Alimak mining is shown in Figure **4**.15.

Details of the drill hole pattern can be seen in Figure **4**.16. The drilling pattern was drilled horizontally from the drill raises. Three holes were spaced along the horizontal line that comprised the width of the stope. The rows of holes were separated vertically by a burden of 3 feet (0.91 metres). Every two rows of holes were blasted. Starting from the bottom, two rows of holes were blasted. After blasting, the Alimak could no longer lower itself in the raise because it was blasted away with the rest of the muck blasted.

The broken ore flowed through the drawpoints on the 23 Level. Only the proportion of ore that swelled was mined. The remaining ore fragmented by the blasting was left in the stope to maintain stability.

Before the mining transpired, a footwall drift was driven on the upper level of the stope (22 Level). This provides access so the Alimak equipment could be recovered as it mines upwards. A scram drift connecting the five drawpoints at the bottom of the stope in the footwall was also developed. A slusher operates in this scram drift to drag the broken ore to a drawpoint.

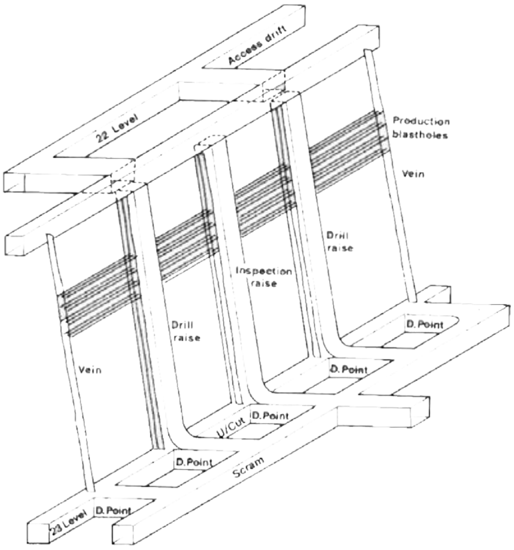

Figure 4.15: An isometric view of 2339 No. 17 stope (Robertson, Vehkala, & Kerr, 1990, p. Figure 3).

An advantage of this mining method in terms of ground control is all work is being conducted under conditioned ground that has been reinforced appropriately. It is not necessary to enter the stopes. Therefore, extensive rock bolting and other ground control measures normally required are not necessary. The orebody would be steeply dipping. The country rock would be sound to minimise dilution.

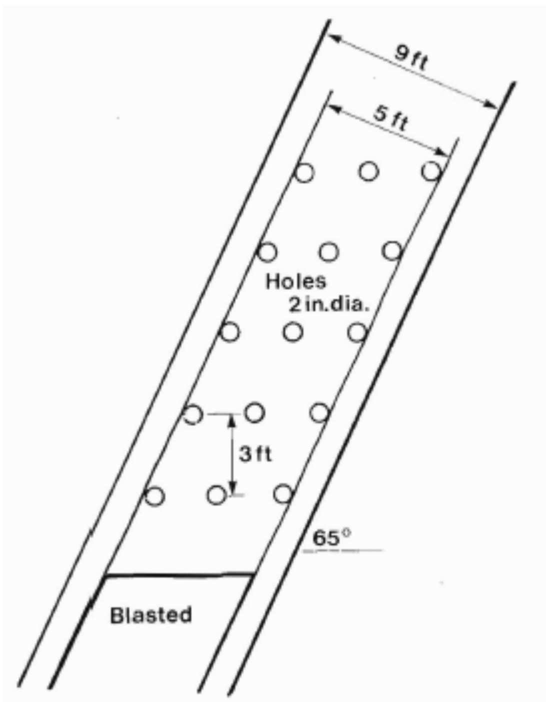

Figure 4.16: A cross-section showing details of the drill hole pattern (Robertson, Vehkala, & Kerr, 1990, p. Figure 4).

5. MINERAL DEPOSIT ACCESS AND TRANSPORT

Notionally the first concept is that the deposit would be accessed through a wide borehole, with a cavity at the bottom allowing assembly (or self-assembly) of a mining robot that would then mine laterally into the mineral deposit.

However, this requires two separate sets of equipment: a drill (which could be a conventional drill rig), and the mining robot.

Boring, rather than traditional excavation methods used for shaft-sinking, is becoming accepted as a standard method for shafts at all scales (Morton, 2021), including large-diameter conventional shafts, but always requires specialist equipment.

Wide diameter drilling is a specialised, energy-intensive and expensive activity, best considered as a form of shaft-sinking. Figure 5.1 shows an example of the type of equipment required for this, which should not be considered a part of the robotic ecosystem.

Figure 5.1: Rig for drilling 1-metre diameter holes.

There are alternative solutions (*Figure 5.2*) which could avoid the need for a specialised drill rig. In a new mine, these could use the mining robot itself to dig its own access route. This could be by a horizontal or inclined drive (adit or decline) or a spiral ramp, both of which are conventional layout options for underground mines, but again, would be energy-intensive. An existing abandoned mine is likely to have access routes already available, though they may require repairs and reconditioning before starting new mining operations.

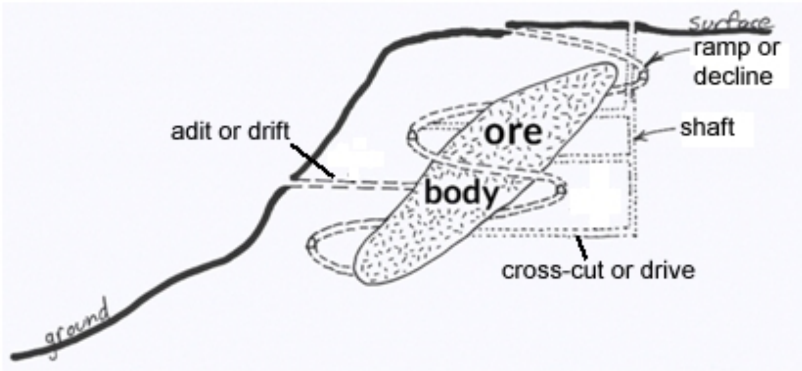

Figure 5.2: Access methods.

Apart from reducing the number of different types of equipment required, using the mining robot to dig its own access route would offer an advantage in avoidance of double-handling of mined material. Transport robots or slurry pipelines would not need to transfer the concentrates or other products to different units for lifting out of the mine, but the material could travel to surface using the same method planned for extraction of material from the intended mining location to the surface.

5.1. Underground rock transport

5.1.1. Introduction

The ore transportation in underground mines is an important part of the mining process and the careful selection of the rock transportation system and associated equipment is an essential part of the ROBOMINERs eco-system. The following parameters have a considerable influence on the conveying method: mining method, properties of the rock/ore to be excavated, production capacity and overall safety. In addition, the operational and economic evaluation also play an important role in the selection process. Typical underground mines are shaped in complex structures and (can) exhibit different excavation levels with both horizontal and vertical turns. This necessitates a combination of several transportation methods which, as a whole, form a sophisticated transportation system/infrastructure. The individual elements of this infrastructure must be very precisely laid out and coordinated during operation to minimize production loss, degradation of efficiency and to keep the overall costs in range. (Darling, 2011).

In Figure , a general classification of rock conveying systems is presented, separated by methods related to haulage and hoisting respectively. Haulage is the transportation from the rock face or draw point to a certain discharge location, mostly in the horizontal plane. Typically used transportation methods for haulage are track or trackless options, or a combination of them. (Tatiya, 2013).

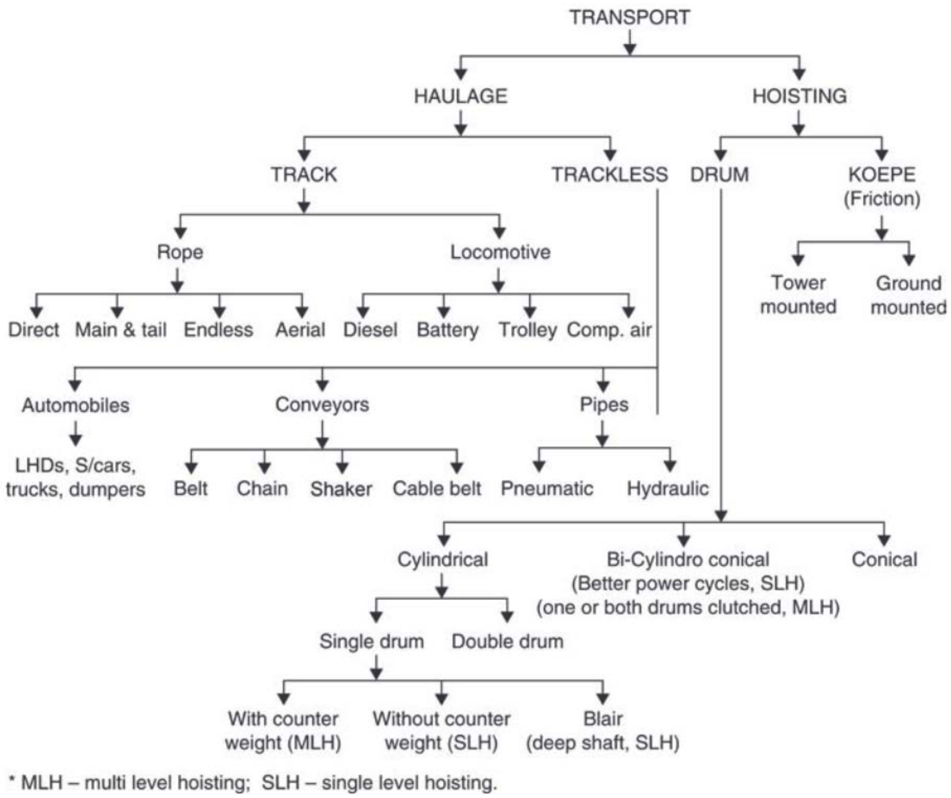

Figure 5.3: General classification of ore transportation systems (after Tatiya, 2013).

Track systems describe fixed rail systems, whereas trackless systems cover mobile vehicles, pipes and conveyor belts. Hoisting systems are used for the vertical transportation of material, divided into drum and Koepe (friction) types. Often, further auxiliary equipment like crushing or sorting machines are needed. (Tatiya, 2013).

Figure shows a different classification of the transportation systems, separated in (semi-) continuous and batch systems.

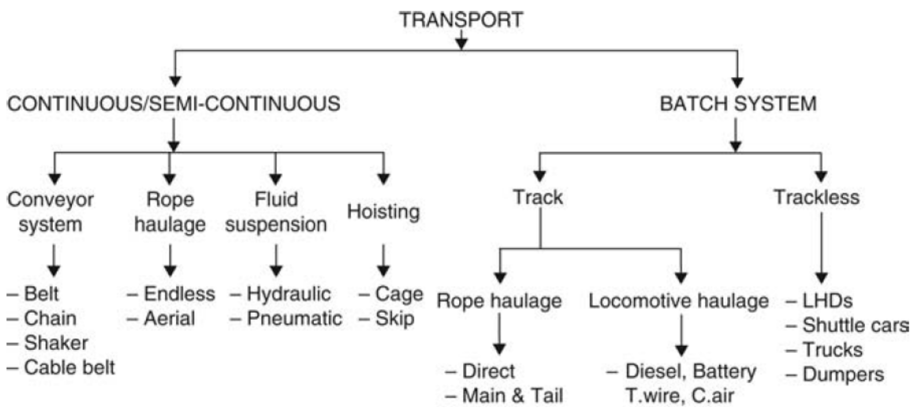

Figure 5.4: Batch and continuous system of transportation (after Tatiya, 2013).

With reference to Figure **, the overall ROBOMINERS eco-system will necessitate both haulage and hoisting methods to transport the excavated ore to the processing plant, which is likely located at the ground surface rather than underground in the mine. In relation to**

Figure , the ROBOMINERS eco-system will most likely use continuous/semi-continuous transportation methods for the (horizontal) haulage part of the transport infrastructure, as the robot miner itself will most likely use a continuous excavation method, such as rock cutting. Further away from the robot miner, the transportation system may also include batch methods, for instance, when a traditional shaft is used with ore transport skips. For the ROBOMINERS project, the focus will lie on the development of transportation concepts directly linked to the robot miner, i.e., continuous haulage concepts. Nonetheless, a short description of standard haulage methods (batch and continuous/semi-continuous) is provided in the following chapter.

5.2. Underground rock transportation methods

5.2.1. Trucks and Shuttle Cars

Generally, trucks are used for long horizontal or inclined transports from the loading point to ore passes or to the surface. Both two-wheel and four-wheel drive trucks can be found in underground mines, whereas two-wheel drive trucks are limited to a roadway inclination of 12%. Favoured road condition is a hard surface without soft and slippery parts. Four-wheel drive trucks are used, when two-wheel drive trucks reach their maximum capabilities. Trucks are available in various options, the most common ones are: Diesel or electric articulated (ADTs) / rigid dump trucks (Figure); diesel road trains (Figure); diesel, electric, or battery shuttle cars (*Figure*).

Figure 5.5: Minetruck MT5020 (Epiroc, 2021).

Figure 5.6: Powertrans Underground Road Train (Powertrans) (IndustrySearch, 2021).

The material is loaded onto the truck by an underground loader (side loading) or by a loading chute at the bottom of an orepass.

Shuttle cars commute between the loading face and the discharge end, which are in general rather short distances. In the center of the shuttle car's body a chain and flight conveyor are installed, which transfers the ore rock from the rear end (where it is loaded onto) to the front end of the shuttle car. Unloading of the material happens onto a conveyor, minecart or similar. Such vehicles are either diesel or electric (by cable) powered and the short distances and easy to handle roadways usually don't require the shuttle car to turn around.

Another variety of haulage machinery in modern underground mines are LHD (Load, Haul, Dump) loaders (Figure 5.8). LHD's combine the operations of loading and hauling minerals to an unloading point. They are similar to conventional front-end loaders but are especially designed for difficult mining conditions. Their manoeuvrability and exceptionally high production capacity make them the most common machinery for handling the excavated material in underground mines.

Figure 5.7: Shuttle Car (Komatsu) (Joy, 2021).

Figure 5.8: Manually operated LHD machine working in an underground mine (Sandvik, 2021).

5.2.1.1. Selection Criteria

After Darling (2011), the selection of the truck fleet depends on the following key factors:

- Ore reserve tonnage
- Production rate
- Haulage distance
- Depth below surface
- Lateral extent of the mine
- Mining method
- Integration with upstream and downstream materials handling processes

Generally, the quantity of the ore reserve is the most decisive point when it comes to equipment selection. Truck haulage is mainly used when the amount of material to be transported doesn't demand the costs of a conveyor or shaft system. Shaft hoisting or inclined conveyor systems are driven by the following factors: lateral extent of the mine, shape of the orebody and distribution of the ore.

One of the bigger advantages of ADTs is their flexibility and mobility, which allows them to operate in various scenarios. They are not as greatly affected as road trains or rigid-body trucks from varying conditions (inclination, temperature, clearance, etc.). Coal and potash mines are the best examples for the application of trucks and shuttle car systems. The narrow seams require low-profile vehicles, which directly interact with the mining machine (e.g., roadheader or continuous miner). This leads to a very efficient material handling systems.

5.2.1.2. Limits

The use of underground trucks demands a special design of the underground access to meet the special requirements of them. Darling (2011) states that there is a risk of water ponding which increases with higher road inclination. To minimize this risk and to ensure good road conditions, it is recommended to keep the inclination gradient typically below 1:50 for all rubber-tired vehicles.

5.2.2. Conveyors

Depending on the mine geometry and the ore reserve, conveyors are used when the overall situation allows it to operate them more cost-effective and efficient than other transportation methods. Generally, a conveyor system consists of multiple units including conveyor belts, chutes and other equipment. Figure shows an underground conveyor belt in North Parkes Mine, Australia.

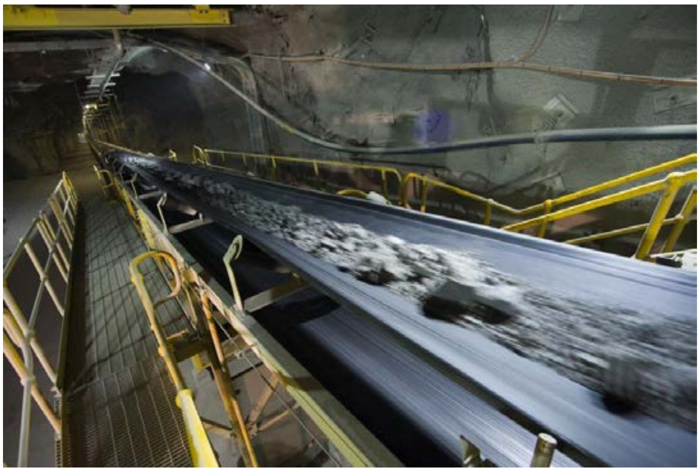

Figure 5.9: Underground conveyor belt North Parkes Mine, Australia (ABC News, 2021).

5.2.2.1. Selection Criteria

Darling (2011) has pointed out the following selection criteria for underground conveyor haulage:

- Inherent safety
- Capacity (steady state and surge flow)
- Simplicity in design and operation
- Dimensions (length, height, and width)
- Manoeuvrability/adaptability to various layouts
- Cost (capital and operating)
- Reliability/availability
- Operating life
- Size of product handled, spillage, and carry-back
- Dust and noise generation
- Automatic, remote operations

Conveyor systems offer a wide range of advantages compared to other hauling systems including high potential of automation, little operating labor, low operating costs and a high reliability with a high level of safety. On the other hand, the rigid structure exhibits less flexibility, a large footprint and high capital costs.

5.2.2.2. Limits of Application

The most limiting factor of conveyor application is the inclination of the stope, with a value typically in the range of 10.5° to 10.7° for conventional conveyors. Although new technologies with lower production rates have provided much steeper conveying inclinations, conveyor belt systems cannot fulfil tight curves and are therefore inflexible. Compared to railway and truck haulage systems they also require considerably higher crushing efforts depending on the ore size. The width of a conveyor needs to be three to four times the width of the largest ore particles. The conveyor is also prone to wear and tear as a result of abrasiveness of the ore (Dammers et al, 2019). Furthermore, the conveyor base frame and the strength of the belt splice set the length and lift limits (Darling, 2011).

5.2.3. Rail haulage system

Rail haulage systems once had a dominant role in the underground mining sector and are still a preferred option for large tonnage (> 5 Mt/a). Usually used for transportation of ore and waste material, rail haulage systems are also used for the transportation of personnel, equipment or other supplies. Another distinguishing feature is the power supply: diesel, batter or overhead electric available in various sizes (from 100 kt/a to 20 Mt/a) (Darling, 2011).

Although rail-bound systems are much less flexible than other transport options, the high potential for automation makes them very interesting for certain applications. In summary, rail haulage systems cannot be automatically ruled out and still have a right to exist. In Figure a typical rail haulage system can be seen.

Figure 5.10: Underground rail haulage systems (LKAB, Kiruna mine, Sweden) (LKAB, 2021).

5.2.3.1. Selection Criteria

The selection of an appropriate haulage system is influenced by a very wide range of parameters as economics, health, safety, mine geometry, shape of orebody on the one hand, and factors associated with the transportation system itself, like reliability, operability, automation grade, maintenance and flexibility on the other hand. Rail systems provide a good solution for lateral movement of personnel, material, waste and equipment and ultimately needs to meet the requirements stated by the shape, nature and size of the orebody within an economically justifiable frame (Darling, 2011).

5.2.3.2. Limits

Compared to the other transportation methods, rail haulage systems exhibit high initial costs accompanied by a long construction time due to the larger scale of the systems. Following [SME], rail haulage systems require:

- Long distances of tunnel development, which take years to excavate
- Orepasses and chute systems for train loading
- Long-term ground support systems
- High upfront equipment capital purchase costs for locomotives, rail, rolling stock, tipplers, trolley line system, and power reticulation equipment (where installed)
- Large construction labour and installation costs

In addition, the rigid structure of rail haulage systems elaborates the extension of existing systems when the mine is developed further. This needs to be considered beforehand.

5.2.4. Hydraulic haulage/hoisting system

Hydraulic ore transport or slurry transportation describes an altogether different transportation method that is used less often than the standard ore transportation methods described previously. In a hydraulic transportation system, a mixture (slurry/suspension) of the ore concentrate and a carrier liquid is pumped (hydraulically hauled), through pipelines, from the rock face to the dispatch location, where the ore is separated from the liquid by a separation and/or filtration system. Alternatively, the slurry is pumped (hydraulically hoisted) directly to the processing plant at the ground surface where the slurry is used in further processing steps such as comminution.
The ore, as a solid, either is in a suspended, pulverulent or granular state. (Darling, 2011, Government of India, 2001)
Darling (2011) lists several risks of the application of slurry transportation in underground mining:

- Pre-treatment and preparation of suitable underground material, beyond typical crushing and sizing
- Wear of pump and other mechanical parts
- Capital costs and equipment technologies for transportation of greater amounts

Nonetheless, the consideration of hydraulic transport methods for the Robominers eco-system could be critical to the project’s success as the main potential mining scenarios for Robominers include flooded mines.

A clear advantage of hydraulic transport methods, when used in a vertical direction, is that the theoretical energy demand for ore hoisting in a flooded mine is significantly reduced, compared to an air-filled mine, when a hydraulic hoisting system is used since the effective density of the ore to be hoisted is reduced by the density of the fluid with which the mine is flooded (water or brine). A further advantage of hydraulic transport methods is the absence of dust in the Robominers ecosystem which could contribute to the longevity and reliability of the robot miner.

A clear disadvantage of the hydraulic transport method, apart from the risks mentioned previously, is the need to produce a slurry from the excavated ore directly after production to avoid the need for a mechanical transport system within the robot. This increases the demand on the production tool to always produce broken ore within a fairly narrow particle bandwidth to deliver a non-settling slurry under the hydrodynamic conditions present in the hydraulic transport system (hoses, pipelines, pumps, vessels, etc.). When the particle size distribution would shift, due to, for instance, teeth wear in the production tool, the slurry can shift from non-settling to settling under the given conditions with (sudden) cloggage as a result, as derived from the information on hydraulic transport systems provided by Wille et al. (2021).

5.2.4.1. Types

A solid–liquid mixture can be transported in various ways depending on the size and distribution of particles, specific gravity and the separation characteristics. The mixture types can be separated into homogenous or heterogeneous types. A mixture is a homogenous type when the particle size is very fine, whereas heterogeneous types have coarse particle sizes with a grain size exceeding a few tenths of a millimetre (Government of India, 2011).

In order to produce an ore slurry to be transported in a hydraulic transport system, it is necessary to slurrifying the (usually) dry/low-moisture ore rock. This can be achieved by either incorporating a slurrification function in the production tool, (see Figure 5.11 for an example where the slurrification takes place behind the cutter head of a micro tunnelling machine), or by adding a separate component such as a mixer, an example of which is shown in Figure .

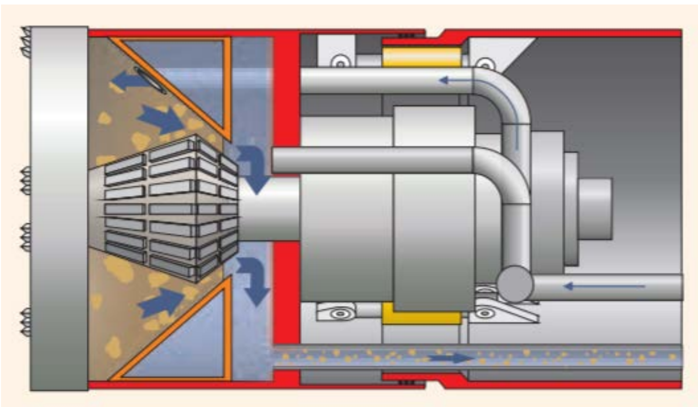

Figure 5.11: Cutter head with central drive for a microtunnelling machine (mtsModularConcept, mts Performance, Germany).

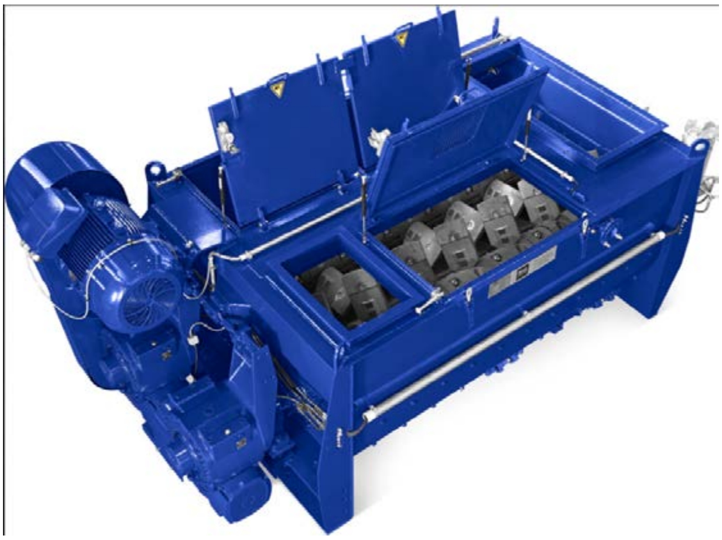

Figure 5.12: Twin-shaft continuous mixer used to produce slurries suitable for pumping (LFK, BHS-Sonthofen, Germany).

The main factors influencing the design and component choice for a hydraulic transport system, in particular the required pumps and pipeline systems, are the solids content of the slurry, grain size distribution and abrasive properties of the ore rock, densities of the ore and the carrier liquid and the distances/geodetic height that needs to be bridged. Although theoretical knowledge and applicable relationships are available, in practice, the design of a hydraulic transport system is largely based on practical (iterative) testing in laboratory and pilot-scale of the actual ore to be transported.
The hydraulic transport of slurry through pipelines can only function effectively when the slurry velocity in the transport infrastructure is high enough to prevent settlement of solids, potentially causing pumping (energy) losses and risk of clogging the pipe. For any particular slurry, depending on the transport distance, a suitable pump type and size can be selected during the design process. Generally, the following pump types are potentially suitable for slurry transport in a mining environment:

- Centrifugal pumps,
- Screw pumps,
- Piston pumps,
- Membrane pumps.

Centrifugal pumps are generally favoured as they are simple, robust more economical in terms of both investment and operational cost than the other pump types. However, centrifugal pumps are limited in their pressure range compared to screw, piston and membrane pumps which limits their application for mining projects to some extent. Especially considering the potential “reserve” capacity of a pump above its normal operating pressure, centrifugal pumps have less ability to deliver a higher-than-nominal pressure in case of (impending) clogging of pipelines or other flow restrictions. Some mine backfill operations for example use centrifugal pumps for normal operating conditions but hold one of the other types available for special/emergency situations in which additional pump force is needed (Wille et al., 2021). .

5.2.5.Pneumatic haulage system

Pneumatic conveying systems are relatively straightforward and well-suited to the transportation of powdered and granular materials in factory, site, and plant settings. A compressed gas source, a feed unit, a conveying pipeline, and a receiver to disengage the conveyed material and carrier gas are all required components of the system (McGlinchey, 2009).

Most of the time, the compressed gas is air. Different gases are used in situations where special conditions exist (e.g., risk of explosion, health, fire hazards, etc.). It can be used in a variety of sectors, including food and beverage, pet food, chemicals and detergents, renewables, and speciality materials. (Klinzing et al., 2010).

5.2.5.1. Pneumatic conveying system types

There are a variety of pneumatic conveying systems available, which are suitable for the transport of dry bulk particulate materials. The vast majority of systems are traditional, accessible, continuously running systems that are installed in a fixed location. Many of these systems will work with positive or negative pressure, or a combination of the two. In Figure , the issue of device selection is depicted. This diagram illustrates the various combinations that can be made with a single air source in traditional pneumatic conveying systems (McGlinchey, 2009).

When it comes to pneumatic conveying, open systems are the standard, particularly when using air. Closed systems can only be used in extreme cases, such as when dealing with extremely volatile and potentially explosive materials. Since materials can be sucked as well as blown, pneumatic conveying can use either pressure or vacuum. This is often a matter of corporate policy or individual choice. Although the majority of pneumatic conveying systems are installed in fixed positions, this is not considered a unique situation. For specific tasks, a range of mobile systems are available (McGlinchey, 2009).

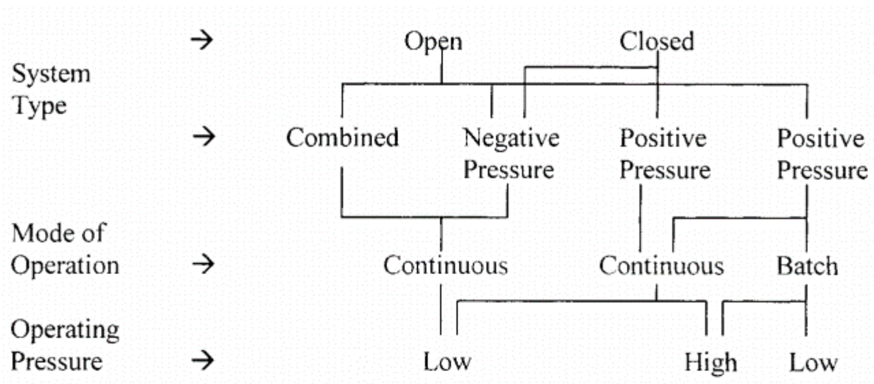

Figure 5.13: The diagram shows the wide range of conveying systems available for conventional systems operating with a single air source (McGlinchey, 2009).

5.2.5.2. Advantages of a Pneumatic conveying system

Pneumatic system is a dust-free transporting method of a wide range of products. The versatility of the road, which can be transported vertically and horizontally by inserting a bend in the pipe, is a merit for the pneumatic conveying system. It is also a low-maintenance and labour cost process since a single pipe can be used for a wide range of goods. This method can safely transport high-value materials, and automating and controlling it is very simple (McGlinchey, 2009).

5.2.5.3. Disadvantages of a Pneumatic conveying system

Extreme temperature changes, as well as vibration, can damage a pneumatic system. In addition, compressed air costs more than electricity. Since compressed air escaping causes energy loss, it is important to ensure that there are no leaks in a pneumatic device. Pneumatic devices are known for their loudness. A silencer can be installed in each dump line as a solution. When the instrument necessitates the use of speciality tubing, the cost of installation rises. Furthermore, pneumatic systems cannot be upgraded to work with smart electronics.

It is a high-power-consumption system with a high level of equipment wear and abrasion. Particle degradation can occur as a result of poor design. Besides, the distance is limited, and high levels of expertise are necessary to design, operate, and maintain systems because of the complex flow phenomena that occur (McGlinchey, 2009).

5.2.5.4. Limitations of a Pneumatic conveying system

Typically, the primary constraint in the use of pneumatic conveying systems is the type of material to be transported. These materials must be dry and relatively easy-flowing, and their free-flowing properties must be precisely measured. Some materials, which are generally not free-flowing, can flow relatively freely when subjected to wind force. In some cases, materials gradually accumulate on the outer radius of the pipe's curves, eventually obstructing the pipe's operation.

Owing to their high power consumption, pneumatic transportation systems are best suited to transporting fine particles over shorter distances (up to a few hundred meters). The majority of existing systems have capacities ranging from 1 to 400 tons per hour over distances less than 1,000 meters and an average particle size of less than 10 mm. Particles greater than 15 mm in diameter are often stated to be unsuitable. There are, of course, exceptions to this law. To prevent blockage within the pipe, another general rule is that the inside diameter of the conveying pipe should be at least three times greater than the largest size of material to be conveyed (McGlinchey, 2009).

5.3. Adaptation to ROBOMINERS

In this section, a number of the main parameters more relevant to the Robominers project are chosen for a rather qualitative comparison. These parameters should give an overview of the differences between methods and their main advantages and disadvantages. A quantitative comparison is subsequently required to compare production capacity and energy requirements in view of the ore reserve.

Main potential mining scenarios for Robominers include flooded mines, where from economical, technical and environmental points of view dewatering the mine is not possible. In such conditions, a hydraulic transport system may be the most logical option for ore transportation. However, in an unflooded mine, other methods of transportation should also be considered. Table 5.1 qualitatively compares the previously introduced transportation systems based on various parameters.

Table 5.1: Comparison of main transportation systems based on some of the most relevant criteria to Robominers project.

		Railway	Automobiles	Conveyors	Piping (hydraulic)	Piping (pneumatic)
Geometrical Adaptability to mining scenarios	**Vertical flexibility**	low (Max 22% inclination)	low (Max 12% inclination)	Moderate to high (for specific types)	high	High
	Horizontal flexibility	low (down to 30 m turning radius)	high (especially for ADTs)	moderate (down to 5-10 m turning radius)	high	high
Mobility		low	high	low	low	low
Operability in hard working conditions	**Uneven or soft floor**	low	moderate	moderate	high	high
	Abrasive material	high	high	moderate	low	low
Automation potential		high	moderate	high	high	high
Independency from transportation infrastructure		low	high	low	high	high
Crushing or pre-treatment necessity		not always necessary	not always necessary	might be necessary	necessary	necessary

The railway system may not be a feasible option throughout the entire ore transportation route. This stems mainly from its low geometrical adaptability to sophisticated geometries predicted for Robominers. Therefore, its possibility of application highly depends on the design layouts of the mining areas. In addition, railway haulage systems need to be applied in favourable working conditions. The railway system also suffers from low mobility, as the railways are bound to a specific pathway. Nevertheless, due to its high automation capabilities, it can still remain a viable option for the main transportation roadways connecting the mining areas to the principal developments of the mine. The railway construction is a necessary first stage in the process. This stage is best integrated with the roadway construction process. Full face cutting machines are one example of simultaneous roadway excavation and railway installation, which can provide a flat surface quite suitable for a long-term railway transport system.

Asexplained before, efficient use of automobiles such as trucks, shuttle cars or LHD's requires a hard surface without soft and slippery areas. Water-bearing formations can also hinder their performance. Such limitations clearly result from the rubber-tired technology of automobiles. However, new technologies such as screw-propelled vehicles can become the future form and assist in difficult ground conditions. Despite some disadvantages, the high mobility of a trackless technology makes it quite attractive in comparison with other methods.

Conveyors particularly suffer from a lack of adaptability to different mining scenarios and low mobility. The vertical flexibility has been significantly improved with new technologies, requiring specific particle sizes. Yet, the horizontal flexibility is normally very low. Some examples of conveyor systems that are able to change direction horizontally without the need for a conveyor belts transfer system exist and are usually called "pipe-conveyors". By "rolling" the conveyor belt to a closed ring (in section view), the conveyor can negotiate turns in all directions, both horizontally, vertically or in-between. But, as for conventional conveyors, also the pipe-conveyors require extensive preparatory works in the erection of the conveyor support structures. As such the applicability of conveyor belts as an ore transport system in a Robominers eco-system is considered limited.

Piping constitutes an isolated system that can be highly protected from environmental conditions of the haulage roadway. One of the main disadvantages is the wear of pumps and other mechanical parts, which should be well predicted in the primary design stage. Although piping systems (pneumatic and hydraulic) are not highly dependent on pre-existing transportation infrastructure, they need excessive pre-treatment facilities to bring the particle size in a functional range. High adaptability to geometries of different mining scenarios makes them quite distinguished among others. Since pneumatic transport systems are only designed for the haulage (and hoisting to a very limited extent) of dry material, its feasibility for ore extracted from a flooded mineis not expected.

Continuous, un-interrupted ore transport from the working face to the main developments is highly preferable due to a significantly lower complexity. However, in case this is not fully achievable, another important parameter for choosing the right transportation system is its capability to be integrated with other transportation systems. Unlike others, piping systems are hardly integrated into other systems in the transportation process. This is mainly due to their specific particle size limitations. As for the hydraulic piping system it is even more sophisticated due to the pre-conducted slurrification of the material.

An important factor to be considered for selection of a proper transportation system is the extent of maintenance demand. This parameter is difficult to analyse in this stage, as a comprehensive analysis of various components of a system needs to be conducted.

6. POTENTIAL BIO-INSPIRED MINE LAYOUTS

Many organisms burrow into unlithified sediment or bore into rock or otherwise make tunnels for objectives such as nutrition, protection and living space. These organisms include arthropods, which include insects. There are also segmented worms or annelids, molluscs, a few vertebrates, plant roots and fungal hyphae. The medium into which they burrow, bore or tunnel is known as the substrate, and sediment affected by such activity is said to have been bioturbated.

To look for inspiration from organisms for mining layouts, the scope is considerably widened if not only modern organisms are considered, but also those from the past that are known from the fossil record. It may be worth examining the physiology of an organism or its fossil to understand its adaptation to burrowing, boring or tunnelling. But more may be gained by researching the structures it creates or leaves behind in the substrate, to understand the method and template it applied to realize its objective. These structures can be preserved as trace fossils, also known as 'ichnofossils'.

Where the substrate is unconsolidated sediment, it is very difficult to examine structures made by organisms directly, which may, for example, involve digging into mobile silt or mud. But if the substrate has hardened or lithified, then intact specimens of it may be taken. If these include trace fossils, then they can be examined visually, microscopically and also by techniques such as CT scanning to understand 3D layouts. Ideally, both the organism's body fossil and its trace fossils would be studied, but often the organism has no body parts that are amenable to preservation. In many cases, only the trace fossils remain, and the responsible organism is unknown or can only be inferred.

The next few sub-sections review a range of trace fossils that may inspire mineral extraction. Rather than using a classification of organisms, it is more focused to select examples from the long list of ichnogenera, or trace fossil types, that have been compiled by ichnologists.

Relevant trace fossil categories include burrows in unconsolidated substrate, borings in rock but probably not wood, and possibly root or fungal hyphae traces. These may be preserved either because the voids left by the departure or demise of the organism are unfilled, or because they have been filled by sediment that is recognisably different to the substrate, or by post-depositional mineralisation. Faecal pellets, or coprolites, which may also be preserved by mineralisation, may be relevant to mine backfilling or disposal of waste or tailings. Surface traces, including trails, trackways, impressions and scratches seem unlikely to be relevant.

In some burrows the organism has created a lining using faecal material or some process of biomineralisation. This may be from a secretion, typically containing calcium carbonate which acts as a cement. Faecal material is often mineralised during diagenesis, and so remains as part of the fossil. The lining supports the burrow and may keep it open. It is analogous to shotcreting in a mine. Other biochemical activity by the organism may also be of interest.

The many ichnogenera have latinised names, given in italics. They may seem arcane to the non-specialist, but those presented here are intended to be straightforward tags for reference to a selection of representative and relevant types. The following text is introductory, and any example that is of interest may be followed-up in more specialised literature.

In each of the following sub-sections, after a brief introduction to the ichnogenera, there are comments on how the layout may be applied in a robotic mine.

6.1. *Scoyenia*, *Taenidium*, *Beaconites* and *Ancorichnus*

These are probably the simplest sub-surface feeding and dwelling traces. They may have been produced by several organisms, mainly arthropods, their larvae, or worms. Members of this group are horizontal, inclined, or less often sub-vertical burrows of circular or oval cross-section with characteristic meniscate backfilling. This means that as the organism moved forward through the unconsolidated sediment, it packed sediment in the burrow behind it to produce a concave surface, or meniscus. Sediment was mobilised at the front end, processed externally or internally to extract organic matter, and then moved or voided behind in pulses, so that a cross-section along the trace fossil may appear as a series of nested crescents with the 'horns' pointing in the direction of travel.

Presumably, the organism steered its burrowing towards more favourable conditions, generally higher concentrations of organic matter.

Sketches adapted from Retallack (2001) and reproduced in Knaust (2017) are shown in Figure 6.1, where in each case, the organism is moving upwards and left, away from the viewer. Unlike the others, *Scoyenia* has a faint lining. *Taenidium* has wider-spaced menisci. *Beaconites* is alternately backfilled on one side and then the other, giving a 'shuffled' meniscate pattern. *Ancorichnus* has an outer 'mantle'. Members of this group also differ in size, sediment type and other details.

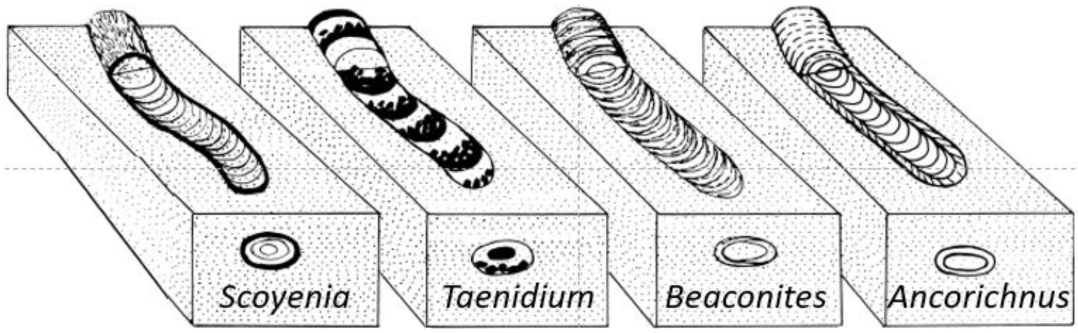

Figure 6.1: Four Simple Burrowing Traces.

6.1.1. Comments on Robotic Mine Application

This inspires not so much a layout as a style of deployment. The robot would be a relatively free agent, and would require its own on-board capabilities for power, comminution, processing and control. As an extraction technique, probably the most efficient would be if the burrows are stacked adjacently as layers of parallel cylinders. But there will still be unextracted material, and other layouts would probably be more efficient.

Possibly this idea could be valuable for exploration, essentially having free rein to determine the extent of a deposit, building up a model of grade etc. as it goes. Replacing most drillholes, it could have virtually no impact on the surface environment. It may determine its location by a form of 'dead reckoning', or by some form of communication and positioning involving, perhaps, ground penetrating radar.

6.2. *Diplocraterion* and *Teichichnus*

These are simple vertical U-shaped dwelling trace fossils made in soft sediments, such as silt and carbonate mud, where, in life, the two upper ends of the 'U' open at the sediment surface. They are end members of a series, where *Diplocraterion* has a curved, semi-circular lower midsection, while *Teichichnus* tends to a box-shape, with right-angles at the base of the verticals, and the horizontal midsection may be the longest part of the burrow. Polychaete worms are considered to be the main responsible organisms.

A particular feature is the presence of 'spreite' (German, plural 'spreiten'), as shown in a vertical-section sketch (Figure 6.2). This is excavated and re-reposited material with a banded appearance. It is produced in response to changes in level of the sediment surface. As sediment is deposited, the animal reduces the burrow depth by excavating sediment from the roof of the midsection and depositing it on the floor. But if, perhaps due to currents, sediment is removed at the surface, the burrow may be deepened by excavating at the floor and moving sediment to the roof. This trace fossil can result in a vertical slot of bioturbated sediment.

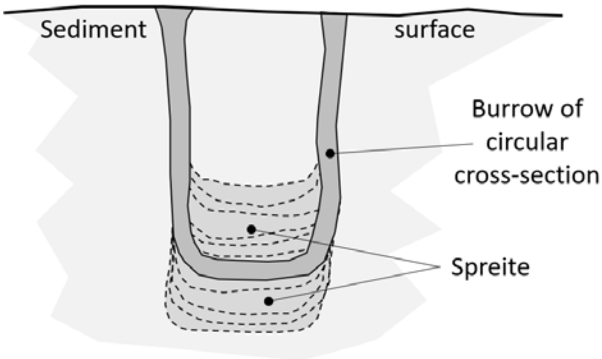

Figure 6.2: Sketch of Diplocraterion.

6.2.1. Comments on Robotic Mine Application

This could inspire an efficient extraction layout for vertical or sub-vertical planar deposits and for three-dimensional deposits. A planar deposit would be extracted as a series of vertical slots arranged end-to-end. A three-dimensional deposit may have many such series of slots, side-by-side.

It is suggested that three adaptations of robot or operating modes may be deployed:

- A vertical miner whose task is to mine the shafts at either end, feeding mined and comminuted material upwards to the surface or underground gallery as a slurry, which is sent to a processing plant and sampled for grade control. It may also apply a lining to keep the shafts open;
- A robot that mines a horizontal connection between the shafts, also feeding mined material upwards;
- A robot that mines horizontally, moving upwards at each pass, to process a next 'lift'. Most of the processing is on-board, and the concentrate is fed upwards, while tailings, perhaps as a setting paste, are stacked behind and below the robot.

A single robot adaptation may achieve all three operating modes, especially if the base of the U-shape is semi-circular, like *Diplocraterion*.

After a slot or series of slots has been mined, since a small proportion of the rock has been removed, there may be a possibility of secondary extraction using a technique such as In-Place Leaching. For example, the robot may produce a concentrate, but with a recovery of significantly less than 100%, some of the minerals that are left in the tailings are amenable to leaching at a slower extraction rate. In-place leaching is described in more detail later.

6.3. *Rhizocorallium* and *Zoophycos*

These are feeding and dwelling traces produced by unknown organisms, but considered most likely to be worms. *Rhizocorallium* is a basic form occurring as a sub-horizontal trace with respect to the bedding, as shown in the sketch plan below. It consists of a loop-shaped tunnel that is moved forward by the organism, while sediment with organic matter removed is stacked behind as spreite.

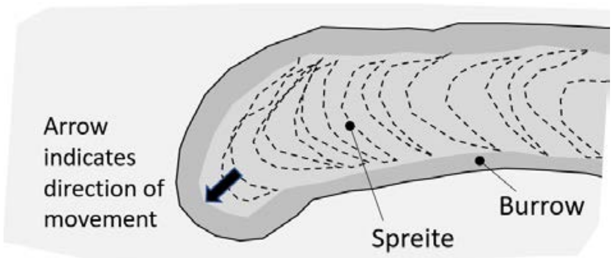

Figure 6.3: Sketch of Basic Plan View of *Rhizocorallium*.

Examples have been found where the loop travels in a circular direction moving upwards or downwards as a spiral. *Zoophycos* is more complex with a tiered, sometimes lobate and possibly spiral arrangement pivoting around a tubular connection to the surface. This is shown in a side view at the centre of Figure 6.4, reproduced from Bromley and Ekdale (1986). Other trace fossils are included to illustrate types that exploit favourable strata at a sequence of depths in a study of trace fossils occurring in the Cretaceous chalk formation in Denmark. Names are given at the sediment surface. *Planolites* is a simple near-surface burrow, while *Chondrites* and *Thalassinoides* are described later.

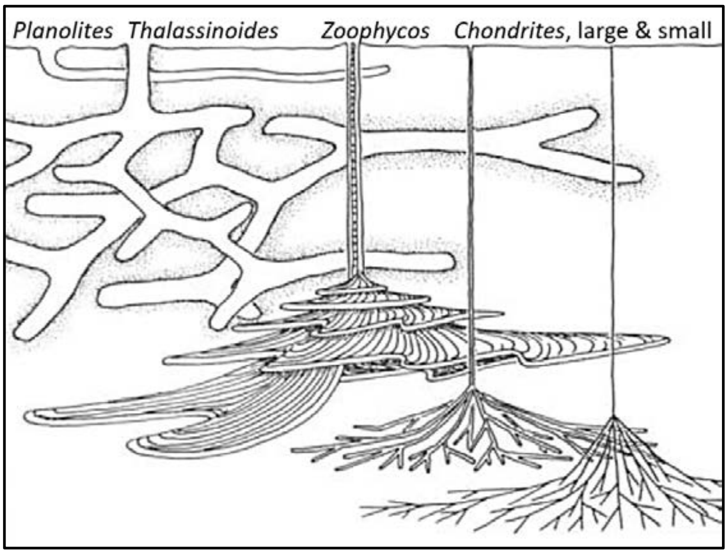

Figure 6.4: Sketch of Side View of Depth-Feeding Trace Fossils.

6.3.1. Comments on Robotic Mine Application

As the figure above suggests, these layouts would be suitable for a horizontal planar or tabular deposit. A planar deposit or seam may require just one extraction layer. The *Rhizocorallium* layout is reminiscent of long-wall mining except that the working face moves outwards instead of inwards, and robotic operation should be able to achieve greater flexibility, particularly with upwards and downwards undulation of the seam.

If multi-layered mining in a tabular deposit is required, then the *Zoophycos* layout may be applicable. This has a single stalk-like shaft from the surface that typically connects to the centre of a roughly circular panel, about which the layout pivots. Many circular or pie-shaped panels with very little wastage could be achieved by following a pattern similar to that described under *Dactyloidites*, below.

6.4. *Chondrites*

As illustrated in Figure 6.4 (above), Chondrites has a vertical shaft from the sediment surface, from which many ramified branches radiate outwards to allow feeding in a favourable stratum at some depth below.

6.4.1. Comments on Robotic Mine Application

This may also be applicable in a deep seam-type deposit, or by applying it in multiple layers, it could be used for a three-dimensional deposit. However, it is probably not efficient at maximising recovery. It may have application where the main extraction method is in-place leaching, as described later in this section.

6.5. *Ophiomorpha*, *Thalassinoides* and *Spongeliomorpha*

These are branched 3D networks of interconnected burrows with linings of faecal material. The main difference is that in *Ophiomorpha* the lining is made of pellets and has a nodular appearance while in *Thalassinoides* it is smooth and in *Spongeliomorpha* it is striated. These fossils are considered to have been excavated by shrimp-like crustaceans, typically in high-energy shallow and deep marine sandy environments. Their purpose appears to be more for living space and protection than for feeding.

Figure 6.5 shows drawings of a selection of the forms of these fossils. They are reproduced from Knaust (2017), which describes *Ophiomorpha* as one of the commonest trace fossils. The drawings are reproduced from work by several other authors. *Thalassinoides* is also shown in Figure 6.4 above.

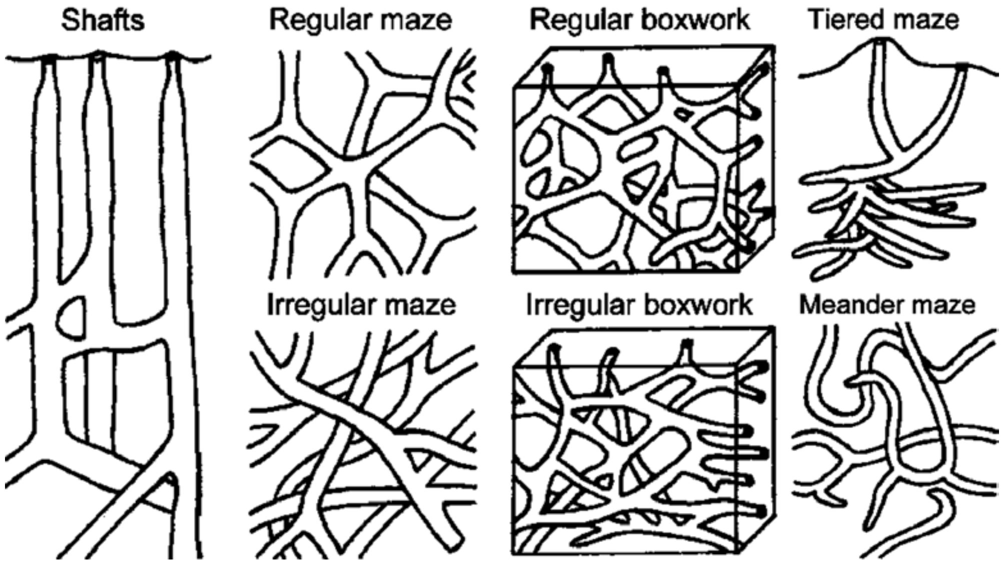

Figure 6.5: Examples of Branched 3D Network Trace Fossils.

A feature of such 3D networks is their degree of interconnectivity, and the term 'anastomosing' indicates essentially that there is more than one route through a network from any location within it to another. The term 'boxwork' is used when there are many interconnections that enable a multiplicity of routes.

6.5.1. Comments on Robotic Mine Application

Network layouts such as these may be applied in a 3-dimensional deposit. At first consideration they do not seem to be suitable for maximizing recovery. However, it can be imagined that if such a network could be back-filled with supportive material, such as setting or cemented paste tailings, it should be possible to mine a second phase network that inter-threads but does not intersect the first. The cycle may be repeated with third and fourth phases, by which time, a high level of recovery would have been achieved.

There may be a regular or systematic 3-dimensional pattern that can serve as a template, modified locally as necessary. But rather than working in a formal series of phases, robotic miners may travel around the deposit, repeatedly returning to partially mined areas where filling has taken place to mine more of what remains.

As they mine the network, robotic miners should:

- 'Remember' where they have mined,
- Continuously develop a best path to
- Maximize present grade and also
- Maximize recovery of the economic deposit.
- Avoid mining close to open or recently filled tunnels, so that good ground conditions are maintained,
- Provide information to direct a second fleet of robots to fill sections of the network while, in some cases, leaving important accesses open.
- Inform re-development of the network plan in response to robot breakdowns, ground failures and adverse ground conditions.

Another use for such layouts would be where the main extraction method is in-place leaching, as described later in this section.

6.6. *Hillichnus*

This complex feeding and dwelling trace fossil occurs in fine-grained sandstone or mudstone and is believed to have been produced by a bivalve. Its structure requires illustration on several levels as shown in Figure 6.6 reproduced from Knaust (2017), in turn reproduced from Bromley *et al* (2003).

Levels A and B show the trace made by the base and body of the bivalve as it moves forward in a series of steps. Moving up to Level C, the traces made by the bivalve's palpal tentacles are seen as they probe the adjacent sediment for organic matter as food. Different traces result in substrates of sand or mud. Levels D and E are above the level being exploited for food. The curved vertical traces are made by the creature's siphon that is pushed upwards through sediment in what is likely to have been a reducing environment to access oxygenated water.

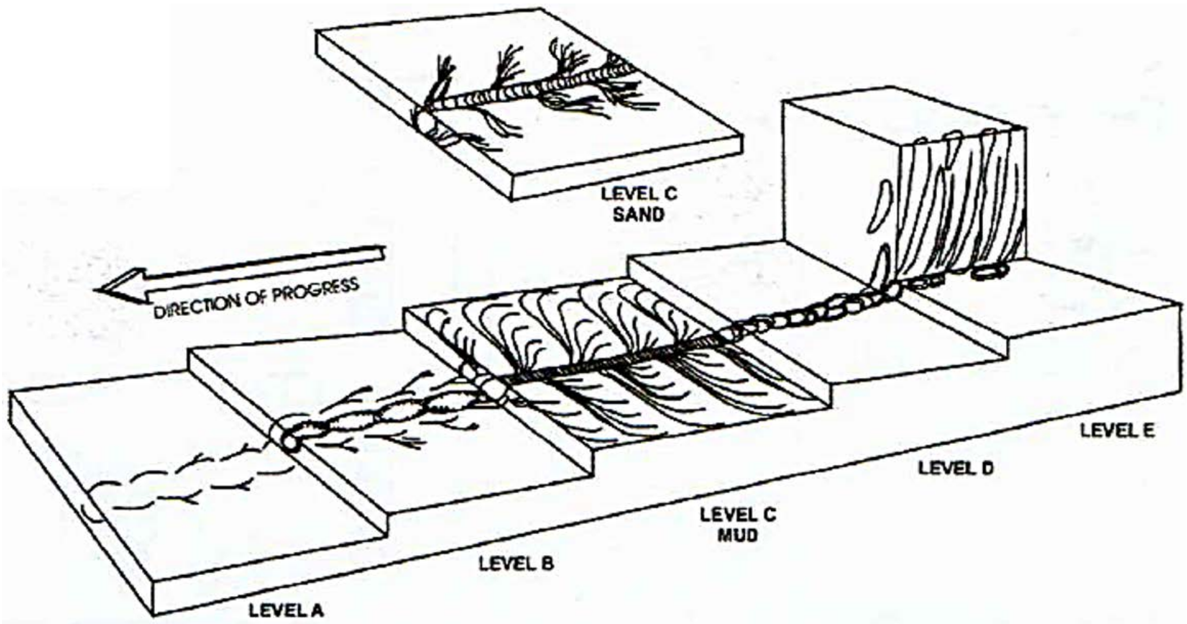

Figure 6.6: Layout of *Hillichnus* in a Block Diagram.

6.6.1. Comments on Robotic Mine Application

There may be some application of such a layout in a shallow sub-horizontal seam type deposit on land. Mining thin seams of evaporite minerals, such as borates or lithium salts in a salar, or lake may be a possibility.

Another application may be in a deep-sea mining robot, to mine or extract from a layer below the seabed. The robot could continue working in all conditions. When the sea is calm, a connection could be made with a support ship, for discharging product and recharging power supplies.

6.7. Dactyloidites

This feeding and dwelling trace fossil has a 3-dimensional layout that has chiefly been investigated and described by Fursich & Bromley (2007). The photograph and sketches in this sub-section are adapted from that paper.

Figure 6.7 shows a typical photograph of a specimen. It consists of clusters termed 'rosettes' of finger-like burrows radiating outwards from a central point. Like many trace fossils, it is difficult to understand the 3D arrangement without dissecting, dismantling or some other destructive technique. In modern times it might be possible to achieve results by a non-destructive method such as CT scanning, but Fursich & Bromley achieved their investigation by cutting and polishing vertical sections.

Figure 6.8 shows sketches of perspective views of (A) rosettes arranged as a stack of layers, which may become approximately vertically cylindrical. (B) shows the internal arrangement of one finger-like burrow. The burrows pivot around a central point which appears to be a shaft-like tube presumably leading to the surface of the sediment to access oxygenated water.

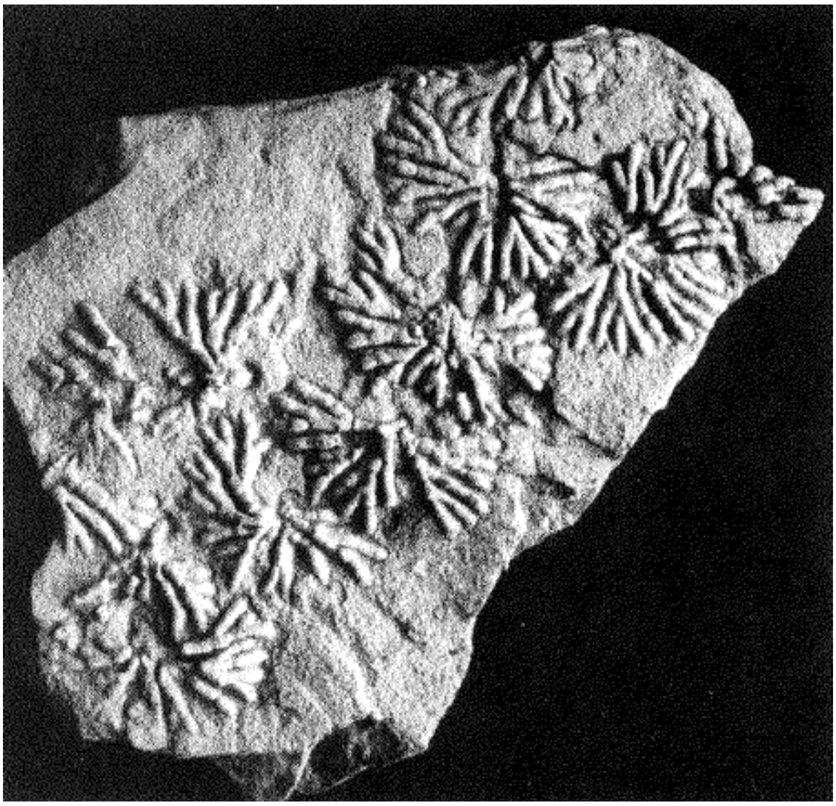

Figure 6.7: Photograph of a *Dactyloidites* trace fossil with several rosettes.

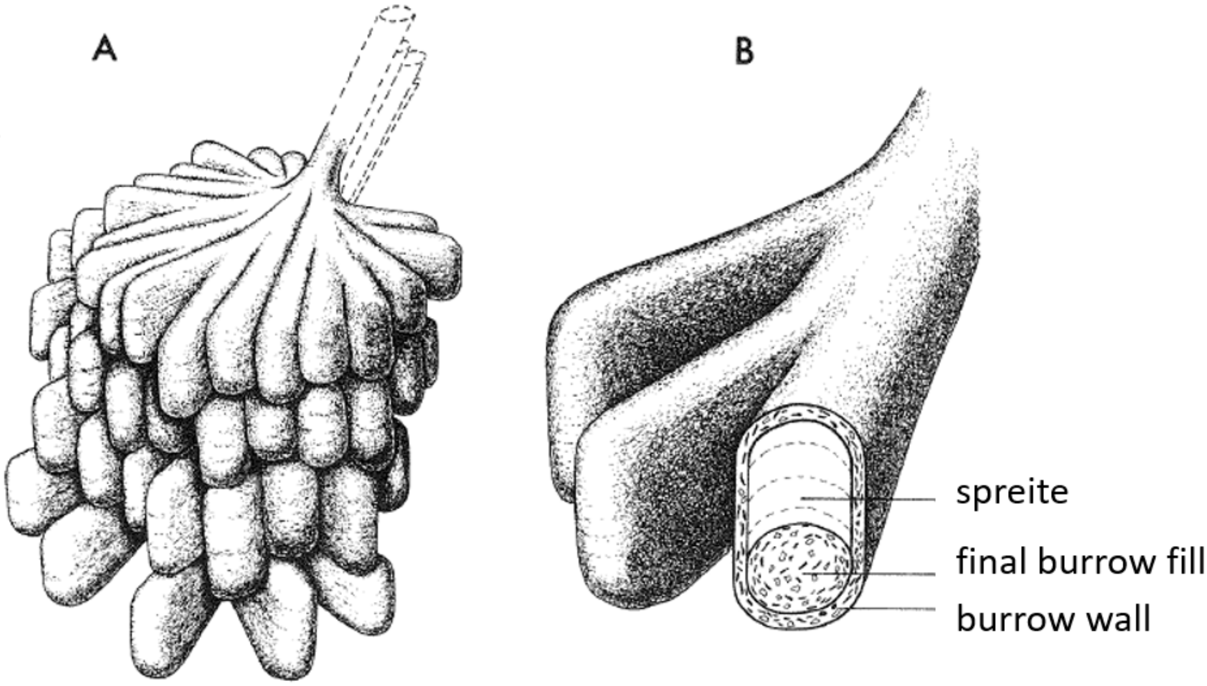

Figure 6.8: Perspective sketch of (A) a rosette of burrows and (B) the internal structure of one burrow.

The rosettes may not necessarily be fully circular, as shown in Figure 6.9 (A). This provides a way that the rosettes, or their part-cylinders in 3D may fit together to achieve very efficient extraction of nutrients in the sediment (Figure 6.9 (B)).

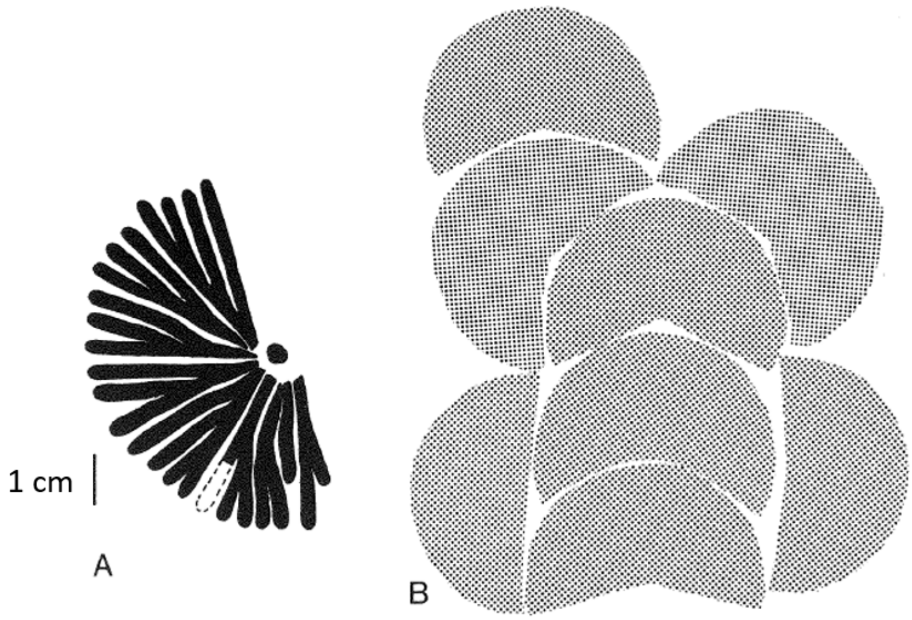

Figure 6.9: Sketch plan view of (A) a rosette and (B) how rosettes may fit together.

6.7.1. Comments on Robotic Mine Application

This is a very promising layout to inspire or adapt to robotic mining, because of the high recovery that it may achieve. In essence, it is a type of cut-and-fill operation that would be suitable for 3D deposits.

Given a deep underground deposit it may be possible to extract it all via just a few shaft head locations. A series of shafts would branch outwards from those locations, each serving a rosette cylinder or part-cylinder.

Each cylinder would be mined in a series of lifts, moving upwards or downwards depending on the geotechnical conditions of the deposit and/or strength of the fill. Each level, or rosette, would be mined and filled before the next one is mined. Possibly, filling would be achieved by a different robot to the one used for mining.

6.8. *Lophoctenium* and *Helminthoidea*

These two are included together because they are both examples of organisms maximising the extraction of nutrients in a thin layer.

Lophoctenium is a spreite feeding trace fossil described by Seilacher (2007), who gives several examples, of which two are reproduced in Figure 6.10. It is included to illustrate how a more complex spreite pattern may loop back on itself, presumably to exploit fully an area rich in nutrients.

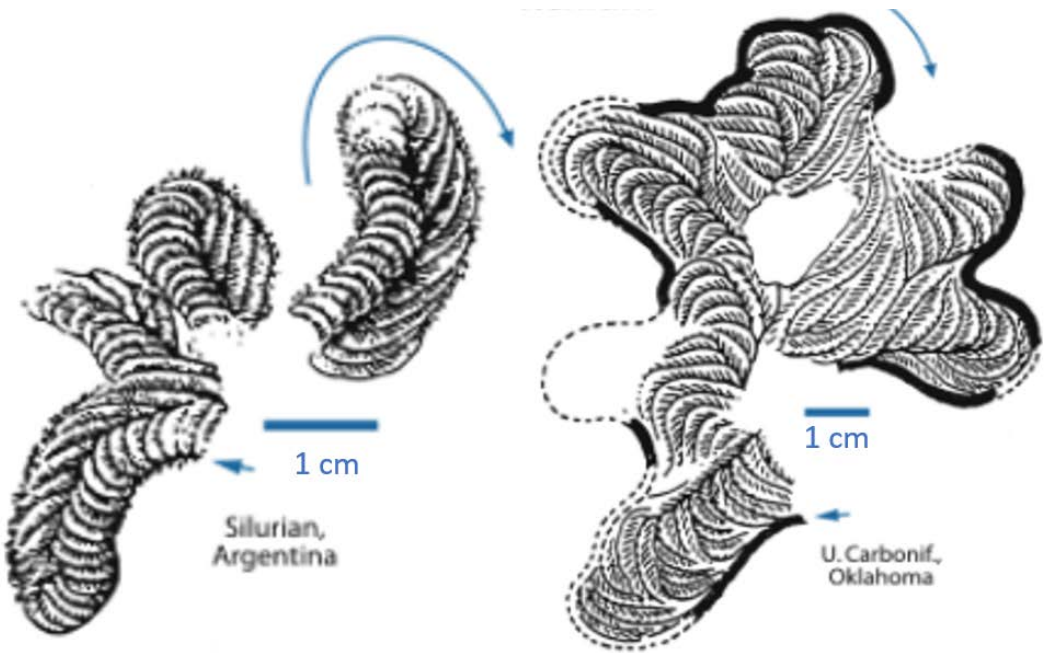

Figure 6.10: Drawings of *Lophoctenium* trace fossils.

Helminthoidea is a feeding trace in the plane of bedding, probably due to types of worm. It consists mainly of burrows that follow the margins of pre-existing adjacent burrows. It is illustrated in Figure 6.11, which was reproduced from 'Trace Fossils' Paleontology Geology 331 website:
http://pages.geo.wvu.edu/~kammer/g231/TraceFossils.pdf .

Figure 6.11: Photograph of a *Helminthoidea* trace fossil.

Sometimes the burrows change direction, generally looping back, seemingly in response to declining nutritional quality of the sediment. But usually, they continue following the previous burrow in a parallel direction, thus ensuring that exploitation of the sediment nutrition is efficient and maximized. The burrows do not branch, cross over or intersect each other. The overall movement is generally concentrically outwards from the starting point, but the area processed is irregular, and presumably reflects the shape of an area of raised nutritional quality.

6.8.1. Comments on Robotic Mine Application

These trace fossils illustrate alternative routes that may be followed by a robot in a thin seam-type deposit, or possibly in layers in a thicker tabular deposit. If the robot is always searching for an upwards ore grade or quality gradient, but avoiding mining the same area twice, then similar patterns may occur or be appropriate, and an economic pathway through the ore will have been achieved.

6.9. Systematic 3D Networks

Figure 6.12 shows a 3D image of ayet unnamed trace fossil that is being studied at the University of Bristol, UK, by CT scanning and other techniques. Partly, the fossil is similar in layout to the *Ophiomorpha*, *Thalassinoides* and Spongeliomorpha 3D network trace fossils described earlier. But in addition, there are relatively straight tunnels that may be described as arterial or service tunnels. Their objective appears to be to enable rapid locomotion from one place to another. The narrower network tunnels are characterized by frequent Y-shaped junctions and thin linings, whereas the service tunnels have few junctions which are generally T-shaped. They appear to have a thick lining that is perhaps an impregnation or bio-mineralisation of the surrounding substrate, and generally, other tunnels do not come close to them.

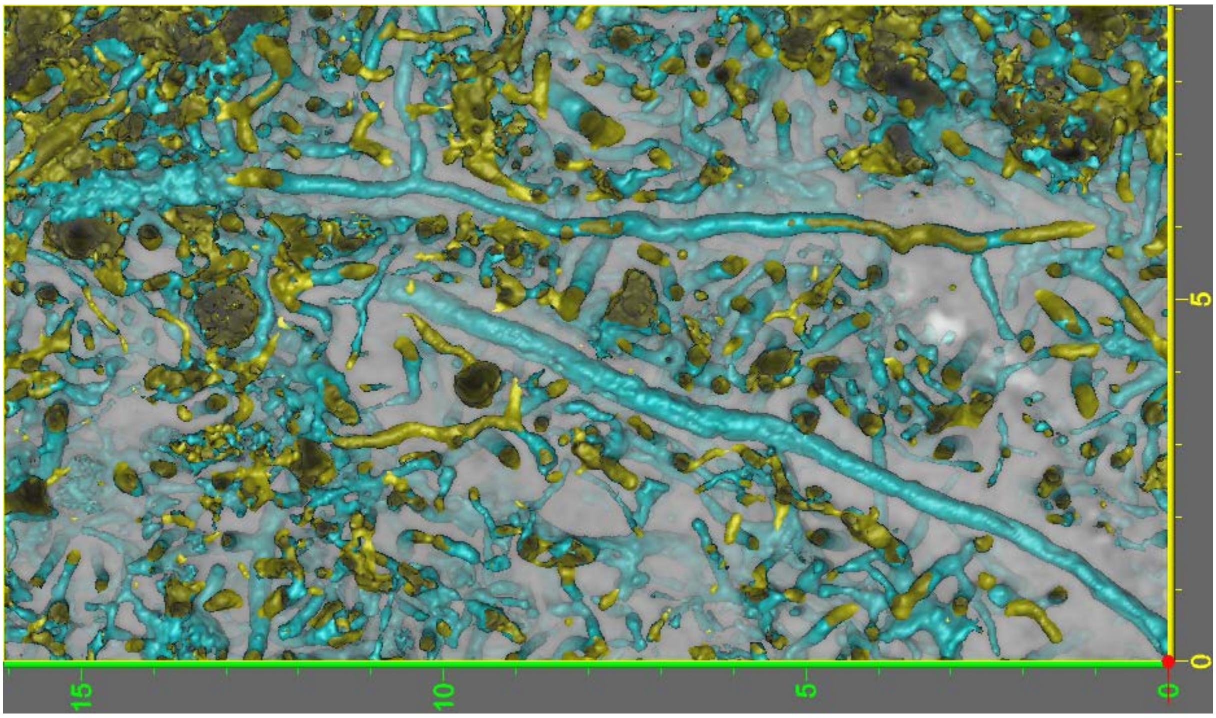

Figure 6.12: 3D Image of an unnamed 3D network trace fossil.

6.9.1. Comments on Robotic Mine Application

This is included to illustrate that in 3D networks, service tunnels may be required to facilitate movement of ore, fill, energy and equipment from one place to another in a robotic mine. These may not be subject to constraints of gradient, ventilation, etc. that characterise mines of the present where there is a need to accommodate vehicles with human operators and drivers.

It is apparent that such a 3D network may not be efficient in terms of extracting most of the deposit. Earlier the idea was introduced of multiple phases to mine material that was not taken in earlier mined and now filled areas.

Alternatively, a 3D network that mines only a small proportion of the deposit may be valuable for the In-Place Leaching extraction method.

6.10. In-Place Leaching (IPL)

This technique is not commonly used but has potential for the future, especially if it can be facilitated by robotic miners. Presently it is mainly used where a mine of a soluble or leachable product such as copper is largely exhausted, but there is still ore remaining that can be leached. An example of its present use is at Ray Mine in Arizona.

IPL is often considered together with In-Situ Leaching (ISL), but this does the former technique a great disservice. In ISL, leaching fluid or lixiviant is pumped underground at injection wells and leachate is recovered at recovery wells. The operation takes place at or above the natural groundwater pressure of the deposit – which can be described as phreatic – and there is a probability that some lixiviant or leachate is lost into the surrounding groundwater. As a result, it can be very polluting.

IPL is more akin to dump or heap leaching, but operated underground, and with only mining a small proportion of the deposit to start with. A network of tunnels or other voids is mined to produce a small proportion of the ore which is hoisted to be heap- or dump-leached. Groundwater is pumped out of the network, and then lixiviant can flow in, but only at a lower pressure than the natural groundwater pressure, and typically little higher than that of ambient air pressure. This environment can be described as vadose. Having been allowed to percolate through mineralized rock, where the fractures may have been enhanced, the fluid, now leachate, is pumped out for processing, possibly via a separate network. By operating at a lower pressure than the surrounding groundwater regime, the groundwater flow is inwards, and lixiviant or leachate is not lost into the surrounding groundwater.

Leachate from a copper leaching operation, whether IPL, dump or heap-leaching, or ISL, generally has copper extracted in a Solvent-Extraction Electro-Winning plant (SXEW) which also produces fresh lixiviant for more leaching.

Much copper occurs in 'Porphyry Copper Deposits' which are often huge rock masses composed of weak, fractured rocks. Conventional mining and processing can produce enormous open pits, waste dumps and exhausted leach dumps or tailings impoundments. Copper only comprises a small proportion of the ore, and the intent of IPL is to leave most of the waste rock in its original place.

To create the IPL network, substantial mining is required, and in weak, fractured rocks, it may be that robotic miners designed for such conditions would be far better than humans.

6.11. Conclusions Regarding Bio-Inspiration for Robotic Mining

Humans are not designed for underground mining and are poorly equipped to achieve this task. To do so, they require substantial amounts of underground space, ventilation and protection, they have poor availability and when things go wrong it can be catastrophic. A modern mine uses a substantial fleet of equipment, but much of the deployment is to create an acceptable environment for humans and is not directly concerned with extracting valuable minerals.

Far simpler organisms have evolved and flourished at times during geological history, that are each adapted to a type of mining. The examples given above are intended as a representative selection of a wide range of types. Generally, each organism could operate in just a narrow range of geological conditions and followed a generic layout with minor adjustment due to local variations. Feeding usually motivates this mining mode of life, to obtain nutrition from organic 'target' matter which is generally a small proportion of the sediment. But often, a co-objective, or the primary objective, is dwelling space that gives concealment and protection from predators and adverse weather or underwater conditions.

An objective of economic (human) mining is to extract ore of highest grade or quality early, and to keep that value as high as remaining ore allows, throughout the mine's life, so that capital costs may be paid off as rapidly as possible and profitability is maximized. This occurs even If the operation is market-constrained, where savings will be made by starting with a small operation that may increase in size as the value per tonne declines. With environmental considerations included, this results in an imperative to maximize orebody recovery, at least of its higher value parts. However, this behaviour is not so often observed in trace fossils. The examples selected above include relatively rare forms such as *Dactyloidites*, *Lophoctenium* and *Helminthoidea* where the layout clearly indicates this behaviour.

Most trace fossil organisms that are of interest had the following capabilities:

- In immediately surrounding substrate, to sense a gradient of nutritional quality and amenability to extraction,
- To steer and move upwards along that gradient,
- To detach and move mineral particles – clasts – from the substrate at the front of the burrow,
- To sense, input and process or otherwise remove target matter that may be around or between the clasts,
- To expel any waste material that was input with the target matter,
- To stack expelled and unwanted clasts at the back of the burrow cavity,
- To withstand the pressure of sediment etc. above and around it,
- To negotiate any unforeseen obstacles in its path.

For a robot miner to emulate a feeding trace fossil layout, these capabilities must be considered and accommodated if not directly replicated. For example, processing might be achieved by piping ore as a slurry to a centralized process plant and the piping waste or alternative material back for use as fill.

Where the primary objective of the organism is dwelling space, then the capabilities are similar, but with more emphasis on removal of target matter. This would be emulated for IPL.

Finally, it must be acknowledged that using bio-inspiration to design layouts for robotic mining could be taken too far. There are huge differences of size and substrate strength between millimetres- or centimetre-scale organisms operating in unconsolidated sediment and metre-scale or larger machines operating in relatively hard-rock environments. Issues such as power supply, vibration, impact and pressure resistance and scaled-down processing routes will surely be primary considerations in mining robots, which seem less of an issue with primitive organisms.

6.12. Practical mining strategies

6.12.1. 2-dimensional low-dip ('seams')

Many conventional mine layouts would be perfectly suitable for robotic mining. For example, versions of room-and-pillar or longwall mining could be suitably adapted (Figures 6.13 and 6.14).

Figure 6.13: *Dactyloidites* feeding pattern as introduced in 6.7 above.

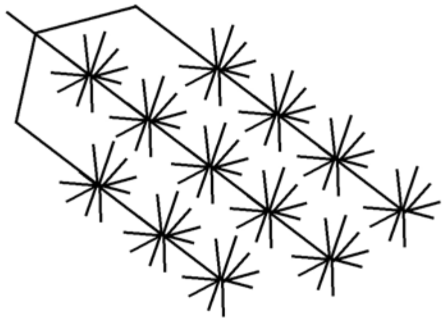

Figure 6.14: A possible room-and-pillar mine layout inspired by *Dactyloidites.*

6.12.2. 2-dimensional high-dip ('veins')

Mining from below requires solid (incompressible) backfill for the robot to stand on when mining the next slice.

6.12.3. Mining the vein in parallel strips, working upwards from below

In effect this is the same as conventional cut-and-fill stoping. Working upwards from below, it uses the principle that "gravity is your friend", with mined material falling to a lower haulage level from whence it is pumped to the surface.

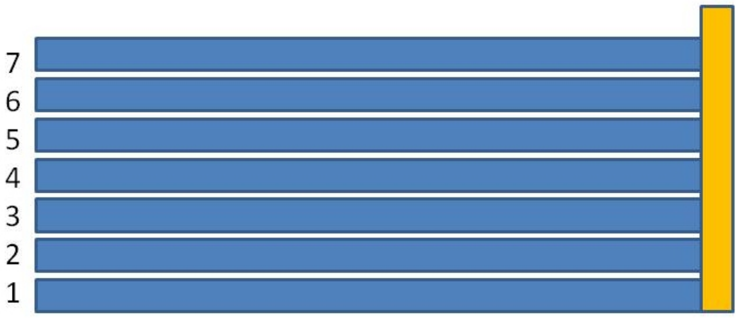

Figure 6.15: Working upwards from below.

6.12.4. Mining the vein in parallel strips, working downwards from above

Mining from above is easier but unless regular pillars are left, no backfilling is possible until the end of mining. Furthermore, it cannot use gravity to assist in extracting ore from the mine.

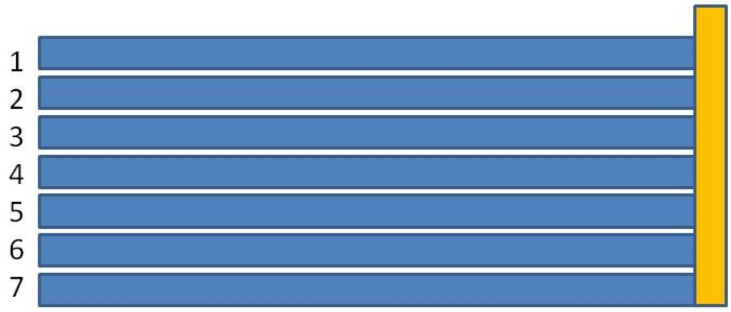

Figure 6.16: Working downwards from above.

6.12.5. Vertical mining strategies

Mining upward (raise boring) is possible if the robot can support itself against the walls. Ore would be dropped down to an access level where it can be collected, crushed, and converted to a slurry for transport to the surface. This implies that the robot miner and the processing unit are physically separate units. This is the method that would be used for "honeycomb" strategy mining of 3D or thick tabular deposits and is a "gravity is your friend" approach.

Mining downward (winze sinking) is possible but requires a method (pumping?) of extracting mined material to be provided. The processing unit would be attached to the miner. Transport of the mined material cannot rely on gravity but must be done mechanically at every stage. This adds complexity and energy costs to the processing and transport. For this reason, such a mining method is probably impracticable.

6.12.6. Zigzag mining of panels

A Zigzag panel-by-panel strategy is possible. The biological analogue is described by Sims et al. (2014) and shown in Figure 6.17 and Figure 6.18. The first figure shows a generalized self-avoiding walk. This is a feasible option but does not necessarily lead to full extraction of the vein. The Brownian walk model shows a version which is more efficient.

This is a simple way to extract all of the material in a flat panel. The mining layout that corresponds to this strategy is shown in Figure 6.19. Mining would start at an upper corner of the panel and would zigzag down to the opposite lower corner. Provided that no walls are left between successive passes, the maximum length for tether and hose will be no great than the diagonal dimension of the panel.

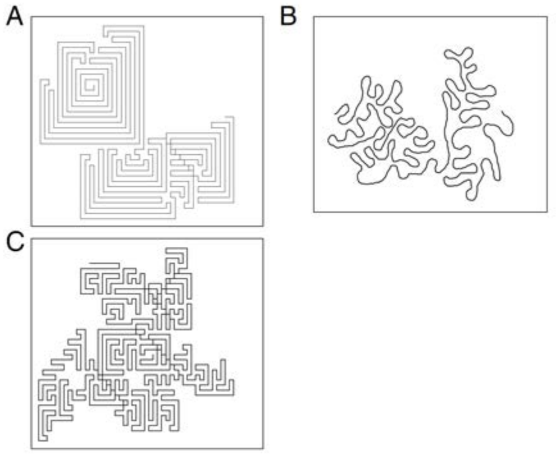

Figure 6.17: Simulated self-avoiding random-walk trails. After Sims et al., 2014.

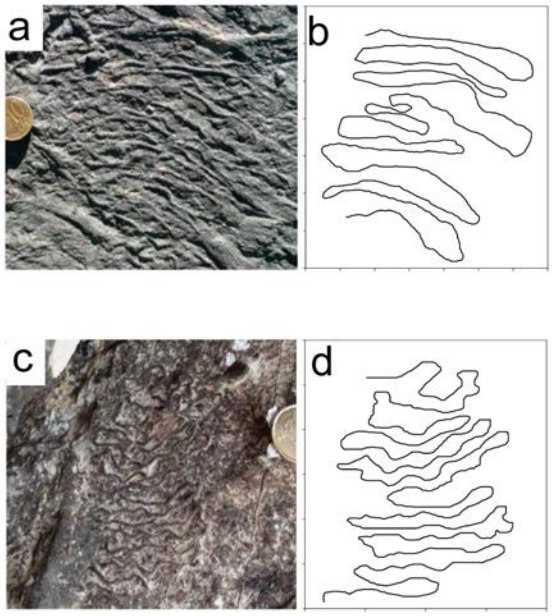

Figure 6.18: Brownian walks in trails of Eocene worm-like animals (a and b) *Helminthorhaphe flexuosa* and (c and d) *Cosmorhaphe tremens*. After Sims et al, 2014.

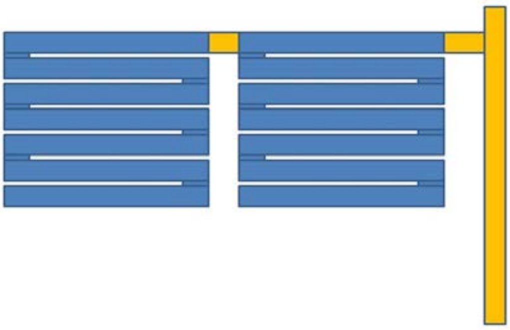

Figure 6.19: Zigzag mining panels inspired by brownian walk strategies.

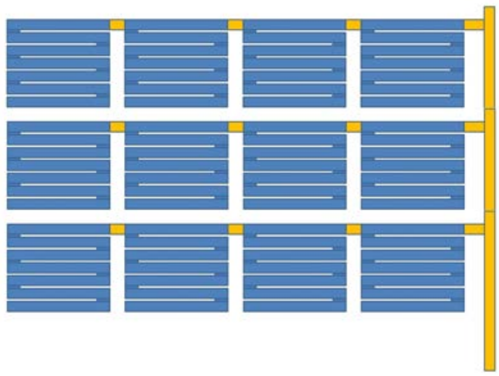

Figure 6.20: Multiple zigzag mined panels to extract vein material. Gaps may be left between panels as support pillars as well as to allow slurry or solid backfill.

This strategy can be used to mine relatively small panels but replicated over the whole extent of the vein, both laterally and vertically, as shown in Figure 6.20, with gaps between the panels to provide support pillars.

6.12.7. 3-dimensional

The additional dimension gives a far greater range of possibilities for different mining strategies. Apart from the simple idea of stacking multiple two-dimensional layouts to extract a three-dimension volume, there are inherently different 3D options. For example, a helical approach is possible (Figure 6.21), or a wide range of different branching burrows (Figure 6.22).

Figure 6.21: Helical feeding pattern trace fossil.

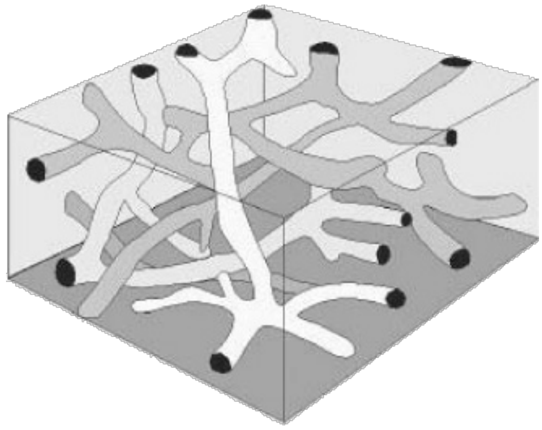

Figure 6.22: *Thalassinoides* burrows.

6.13. Honeycomb- inspired mining strategies

The "Honeycomb" approach to mine design, developed by IPKON Institute and MISYS, Moscow, Russia, combines bio-inspiration with the operational efficiency of conventional mine layouts, and reduced losses in non-removable pillars. This concept is appropriate for 3-dimensional and thick tabular deposits.

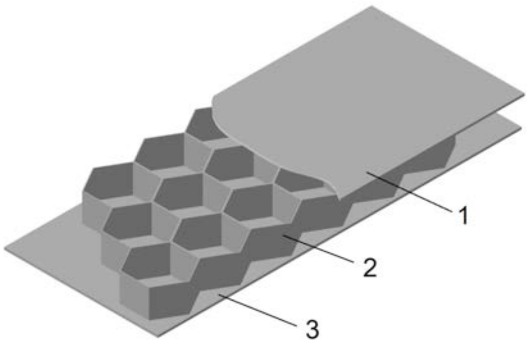

Figure 6.23: A hexagonal honeycomb pattern of mined cells between footwall and hanging wall.

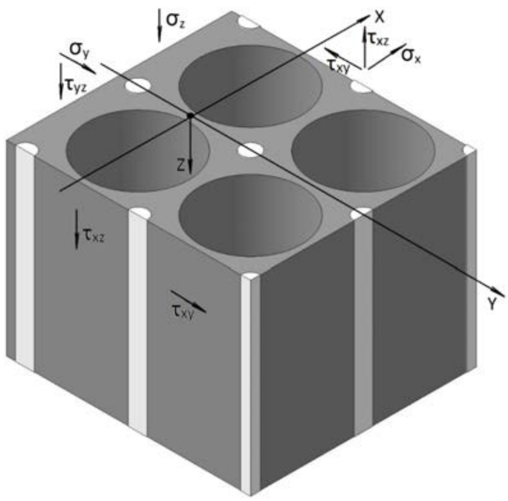

Figure 6.24: cylindrical raises leaving pillar supports.

The appropriate mine layouts are dependent on the ore deposit geometry – the size, shape, and orientation. As listed above in 6.1 - 6.10, there are a very wide range of biological models ('ichnofossils') that can be used as an inspiration[2].

[2] https://www.geol.umd.edu/~jmerck/geol342/lectures/03.html

7. BACKFILL

7.1. General considerations for the Robominers eco-system

One of the drivers for the Robominers technology is minimisation of environmental damage such as caused by heavy-metal contaminated elutes from above-ground mining and processing waste heaps, subsidence of the ground surface or induced seismicity Especially in an urbanised region, it is unacceptable or even impossible to build large surface heaps of waste material or allow subsidence. Therefore, it is imperative to return as much mining and/or processing waste as possible to the mine workings, as backfill. In addition to the environmental benefits of placing mining and processing wastes in mined opening, a further possibility exists to use the backfill as mine support. By conditioning wastes to a qualified, geotechnically supporting, backfill product which can be placed in the mined opening in a controlled matter, the use of backfill can increase the stability of mine openings, and with it the safety performance, as well as potentially increase the extraction ratio of the mine by for instance allowing a secondary pillar mining phase supported by backfill.

Mine designs for the Robominers eco-system need therefore to be selected with backfill placement in mind as a high priority. It can most likely best be achieved by having relatively short mined production drives that can be backfilled with waste after a robot miner has backed out of the drive, so that equipment is not trapped. If the eco-system and mining layout design also allows for backfill to act as support pillars while material between backfilled drives is mined, this also allows maximum extraction of the valuable mineral. Figure 7.1 shows an example of such a strategy, in a elongated room-and-pillar mine layout for mining a horizontal seam.

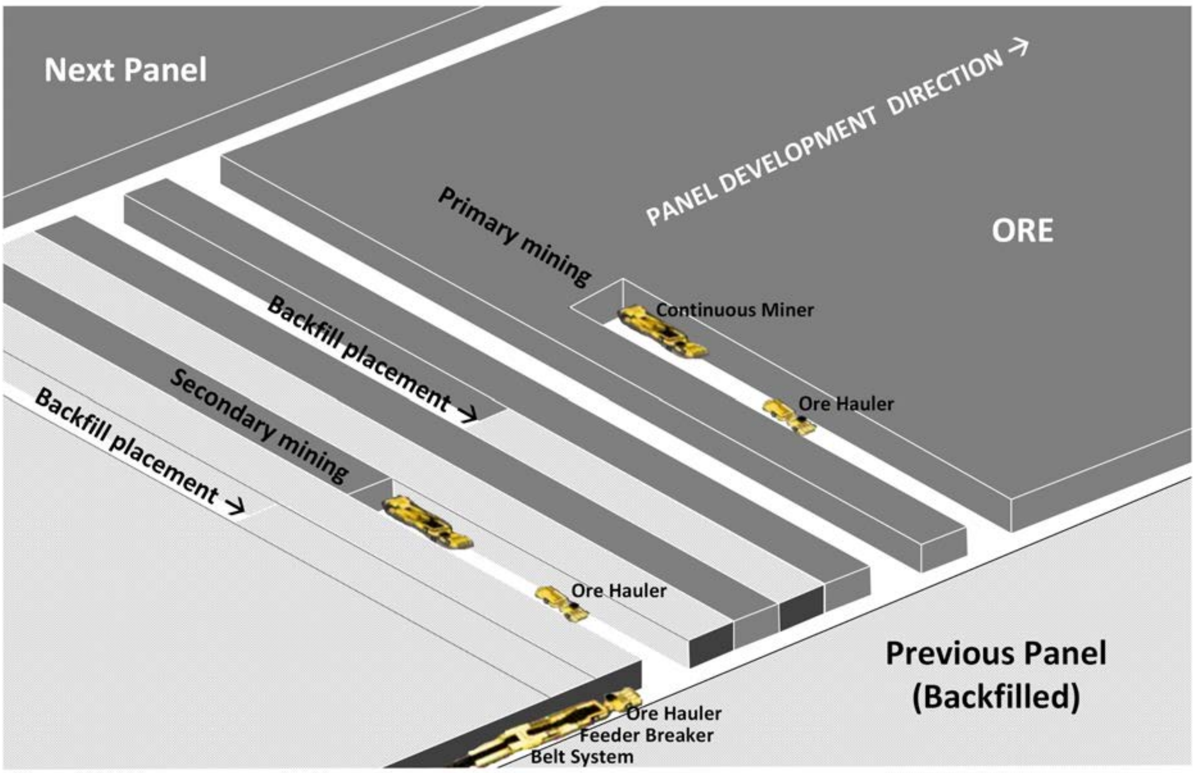

Figure 7.1: Elongated room-and-pillarlayout with backfill and secondary mining of pillars (K-UTEC AG Salt Technologies, Sondershausen, Germany).

Backfilling of mine openings may be carried out immediately after mining and first-stage processing, within the confined of the robot miner, to separate waste from an ore concentrate, as shown in Figure 7.2. This avoids the need to transport much of this material out of the mine, but in most mine layouts would result in loss of expensive umbilical cables and water and slurry pipes. Furthermore, such a layout would also require the robot to operate autonomously to find a return path (and attach a new umbilical) for the next production run. This could be alleviated by letting the robot miner excavate mine openings between two parallel panel roadways. In this case, the robot miner, when finished with a room, is rotated 180°, reconnected to an umbilical and send back for the next production run. Such a layout would require two sets of supply systems allowing the robot to be connected, via the umbilical, from either of the two parallel panel roadways.

A much simpler approach would allow the use of a small temporary waste heap outside the mine (which could also contain waste material from a secondary concentration plant at the surface). This material would then be returned to the mine to be used in a planned backfill operation by a separate set of robots. This can be further illustrated by referring to Figure 7.1 and imagining the excavation crew (continuous miner, shuttle cars, etc.) is replaced by a robot miner and the backfilling crew is replaced by a backfill robot being supplied from a separate (hydraulic) backfill transport infrastructure.

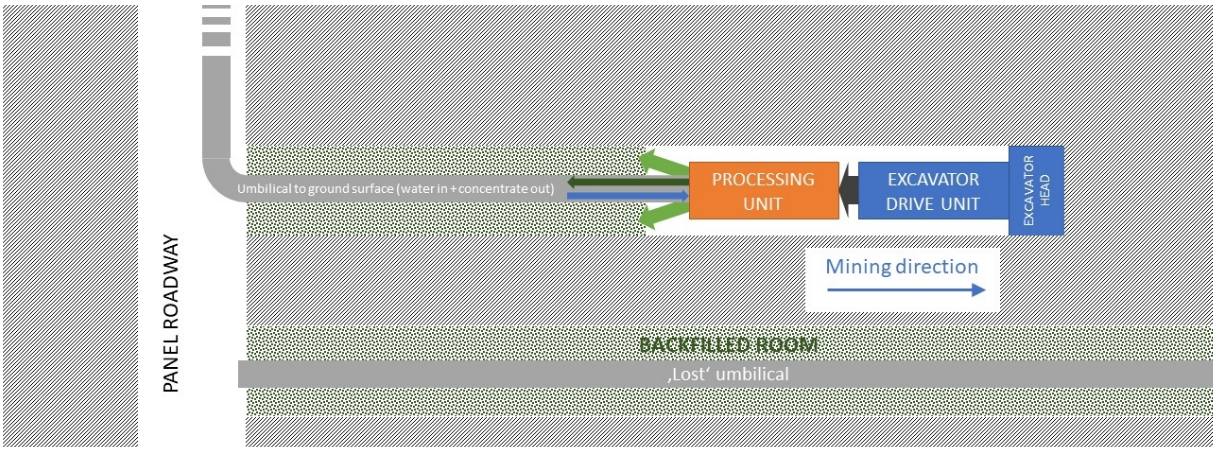

Figure 7.2: Elongated room-and-pillar layout with immediate backfill and the use of lost umbilical segments (cable and slurry hose).

When considering backfilling of mined openings with mining and/or processing wastes, it should be noted that the backfill does not necessarily replace the in-situ rock in terms of geotechnical performance. Stress does not flow through a backfill body in the same manner as for the original in-situ rock. When a stress field encounters another medium, such as backfill, it flows around it. An illustrative analogy would be light flowing through two lenses with different refractive indices. In this case, the light refracts. This is similar to stress flowing through different materials, be it different types of rock or backfill. This does however not mean that backfill cannot replace the supporting function of the host rock (for instance in pillars normally left behind in a conventional, non-backfill-based, mining strategy), just that the composition of the backfill needs to be considered in detail and the use of additives may be necessary.

For instance, where additional strength and/or water binding capacity may be required, addition of Portland cement or other binder agents to a waste slurry can improve the compressive strength of the placed backfill after an appropriate curing period. Such geotechnically supporting backfill may be emplaced either in the form of a slurry, using the same slurry-transport methods as for transfer of ore slurries to the surface processing plant, or in much dryer form using conventional trucks, conveyors or rail carts. In either case, if sufficient water is either expelled from the placed backfill or bound by binder agents, there may well be sufficient strength to support the mine openings. Assuming a dewatered (drained) or cured backfill body has enough strength to principally counteract the stresses in the mine's host rock (pillars), the actual support delivered by the backfill will first be initiated by convergence of the mined opening. It is normally not possible, at least in (near) horizontal mining layouts, to place backfill in such a manner that significant pre-loading of the hanging wall (roof) of the mine can be achieved without allowing some convergence of the roof. For steep and near-vertical mining layouts this is different as the density of the backfill slurry will, proportional to the height of the backfill column, exert a counterforce to both the foot- and hanging-walls of the mined openings, thus stabilising the mine opening.

The methods presented in the following section will be further detailed in Deliverable 5.4 of the ROBOMINERS project. Potential application examples for the Robominers eco-system as well as concepts for their integration into the Robominers eco-system will be provided in that deliverable. The following is therefore only a brief overview of the current practice with a limited assessment on applicability to the project.

7.2. Placing Backfill in mine openings

The are principally four methods used in the mining industry today to place backfill in mining opening such as stopes, room-and-pillar mines or longwall mines (Masniyom, 2009). These are:

1. Mechanical backfill;
2. Pneumatic backfill;
3. Hydraulic backfill;
4. (Pumped) paste backfill;

Extensive experience with the first three of these methods has been gained in rather small geographic area in the world, namely Central Germany. Many of the former state-owned potash mines of the German Democratic Republic caused significant surface subsidence and seismic events in the mid 1990's. By backfilling the mine openings of the former potash mines with initially, salt mined in other (more stable) areas of the mine, and later industrial wastes such as fly-ash, these mines today no longer cause significant subsidence and/or seismic events (Fliss, et al., 2011). The following examples of the listed types of backfill are based on the experiences in Central Germany and are mostly directly applicable to (near) horizontal mining layouts. The potential applicability to steep/near-vertical layouts is less direct but the equipment and other technical components used are mostly interchangeable between these layouts. Paste backfill, gravity driven or pumped, is widely used in hardrock mining in mining layouts using backfill (e.g. cut and fill stoping, paragraph 4.2) (Belem & Benzaazoua, 2007) or where roof support is crucial for mine stability such as in very deep mines. Paste backfill is a form of hydraulic backfill in which the fluid content of the backfill slurry is minimised whilst maintaining suitable rheologic properties to allow for pipeline transport.

7.2.1. Mechanical backfill

The mechanical backfill comprises all backfill placement methods involving mechanical transport and manipulation equipment, such as dump truck, wheel loaders, conveyor belts and slinger machines. Both batch-wise and continuous backfill placement is possible. Figure 7.3 presents two mechanical backfill methods used in the potash mines in central Germany, namely so-called big-bag backfill and slinger backfill. Compaction of the backfill can be left to self-weight consolidation or actively promoted during (or shortly after) placement by vibrating roller or alike. The bucket of a wheel loader is also often used to push material into the void and compact the material to some extent.

Figure 7.3: Mechanical backfill methods: Big-Bag backfill and slinger backfill method in practice in the K+S mines in Central German (Pictures REKS GmbH & Co. KG, formerly K+S Entsorgung GmbH, Kassel, Germany).

Recently, K-UTEC AG Salt Technologies developed a special slinger backfill method, where the kinetic energy of relatively dry backfill material (i.e. with a moisture content of 5-15 %) being projected by a slinger machine is actively used to compact the backfill during placement. Whereas slinger machines normally (compare Figure 7.3-right picture) use this kinetic energy to bridge a certain distance or height, the so-called High Yield Kinetic Energy (HYKE) backfill uses the impact of the material on the mine walls or previously placed backfill to significantly increase the backfill density through compaction. For the Robominers eco-system, this HYKE backfill system could be used to place backfill which is required to have a high initial density and strength without the need for a high binder content. The compaction upon impact of backfill material with a carefully managed moisture level (allowing optimal compaction), combined with the addition of limited amounts of binder agents, can potentially reach much higher densities and strengths as encountered in the current mechanical mine backfilling practice. A two-year research and development project, funded by the Thuringia Development Bank, has commenced in March 2021 to further develop this concept and prepare a market introduction. Updates on this development, where relevant, will be included in further deliverables in the ROBOMINERS project.

7.2.2. Pneumatic backfill

The pneumatic backfill method uses compressed air (or another gas) to transport backfill material (pneumatic conveying) through pipelines and/or pneumatically project the material from a nozzle. Pneumatic transport of backfill material is only possible if the moisture content of the material is sufficiently low. Apart from the moisture content of the backfill material itself, also the moisture content of the carrier gas (compressed air) must be considered in conjunction with pressure changes and consequent dew-point changes in a pipeline system under pressure or vacuum as a slight change in the moisture content for relatively fine-grained material can lead to the material demonstrating a paste-like behaviour and consequently sticking to the pipeline walls with pressure loss and or clogging as a result (Hilbert, 2016). The applicability of pneumatic conveying for the Robominers eco-system is considered very limited if not non-existing due to the targeted flooded mines and the consequent wet transport and processing methods. Although it is possible to dewater and dry mining and processing wastes to be used as backfill, the cost for such processes would most likely exceed the benefit for what is essentially a waste management operation, i.e. only a cost factor in the overall economic assessment of a project. Pneumatic placement of backfill material can either be directly from the pneumatic conveyor pipeline through a nozzle or via a separate pneumatic material placement machine, for instance such as used in dry shotcrete applications (Lindlar, Jahn, & Schlumpf, 2020). In the latter case, the transport of backfill material to the pneumatic placement machine does not necessarily have to be pneumatic as the pneumatic placement machine can be fed from a silo and/or directly from a conveyor belt. The applicability of pneumatic placement methods for the Robominers eco-system is high, especially when implemented for mining wastes that are separated from the ore concentrate before being channelled to the ground surface. Such direct backfilling of mining wastes using compressed air can also benefit from the HYKE principle described in the previous paragraph.

7.2.3. Hydraulic backfill and (pumped) paste backfill

The definitions of hydraulic backfill and (pumped) paste backfill differ between regions and industries, especially when considering translations (compare (Masniyom, 2009), (Schlotzhauer, 2005), (Michalzik, 2000)). For this report, all backfill methods involving some type of slurry transported through pipelines are collated under the term hydraulic backfill, i.e., including (pumped) paste backfill. By this definition, hydraulic backfill methods include:

1. Flushing (draining) backfill
2. Viscous backfill
3. (Pumped) paste backfill

The first of these methods has been widely applied in the former potash mines of Central Germany, both in the active mining period using fertiliser processing wastes and currently using industrial wastes (such as fly-ash) to stabilise these mines (Fulda, Gruchot, & Michalzik, 1966), (Fliss, et al., 2011), (Marx, Lack , & Krauke, 2005). A flushing, or draining, backfill is transported as a slurry and placed hydraulically directly from the transport pipeline. The placed backfill is allowed to drain, using dams with filter elements at the lower side of a mining panel, thus promoting consolidation of the backfill material. The drained carrier liquid is collected and pumped back to the backfill plant at the ground surface to be used in further backfill slurry production. The layout of the mine, in particular the geodetic height variations, must be suitable for the flushing (drained) backfill method to avoid the need for extensive dams and flow barriers. If however a mine layout is designed with a flushing backfill requirement as a design criterion, the flushing backfill method can be a very effective and reliable method. This is due to the much higher fluid content of the slurry which makes pumping easier and lowers the risk of scaling and clogging of pipelines. The consistency of a flushing backfill slurry can be described as having a low viscosity, observed as nearly free-flowing as water. On entering the mine opening, the solid material will start to settle, and coarser particles will collect around the injection point whereas finer particles may be flushed further into the opening. Further slope instabilities of accumulated heaps of material and turbidite-like behaviour (in a flooded environment) of backfill material will further transport the backfill material downstream into the mine openings.

The second method is currently being used in the mine backfill industry in Central Germany for instance in the Teuschenthal Mine though the use of so-called Dickstoffversatz (Viscous backfill; (GTS GRUBE TEUTSCHENTHAL SICHERUNGS GMBH & CO. KG, 2021). A viscous backfill differs from a flushing backfill by the absence of a drainage requirement. All, or most, of the carrier liquid remains in the placed backfill after its placement and consolidation. The way this is achieved is multi-fold and hard to quantify exactly, however the two main processes involved are a slurry with a much lower fluid content, compared to flushing backfill, and a considerable water binding capacity of the backfill material itself. The water binding capacity in backfill based on mining and processing wastes usually requires binder agents (e.g. Portland cement) to be added (Belem & Benzaazoua, 2007), however the industrial wastes used in Central Germany for mine stabilisation contain many minerals capable of binding (many) water molecules in their crystalline matrix, such as ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$) (Marx, Lack , & Krauke, 2005) thereby avoiding the need for additional binder agents. The clear advantage of a viscous backfill is the absence of a drainage infrastructure which greatly simplifies the layout of a mine aimed to be backfilled. Also, the demand on dams and flow barriers is much lower as complete mining panels (when some geodetic height difference is available) could be isolated by a single dam and backfilled from a single injection point. The consistency of a viscous backfill slurry is very different from the water-like behaviour of a flushing backfill slurry. A viscous backfill slurry can be described as having a fairly high viscosity, comparable with a thick syrup or mudflow. On entering the mine opening, a viscous backfill will (ideally) flow out as a homogenous mass in a nearly self-levelling fashion. Some build-up of material around the injection point can be expected, but the design of the backfill composition should mostly avoid this.

The third method, (pumped) paste backfill only slightly differs from viscous backfill, mainly in terms of fluid content of the slurry and the number of additives used in the production. As such, a clear distinction cannot be made. Nonetheless, a paste backfill is again a slurry comprising backfill material in a carrier liquid. As the word “paste” clearly indicates, the consistency of a paste backfill slurry is usually highly viscous and can have a toothpaste-like behaviour on outflow. As such, it is less suitable for use in (near) horizontal mining layouts but highly suitable for steep and near vertical layouts where gravity will eventually allow the backfill material to self-level over time in a stope, regardless of its viscosity.

8. PATHOLOGICAL SITUATIONS AND BOTTLENECKS

Although there is a general intention to develop bio-inspired mining solutions, including the use of biological feeding patterns as a guide to development of mineral extraction strategies, there are constraints on a mining operation which are different from those on biological organisms. In particular, biological organisms ingest food and excrete waste which does not need to be delivered anywhere in particular. In contrast, a miner robot will ingest minerals and needs to deliver them to surface for onward processing and distribution. Thus – whether tethered or autonomous – a miner robot must have a continuous link with the surface. This rules out any scheme that involves back-fill immediately behind the miner, unless a lost umbilical system is applied.

General constraints on mine layouts for ROBOMINERS

- **Geology**: geometry and physical properties of the mineral deposit and the surrounding rock
- **Short working sections**. Avoiding the need for frequent replacement of shorter cables and slurry hoses by longer.
- **Topology**: avoid complex routing – dendritic patterns, no circular routes for individual miner robots which would require detachment and withdrawal of cables and hoses. All trajectories must be 'there-and-back' by the same route.
- **Space problem**: relative volumes of mineral concentrate and waste rock to be separated underground
- **Robot tether** requirements: electrical connections
- **Slurry transport** requirements: fluid (slurry, hydraulic, etc) connections
- **Minimal support requirements**: emplacement of rock-bolting or other supports which sterilise ground. Use of natural pillars where possible, removable by subsequent mining.
- **Pillar dimensions** are controlled by mechanical strength of rocks
- **No backfill blockage** of return routing can be allowed.
- **Turning radius** limits on branching angles
- **Maximisation** of mineral extraction
- **Minimisation** of failure risk

These are absolute constraints.

8.1. The scale problem

The scale of legged burrowing insects or worms, used as bio-inspiration for ROBOMINERS, is normally a maximum of a few centimetres, though of course their burrows can be much longer. The ROBOMINERS scale (of the mining robot itself) is around a metre. In other words, the robot is 10 to 50 times larger in linear scale or 1000 to 125,000 times larger in volume. Capabilities and strength do not scale linearly.

Burrowing insects, earthworms, and moles generally operate in soft substrates - sediments, rotten wood, etc. Marine worms can operate in harder substrates, including fresh wood (ships' hulls) or even rock (generally limestone, which they can dissolve).

The scale factor must be taken into account in designing the mining robot but it is also significant in designing the mining operation as a whole. While millimetre to centimetre sized tube networks may stay open indefinitely even in soft media such as topsoil or alluvial mud, the same is certainly not true of larger openings on the metre scale. However, the strength of the rock media in a mining operation is usually much greater than that of topsoil or alluvium. Geomechanical considerations are discussed in more detail in Deliverable D5.2.

8.2. The space problem

When rock is fragmented, the volume increases, typically by a factor of 1.2 to 1.5. In conventional surface and underground mines all of the material is removed sufficiently far from the working face not to impede the mining operation.

In a robotic mine we would hope to minimise material movement. However, a similar consideration must apply. Although backfill is desirable, the tunnel behind a mining robot cannot be backfilled in a way that prevents operation of the robot miner or impedes the transfer of the required mineral materials to the surface, or that prevents relocation of the robot miner to another working face when required.

Case 1 - all or most of the mined material is required e.g., salt or gypsum.
There is no problem here, as all mined material is required to be transferred to the surface. There is little or no waste material to be considered if the robot miner is working entirely within the mineral seam or orebody. There will be no backfill, and mined tunnels will remain open. There could be a long-term rock stability issue, or the mined spaces could be allowed to collapse, or they could be backfilled by waste materials from elsewhere.

Case 2 - the desired mineral is only a small fraction of mined material.
If the required mineral is to be separated within or close to the robot miner, there will be two streams of material to be handled: the mineral or concentrate and the waste. The mineral or concentrate stream will always be taken to surface for sale or further processing as required. At the start of mining the waste must also be taken to surface to avoid clogging necessary transport routes within the mine. Subsequently, during the mining operations, the need for transferring waste material to surface should be minimised by direct transfer to back-fill locations. However, because the volume of waste is likely to exceed the backfill space available, there will be a continuing need to transfer some waste material to surface.

There will be constraints on mine geometry and mining operations when it is required to start backfilling mined-out spaces, in order to avoid blocking transport routes

a) from robot miner to surface
b) from surface to backfill location
c) from robot miner to backfill location.

It is not only material transport routes that must not be blocked, but also exit routes for robots and ancillary equipment, and supply routes (electricity, compressed air, water, etc) to the robot miner and the mineral separation robot.

These considerations eliminate some bio-inspired options from further consideration. For example, the "earthworm" model in which a tunnel is backfilled immediately behind the robot miner, is clearly not feasible. Also, a simple spiral layout is unsuitable, because there is no backfill location which is not on the (ever-lengthening) transport route from robot miner to surface. Models which potentially remain feasible include some conventional mine layouts such as parallel drives with long-wall extraction crosscuts between them, cut-and-fill stopes, and room-and-pillar grid layouts with or without extraction of pillars.

Less conventional (including bio-inspired) options which are feasible include non-rectilinear fractal dendritic branching networks (such as in Figure 8.1) with many short branches, or local multiple spiral layouts.

Some such geometries are dependent upon the mechanical strength of the backfill in order to achieve 100% extraction without a requirement for leaving support pillars. If that cannot be guaranteed, there will be some reduction in the resource that can be mined because of the requirement to leave pillars.
Dendritic networks are potentially of great interest because short branches allow flexibility for real-time ore following without any requirement for a pre-determined mine layout geometry, and will also tend to reduce the total transport distances, especially if shortcut tunnels can be introduced at later stages of mining if the deposit itself has a complex shape. Care would need to be taken in scheduling material transfer, as the same 'main' tunnels will be used for extraction of mined material and for the introduction of backfill material.

Material transfer itself could be either in solid form or as slurry, pumped or in separate tanker transports; in each case short transport routes would minimise the energy requirement.
Backfill could be introduced into mined sections of the fractal tree without necessarily ensuring that there is no further mineral to be extracted beyond that section. The nature of the branching method means that the mineral could be extracted subsequently from a different direction. However, the use of pilot drilling ahead of the mining operation could minimise the risk of losses or inefficiency in mineral extraction.

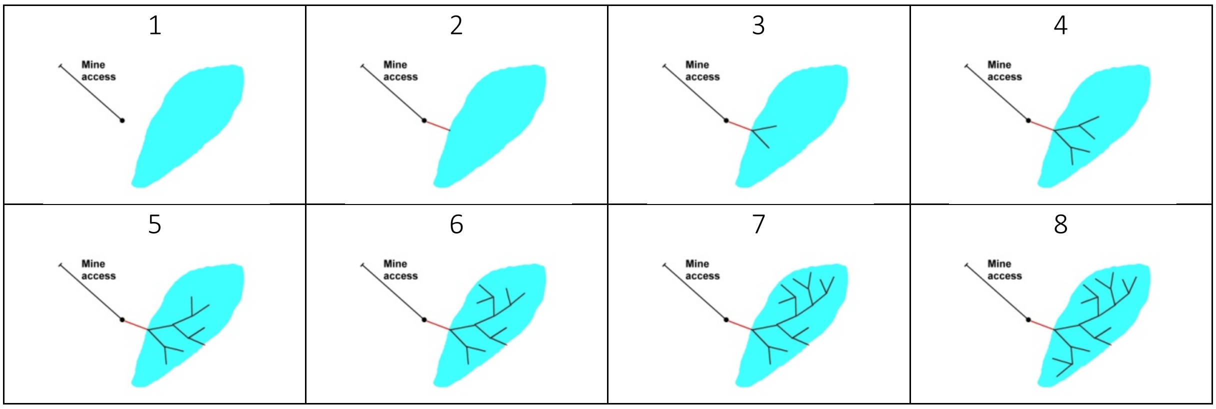

Figure 8.1: Non-rectilinear dendritic fractal mine layout for automated ore-following robot miners.

8.3. Robot Tether Requirements

The type and method of attachment of tethers will be a significant controlling factor in mine layout design. A few options could be considered, and the list below is certainly incomplete. In each case it is assumed that the tether includes all necessary communication channels.

a) simple wire or fibre tether from surface, attached to the mining robot and played out from a reel on the surface as the robot advances

b) a wire or fibre tether from surface with fixed length to a communication hub in the mine. Extension tethers to further hubs added as required to extend the range as mining progresses. Communication hub either a Wi-Fi hotspot or a cable connector (e.g., Ethernet or USB)

In case (a), there must be some way to retract the tether when the mining robot reverses out of a mining drive, to avoid any risk of tangling or breaking the link.
In case (b), it will be necessary to have an ancillary robot whose function is to attach new communication hubs as needed. Also, mining drives will need to be short, to avoid damage to their link with the hub, or (particularly if underwater) to avoid loss of Wi-Fi communication.
If there are multiple mining robots, option (a) becomes increasingly impractical even if it can be automated, because of the risks of confusion and tangling of multiple cables. Option (b) allows multiple robots to use the same set of communication hubs, with just a single cable or fibre to the surface.

8.4. Slurry transport requirements

This constraint shares some similarities with tethers, but there are also significant differences. Slurries (mineral or waste) generally have to be transported to the surface. In practice this means to the shaft, from where they will be pumped to surface. Transport to the shaft can be done in two ways:

a) in continuous mode, by slurry pipe from the back of the mining/processing robot system
b) in batch mode, by transport robot 'tanker' which is filled by the mining/processing robot system and then carries the slurry to the shaft, where it is pumped out either directly to the surface or into a holding tank or cistern

There is a problem with using slurry pipes, that these need to be not only flexible but extensible, as the mining robot advances - and allowing it to reverse out of the mining drive. Flexible and extensible hoses do exist - such as the concertina hoses commonly used on vacuum cleaners - but their extendibility is strictly limited, and would place a major constraint on the length of mining drives. A form of telescopic pipeline connection between a dispatch point and the robot miner could be imaged, however the extension length will be limited and the direction not very flexible. Using transport robot tankers, especially if these can be made semi- or fully autonomous to carry out their simple functions, reduces mine design constraints.

8.5. Support requirements

Geomechanical properties of the rock being mined may dictate a need for additional support to maintain a safe opening for the robot miner to operate in. A wide variety of options are available to the mining engineer in a conventional mine, but not all of these would necessarily be feasible in a purely robotic system. for example, rock-bolting and netting are very commonly used, but their use often requires a great deal of professional judgement and manual intervention. This question is discussed further in D5.2.

8.6. Pillar dimensions

The minimum feasible size of pillars that are left to support the roof or hanging wall is something that is a conventional constraint for mine design, and well understood by mining engineers. It is dependent on rock strength and local geological/geomechanical properties. It is discussed further in D5.2. In a fully robotic mine, instrumentation will be required in the mining robot or another robot in the ecosystem to check ground conditions, and either take remedial action (such as supports - see 8.5 above) or supply information to a surface control room to allow modification of the mine design.

8.7. Backfill blocking access

Figure 7.2 shows one aspect of this pathological situation, in which lengths of umbilical and slurry pipe become embedded in backfill and are lost. If no exit route has been provided for the robot miner itself, then the sitution becomes pathological as a mining robot would be lost in every drive. This would be the result of using some of the possible bio-inspired mine layouts such as *Helminthoidea* spiral patterns (section 6.8, Figure 6.11).

8.8. Turning radius

A robotic system will have constraints on its turning radius, set by the mechanical design, even if it is designed to be able to turn within its own length. The reason is that unless a robot is perfectly spherical, turning within the confined space of a tunnel or shaft which it has excavated is not a simple process. The length of the robot will generally be greater than its width, so it cannot turn in-place. In practice, moreover, we shall not be considering a single robot but a train of robots (Figure 8.2) with different functions. Figure 8.3 shows this situation and Figure 8.4 indicates its effect on mine layout design.

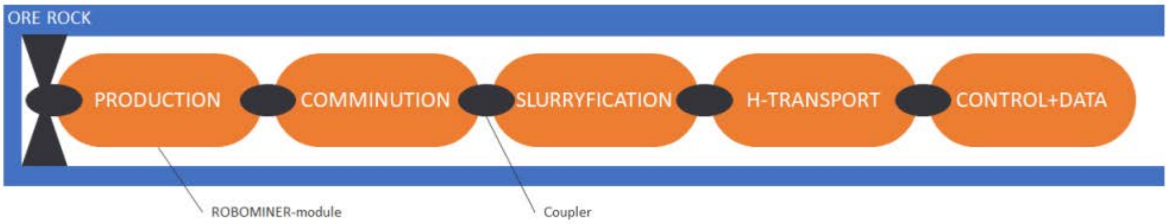

Figure 8.2: A notional train of robot modules with different functions.

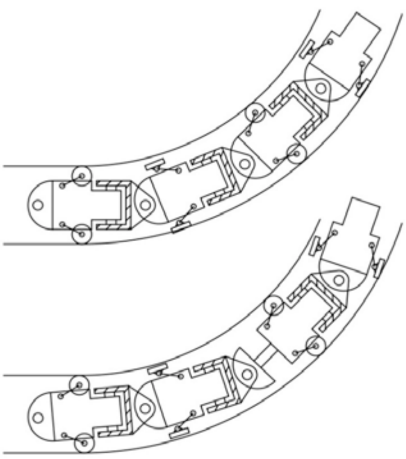

Figure 8.3: Turning radius constraint for a train of robots.

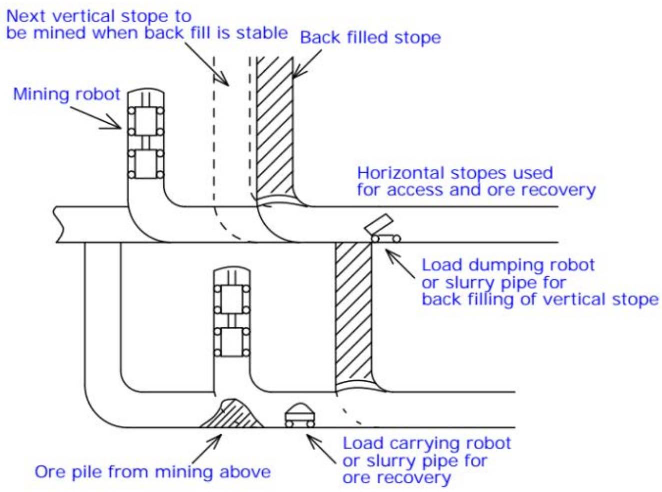

Figure 8.4: Mine layout with access controlled by turning radius constraints.

8.9. Maximising mineral extraction

Maximum mineral extraction implies minimising the amount of mineral that must be left in place to serve as support pillars. This is best achieved by having the same proportion of pillar material everywhere. A rectilinear mine layout allows this to be done; with a radial layout it is much more difficult as the pillars will be narrow near the centre. If the mine is shallow and underlies an urban district, pillars must remain permanently or must be replaced by competent solid backfill. In less sensitive districts or in deeper mines, such a constraint is less important, and if a pillar-extraction schedule can be devised, the geometric options are less circumscribed.

8.10. Minimising failure risks

There are many potential failure modes, such as the geology (geomechanical failure: collapse of workings), loss of communications (cable breaks), blockages (failed robots or twisted pipes). In a conventional mine, it is a normal requirement to have at least two emergency egress routes. In a robotic mine, if there is only one egress route, then such failures can risk total loss of the mine and all equipment. If the option of human access is excluded, then a mine layout design needs to include some means of access for a survey/repair robot other than through the main shaft.

8.11. Geometric problems

Conventional mine layouts have developed using engineering principles and generally those that are widely used (see section 2 above) have no significant associated geometric problems if human operation is replaced by robotic operation. However, bio-inspired layouts may have properties that pose unexpected problems in practice. Some of these are identified and described below, but necessarily this is not an exhaustive list since not all possible situations can be predicted.

8.11.1. Convergence of mine workings

Dendritic mining patterns are in general much less regular than conventional mine layouts. If the robot miner is allowed to develop its mine layout with no prior plan or control, especially if using an ore-following algorithm, the result could easily be a concentric layout, spiralling inwards towards a high grade zone – with no clear route to further mining. Such a mine layout may entail ever-increasing length of umbilical and slurry pipe, leading to inefficiencies and even to difficulty in communicating with a surface control room.

8.11.2. Mining into a 'corner'

Selective mining using an ore-following algorithm can lead to the development of a mine which follows the length of a lenticular orebody, with no clear strategy for continuation of the mining operation. It is possible to define manual or automated solutions to this problem, involving back-tracking to locations which offer alternative ore-following paths into other mineralised areas, but of course with a robot 'train' (Figure 8.2) such back-tracking will require reversal of the robot and some mechanism to retract both the umbilical cable and the slurry pipe to avoid tangles and tears.

8.11.3. Branches and 'islands'

Ore-following may lead a robotic miner into high-grade but short branches of an orebody. In general, advance exploration should identify major geometric features of the ore deposit, but small-sale structures (<5m for example) will not be detected even by closely spaced infill drilling. Similarly, there may also be 'islands' of waste material within an orebody, not detected by exploration drilling, and which might be avoided by an ore following algorithm. Blindly following or avoiding such small-scale geometric features could lead to inefficient mining of a deposit. Manual intervention from the control room may override the algorithm, but a more intelligent approach would be to include short to medium range exploration instrumentation (geophysical, geochemical, drilling) in the mining robot which allows real-time local update of the deposit model. This is to be discussed in more detail in D6.6.

8.12. Groundwater contamination

The potential for a mining operation to lead to contamination of groundwater is a common problem, but if robotic mining allows the development of mines closer than usual to population centres which rely on groundwater for their drinking water supplies, it becomes a crucial matter. This may not be a problem that affects the mining process directly, but is most certainly one which can cause the mine to be closed or radically re-designed, or to force expensive remedial action or compensation. More general water-related constraints are discussed further in D5.2.

8.13. Ultra depth and rock strength limitations

There is a wide variety of rock strength and other geomechanical constraints, discussed in detail in Deliverable D5.2. Difficulties that may occur at depth would transpire in:

Hoisting
Rock Mass Characteristicsation
Mine Design

8.13.1. Hoisting (Diering, 1997)

When hoisting with a hoisting machine, difficulties occur when mining at depth. The amount of rope required does lead to hoisting a large weight. Care must be taken in rope construction to ensure that it is torsionally neutral. Finally, the machine used to wind the rope has to be large to be able to both store the rope and to physically wind it.

8.13.2. Rock Mass Characteristics

At depth, the rock is highly stressed. A key concern is whether ground will fail violently or passively. At depth, the weight of the rock increases, so both the vertical and horizontal stresses are high. This is discussed in section 3.2.1 of Deliverable 5.1.

When the rock is highly stressed it is closer to failure. It is often highly confined which leads to interlocking and elevated strength. This rock is also more brittle. (Kaiser, Amann, & Bewick, 2015).

The high stresses make it possible that there will be a rock burst and the rock will fail violently. This is discussed in Deliverables 5.2 and 5.4.

8.13.3. Mine Design

At depth, to keep stresses acting on underground openings, the size of the openings must be kept low. Larger pillar sizes between openings will allow stresses diverted from the openings flowing through these pillars to spread out. This results in less stress being concentrated in the pillars.

9. REFERENCES

ABC News, Underground conveyor belt Northparkes Mine, available at https://www.abc.net.au/news/2010-02-05/underground-conveyor-belt-northparkes-mine/6209646?nw=0 (accessed on April 26, 2021.606Z)

Bauer, J., Puła, W., Wyjadłowski, M. (2015): Effect of partial mining of shaft protection pillar in terms of reliability index, Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 9:4, 242-249, DOI: 10.1080/17499518.2015.1104548

Belem, T., & Benzaazoua, M. (April 2007). Design and Application of Underground Mine Paste Backfill. *Geotechnical and Geological Engineering*.

Borg, G., Piestrzynski, A., Bachmann, G. H., Puttmann, W., Walther, S. And Fiedler, M. (2012) An overview of the European Kupferschiefer deposits. In Hedenquist J. W., Harris M. and Camus, F.: Geology and Genesis of Major Copper Deposits and Districts of the World – A tribute to Richard H Sillitoe. Society of Economic Geologists, Denver, Special Publication 16, 455–486.

Bromley RG, Ekdale AA (1984) Chondrites: a trace fossil indicator of anoxia in sediments. Science 224:872–874CrossRefGoogle Scholar

Bromley RG, Uchman A, Gregory MR et al (2003) *Hillichnus lobosensis* igen. et isp. nov., a complex trace fossil produced by tellinacean bivalves, Paleocene, Monterey, California, USA. Palaeogeogr Palaeoclimatol Palaeoecol 192:157–186CrossRefGoogle Scholar

Dammers, M., L. Barnewold, A. Merchiers, P. Jeschke, M. Pütz (2019), Development of an Underground Haulage System Evaluation Tool for Feasibility Studies, Mining, Metallurgy & Exploration 36 (2019) 487–494. https://doi.org/10.1016/10.1007/s42461-019-0055-9.

Darling, P. (2011) *SME Mining Engineering Handbook.* 3rd ed. Littleton: SME. ISBN 978-0-87335-264-2.

Dominy, Simon; C.J.S., Sangster; Camm, Godfrey; F.G., Phelps (1998): Narrow-vein stoping practice: a United Kingdom perspective. In *Transactions Institution of Mining and Metallurgy, London. (Section A* 19, A122-136.

Epiroc (2021), Minetruck MT5020 Epiroc, available at https://www.epiroc.com/de-at/products/loaders-and-trucks/diesel-trucks/minetruck-mt5020 (accessed on April 26, 2021.283Z).

Fliss, T., Marx, H., Thoma, H., Stäubert, A., Lindenau, A., & Lack, D. (2011). Backfilling and Pillar Re-Mining in Potash Industry. *MINEFILL 2011 - International Conference on Mining with Backfill.* Cape Town.

Fulda, D., Gruchot, G., & Michalzik, A. (1966). *Handbuch für den Spülversatz im Kalibergbau.* Leipzig: VEB Deutscher Verleger Verlag für Grundstoffindustrie.

Fuławka, Krzysztof; Pytel, Witold; Mertuszka, Piotr (2018): The effect of selected rockburst prevention measures on seismic activity – Case study from the Rudna copper mine. In *Journal of Sustainable Mining* 17 (1), pp. 1–10. DOI: 10.1016/j.jsm.2018.03.001.

Fursich, F. T. & Bromley, R. G. (1985): Behavioural interpretation of a rosetted spreite trace fossil: Dactyloides otto: (Geinitz). Lethaia 18, 199-207.

Government Of India - Ministry Of Mines (2001) *Slurry Transportation in Indian Mines*.

GTS GRUBE TEUTSCHENTHAL SICHERUNGS GMBH & CO. KG. (2021). *Versatzarten*. Von https://www.grube-teutschenthal.de/w/gts.nsf/id/pa_de_versatzarten_versatzbergwerk_versatzarten.html abgerufen

Harraz, H. Z., (2010), Underground mining Methods, DOI : 10.13140 / RG.2.1.2881.1124

Harraz, H. Z., (2014), Shrinkage stoping and vertical crater retreat stoping, DOI: 10.13140 / RG.2.1.5109.3360

Hartai, É., Németh, N., Földessy, J., Henley, S., Žibret, G., Galos, K. (2020): Review Document Giving Scope and Examples of Deposit Types of Interest. *ROBOMINERS Deliverable D5.1, 77p.*

Hilbert, J. D. (March 2016). Pneumatic point to ponder... Preventing material buildup in pneumatic conveying lines. *Powder and Bulk Engineering (PBE)*.

IndustrySearch.com.au, Underground Road Train | Powertrain T930 - IndustrySearch Australia, available at https://www.industrysearch.com.au/underground-road-train-powertrain-t930/p/97804 (accessed on April 26, 2021.345Z).

ISO. (2011). *ISO/IEC/IEEE 42010-2011 – Systems and software* GTS GRUBE TEUTSCHENTHAL SICHERUNGS GMBH & CO. KG. (2021). *Versatzarten*. Von https://www.grube-teutschenthal.de/w/gts.nsf/id/pa_de_versatzarten_versatzbergwerk_versatzarten.html abgerufen *engineering – Architecture description.* International Standards Organization.

Joy Shuttle Cars - Underground Mining | Komatsu Mining Corp, available at https://mining.komatsu/product-details/shuttle-cars (accessed on April 26, 2021.802Z)

Klinzing,G.E., F. Rizk, R. Marcus, L.S. Leung, Pneumatic Conveying of Solids, (2010): A Theoretical and Practical Approach, 3rd ed., Springer Science+Business Media B.V, Dordrecht

Knaust, D., (2017) Atlas of trace fossils in well core: appearance, taxonomy and interpretation, Springer International Publishing AG, ISBN 978-3-319-49836-2

Lindlar, B., Jahn, M., & Schlumpf, J. (2020). Sika Sprayed Concrete. Zürich, Switzerland. Von https://www.sika.com/dms/getdocument.get/664de18e-dbcb-4184-87b7-162e9dd260d5/glo-sprayed-concrete-handbook-2021.pdf abgerufen

LKAB (2021): Developing the mine of the future, available at https://www.lkab.com/en/news-room/news/developing-the-mine-of-the-future/ (accessed on April 26, 2021.431Z).

Marx, H., Lack , D., & Krauke, W. (2005). Substantial Aspects of the Recycling of Industrial Wastes as Backfilling Material in Salt Mines . *20th WORLD MINING CONGRESS & EXPO2005.* Tehran.

Masniyom, M. (2009). *Systematic Selection and Application of Backfill in.* Freiberg: Fakultät für Geowissenschaften, Geotechnik und Bergbau.

McGlinchey, D. (2009), Bulk solids handling: Equipment selection and operation, Blackwell Publ, Ames, Iowa

Michalzik, A. (2000). Rückblick uf die Anwendung des Spülversatzes aus Rückständen der Kalirohsalzbearbeitung im Kalibergbau. In H. Rauche, & P. Sitz, *Freiberger Forschungshefte A 855 Bergbau und Geotechnik - Spülversatz im Salzbergbau* (S. 17-31). Freiberg: Technische Universität Bergakademie Freiberg.

Morton, J. (2021). The Future is Boring. Engineering and Mining Journal, April 2021, p.26-33.

OMG. (2019). *OMG Systems Modeling Language (OMG SysML™) Version 1.6.* Object Management Group.

Ramalho, E. C., Matos, J. X., Carvalho, J. G. (2017): Report on data availability: Portuguese Iberian Pyrite Belt. *CHPM2030 Deliverable D1.2 Appendix 1.2.2*, 38p. URL: https://www.chpm2030.eu/wp-content/uploads/2017/02/CHPM2030_D1.2_public_small.pdf

Ramalho, E. C., Matos, J. X., Carvalho, J. G. (2019): Report on PILOTS: Portugal Iberian Pyrite Belt. *CHPM2030 Deliverable D6.2.2*, 53p. URL: https://www.chpm2030.eu/wp-content/uploads/2019/05/D6.2.2-LNEG.pdf

Rauche, H. (14.09.2015). *Die Kaliindustrie im 21. Jahrhundert: Stand der Technik bei der Rohstoff¬ge¬winnung und der Rohstoffaufbereitung sowie bei der Entsorgung der dabei anfallenden Rückstände.* Berlin Heidelberg: Springer Vieweg.

Rauche, H., & Sitz, P. (2001). *Spülversatz im Salzbergbau - Freiberger Forschungsheft A 858.* Freiberg: Technische Universität Bergakademie Freiberg.

Retallack G.J. (2001) Scoyenia burrows from Ordovician palaeosols of the Juniata Formation in Pennsylvania. Palaeontology 44:209–235 CrossRefGoogle Scholar

ROBOMINERS. (2019). ROBOMINERS. Project no. 820971 Contract. Annex 1 - Description of Action (part A).

Sandvik Mining and Rock Technology (2021), Fortschrittliche Untertage-LHDs wurden für eine maximale Betriebszeit entwickelt, available at https://www.rocktechnology.sandvik/de/produkte/untertagelader-und-muldenkipper/fortschrittliche-untertage-lhds/ (accessed on April 26, 2021.835Z).

Schlotzhauer, J. (2005). Spülversatz im Grubenbetrieb Unterbreizbach,des Werkes Werra der K+S KALI GmbH. *Kali und Steinsalz, 2*, 34-39.

Seilacher A (2007) Trace fossil analysis. Springer, Berlin, pp 226Google Scholar

Sims, David W., Andrew M. Reynolds, Nicolas E. Humphries, Emily J. Southall, Victoria J. Wearmouth, Brett Metcalfe, and Richard J. Twitchett, (2014), Hierarchical random walks in trace fossils and the origin of optimal search behavior. PNAS v 111 (30) pp11073-11078

Tatiya, R.R. (2013) *Surface and underground excavations. Methods, techniques and equipment.* 2. ed. Leiden: CRC Press/Balkema. ISBN 978-0-415-62119-9.

Wardell Armstrong International (2017): NI 43-101 TECHNICAL REPORT FOR THE NEVES-CORVO MINE. Available online at https://www.lundinmining.com/site/assets/files/3643/neves-corvo-technical-report.pdf

Walden, D. D., Roedler, G. J., Forsberg, K. J., & Hamelin, R. D. (2015). *INCOSE Systems engineering handbook. a guide for system life cycle processes and activities v4.0. Technical Publication INCOSE- TP-2003-002-04.*

Western Mining Corporation Ltd, (1979). Gold : a review of the technology of eploration and mining. Volume II Mining and Metallurgy. Melbourne, Australia

Wille, S., Pinkse, T., Quensel, R., & Schneider, G.-S. (2021). *Review of cavern backfilling techniques.* Clifton Park, NY 12065, USA: SOLUTION MINING RESEARCH INSTITUTE.