Roadmap for the Management of Mineral Gangue - Pyrite and the Environmental Cost Impact

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ABSTRACT

Green and smart mining in today's industry has become one of objectives target to be fulfilled by the mining operator, it respectively in looking into current and future challenges of climate changes along the strategy implementation of decarbonization and energy conservation. The orebody containing negative characteristic of geochemical lead into the needs of effort to handle them in later stage of mining process. It's created an extra cost due to the needs to perform activities meeting standard compliance and or paying the consequences following fail in fulfil the contractual obligations. Composition of metal concentrate containing un-expected residual mineral or gangue could create an extra effort for the facility of metal refinery or smelter for handle it. Especially at containing gangues who can negatively impacted and suffering the environmental. The better understanding of value impact since this presenting of negative chemical ores can further provide a sufficient program and preparation of resources upfront for risk mitigation. On the other side of risk positive, there is benefit generated by use this pyrite on another application. It then calls for a need of resources to handling and converting them to become valuable product for selling. Planning for resource allocation under the establish program to better of managing the risk and lead into success of organization to execute the target. It therefore there are two essential things shall organization be considered in address this, they are: establish roadmap or program for properly managing the pyrites and make the determination at the needs of resources to be allocated into each activity under it's setup roadmap. This written paragraph aiming exercise the key criteria in establishing the roadmap of handling pyrites by firstly understand the cost consequences into the living environmental at the do-nothing action. The determination of roadmap itself is achieved by conducting the risk assessment to early engineering design process activities and the effectiveness of exist control with residual risk to be continue review and monitor under the setup of roadmap program.

Preliminary Study of the Geoenvironmental of the Grasberg Ore Body

Pyrite, also known as "Fool's Gold," has long been recognized for its economic value when managed well. Although it may not have the same value as gold or other precious metals, pyrite remains an important mineral in today's economy. Pyrite has a number of uses across various industries, ranging from construction to electronics. Pyrite is also a source of sulfur, a basic material in the production of sulfuric acid, which is used in a variety of applications including fertilizers, detergents, and dyes. In mining with metal commodities from the sulfide ore body group, there are occasionally pyrite gangue minerals present. This creates a need for special handling in order to maximize the recovery value of processing facilities and also poses a risk to the environment due to its negative impact in generating acid mine drainage. Pyrite as an impurity mineral can be considered beneficial when managed properly. In several applications, its use can be as:

1. Civil infrastructure and construction work: One of the most common uses of pyrite is in the construction industry. It is often used as aggregate in concrete and as a building material. The strength and durability of pyrite make it an ideal material for these applications; however, its acidic, corrosive nature and its impact on the durability of buildings warrant separate studies. Additionally, because of its unique and eye-catching elements, pyrite can be used as decorative stone in buildings.

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2. Electronics industry: Pyrite is also used in the electronics industry, particularly for the production of computer chips due to its good semiconductor properties and its ability to manage the flow of electricity within the chip. This makes pyrite an important component in electronic devices.
3. Sources of sulphur: Pyrite is one of the sources of sulphur and a raw material for the production of sulfuric acid. Sulfuric acid is used in various applications such as fertilizers, detergents, and dyes. Pyrite is also used as a raw material in the production of sulphur dioxide, which is widely used for bleaching paper and as a preservative for wine. Pyrite is also an important raw material in the energy sector, being used in the production of natural gas and crude oil. Without sulphur, the production of these resources would be limited, and their prices would soar.
4. Jewellery: Pyrite is used to make jewellery and decorative objects. It is often used as a substitute for gold due to its similar appearance.

While pyrite can provide economic benefits, it cannot be denied to also have negative environmental impacts. This occurs when pyrite is exposed air, oxidated and flow or entering water bodies then producing acid mine drainage. This then results in serious consequences in the form of degradation of water quality and aquatic life. Additionally, pyrite can release harmful metals such as arsenic and lead into the environment. The economic value of pyrite can be enhanced by its usage beyond what is currently considered as merely 'fool's gold', especially if it can be managed well. Its use in the construction, electronics, and as a source of sulphur in the energy industry can make it an important mineral today and in the future. Nevertheless, the negative impacts of pyrite on the environment also need to be addressed to provide guidelines for planning mitigation measures. Pyrite, long known as 'fool's gold', has been an important mineral for centuries due to its economic value. However, the potential negative impacts on the environment also highlight the importance of engineered design for its management. The oxidation of pyrite can generate acid mine drainage (AMD) due to the acidic solution containing high levels of heavy metals, which can significantly affect the water quality in the surrounding environment. This can have a devastating effect on aquatic ecosystems, including the death of fish and other aquatic life. In addition, the release of AAT can also lead to soil contamination and can affect the health of plants and animals. To address environmental issues related to pyrite, various measures have been taken. Here are some perspectives on dealing with pyrite:

1. AAT Processing: is a primary method to address the environmental impact of pyrite through AAT processing. This can be done through various techniques, including the addition of materials with alkaline properties to neutralize the acidity of the solution and the use of other chemical treatments to remove heavy metals from water.
2. Removal of negative effects of pyrite: In some cases, mitigating the negative effects of pyrite can be achieved by tracing the geological formation of the rocks and planning mixing operations as part of the mining activities conducted. This can help prevent the release of Acid Rock Drainage (ARD) and other environmental impacts associated with mining on ore bodies containing pyrite.
3. Land reclamation: Another approach to addressing the environmental impacts of pyrite is through land reclamation. This involves restoring mined land to conditions similar to those before mining, liming, isolating deposition areas including replanting vegetation and restoring water pathways.
4. Recycling: Although pyrite has economic value, this mineral can be recycled for other purposes while still considering due diligence to handle its negative impacts. For example, pyrite can be used as a source of sulfur supply in the production of sulfuric acid, a basic component in fertilizer production and applications in other industries.

Although pyrite has economic value as mentioned above, it is important to consider the potential environmental impacts of its exploitation and use. Considering control measures aims to ensure that the economic benefits of pyrite can be achieved without causing undue harm to the environment.

The management of pyrite today is more focused on addressing the impacts when it comes into effect for the environmental following the presence of acid mine drainage. Effort programs in eliminate of potential negative impacts while simultaneously enhancing the positive benefits in existence of pyrite in orebodies present a study that outlines challenges align into treatment while opportunities align into potential of utilization that needs to be developed. Considering the opportunities and the risk of environmental issue, it can be accommodated throughout the Geometallurgy and Geoenvironmental modelling study program. The modelling

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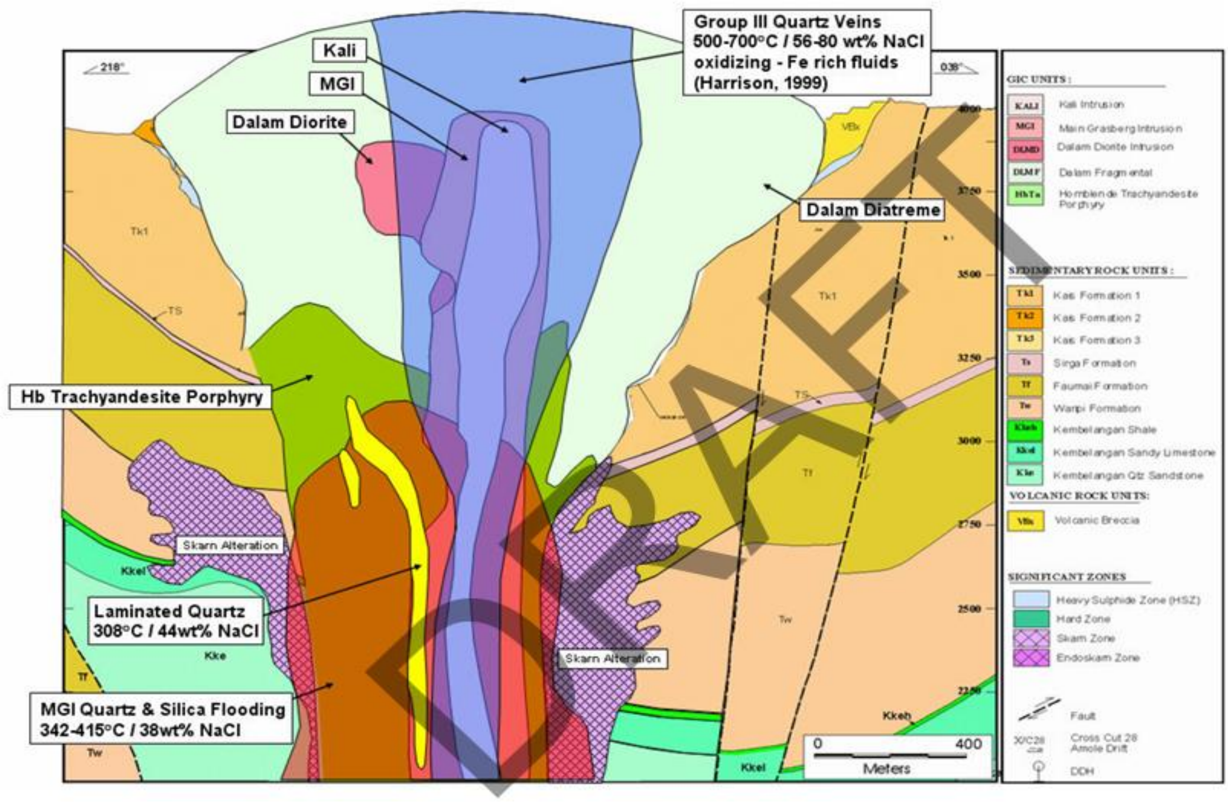
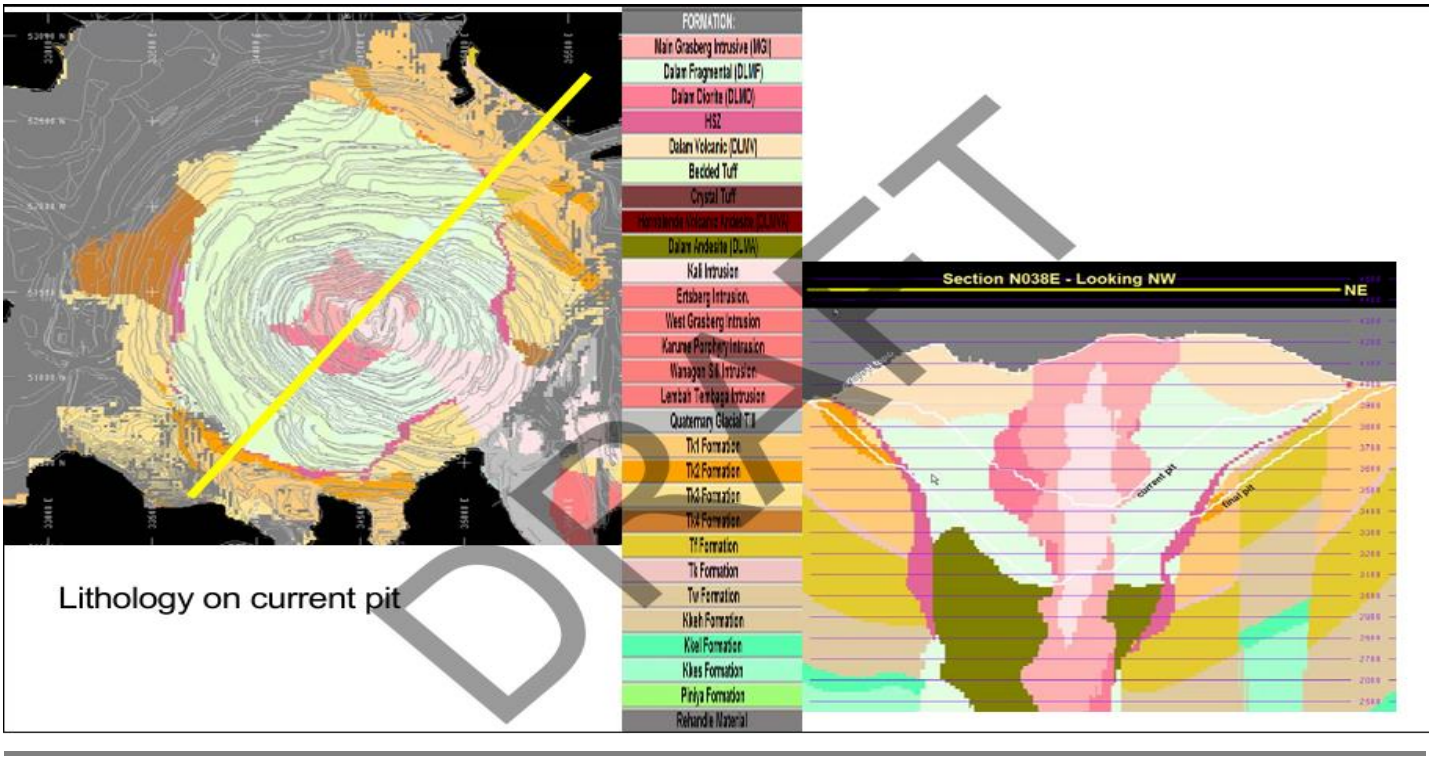
includes objective program to make all information are available for the stakeholders, as such availability for utilization in industries, guidelines for policymakers, operational references for mining operators, and the public knowledge. Modelling not only presents the potential environmental issues that may arise related to certain types of mineral deposits with negative chemical characteristics of the rocks, but it also provides information on how the environmental impacts associated with mineral deposits can be avoided, minimized, and or mitigated.



The research study for the Grasberg porphyry to indicate orebody has hosting by carbonates material, which could provide potential natural mitigation of acid mine drainage generation due to the presence of sulphide rock minerals- pyrite. Large amount of pyrites in the orebody create a need of assessment for environmental risk mitigation while see into future possibilities of commercialize the pyrites.



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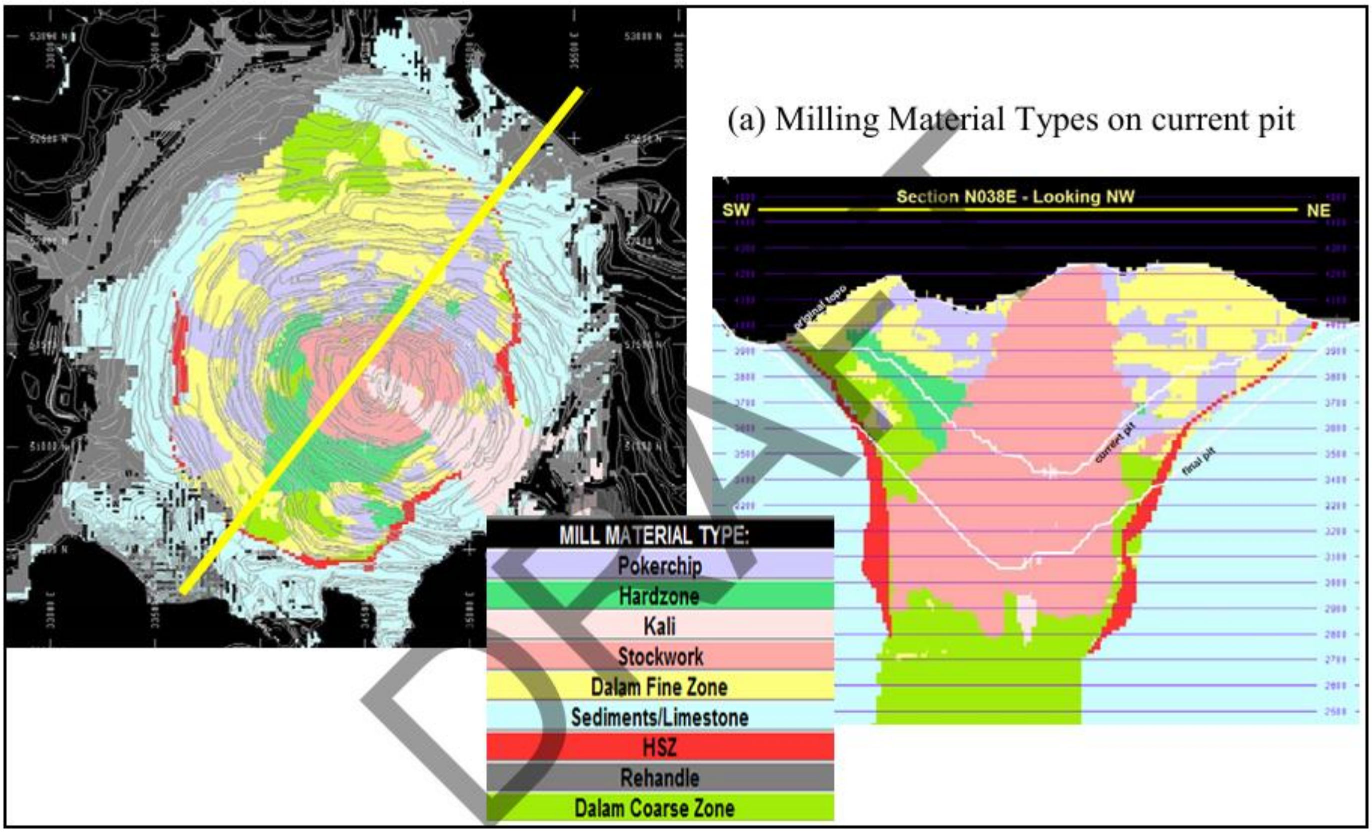

The general lithology observed in the Grasberg Intrusion Complex (GIC) consists of:

- ❑ Early volcanic pile (banded clay, bonded tuff, unbonded tuff, volcanic breccia, andesite flows)
- ❑ Fragmental In (andesitic composition)
- ✓ Intrusive In (dioritic composition)
- ❑ Main Grasberg Intrusion
- ✓ Late intrusion phase: plagioclase dike, South River Intrusion, gravel dike breccia
- ❑ Heavy Sulphide Zone

The main copper minerals in the Grasberg orebody are chalcopyrite, bornite (less than 20%), and digenite, covellite and chalcocite in small amounts. Bornite has a composition on the upper body of the Grasberg ore but becomes more abundant at the depth elevation. Covellite occurs on the perimeter side of the ore body with a content of one percent copper equivalent. Pyrite is only an accessory component of sulphide mineralization in the ore zone and increases in terms of composition volume at depth. The mining complex has two large intrusion complexes, namely the Grasberg intrusion (GIC) and the potassium-rich Ertsberg intrusion, commonly referred to as the "alkaline" intrusion. The Ertsberg rocks are classified as Monzo diorite, quartz Monzo diorite, monzonite, trachyandesite, and trakhidacete. The location, size, and shape of intrusions in this area vary over time. Older intrusions (4-5 million years ago) occurred in the southern part of the ore body up to younger intrusions (2.6-3.5 million years old) on the northern side of the ore body. The mass of the ore body consists of primary, original K-feldspar, plagioclase, and quartz, which has been partially replaced by altered quartz and K-feldspar. Magnetite (0.2-0.6 mm) makes up ~1 to 2% in the unaltered rock and is locally associated with ferromagnesian minerals. In this mass composition, the composition of magnetite rock is very fine. Compared to the type of deep Diorite rock, the plagioclase phenocrysts from the Main Grasberg Intrusion generally have a more solid composition. The Heavy Sulphide Zone (HSZ) is an irregular and non-continuous narrow boundary/zone at the contact between the Grasberg Intrusion Complex (GIC) and sedimentary rocks, especially limestone, as its parent rock. HSZ consists of sulphide minerals (pyrite, pyrrhotite, chalcopyrite), but also contains magnetite-hematite and epidote-chlorite minerals. The definition of high pyrite zone (HSZ) itself is considered to have at least a volume of pyrite greater than 20%. Magnetite rocks generally have a composition that is more closely related to limestone than pyrite. Epidote rocks seem to appear at the top of the high sulphur zone (HSZ) system. The origin of the formation of minerals in the high sulphur zone (HSZ) area is still under research, but it is highly likely that it is related to the formation of the Wild Cat ore body reserves that occurred post-mineralization of the Grasberg ore body.

Anhydrite and actinolite become more common with depth at the margins of the Grasberg deposit. Actinolite occurs in localized zones and as patches of coarse aggregates on the centimetres scale in veins, or as a very fine-grained replacement of igneous rock. Anhydrite is virtually absent in the core of the deposit. Anhydrite occurs in banded zones located about 500m from the centre. Anhydrite replacement occurs as white to purple veins that are wide up to several centimetres and as fine-grained material (≤ 0.5mm, poker chip type and hard zones). MacDonald and Arnold (1994) estimated anhydrite content ≥ 5% in the interior of the Grasberg porphyry system. At an altitude of 3500m, anhydrite and gypsum have been washed away by groundwater. Near the edge of the Grasberg volcanic structure, anhydrite is either crushed or transformed into gypsum by groundwater and through a process of alteration involving illite-pyrite.

Through a case study on the Grasberg ore body with steps to identify the potential generation of acid mine drainage by the presence of the gangue pyrite, it provides considerations for managing environmental impacts. Engineering considerations for mining operation design to meet compliance in properly managing the risk on potential acid generation covers:

- Challenges in the provision of pyrite concentrate processing facilities
- Processing ores with high content of pyrite
- A significant tendency towards oxidation processes and acid formation
- Potential impact on the geochemical stability of waste rock dumps in deposition areas.

The management solutions taken to manage pyrite:

- Modifying the flotation circuit to separate pyrite concentrate
- Channelling the pyrite concentrate to the deposition area via piping
- Handling pyrite in the deposition area through encapsulation.

It is a common practice in mining operations address potential impact since of acid mine drainage due to the presence of pyrite in orebody. Nevertheless, there are potentials areas which can be optimized through improvements of engineering design of mining operations in eliminate environmental impact. It respectively by look into program of managing the pyrites from the upstream process of mine design and incorporate into plan strategy achieving green mining concept. This differ than what is commonly done today, which focus on handling the pyrites at the mill-plant facilities and paying the cost consequences. The early mitigation program can provide more benefit for planning for resource and will certainly be more effective in perspective of financial cost. Opportunities gaining by investigate option commercialize the pyrites may limit in this assessment due to its linked with other requirement of assessment for the industry who buy the final product. It however, this study will only include a brief commercial benefits and roadmaps when it comes into apply.

LITERATURE REVIEW

Julie Hunt et al. (December 2023) through their research and study entitled A Special Issue Dedicated to Geometallurgy: Preface arguing the prevention and proper management of the negative impacts of chemical elements in rocks can be achieved through a study of geometallurgy aspects. In modern mining today, at advances of exploration technologies, prediction of rock characteristics along requirement of more detail data targeting an outcome for efficient and minimum environmental impact is find more attainable. The facing challenge is more about the differences way on way of deploying the methods in optimizing the values. As such obtain the full benefit from the final product by evaluate mill-plant recovery performance while reduce the environmental consequence following the presence of rock chemical composition in the orebody. This research and technical paper writing do not specifically discuss the presence of pyrite and outline the mitigation roadmap from a geometallurgical standpoint. Faramarz Doulati Ardejani et al. (March 2022) in their research and journal writing entitled Developing a Conceptual Framework of Green Mining Strategy in Coal Mines: Integrating Socio-economic, Health, and Environmental Factors describe seven main achievement targets from the implementation of green mining. The seven achievement targets include; becoming an important means in creating innovative technology in sustainable improvement programs, a medium for developing conservative business practices in the use of materials, water, and energy to reduce environmental impact, maximizing the use of minerals by reducing waste material left for future generations, minimizing environmental impact at every stage of mining, helping organizations establish safe working procedures and eliminating the risk of occupational diseases, and modeling reclamation efforts and land use conversion in the post-mining stage. The research and this technical paper writing do not take case studies on metal-mineral mining/only for coal mining. While cover the green mine concept, its not fully depicting the plan for handling the negative impact since the presence of chemical element of rocks. Mayra Jefferson et al. (July 2023), in their research and technical paper writing entitled 'Effect of pyrite textures and composition on flotation performance: A review,' stressed the influence of the size and shape of pyrite grain into the recovery process in the processing plant. Pyrite flotation performance can be varied due to the ore size and other features which can further affect the flotation ability where is crucial for an efficient depression process and better handling of the negative impacts of pyrite. This study provides a reference at the needs of proper comminution programs which recommend for an effective grading of pyrites and its particle size that suit for processing facilities. It however, research does not specifically outline a roadmap for managing size reduction efforts and its consequences in terms of impact to environmental aspects for not doing it. Anita Parbhakar-Fox and Bernd G. Lottermoser (December 2015), through their research and journal writing entitled 'A critical review of acid rock drainage prediction methods and practices,' arguing the failure to predict the formation of acid mine drainage (AMD) will have a long-term impact into ecosystems, human health, and will also adding extra cost and reputational consequences for mining operators. Thus, modelling of ore reserves from a geoenvironmental perspectives becomes the critical things to be managed. As such to have an early prediction on the natural mineral's concentration along with their future potential negative impacts. The integration process enables predicting of upcoming potential occurrence of acid mine drainage from earlier stage of mine will provide recommendations for effectively handling the issues and reduce the financial impact in the final stages of mining. Nonetheless, this writing paper has not elaborated in more detail on the steps to get process in fully integrated. Tomás Martín-Crespo, David Gómez-Ortiz, and Silvia Martín-Velázquez (2019) in their research and technical paper writing entitled 'Geoenvironmental characterization of Sulphide Mine Tailing' believed controlling environmental quality degradation could happens through doing the process of early identification of potential acid generation by understanding the geoenvironmental characterization, indicate evolutionary process duration, and observation material composition presence in the mining sediment area. This study was conducted in several locations of ex used mining lands that are no longer in operational with not fully investigate an early mitigation program from the mining operator which prepare since the initial stages of design engineering. Nevertheless, it can serve as a good reference in conceptualizing a roadmap for managing the environmental risk aspects. Gerard F. Laniak et al. (2013) in their research and written paper entitled Integrated Environmental Modelling: A Vision and Roadmap for the Future emphasizes the modelling in properly managing the environmental issues in today's modern world can be done through the computerized systems. Decision-making can be conducted effectively and in a timely manner due to well-integrated data and information. This research and paper writing provide a reference on conceptual roadmap for addressing environmental aspects in the future, although it does not specifically discuss handling the issues happens in the mining industry. Suhejla Hotia, Laurent L. Pauwelsb, and Michael McAleer (2004) through their research and writing paper entitled Measuring Environmental Risk, describing an essence of the use Environmental Sustainability Index (ESI) in quantifying the consequences of risks related to environmental aspects. This study writing provides a good reference in identifying the impacts but does not in deep address environmental risks in associated to the mining operations. Wiktoria Sobczyk, Koji Cristobal Ishimi Perny, Eugeniusz J. Sobczyk (2021) through research and written journal entitled Assessing the Real Risk of Mining Industry Environmental Impact: Case Study emphasizes the analysis of key risks in mining operations related to the environmental impact. This especially concerning the assessment of impacts on major water resources affected

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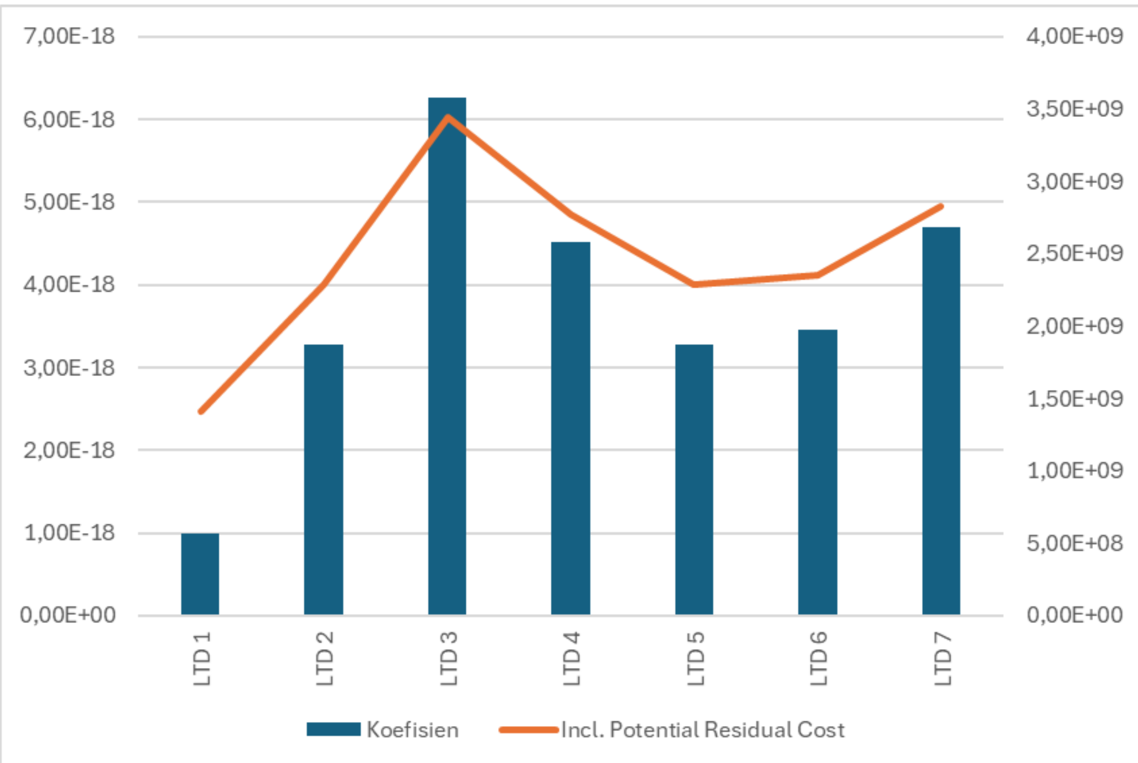
by mining activities. The research highlights the impact on water availability and aquatic environments which can be served as a reference, although it differs from study to discuss environmental impacts since presence of pyrite in the orebody. Rafael Fernandez Rubio (2015) in research and technical paper writing entitled Sustainable mining: Environmental Assets, persuade the investment through the procurement of items and environmental infrastructure support in the mining operations has an essential value in managing and address environmental issues for future. This study does not specifically discuss facilities and infrastructure for handling sulphide rock and the potential impact of acid mine drainage. Mark Sharfman and Chitru S Fernando (2008) through their research and technical paper writing entitled 'Environmental risk management and the cost of capital,' arguing study conducted on 267 companies in the United States who has done the improvements in environmental risk management proven as the organization with the lower investment cost. This value of investment is compared to the costs incurred as result for consequence payment to meet environmental standards, which generally seen greater. This study helps for building the theory regarding the benefits obtained by improve environmental risk management from the early stages of operation for an enterprise. Although it is not specifically related to the mining operations but can be used as another reference in forming the roadmap for environmental control of mining activities. The overall literature review that has been conducted provides beneficial references for this research and writing; however, it does not fully depict the relationship with the handling of the gangue pyrite in the orebody and its negative impact for the quality degradation of environmental. It respectively on way of build a robust roadmap in efficient and effectively handling the pyrite.

Study of Environmental Aspects in the Control of Pyrite

In refer to separate simulation happens through the system dynamic, its indicate there is potential future financial risk due to the environmental impact by do nothing on pyrite handling actions. The estimate of value impact using dynamic system modelling with the vensim software. Based on that simulation under 7 mining operation scenarios without handling efforts in the mining operations and only relying on processing at the plant, there will still be residual risks of tailings dam leakage and seepage. It presents in the graph as below LTD 3 who shows the greater impact compared to rest other plan operational scenarios. The magnitude of this residual risk can be described as:

Leakage of tailing dam (leakage of tailings dam, direct evaporation, or seepage);

Pyrite Cost ($386,449,000 x Coefficient) + Closure Cost ($1,021,949,000).



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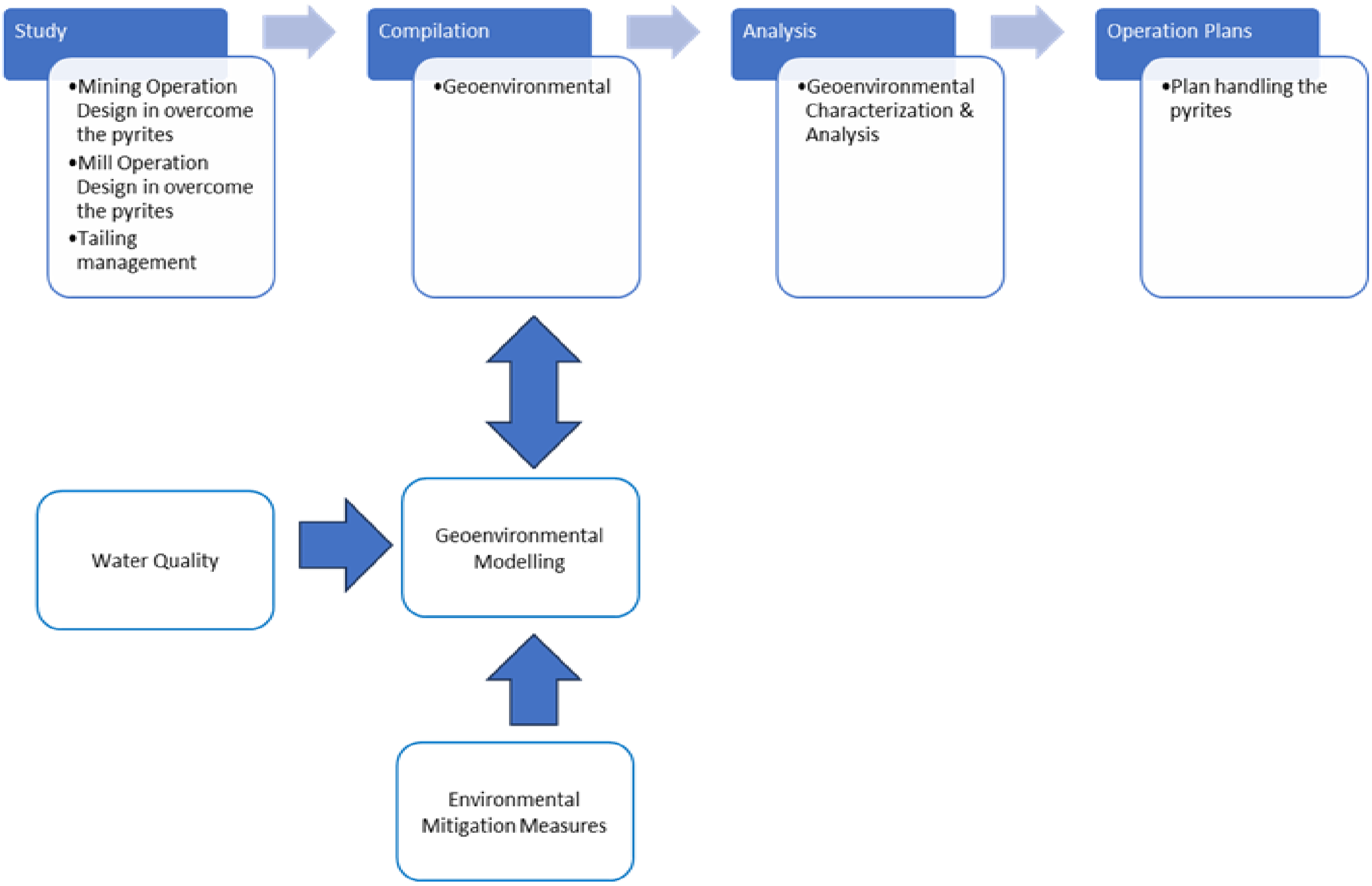
Through this analysis of potential residual risks, actions of properly handling the pyrite from the early stages of mining operations become more important. There will be a needs of roadmap program ensuring handling steps for pyrite are carried out through a standard process as part of strategic mine planning, visible in execute, along with program for monitoring which agree by mining operators and the control of authority agent. The mitigation steps following the potential negative impact due to the presence of pyrite in the orebody commence by conducting a study into activity area that is in direct influence. There are three major areas who has direct influence with the pyrites, they are mining area, mill-plants and the sedimentation pond area. These three major areas will be the focus for study at the things which requires any efforts to control their negative impacts. The series of processes can be illustrated in the following diagram:



The study in these three locations to describe activities that will directly influence into aspect of properly managing the pyrite. As such.

a. Mining operation study

The engineering study for mining operations is conducted to see if anything can be putted in place allows for better of managing pyrite and reduce the workload of processing facilities.

b. Ore processing facility study Engineering of processing facilities that can effectively managing and control the pyrite on its possibility of generation acid mine drainage.

c. Study of mining waste management facilities (tailings pond)

To look into effort for minimizing until eliminate any residual risk of tailing permeabilities and the failures of storage ponds wall.

Mining Operation Study

A case study on the handling of pyrite in the Grasberg ore body using a simulation model of the ore handling system with a production target of 160,000 tons per day. This production capacity considers the composition

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and volume of pyrite with the solution to handling them as part of mining operation scenario. Study to includes the impact on fragmentation programs and the efficiency of ore processing at the mill-plant due to the scenario of blending pyrite-ANC along its impact into demand of electrical power feeding. Simulation models will evaluate engineering design of the mine along the needs of infrastructure to support mine productivity through a best fit of ore handling system. There are possibility adjustments needs who caused by requirement of ore handling system. The study impact to includes equipment and its ore characterization, the needs of process, number of availabilities drawpoints, ore fragmentation, and mining operation procedures. Ore handling simulation along with engineering design of mining operation in consider above aspect as of follows.

- Understanding the operation-production scenarios with an effective program of fragmentation, secondary breakage, and special handling needs for ores with a specific geological characterization.
- Conceptualizing and developing accurate graphic and mathematical models of ore handling systems.
- Defining the input and output requirements of the model. Simulating the program using Arena software to illustrate graphics and mathematically model ore extraction.
- Verifying that the Arena simulation accurately represents the production operation model.
- Validating that the model accurately represents the proposed operations.

Mapping of ore and readiness of the drawpoint for production mucking are key factors in effectively modelling the underground block caving operations. Mapping the ore based on the level of economic value and the determination of readiness to extract ore from the cave, meeting the criteria for rock fragmentation programs are vital and essential for successful for mine production. The size of the rock blocks that are not optimally reduced through production blasting can create an effort for additional size reduction activities. In general, the evaluation happens under three conditions as defined to high/medium-hang-up, low-hang up, and block sizes that do not allow for ore extraction from drawpoints. High hang up was not much considered in this simulation because mining engineering handling has accommodated this and the frequency of its occurrence will be low by look into geological structure. Medium and low hanging rock conditions in prediction will occur more frequently and are modelled in this simulation. Medium and low hanging occurs at or above the threshold of the pull space with a height of about 3 to 5 meters. Data on the possible conditions can be mapped from geological data into the following matrix table.

Production Block	Year	Low Hang-Ups (tonnes)	Drawpoint Oversize (tonnes)	Rock Break (%)	Blocks (per 100 tonnes)
PROD1	2023	505	63	36.3%	9.30
	2027	381	66	33.7%	8.42
PROD2	2023	1,655	72	39.7%	10.48
	2027	1,686	68	38.4%	10.39
PROD3	2023	1,667	46	50.7%	13.14
	2027	381	66	33.7%	8.42

This additional handling includes scenarios through six blasts per day to support the effectiveness of the rock fragmentation program. Secondary size reduction of the rocks is also carried out using a stationary mechanical rock breaker above the production pit. Analysis of the size/distribution of secondary blasting and breaking provides details about the sequential drilling and secondary blasting for low and medium-hanging rocks, which will serve as a reference for adjusting the activities of extraction from the collapse space. These possibilities need to be simulated into production operation scenarios, including their impact on the planning of pyrite-ANC mixing.

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CALCULATION SHEET

Client: PT Freeport
Project: 203523
Subject: Grasberg - Block Cave Fragmentation - Average (Rockbreaker and Chute)

Based on the CNI and PTFI's recent fragmentation work updates to previous fragmentation curves have been made. These curves are not attached.

Aspect Ratio = 3

Volume	0.005	0.578	1.000	2.000	10.000	100.000	177.828	m^3
Short Side	0.119	0.578	0.693	0.874	1.494	3.218	3.899	m
Longest Side	0.205	1.000	1.201	1.513	2.587	5.574	6.753	m
Avg. % Passing	5.8	17.5	23.2	33.0	65.2	98.8	100.0	

Summary of Table	Criteria (Side-m)	Volume - m^3	% Passing
Passing Crusher	0.203	0.005	5.8
Passing Grizzly	1.000	0.578	17.47
Passing Boulder Buster	1.513	2.000	33.00
Passing Drill and Blast	2.587	10.000	65.21
Passes Draw Point	3.899	177.828	100.00

Test Assumptions:

To test the material volumes impact on productivity and cost for secondary breakage the following analysis and rules are assumed.

The initial distribution of material is based on the volumes related to ore flow passing key material flow points. The estimated impact of activities taken to pass each point are reflect as new percents passing after a "sizing distribution" event.

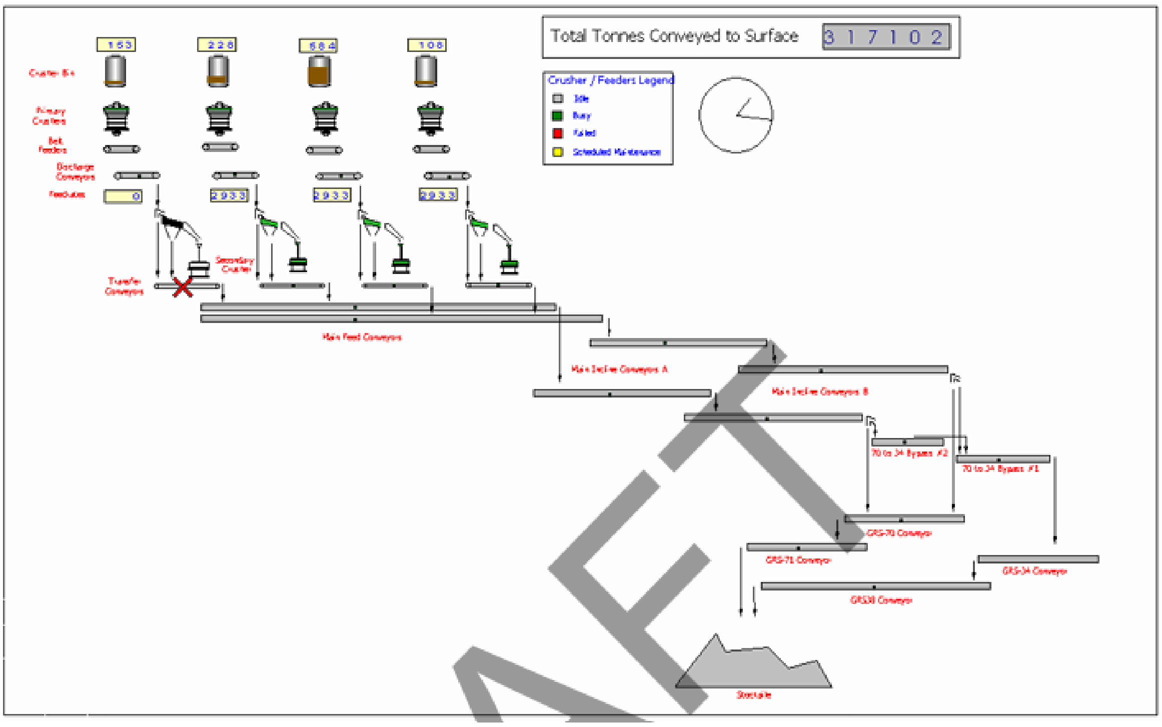
Tonnes produced. 100

		% Pass Crusher	% Pass Grizzly	% Pass BB	% Pass DB	% LH	% HH	Total
							% DB	
Initial		6	12	16	32	35	-	100.0
% Drill/Blast Distb'n		10%	40%	40%	10%			
Drill/Blast Tonnes		3	14	14	3	(35)		-
After Drill Blast		9	26	29	36	% BB		100.0
% BB Distb'n		20%	50%	30%				
BB Tonnes		7	18	11	(35.7)			-
After - BB (Conservative)		16	43	40				100.0
Adjust for Effective Dumping	50%	16	64	20	% Rockbreaker			100.0
% Rockbreaker Distb'n		20%	80%					
Rockbreaker		4	16	(20)				-
After Grizzly/Rockbreaker		20	80					100.0
To Crusher		20	80		% to Crusher			100.0
Final %		20%	80%					

Based on 115,000 Tonnes per day operation

91,504 Tonnes per day require crushing

Several other considerations need to be made as steps to optimize the size reduction activities through the improvement of the rock fragmentation program. This is done through the study of blasting activities and the development of rock slopes to produce ore size gradation and lighten the burden on processing facilities. In the effort of mixing pyrite-ANC, it adds extra load to the processing facilities to grind the acid-neutralizing material (ANC). Thus, considerations in the rock fragmentation program mined need to include the characteristics of the ANC material.



The content of pyrite that is transported to the ore processing plant will reaching 9.5% per year from the total of volume ore at 93Mt for total duration of mine life. The grade and amount of pyrite from this underground mine are significantly higher than the previous Grasberg open-pit mine where additional handling efforts were not included in the previous planning. Since the pre-feasibility study phase in 2003, 309 composite ore samples have undergone for rock characterization testing. Handling ore samples from exploration drilling requires separate management to prevent damage during their delivery to the laboratory. This is particularly due to additional cracks or fractures that may occur during the transportation, it can affect the recommendations in the fragmentation program. In addition to that, collecting ore samples from the drill respectively to correct locations is important. This contributes into the accuracy of geological data and provides better results in testing and characterizing the ores. The need for data and information regarding the potential environmental impacts since of the development Grasberg deposit reserves requires an integration process from early stage of exploration program. The Grasberg deposit reserves have the potential to generate high acid water and high metal content, thus making it necessary to address geometallurgical aspects from the early stages of mining.

Engineering of Processing Facilities

To process ore from the Grasberg mine with a high level of pyrite to call for modifications and additional new facilities at the mill-plant. It includes the addition of a grinding facility (SAG Mill) fulfil requirement of finer particle size, and for the waste material can be effectively managed in the sedimentation pond area. Furthermore, the addition of a copper cleaner facility was also implemented to separate pyrite from other materials before being released into the sedimentation area. The separated pyrite is then pumped through pipes to the storage pond after undergoing for thickening processes. The concentration flow of GBC pyrite has been designed to recover 85% of the pyrite at a high grade (85%). Therefore, the concept of reducing the volume of pyrite along with the needs for transportation and storage will make the cost of this facility become more effective. The design parameters for the handling and storage of pyrite will require the addition of limestone to minimize the possibility of acid formation. The total cost investment for the processing of Grasberg ore reaches $797 million, with $132 million for the installation of the ore regrinding circuit along with improvement on effectiveness of the flotation process, $480 million for pyrite concentrate along with handling and storage, $29 million for the distribution of the electrical network, and $156 million for providing an additional power supply of 45MW during the operation of the new facility.

The processing of the Grasberg Block Cave ore requires the following circuit installation:

- ❑ The Cu regrind circuit with:

- ✓ Six (6) new mills with a capacity of 1500hp are required, in addition to two existing grinding facilities (ball-mills) with a capacity of 2500hp, namely BM14 and BM20, aimed at regrinding coarse concentrates from the C3 and C4 reduction facilities before the modified copper cleaning circuit. The demand increase is almost threefold from the previous capacity of 5000hp to 14000hp. This arises due to the characteristics of GBC ore and the additional load of carbonatite reduction due to mixing activities (pyrite-ANC). Coarse Cu grinding will produce approximately twice as much as the Grasberg ore from the previous open pit mine.

- ✓ Six (6) additional Knelson gravity separation facilities have been introduced to ensure that gold is processed more easily and effectively. This is due to the need for grinding the main copper mineral which requires a certain level of fineness, so modifications also need to be made to the process recovery of gold prevent them from being wasted.

- ❑ Copper cleaning circuit with:

- ✓ Five (5) column cells 18’øx50’ to clean and separate coarse concentrate for re-grinding into the final copper production.

- ✓ Six (6) cells of 18'Øx50' to clean the tailings in the cleaner column and produce the final copper concentrate product.

- ✓ Three (3) banks consisting of nine (9) mechanical scavenger cells 3000ft2 that process scavenger cleaner tailings to produce tailings rich in pyrite and supply them to the pyrite cleaner circuit.

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- Pyrite cleaning circuit with:
  - ✓ Three (3) 1500hp mill towers to polish the pyrite-rich tailings from the Cu cleaning circuit. In this way, the surface of the pyrite mineral will be clean and ready to be reactivated by flotation reagents and purified at the pyrite cleaning facility (pyrite cleaner).
  - ✓ Eight (8) column cells with a diameter of 18' and a length of 50' to produce pyrite concentrate.
- Thickeners circuit for pyrite concentrate with:
  - ✓ One (1) thickener sized 200'ø to produce pyrite concentrate with reduced water content value.
- Storage and pumping of pyrite concentrate with:
  - ✓ Four (4) storage tanks for pyrite concentrate with a capacity of 850,000 gallons.
  - ✓ Three (3) Geho slurry pumps to pump the pyrite concentrate to lower areas through a special pipe.
- Pyrite Concentrate Pipeline
  - ✓ Two (2) 10" pipes capable of handling 12ktpd at 65% solid composition
- Pyrite Concentrate Storage in the settling area, consisting of:
  - ✓ Two (2) storage ponds 1.35km x 1.35km 56.8Mt
  - ✓ One (1) emergency storage pond 0.75 x 0.75km 8.4Mt

The schedule for the installation of new circuit equipment is shown below, with the following notes:

- The existing SAG cleaning circuit is sufficient to process GBC ore until 2022 when mining operations reach full capacity of 160ktpd.
- A second pyrite concentrate line is needed in 2021 because new pyrite production will exceed 11ktpd, which exceeds the nominal capacity of the first pipe.
- A second holding pond is not required until 2028.

Circuit	2017	2021	2028
Cu regrind		√	
Cu cleaner		√	
Pyrite cleaner	√		
Pyrite concentrate thickening	√		
Pyrite concentrate storage and pumping (50%)	√		
Pyrite concentrate storage and pumping (100%)		√	
Pyrite Concentrate Pipeline #1	√		
Pyrite Concentrate Pipeline #2		√	
Pyrite Impoundment (50%)	√		
Pyrite Impoundment (100%)			√

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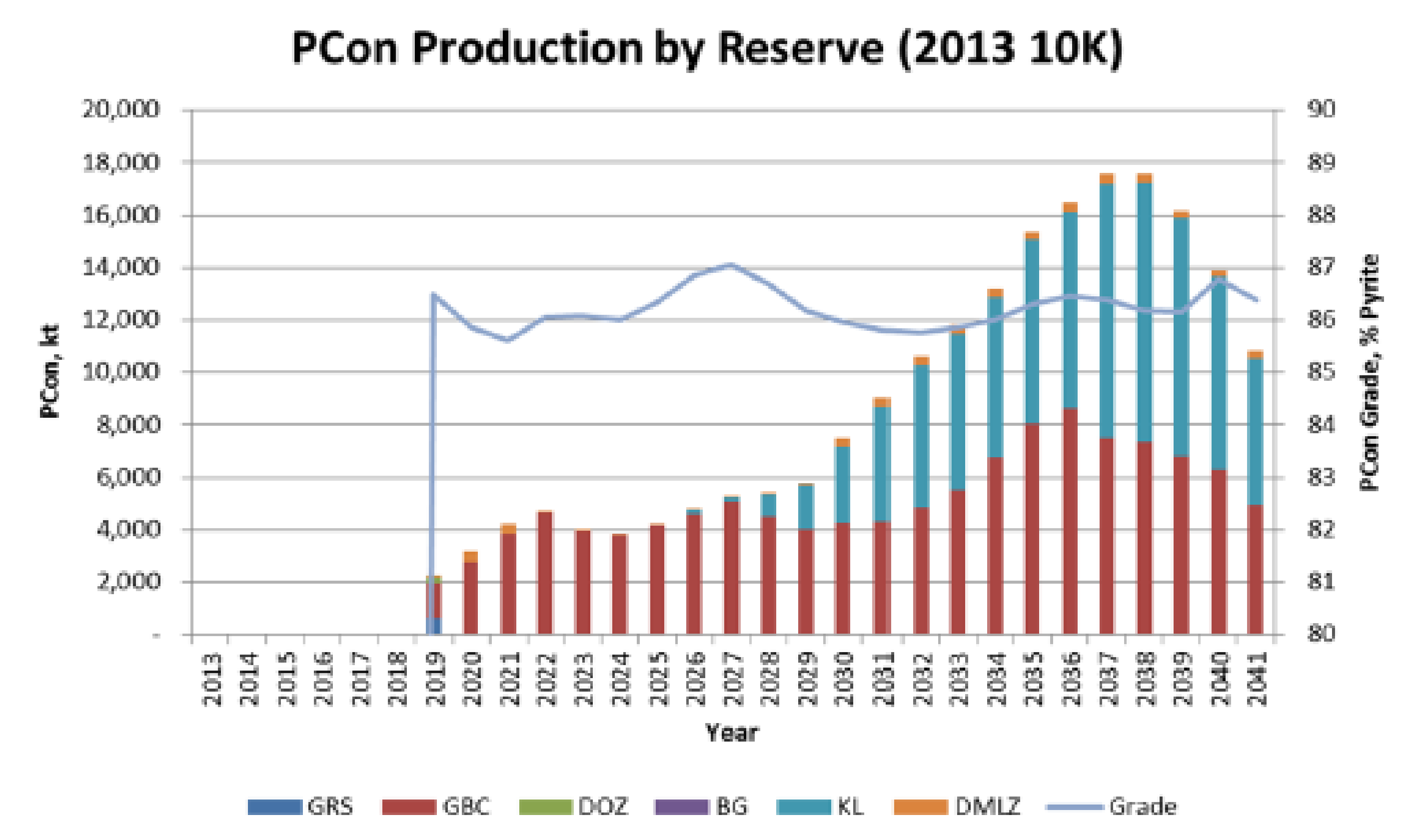

Tailings Management Engineering

The Grasberg ore body during mining at depth has a high mineralogical content of pyrite sulphide. The pyrite content during full mining operations of the underground mine (GBC and KL) can reach 24%, while the pyrite content from the tailings currently stored in the deposition area is less than 3%. To prevent the formation of acid mine drainage due to the oxidation of pyrite content in the deposition area, additional efforts are needed. A series of separation processes to reduce the content of pyrite before being transferred to the deposition area has been carried out. The waste of mineral contaminants from pyrite must be separated before being transported to lowlands through special pipelines to be managed in designated deposition ponds. According to a geoenvironmental study, 240 million tons of pyrite tailings will be produced by the end of the mining period and will be contained and managed in a special pond. The design engineering of the containment and deposition pond based on the results of the preliminary study has included site investigation, liquefaction assessment, deformation and stability analysis, laboratory experiments on pyrite waste, as well as water quality modelling, with plans to construct three pyrite deposition ponds.

Pyrite Tailings Storage (Million Ton)	38	82	129
Average Thickness of Sediment in Pyrite Tailings (m)	13	20	22
Pond Fill Elevation (asl)	103.2	99.2	91.0
Pond Height (m)	21	26	30
Maximum Pond Height (m)	28	34	36
Technical Age (year)	8	8	7

The waste mineral byproduct of pyrite will be transported through pipes to a tailings storage location made with a waterproof layer on the walls of a pond built above ground. The bottom of the pond will be excavated gradually to a depth of 3 meters below the groundwater surface to produce construction material. This management approach was chosen to maintain the saturation level of pyrite, minimize leakage from the storage facility, and comply with government regulations regarding wastewater management from pyrite storage facilities.

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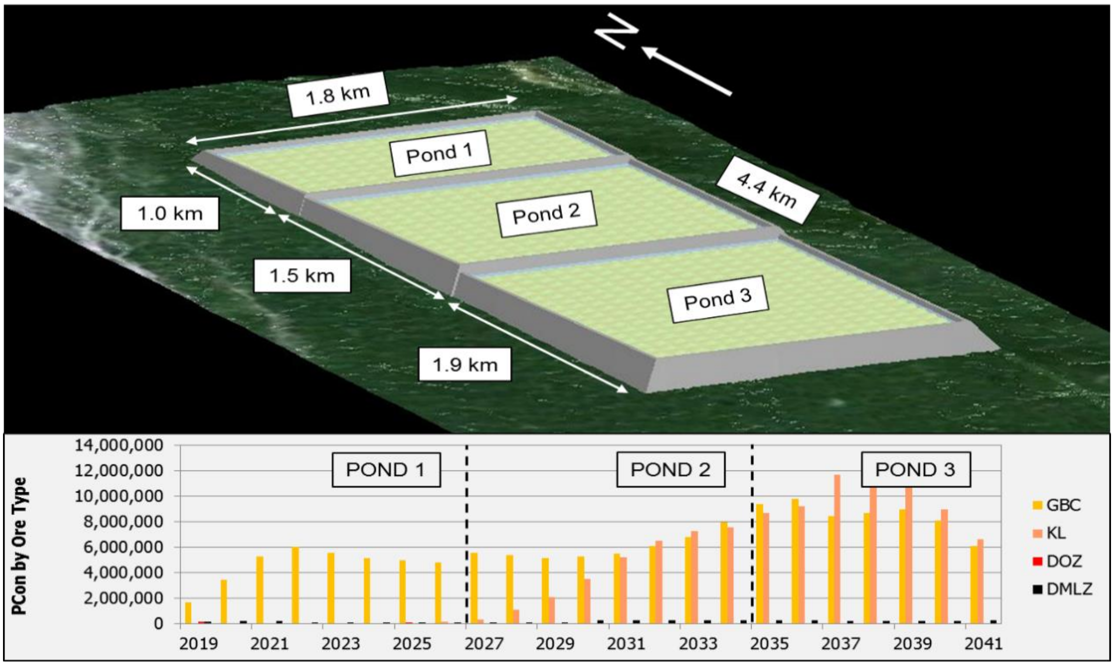
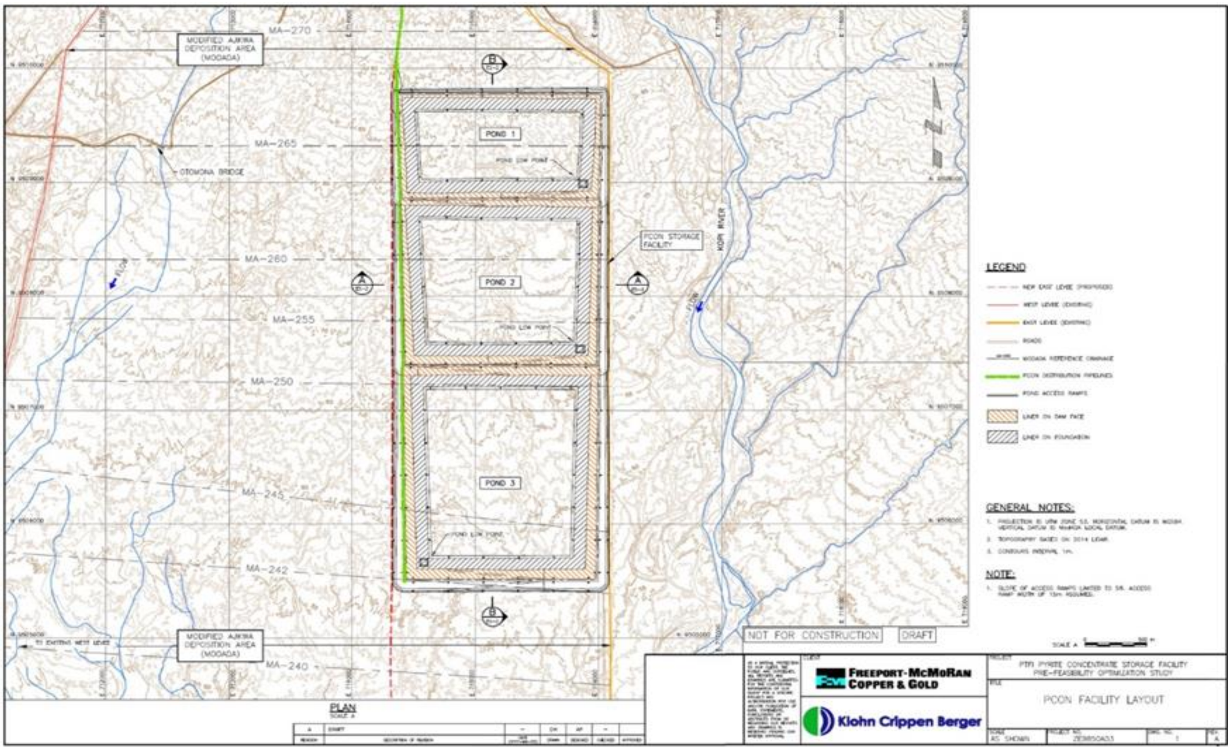


The layout of the pyrite storage facility has been optimized based on the results of investigations and evaluations of supporting data. The design of the tailing storage facility consists of three rectangular ponds bordered by embankment walls. These ponds will be built from north to south and operated sequentially, where each pond will operate for 7 to 8 years.

Pond	Length (m)	Width (m)	Ground Elevation (ml)	Average Slope of Pond Base (%)	Crest Elevation (m)	Embankment Height (m)	Pyrite Tailing Thickness (m)	Stored PyriteTailing Tonnage+ 20% Surplus (Mt)	Years of Storage
1	1,080	1,800	78 -88 (83 average)	1.7	103.2	13 – 28 (21 average)	8 – 18 (13 average)	38	8
2	1,490	1,800	68 – 82 (75 average)	1.7	99.2	18 – 34 (26 average)	15 – 24 (20 average)	82	8
3	1,890	1,800	57 – 68 (63 average)	1.3	91.0	23 – 36 (30 average)	20 – 24 (22 average)	129	7



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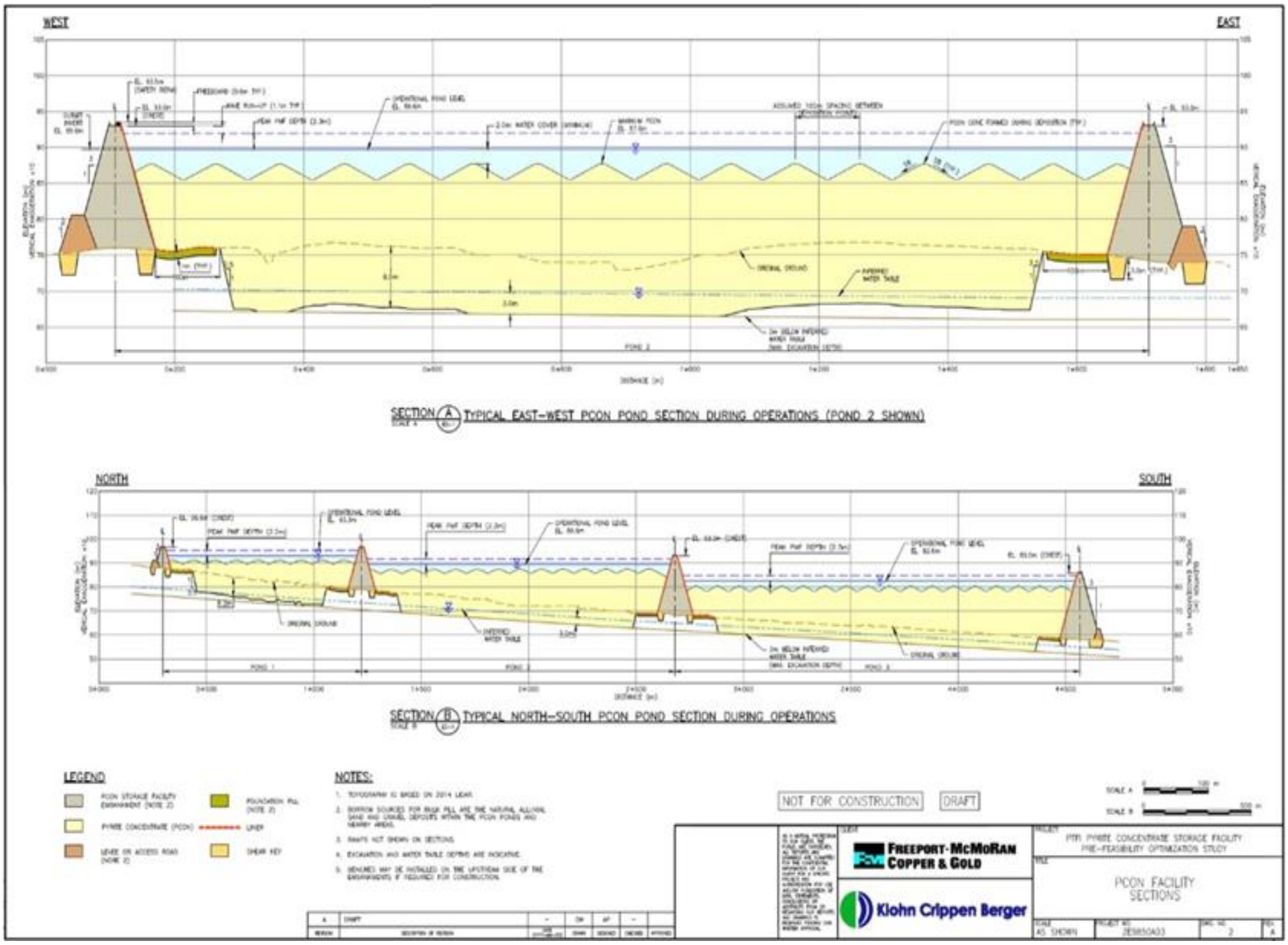
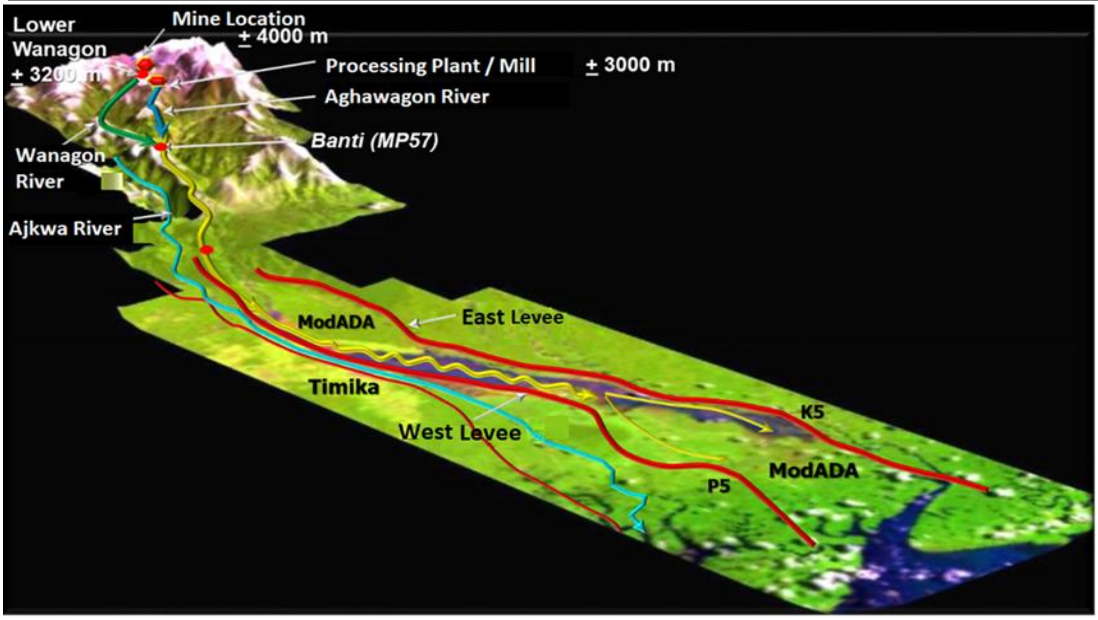


During the operation of this facility, rainwater and pyrite tailings process water will be mixed and discharged from each pond separately. After the pond is full, discharge is expected to occur throughout the day due to the inflow of slurry water with an estimated average monthly volume between 0.3 m3/second and 1.4 m3/second. During operation, water discharge will be conducted through two HDPE pipes designed for the highest flood conditions. Tolerance limits for the highest flood peaks and wave heights have been considered when determining the highest peak height of the embankment. The collected discharge water in the northern part of the pyrite tailings storage facility will be redirected to the settling area to reduce water pressure on the tailings foot embankment pond. Diversion can be done by aligning access roads, installing ditches and culverts, or damming the lowest parts to redirect the flow to the settling area.

The leakage from the pyrite tailing storage facility, which is partially lined with a waterproof layer, to the groundwater will be minimized by the presence of a waterproof layer on the embankment that has been designed and the low hydraulic conductivity of the pyrite tailings as well as the base of the deposited pyrite tailings. The predicted leakage rate for each storage facility until the end of operation (when the embankment and pyrite tailings are at maximum height) ranges from 42 l/s (storage facility 1) to 94 l/s (storage facility 3). Immediately after completion, the storage facility will be filled with rainwater and the low hydraulic conductivity pyrite tailing layer has not yet formed at the base of the storage facility, so leakage at that time will be higher, estimated to range from 76 l/s (storage facility 1) to 15 l/s (storage facility 3); this condition will be temporary, lasting only for a few weeks or several months.

Numerical modelling shows that the percolation water flow from the pyrite tailings storage facility entering through the bottom of the storage facility will flow together with groundwater to the south. Unpredictable percolation water from the pyrite tailings storage facility flows towards Kwamki Lake or towards drinking water wells in Timika. The estimated flow rate is very low (around 0.4 m/day) and percolation will mix with the regional groundwater flow that flows beneath the pyrite tailings storage facility.



To achieve the results of pyrite management planning, a study of Geoenvironmental characteristics needs to be conducted. This involves tracing the activities that must be carried out at each stage of mining and modelling efforts to minimize the impacts arising from environmental aspects. The initial stages of exploration activities and sample testing provide an estimate of the geoenvironmental characteristics of a mineral deposit. Understanding the characteristics of the rock provides a reference for recommendations on waste rock management, including the management of other mineral impurities more effectively along with planning for rehabilitation. The chemical characteristics of the rock can be determined through studies and analyses of many rock samples.

Nevertheless, due to the extensive coverage of the mining area, there is a possibility that some locations are inaccessible, so statistical analysis can be used to supplement the missing data. Alternatively, this may serve as a guide to conduct exploration activities alongside development and production operation phases. Another action that can be taken is to investigate the sulphur content levels in the ore body to assess the potential impact on the environment. Sampling through exploration drilling activities and laboratory testing can demonstrate PAF (Potentially acid forming) characteristics as shown in the following table.

Lithology	Paste PH	ARDI	Total Suplhur (%)	NAG pH	ANC (kg H_2SO_4/l)	NAPP (kg H_2SO_4/l)
Clastic Sediment	8.6	17.9	1.2	2.4	18.7	39.9
Dacite	8.4	19.5	0.7	-	-	-
Volcaniclastite	7.9	21.7	0.6	2.8	11.1	19.2
Basalt	8.2	21.5	0.4	2.9	13.7	9.9

This table data shows that the mineralogy per lithotype (the formation of sedimentary rocks through precipitation activity or magma solution) is not displayed due to the varying impacts of hydrothermal pressure changes. From this sample investigation, both volcaniclastics and clastic sediments show potential geoenvironmental risk with a high ARDI (Acid Rock Drainage Index) and total sulphur; low values of ANC (Acid Neutralizing Capacity) and NAG pH (Net Acid Generation) (i.e., <pH 2.8). The type of mineral group in the rocks that potentially offers neutralization of acid is basalt rock (which has the lowest NAPP - Net Acid Producing Potential), however, its distribution is sometimes sporadic. The exploration of rock characteristics from the chlorite–sericite alteration zone, phyllites, propylitic, and potassium requires further observation through advanced drilling programs and sampling. Phyllites alteration is estimated to increase acid generation capacity (this group of rock types includes: quartz, sericite, and pyrite); potassium (which consists of potassium feldspar, biotite, and anhydrite) is considered to reduce acid generation because coarse feldspar reduces rock reactivity, and propylitic alteration tends to enhance acid buffering capacity because calcite (along with epidote, chlorite, and pyrite) is a group of rocks that are generally present in ore bodies. Large porphyry copper reserves are likely to contain a significant volume of pyrite dispersed at the outer boundary of the mineralization zone. However, some observations indicate that pyrite is not always the dominant type of

sulphide rock outside the mineralization zone. This occurs because sulphides have different acid-forming potential, and understanding this proportion can refine the total potential for acid production. Evaluating how these observations relate to the geoenvironmental model of porphyry deposits (USGS) requires full-scale mapping of the alteration zone in both the cover rock domain and the contaminating minerals. The use of the latest technology such as hyperspectral core drill scanners (e.g., Corescan or Terracore) will aid in identifying which part of the ore body formation it originates from and allow refinement through the reconstruction of the mineralization process in the past. Despite the, observations show that the volume of sulphide rock does not have a predictable distribution within each alteration zone, which also indicates that the introduction of sulphide mineralizing fluids into this system is a late-stage multi-episode event (as indicated to have occurred in the Wild Cat ore body that happened after the Grasberg porphyry). With the challenges faced in the study of geoenvironmental characteristics, several other methods can be used to effectively predict the potential for acid generation from sulphide rocks. An alternative is through mapping based on the criteria for classifying cover rocks, accessory minerals, and contaminant minerals, which are typically developed using a combination of total sulphur, NAGpH, NAPP, or net neutralization potential (NPR) ratio values. Referring to classification practices in mining operations at Diavik, Canada, cover rocks are categorized into three different types based on sulphur content (i.e., Type I—< 0.04% S; Type II—0.04 to 0.08% S; Type III—> 0.08%). Such an approach could be adapted for this site, with ARDI values, Hy-GI (HyLogger geoenvironmental index), and total sulphur being used instead.

Type I:

total S: <0.1%; ARDI: <0/50; Hy-GI: >10,000 Lowest risk/ANC offered

Type II:

total S: 0.1 to 0.3%; ARDI: 1 to 20/50; Hy-GI: 1000 to 10,000 Low risk/NAF

Type III:

total S: 0.3 to 1%; ARDI score: 20 to 30/50; Hy-GI: <1000 High risk/AMD probable

Type IV:

total S: >1%; ARDI score: >30/50; Hy-GI: <500 Highest risk/rapid AMD

Type IV materials have the highest risk of generating acid on-site, and require greater attention in planning their handling through separation. Conversely, if encapsulation is seen as a solution, then the method of placing it in the middle of the pile requires primary consideration. Closure can be done using type III cover rock, but it should be noted that although acid formation will be less than before, it is still possible to occur in this type. An outer type II shell can then be used to finalize the waste rock pile before it is capped with type 1 and other ANC materials, and finally covered with clay. In some mining locations with an imbalanced composition of NAF and ANC, additional external supplies will be required, which will increase project costs.

Initial Handling and Control Plan

The management of environmental impact risks starts from the early stages of mining operations and determining control planning, providing opportunities for better resource preparation. This includes allowing for the evaluation of appropriate actions based on effective control hierarchy levels. By identifying this early in the project phase, this funding can be accounted for in the budget. Acid mine drainage has implications for acid formation from sulphide rocks, metal mobility, and the release of these products into the environment. Evaporation caused by high tropical temperatures can affect evaporation and precipitation rates, making it also a consideration in the initial handling review. Similarly, the permeability value of the cover waste rock pile in the deposition area can vary due to the influence of grain size and the density level of the material. These factors require consideration when designing retention ponds and sedimentation areas. Copper porphyry ore bodies (Cu) are known to potentially generate waste materials that produce acid. The discovery of new porphyry deposits will necessitate engineering studies to predict geo-environmental characteristics efficiently

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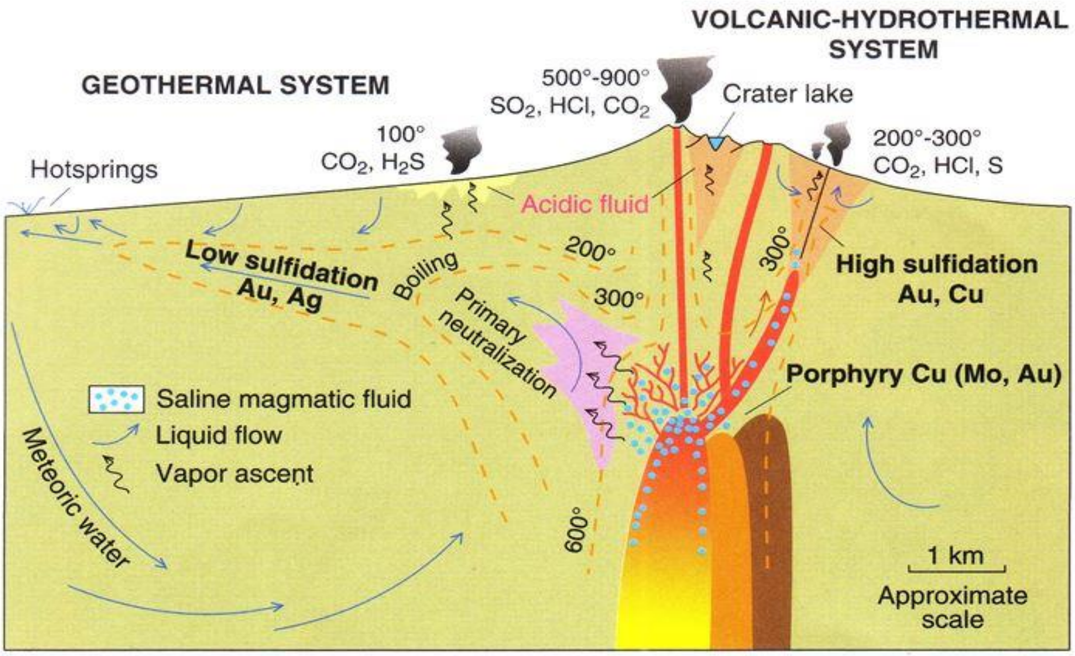
during the exploration phase. In this study, two new methodologies (modified ARDI and Hy-GI) can be developed as complementary prediction tools to drilling data, which helps in understanding the chemical characteristics of the rocks present in the ore body. Sample data from the exploration drilling results of the Grasberg ore body can provide a mineralogical assessment of this porphyry deposit and reveal the complex mineral distribution related to alteration processes, such as epidote, biotite, and calcite with variable proportions of pyrite, pyrrhotite, and chalcopyrite. Using a combination of mineralogical and chemical data, four waste classes are proposed and should be used to assist with the early engineering of waste stockpiling. From the identified waste units, volcaniclastic and feldspar porphyry are considered as Type III/IV while basalt and diorite intrusive units are more akin to Type II. This study shows that by using modified ARDI and Hy-GI, waste properties can be effectively predicted before the official static testing program begins. Doing so will allow mine operators to start developing a plan for handling mineral contaminants with negative chemical elements more effectively.



J	Massive quartz containing cm-scale pyrite with Fe-oxide weathering rind	Quartz: 66%, pyrite: 24%, rhomboclase: 4%, szmolnokite: 2%, anglesite: 1%
K	Matrix (magnetite-dolomite) supported breccia, with intense potassium feldspar alteration	Magnetite: 27%, ankerite: 22%, potassium feldspar: 15%, quartz:11%, plagioclase: 9%, epiodote: 5%, chlorite: 5%
L	Porphyritic breccia. Strong to intense potassium feldspar alteration with cross-cutting pyrite and chalcopyrite bearing carbonate and magnetite veinlets	Potassium feldspar: 63%, quartz: 14%, calcite: 11%, magnetite: 4%, chlorite: 3%, chalcopyrite: 2%, pyrite: 2%

Table 5
Summary of GMT approach classifications of the lode-Au waste rock groups A–J (NAF – not acid forming; UC – uncertain; ANC – acid neutralising capacity; AF – acid forming; PAF – potentially acid forming).

		A	B	C	D	E	F	G	H	I	J
Stage-one	ARDI	NAF/ANC	NAF/ANC	NAF	NAF/ANC	PAF	NAF/ANC	PAF	EAF	NAF/ANC	EAF
	S_{TOTAL} V ARDI	NAF/ANC	NAF/ANC	NAF	NAF/ANC	PAF	NAF/ANC	PAF	EAF	NAF/ANC	EAF
	S_{TOTAL}V paste pH	NAF	NAF	NAF	NAF	NAF	NAF	PAF and NAF	PAF	NAF	EAF
	ARDI V paste pH	NAF/ANC	NAF/ANC	NAF	NAF/ANC	PAF	NAF/ANC	PAF	EAF	NAF/ANC	EAF
	Calcite: pyrite	NAF	NAF	PAF	NAF	PAF	NAF	PAF	PAF	NAF	PAF
	CLASSIFICATION	*NAF*	*NAF*	*NAF*	*NAF*	*PAF*	*NAF*	*PAF*	*EAF*	*NAF*	*EAF*
Stage-two	NAPP V NAGpH	NAF	UC	PAF	NAF	PAF	NAF	PAF	PAF	NAF	PAF
	NAGpH V paste pH	NAF	NAF	NAF and PAF-low risk	NAF	PAF – medium risk	NAF	PAF – medium and high risk	PAF – medium risk	NAF	PAF – high risk
	MPA V ANC	NAF	NAF	PAF	NAF	PAF	NAF	PAF	PAF		PAF
	Deleterious elements V Mesotextural group	Intermediate (ML)-low risk	Low risk	Intermediate (ARD)-low risk	Low risk	Intermediate (ARD)-low risk	Low risk	High and Intermediate (ARD) risk	Intermediate risk (ARD)	NAF	High and Intermediate (ARD) risk
	CLASSIFICATION	*NAF*	*NAF*	*PAF*	*NAF*	*PAF*	*NAF*	*PAF*	*EAF*	*NAF*	*EAF*
Stage-three	M-NAG V NAG	NAF	NAF	NAF	NAF	PAF	NAF	PAF	EAF	NAF	EAF
	M-NAG V S-NAG V NAPP V NAG pH	NAF	NAF	NAF	NAF	PAF	NAF	PAF	EAF	NAF	EAF
	K-NAG	N/A	N/A	N/A	N/A	N/A	N/A	Currently testing	Currently testing	N/A	EAF: 9–11 weeks to acid generation
	Deleterious element issues	No	No	No	No	No	No	Yes – Cd, Zn, Bi	Yes – As, Co	No	Yes – Cu, Pb, Sb
	MLA textural analysis*	N/A	N/A	NAF	N/A	NAF	N/A	PAF	EAF	N/A	EAF
	CLASSIFICATION	*NAF*	*NAF*	*NAF*	*NAF*	*PAF*	*NAF*	*PAF*	*EAF*	*NAF*	*EAF*

Table 6
Summary of GMT approach classifications of the IOCG deposit groups K-Q (NAF – not acid forming; UC – uncertain; ANC – acid neutralising capacity; AF – acid forming; PAF - potentially acid forming).

		K	L	M	N	O	P	Q
Stage-one	ARDI	NAF/ANC	NAF/ANC	NAF/ANC	NAF/ANC	NAF/ANC	NAF and PAF	NAF and PAF
	S_{TOTAL} V ARDI	NAF/ANC	NAF/ANC	NAF/ANC	NAF/ANC	NAF/ANC	NAF and PAF	NAF and PAF
	S_{TOTAL}V paste pH	NAF	NAF	NAF	NAF and PAF	NAF	NAF and PAF	NAF and PAF
	ARDI V paste pH	NAF/ANC	NAF/ANC	NAF/ANC	NAF/ANC	NAF/ANC	NAF and PAF	NAF and PAF
	Calcite: pyrite	ANC	ANC	ANC	ANC	ANC	AF	AF
	CLASSIFICATION	*NAF/ANC*	*NAF/ANC*	*NAF/ANC*	*NAF/ANC*	*NAF/ANC*	*UC*	*UC*
Stage-two	NAPP V NAGpH	NAF	NAF	NAF	NAF and UC	NAF	NAF and UC and PAF	UC and PAF
	NAGpH V paste pH	NAF	NAF	NAF	NAF and PAF-low risk	NAF	NAF and PAF-low risk	NAF and PAF-low risk
	MPA V ANC	ANC	ANC	ANC	PAF	ANC	PAF	PAF
	CLASSIFICATION	*ANC*	*ANC*	*ANC*	*UC*	*ANC*	*UC*	*UC*
Stage-three	M-NAGpH V NAGpH	–	NAF	NAF	NAF	NAF	NAF	NAF
	M-NAG V NAPP V NAG	–	–	–	–	–	–	–
	K-NAG	–	–	–	NAF	–	–	–
	ABCC	Effective neutraliser	Effective neutraliser	Effective neutraliser	–	Effective neutraliser	–	–
	CLASSIFICATION	*ANC*	*ANC*	*ANC*	*NAF*	*ANC*	*PAF*	*PAF*

Initial investigations into the rock formation of ore bodies can provide a reference for the potential formation of acid mine drainage. Looking at the data tables and the mineral composition of the rocks in the Grasberg ore body, they can be grouped into classifications J, K, and L which are combinations of Extremely Acid Forming (EAF) and effective neutralizer ANC. This classification then provides a reference for control plans by adding anticipation programs for the potential occurrence of acid mine drainage into design engineering activities:

- Mining operations, consideration of pyrite-ANC mixing
- Ore processing facilities, optimization of grinding, treatment of leftover material (tailings), and potential utilization of pyrite contaminant minerals
- Management of overburden waste (tailings)

Establishment of Steps or Roadmap for Impact Risk Management of Pyrite

The main goal of the Geoenvironmental modelling described in this compilation is to provide information that can be used to understand, anticipate, minimize, and remedy the environmental effects of mineral deposits and mineral resource development. Mine operators can use these models to develop perspectives on historical environmental impacts and potential future impacts related to mineral reserves. Additionally, these models should help in developing mitigation strategies and ecosystem-based land management plans. Many models include data, such as the natural environmental baseline before mining, which can be effectively applied during post-mining remediation efforts. These models include objective information available to all stakeholders; they have the potential to benefit industries, regulators, land managers, and the public. Some models not only present potential environmental issues that may be related to certain types of mineral deposits, but also provide information on how to avoid, minimize, or mitigate the environmental impacts associated with mineral deposits. A roadmap is a strategic planning technique that sets targets and achievements within measurable time frames. Mining operations are closely related to the potential disruption to the environment, thus requiring proper management planning throughout all stages. Taking the case study of the Grasberg sulphide mineral ore body, the environmental impact and influence can be described through the implementation of the following activities:

Survey of baseline environmental conditions before mining

Considerations for more effective, technology-feasible, and realistic handling must be conducted to remediate mining locations to their original conditions caused by acid mine drainage. This begins with tracking the initial conditions before mining takes place along with the potential impacts that may arise and affect the environmental quality standards. This is primarily due to the potential formation of acid mine drainage by the

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contaminating mineral content of pyrite. At the initial condition before mining operations commence, there may already be surface outcrops of pyrite-contaminating minerals that have oxidized due to natural conditions, thus generating acid from the start. Measurement and identification of this aspect need to be conducted to understand the exposure that has occurred since the beginning. Mapping the potential impacts, management forms, and involved parties can be performed through the following tabulation:

A. Study of Environmental Impact Potential
✓ The formation of acid mine drainage with the consequence of declining surface water quality.
✓ Oxidized pyrite sulfide rocks that are not neutralized can form acid rock drainage.
✓ The formation of Acid Mine Drainage (AMD) can be controlled so that the impact on surface water quality can be minimized with indicators: ✓ Monthly pH value recording on the Wanagon River in Banti Village (#57) ≥ 6 ✓ No increase in the concentration of dissolved metals (Cu, Cd, Zn, Pb, As, Ni, Cr, Hg) in surface water was found in the long term. ✓ The drainage water from the mine and the overburden can be utilized and used directly.
B. Study of Environmental Management Forms
✓ Ensuring that all stockpiles of overburden rock with pyrite content are mixed with lime. ✓ Channeling the drained water from the overburden waste pile to the ore processing plant through the established network (lime canal) ✓ Draining surface runoff and seepage water through limestone rock drains. ✓ Ensure that all sediment flows into the designated sedimentation area. ✓ Reclamation of areas covered with overburden adjusted to the mining reclamation plan. ✓ Determination of the capacity for Net Acid Production (PAN) of waste rock from the excavation and drilling of blast holes to classify the category of waste rock based on its geochemical characteristics. ✓ Performing engineering operations for the mixing of mining ore between acid-forming rock and acid-neutralizing rock. ✓ Modify the collection pond and sedimentation area to accommodate the pyrite content in the ore body.
✓ Sample collection from blast holes and excavation areas ✓ Location of stockpiling waste overburden ✓ Sample of underground drainage water ✓ Sample of ore processing plant
Carried out during the life of the mine
C. Liability - Environmental Management Institution
Environment Department - PTFI
✓ Environmental Agency of Mimika Regency ✓ Environmental Agency of Papua Province ✓ Ministry of Environment and Forestry
✓ Environment Agency of Mimika Regency ✓ Environment Agency of Papua Province ✓ Mining and Energy Agency of Mimika Regency ✓ Mining and Energy Agency of Papua Province ✓ Ministry of Environment and Forestry ✓ Ministry of Energy and Mineral Resources

The initial measurement of pH value as a reference for the environmental index regarding the potential risk of acid mine drainage before the underground mining operations are carried out shows a value of ≥ 6. This value is taken from the Wanagon River in Banti, which is the final discharge point of wastewater from the mine.

Assessment of potential impacts through data exploration studies

Knowledge about the potential environmental effects related to mineral exploitation with specific rock chemical element content can be integrated into exploration programs to complement mining planning data. Mining an ore body with a high potential to generate acid mine drainage may provide lower environmental mitigation financing if abundant carbonate rocks or other types of rocks that can neutralize acid are also found at the same location. Potential risk assessments can be conducted in various ways, such as through ARDI (Acid Rock Drainage Index) assessment based on exploration data and field sampling. Sampling through exploration drilling activities and laboratory testing will describe the characteristics of the rocks and their influence on PAF (Potentially Acid Forming) and requires an integrated program. The study not only considers the need for process optimization based on metallurgical aspects but also includes the chemical elements of the rocks that will affect the overall mining operation towards the ultimate goal of achieving green mining. Conducting an effective environmental ore characterization study at the pre-feasibility/feasibility stage is very important for efficient mining operations, as well as reducing post-production environmental impacts. Environmental parameters that need to be characterized include the tendency of rock in the ore body to form acid, chemical reactions of hazardous elements, and the toxic potential of heavy metals. A common practice in predicting the formation of acid rock drainage (ARD) that is widely developed today is carried out through geochemical assessments based on laboratory tests and is examined in conjunction with mineralogical evaluation of the ore body. Assessment of rock texture in the context of ARD requires a clear explanation and includes measurements of sulfide content and main neutralizing minerals. This assessment also includes the evaluation of mineral groups in the rock at each stage in the process of forming acid. More consideration is given to the reactivity of rocks during the acid formation stage, particularly concerning the specific surface area. Textural characterization studies are an example of a method that is considered effective to this day in assessing the potential for rock acid formation, focusing on micro-scale evaluation.

Planning and development of mines that accommodate environmental aspects

Predictive capabilities that can be enhanced through geoenvironmental modelling will enable mine planners to better estimate, plan, and mitigate potential environmental issues, rather than dealing with them later. This is especially relevant to the view of technical challenges with issues that will increasingly evolve and become more complex. Additionally, there will be the possibility of financing that will be much greater if the environmental impact issues have created exposure and require urgent handling. The inherent geological characteristics of a particular deposit can be utilized to help mitigate potential environmental disturbances that may occur in the future, for instance by using natural resources in the form of carbonate rock content from the ore body itself. Similarly, other types of chemical elements in the rocks can function as acid neutralizing media and mitigate the potential occurrence of acid mine drainage based on prior predictions. Planning mining operations, ore processing, and managing rocks with the potential to generate acid mine drainage should be considered from the early stages of mining with studies on the use of natural media present in the ore body itself. The study of geoenvironmental aspects that has not been effectively involved in current mining operation engineering has become its own discussion literature and requires a roadmap to ensure that it becomes an important part of strategic mining operation planning. The focus of geoenvironmental study is on geospatial modelling in fields related to the earth's environment concerning industrial activities, ecology, hydrology, management of sedimentation ponds or reservoirs, potential geological risks, estuary ecology, groundwater, agriculture, climate change, land-water resource, and forests. Geoenvironmental modelling techniques have developed over the last few decades within the earth and social environmental science research community due to their ability to understand various complex issues and to develop new approaches to addressing environmental disturbances caused by industrial activities. Geoenvironmental modelling in the mining industry can clearly and effectively help align operational planning that meets the context of green mining.

Remedial Program

The model presented in this compilation summarizes crucial geological, geochemical, and hydrological information (such as geological control over groundwater flow, ore mineralogy, and material geology) needed by mining professionals to develop effective remediation plans at mine sites. Some of the remediation plans currently being implemented overlook or greatly simplify geological information that is important to determine the improvement program in case failures occur at early stages. Identifying pockets of water or potential seepage flows that will inundate locations with large volumes of pyrite will then determine the remediation program through water diversion. The engineering of water diversion can take the form of creating drainage holes or sealing rock fractures through high-pressure injections of cement or flocculating liquids. Geoenvironmental modelling can be used to identify the type of deposits with the geological structure of rocks,

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faults, or other natural hydrological pathways that may occur. Reducing the flow rate of water and redirecting it to designated paths can reduce the exposure of key elements that form acid mine drainage, making it a part of the remediation solution study.

Post-Mining Guarantee Considerations / Addressing the issues of former mining land

Although mineral resource extraction has been carried out for several millennia, minimizing environmental effects has received minimal attention in recent decades. This has resulted in many abandoned mining and mineral processing sites that are now potential sources of environmental pollution. In some countries, such as the United States, land management agencies are currently facing the daunting task of identifying and prioritizing the remediation of all abandoned mining lands that have become public land. Some remaining mining land, although not requiring serious repairs, still poses an additional burden for the government regarding the land use conversion. The geo-environmental modelling presented in this compilation provides an initial study on the potential of land use conversion and future planning once a mine is no longer operational. The roadmap developed offers opportunities for strategic studies of mining operations while also considering the post-mining period. Mitigation programs through the early identification of environmentally friendly mining achievements also consider long-term programs at each stage of mining, from exploration, development-construction, production and processing, mine closure to post-mining. This includes prioritizing environmental studies and developing remediation plans for former mining lands containing chemical elements of rocks that may pose environmental risks.

A series of laboratory-scale research/tests consisting of static geochemical studies (Acid Base Accounting Test) aimed at characterizing the geochemistry of the Grasberg rock. The results of this characterization test indicate that the geochemical study of the rocks can be classified into four types, namely:

- Green Type, Acid Consumer, NAG = 0
- Blue Type, Acid Producer, with NAG = 1 – 35 kg H2SO4/ton, Pyrite: 1-3%
- Red Type, High Acid Producing Capacity, with NAG > 35 kg H2SO4/ton, Pyrite: 3-20%
- HSZ Type, High Acid Producing Capacity, Pyrite > 20%

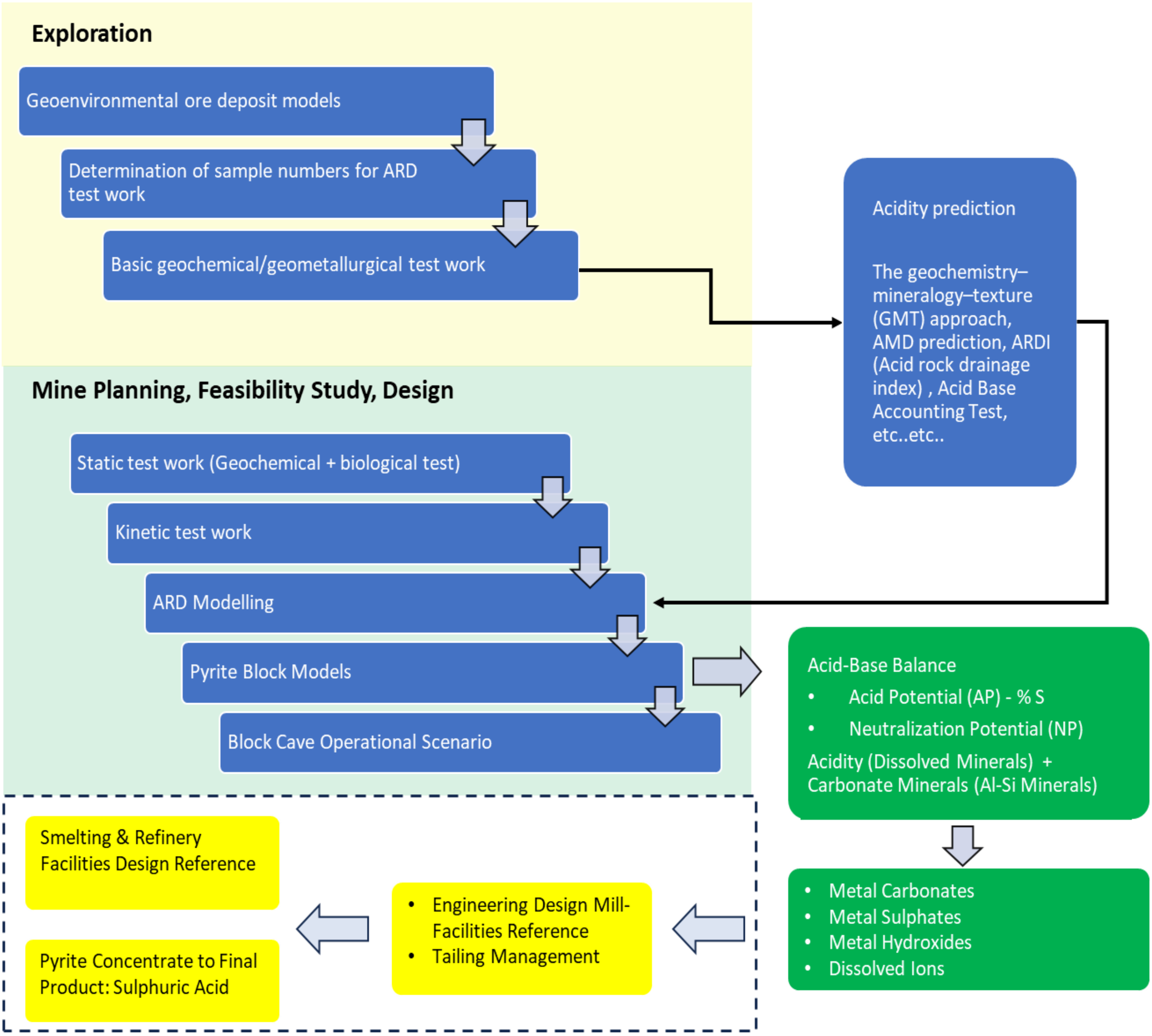
Research has been conducted to test the success of covering the cap rock using limestone with a thickness of 2 meters. The study was carried out by piling limestone on one of the cap rock panels that contained sulfide minerals. The results of these tests can also be used as a reference for the planning of mixing operations.

The data from this research is as follows:

- The mixing of blue and red cover rocks with limestone in a ratio of 75%: 25% and 50%: 50% is effective in controlling the formation of AAT.
- Covering with limestone can neutralize the formation of AAT in BP stockpiles at a rate of 0.2 - 0.5 m/year. Covering also slows down the oxidation process, which is presumed to be due to high rainfall factors that increase the amount of dissolved alkalinity intake from the limestone covering into the body of the stockpile rock.
- The placement of limestone and cover rocks in layers is not effective in controlling the formation of AAT because the limestone layer will create a coarse layer that facilitates the flow of oxygen to the interior of the pile.
- The release of acid from blue and red type cover rocks occurs over a short period, while acid release from cover rocks rich in pyrite minerals (HSZ) will take a very long time. This is believed to be due to the fact that pyrite minerals that form HSZ are more stable and not very reactive to water and air. In the mixing process, the layering of pyrite minerals by jarosite and aluminosilicate will slow down the oxidation process.

The characteristics of rocks can be determined based on the geochemical characteristics of the rocks through a series of tests, namely static tests with measurements of Total sulphur, pH paste, NAG pH, ABA method, which will be verified by kinetic tests through the Free Draining Column Leach Test (FDCLT) by measuring physical and chemical parameters, as well as mineralogical tests with X-RD to determine the mineral composition contained in the rocks. The prediction of potential acidity levels can be obtained through a collaborative program between exploration activities and the initial engineering design phase of mining operations. This program requires a flow of implementation that can be used as a guideline in executing the work.

The determination of steps or a roadmap for managing the potential impact of pyrite contaminating minerals from the upstream production operations can then be illustrated in the following chart.



The analysis strategy regarding the handling of pyrite contaminating minerals requires achieving results in the early stages of mining operations, which is to obtain the acid potential value and the neutralizing acid potential value. From these two assessments, the mining operation pattern is then determined with the aim of balancing ore extraction from the drawpoints. For the block caving mining method, the design engineering of production operations not only focuses on mapping for economic benefits in terms of mineral content grade but also considers the composition of pyrite. This is done by establishing patterns and directions of caving based on the pyrite block model and the simulation of acid-neutralizing rock (NP) mixing.

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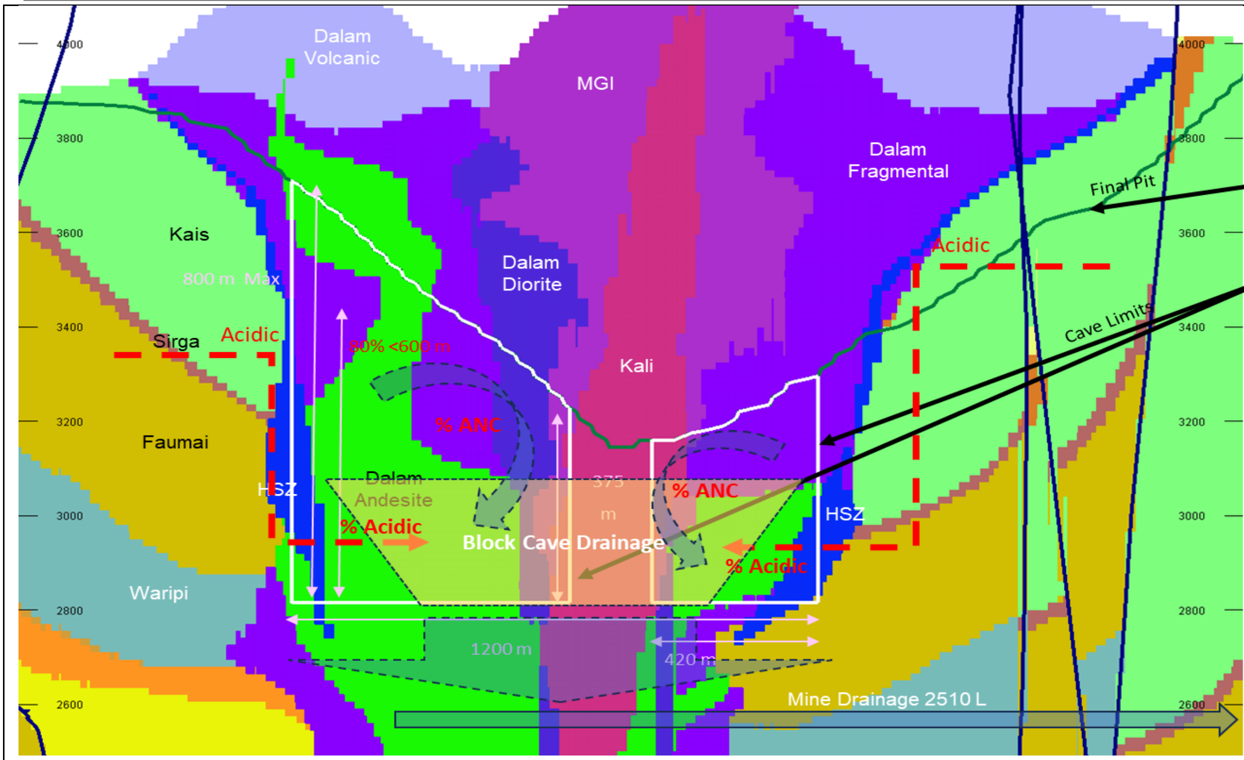
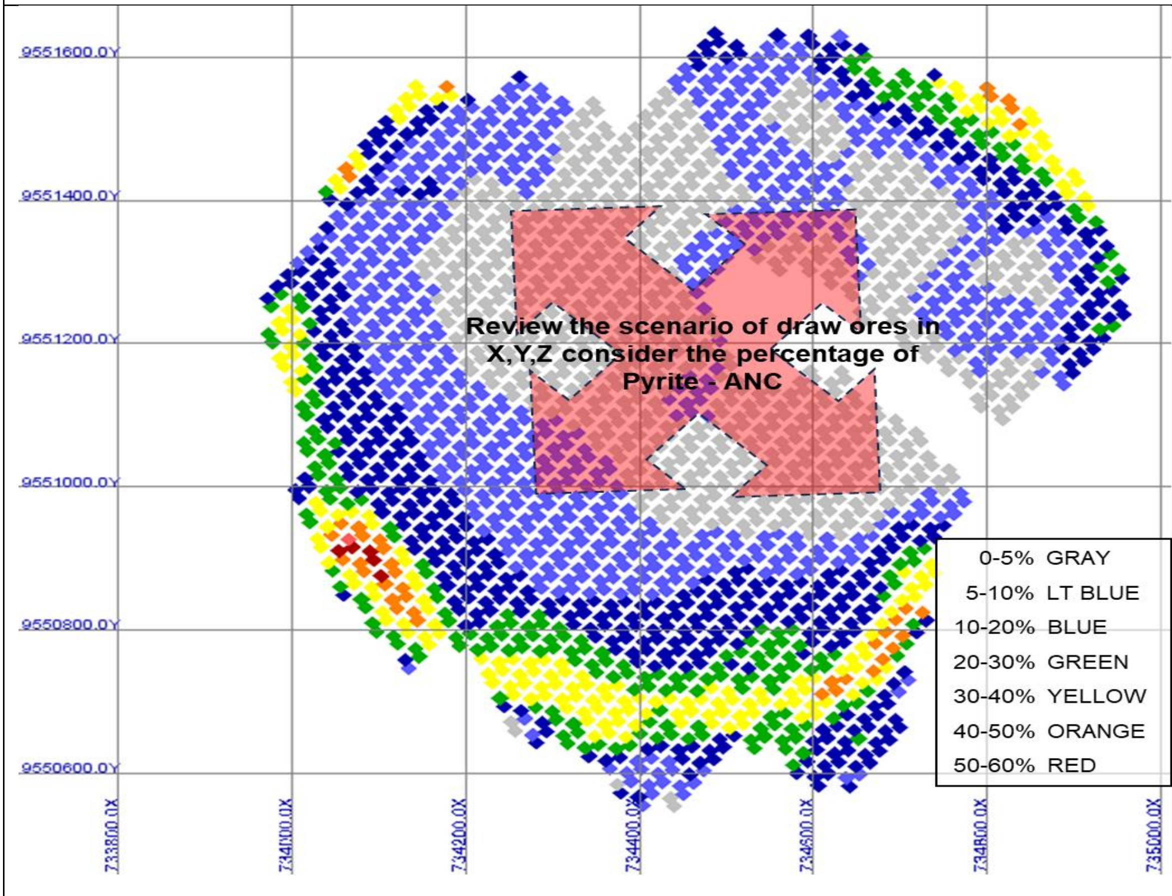
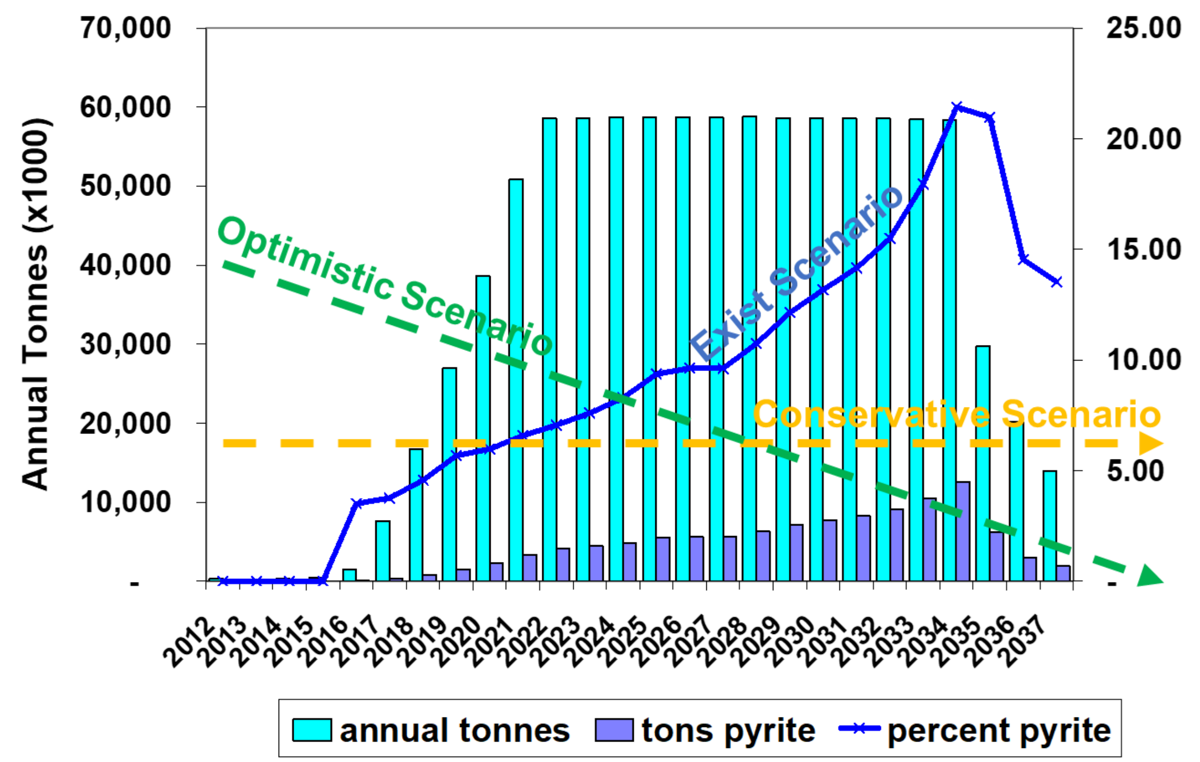


The initial prediction of rock composition with acid-generating potential and acid neutralization potential is obtained through exploration data and mixing tests that are conducted. In the Grasberg porphyry ore body, it shows a balanced composition between sulfide rock groups and carbonate rock groups. The mining operation scenario can consider a balanced extraction by first creating acid rock drainage (ARD) modeling and creating a pyrite block model.

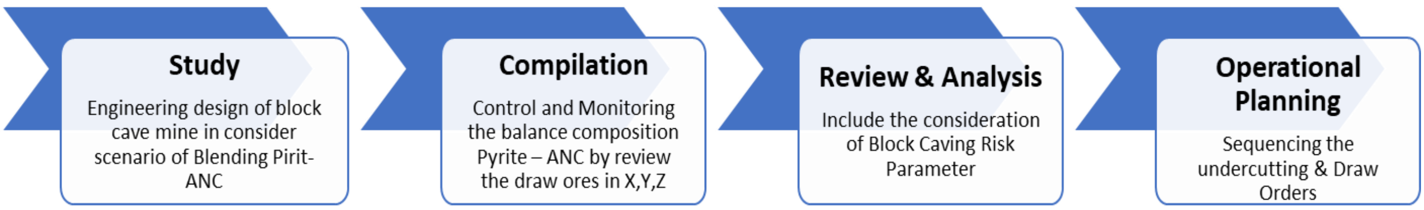


Mapping of pyrite through this column block model allows for the simulation of ore extraction from the cavity along the X, Y, Z axes for achieving balanced composition of Pyrite - ANC.



Planning for draw order with the objective of balancing the percentage composition of pyrite – ANC during the mining lifetime can be simulated in several achievable operational scenarios. The strategy scenario in plan for implementation in this situation of complexity geometallurgy of orebody covers; adjustment of cave sequence in properly managing the pyrite, optimizing the performance of processing facilities and the consistency of energy supply, reduce potential residual risks in the period end of mining and/or stage of post-mining.

The handling of pyrite and its potential negative impacts who can generate acid mine drainage requires a specific and integrated management roadmap. This especially in supporting scenario of achieving an efficient operation scenario considering the cost effectiveness without suffering the quality of environment. The proposed handling roadmap will serve as a reference for preparation AMDAL (Environmental Impact Analysis) and the development of the scope for monitoring activities.



Risk mitigation is carried out through the engineering design targeting efficiency and environmentally friendly on mining operations who require a robust guideline to ensure that all aspects have been taking into consideration. This includes for any requirements coming from various stakeholders in propose to meet and shall align with the plan operational scenario. The authority agent as such Government agency who are responsible for managing, supervising, and making decisions can perform their duties effectively in accordance with the availability and sufficient information is provide on data. In regard to the Environmental Management Plan (RKL) and the Environmental Monitoring Plan (RPL), the establishing roadmap also provides a reference for:

a. Environmental Management Plan (RKL), which includes studies and evaluations concerning:

- ❑ Managing environmental impacts

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- ✓ Impacts that arise
- ✓ Sources of impacts
- ✓ Indicators of success in environmental management
- ❑ Forms of environmental management
- ✓ Environmental management efforts
- ✓ Management locations o Management period
- ❑ Environmental management institutions
- ✓ Implementers
- ✓ Supervisors
- ✓ Report recipients

b. Environmental Monitoring Plan (RPL), which contains studies and evaluations regarding:

- ❑ Monitored Environmental Impacts
- ✓ Arising Impacts
- ✓ Sources of Impacts
- ✓ Impact Parameters

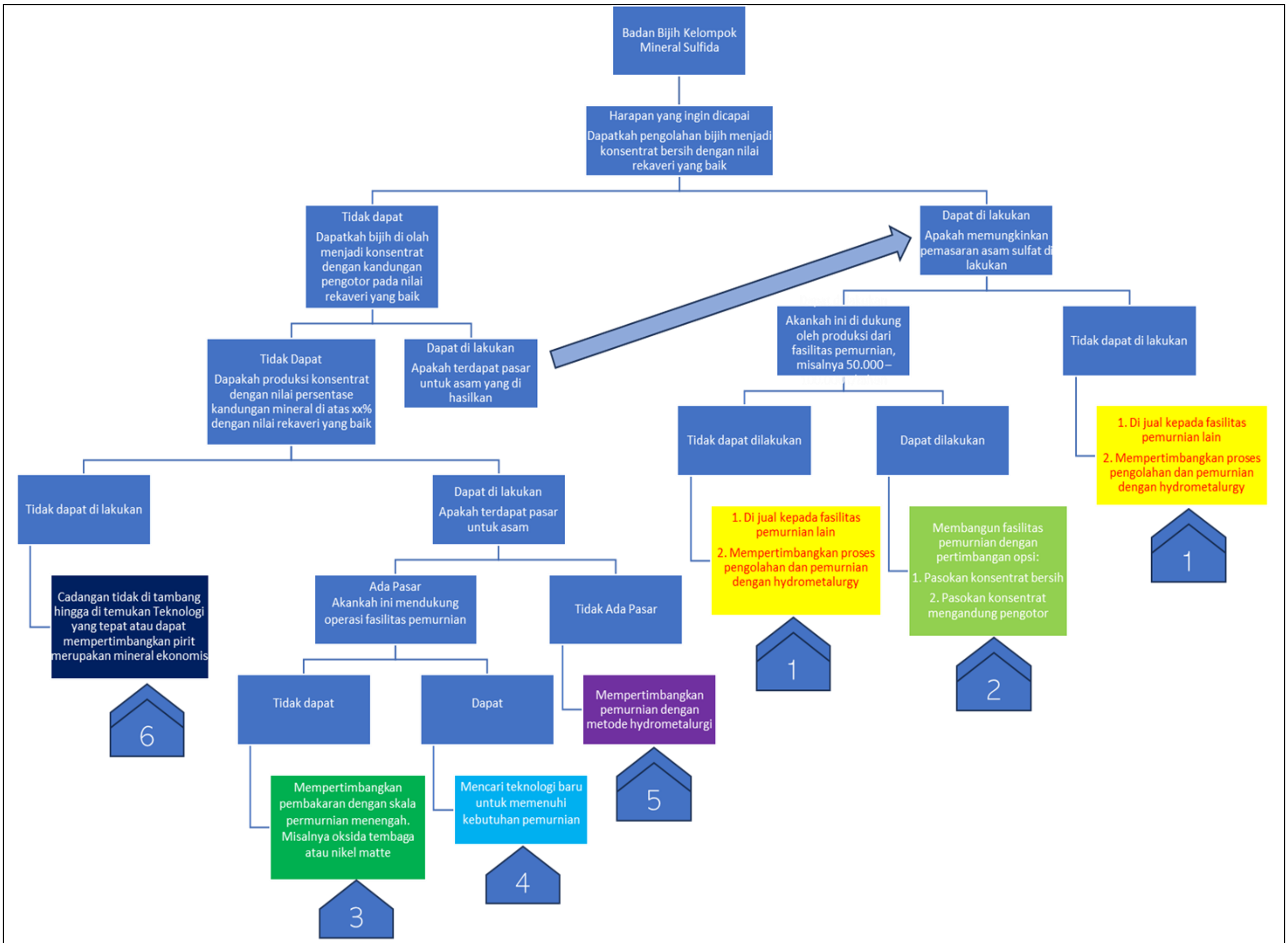
❑ Forms of Environmental Monitoring

- ✓ Data Collection Methods
- ✓ Data Analysis Methods
- ✓ Monitoring Locations
- ✓ Monitoring Time & Frequency
- ❑ Environmental Monitoring Institutions
- ✓ Implementers
- ✓ Supervisors o Report Recipients

The risk mitigation program through integrated mining design engineering can function well and provide assurance for the management of potential impacts if a standard implementation roadmap is created and make to available.

CONCLUSION

The handling of pyrite requires a roadmap that allows for the execution of work to be carried out completely, comprehensively, and independently. The management of negative impacts from the chemical components of rocks requires special treatment considering it involves different knowledge backgrounds and has significant impacts if not done correctly. The financial impact of improper handling is not only on the internal funding of production operations but also on the potential extra cost due to the consequences of degraded standard quality of environmental. In addition, there are positive benefits from the presence of pyrite-contaminating minerals in other industrial uses that can be discussed in a separate study. All of this can be studied in an integrated manner between the efforts to handle the negative impacts of pyrite and the positive benefits of using pyrite in separate industries through the creation of a roadmap (Pyrite Roadmap). The created roadmap will provide guidelines for the implementation on each stage of the mining operation starting from the stage of exploration, sampling and testing, and finally the stages of engineering design for mining operations. The roadmap for handling pyrite is to setup based on the steadiness value that will be achieved in the concept of eliminating the potential environmental risk that caused by pyrite oxidation, which enters waterways and generates acid mine drainage, while also considering the potential benefits of using pyrite in the other applications.



Propose Roadmap of Handling and Managing the Pyrite through exercise treatment of negative impact while enhancing the opportunity to commercialize Pyrite.

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