Application of data analytics to predict gold recovery from glycine-based bottle roll tests using Witwatersrand supergroup composite ore

V. Notole[1], G. T. Nwaila[1], J.E. Bourdeau[1,2], and S.E. Zhang[1,2]

[1]University of the Witwatersrand, South Africa.
[2]Geological Survey of Canada, Canada

Gold ores of the Witwatersrand Supergroup are known to be amenable to various extractive metallurgy processes such as cyanidation. However, Elsburg reefs are characterised by unliberated gold, inclusion rich pyrite and sub-rounded quartz. Therefore, the process of leaching gold from these deposits can be complex and time-consuming. To mitigate these factors, integration of ore geometallurgical characteristics with data analytics can be used to model leaching kinetics and predict the duration required to achieve optimal gold recovery, specifically using glycine and potassium permanganate as leaching reagents. The use of alkaline glycine for gold leaching is a non-toxic and environmentally friendly alternative to cyanide-based methods. Glycine leaching is primarily influenced by parameters such as ore geometallurgical characteristics, reagent concentrations, temperature and duration. A total of six bottle roll test outcomes using Elsburg reefs showed that a gold recovery of up to 42% can be achieved after 50 hours of leaching with a solution of 1500 ppm glycine and 3000 ppm potassium permanganate. Geometallurgical results, combined with data analytics, predicts a leaching time of around 100 hours to reach ~85% gold recovery under the same conditions as the initial test work. The validation experimental data suggest that we can achieve a maximum of 86% gold recovery within 101 hours of leaching. Overall, the application of data analytics can augment experimental results and help optimise leaching parameters, thus reducing the number of experimental tests.

Keywords: Geometallurgy, gold, pyrite, glycine, auriferous conglomerate, Witwatersrand Supergroup, leaching, data analytics

INTRODUCTION

Geometallurgy involves integration of geological, mineralogical, and extractive metallurgical data within a three-dimensional framework to construct a predictive mineral processing model that takes spatial awareness into account (Zhou and Gu, 2016). This model, known as a geometallurgical model, expands upon the traditional mineral resource or reserve modelling (Dominy *et al.*, 2018). While geometallurgy originally emerged as a subset of mineral processing, it has evolved into a discipline that offers advantages throughout the mineral value chain (Dominy *et al.*, 2018; Lishchuk *et al.*, 2020). Geometallurgy captures the inherent variations present within a mineral deposit, quantifies and assesses the repercussions of variables (e.g., ore grade and liberation) influenced by geological and mineralogical factors on milling, leaching, and metal recovery processes (Nwaila *et al.*, 2020). Automated mineralogy is widely adopted by the minerals industry and research organisations for characterising ores (Lishchuk, 2016).

Generally, automated mineralogy employs scanning electron microscopy hardware as a foundation, paired with software, to provide insights into mineral phases, composition, liberation, associations, particle size distribution, and metal distribution. Its significance extends to both geometallurgical and hydrometallurgical studies, particularly gold ore characterisation.

In the realm of mining and metallurgy, the recovery of valuable metals, such as gold, from ore deposits plays a crucial role in determining the economic viability of mining operations (Wills and Finch, 2015). Achieving efficient recovery from complex ore deposits requires the optimisation of various processing parameters, including leach kinetics (Altinkaya *et al.*, 2020; Larrabure and Rodríguez-Reyes, 2021). Leaching is a process that involves extracting target metals from ore using a solvent and is commonly used for gold recovery (Wilson *et al.*, 2014; Ashiq *et al.*, 2019). The most preferred leaching method for gold in the Witwatersrand Supergroup (South Africa) is cyanidation (Marsden and House, 2006; Nwaila *et al.*, 2020). The Witwatersrand Supergroup ore deposits that are renowned for their substantial gold content (Fuchs *et al.*, 2016; Frimmel, 2019) may present significant processing challenges due to their increasingly complex mineralogy and variable geometallurgical characteristics (Nwaila *et al.*, 2020). Optimising leaching parameters (duration, temperature, reagent concentrations, etc.) is essential to achieve acceptable gold recovery (>85%) (Birloaga and Vegliò, 2022).

Traditionally, the optimisation of leaching kinetics, including the leaching duration, has relied on empirical methods and laboratory experiments, which are time-consuming, costly, and often limited in their ability to capture the complexities of the ore composition (Dominy *et al.*, 2018). To overcome these limitations, modern data analytics can be leveraged to infer optimal leaching parameters and improve gold recovery rates. Data models offer the potential to capture intricate relationships between various ore characteristics, leaching parameters and experimental gold recovery outcomes, thereby enhancing geometallurgical results (Mokarian *et al.*, 2022; Saldana *et al.*, 2022). By harnessing data from laboratory experiments and incorporating a range of parameters that influence leaching, a predictive model that is capable of estimating optimal leaching duration of gold from different ore deposits can be developed.

In this study, we integrate mineralogical (including ore texture), extractive metallurgical (leaching experiments), and analytics-based modelling to estimate the required leaching duration to achieve acceptable gold recovery (>85%) from Witwatersrand Supergroup composite ores (i.e., Elsburg reefs). Specifically, we utilised glycine and potassium permanganate as the leaching agents. The results of this study contribute to the advancement of gold recovery methods by providing a reliable and efficient means of estimating optimum leaching residence time. This, in turn, will help optimise the overall ore processing workflow and enhance the sustainability of gold mining operations. Furthermore, the integration of data analytics in geometallurgy and hydrometallurgy holds promise for accelerating research and development efforts, facilitating the adoption of data-driven methods within the minerals industry.

GEOLOGICAL CHARACTERISTICS

The 3.66 to 2.67 billion years old Witwatersrand Basin is situated in the central part of the Kaapvaal Craton (Figure 1; Kositcin and Krapež, 2004; Kröner *et al.*, 2019; Zeh *et al.*, 2020). The craton is characterised by various lithological formations (rock types) such as greenstone-granite belts, volcanic rocks, and sedimentary successions from the Witwatersrand Supergroup (Phillips and Law, 2000; Frimmel, 2014; 2019). Notably, the Witwatersrand Supergroup contains gold-rich pebble-sized quartz conglomerate beds called 'reefs' (Frimmel, 2014). This study examines the Elsburg reefs located at the South Deep Mine near Westonaria, about 45 km southwest of Johannesburg. The Elsburg reefs consist of multiple layers (i.e., nine major layers) of auriferous conglomerate separated by a barren quartzite layer from Ventersdorp Contact Reef (VCR) (Manzi *et al.*, 2013; Osburn *et al.*, 2014; Tucker *et al.*, 2016). Each layer has unique mineralogy, geochemistry and gold grade. For example, Modderfontein Intermediate Top bed (MIT) is more auriferous and generally has higher concentrations of all trace elements (e.g., V, U, Pb, Cu, Ni and Au) as compared to the underlying Elsburg Conglomerates Top bed (ECT) layer. These layers are part of a clastic wedge that diverges in an easterly direction (Fields, 2012).

The total thickness of Elsburg reef at South Deep Mine is ~ 130 m (Fields, 2012). The mineralogy of the reefs comprises quartz, pyrite, pyrrhotite, chalcopyrite, chlorite, and trace amounts of zircon, rutile and other minerals (e.g., gersdorffite, arsenopyrite, columbite etc).

Unlike most gold in the Witwatersrand Basin, the Elsburg reefs are characterised by unliberated gold, particularly in the ECT layer. Gold in Elsburg reefs layers (MIT and ECT) is often found in gangue minerals, appearing as intergrowths, micro-veinlets and micro-inclusions. Gold grade in these reefs varies, with an average grade of 6.5 grams per tonne of gold (g/t Au). The thickness of the conglomerate layer is positively correlated with the gold enrichment in the Elsburg reefs (Frimmel, 2019; da Costa *et al.*, 2020; Frimmel and Nwaila, 2020). Mineral reserves at the South Deep Mine are primarily contained in the Elsburg reefs (approximately 99%) with lesser proportions in the Ventersdorp contact reef (approximately 1%) (Tucker *et al.*, 2016; Mngadi *et al.*, 2019).

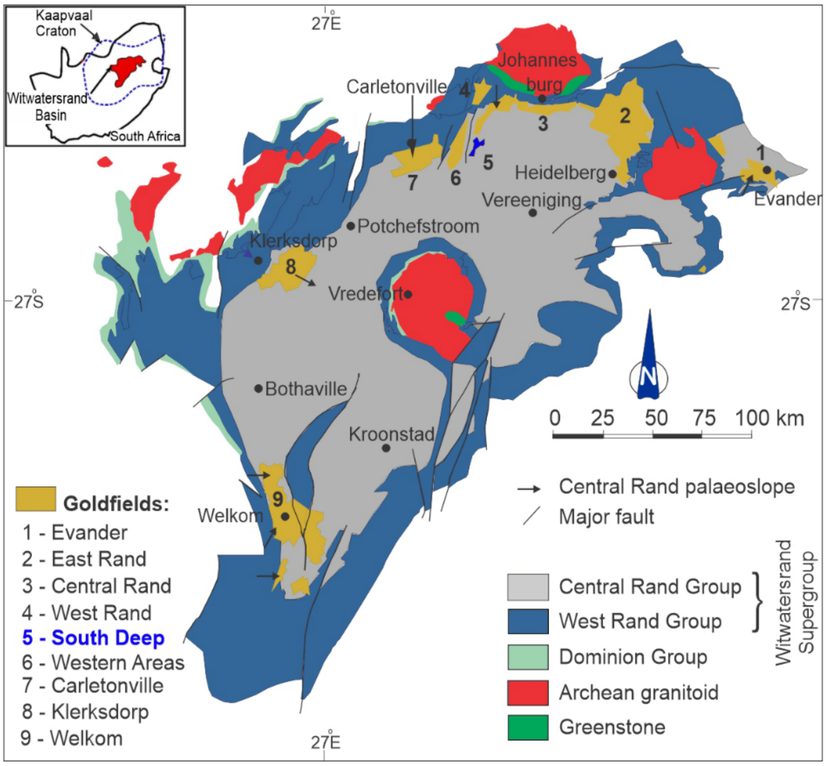

Figure 1. The simplified geological map of the Witwatersrand Basin showing the Witwatersrand Supergroup, location of South Deep and other goldfields (modified after Frimmel, 2019).

REVIEW ON GOLD LEACHING USING GLYCINE

Previous studies on gold leaching using glycine and potassium permanganate have shown promising results in enhancing the efficiency of gold recovery processes. Specifically, a study investigated the leaching behaviour of gold from a refractory ore using a glycine-potassium permanganate system (Perea and Restrepo, 2018). The researchers found that combining glycine and potassium permanganate significantly improved gold extraction compared to traditional cyanide leaching methods. The presence of glycine in the leaching solution facilitates the formation of stable gold-glycine complexes, which promote gold dissolution (Tanda *et al.*, 2017). Furthermore, the addition of potassium permanganate that act as an oxidant, thus enhancing the reaction kinetics and overall leaching efficiency (Oraby *et al.*, 2020). These findings highlight the potential of using glycine and potassium permanganate as alternative reagents for gold leaching, offering a safer and more environmentally friendly approach than the conventional cyanidation process.

In another study, Oraby *et al.*, (2020) investigated the effect of various parameters on the glycine-potassium permanganate leaching system. They explored the influence of glycine concentration, potassium permanganate dosage, temperature and particle size on gold extraction. The results indicate that higher glycine concentrations and potassium permanganate dosage result in improved gold recovery rates. Additionally, higher temperatures and finer particle sizes enhanced the leaching kinetics and overall gold extraction. These findings provide valuable insights into the optimisation of the glycine-potassium permanganate leaching system, suggesting potential strategies for improving gold recovery processes in future.

Overall, previous studies on gold leaching using glycine and potassium permanganate demonstrate the feasibility and effectiveness of this approach as opposed to the traditional cyanidation process. Combining glycine as a complexing agent and potassium permanganate as an oxidant offers a viable and environmentally friendly alternative to cyanide-based gold extraction methods (Tanda, 2017; Li *et al.*, 2022). Further research and optimisation of process parameters can contribute to the development of a sustainable and efficient gold recovery process that minimises environmental impacts and ensures the responsible utilisation of valuable mineral resources.

MATERIAL AND METHODS

Sample Collection and Preparation

Two batches of bulk samples with a total weight of 40 kg were collected from the Elsburg reefs at South Deep Gold mine. One batch of high-grade samples (20 kg) was from the MIT and another batch of low-grade samples (20 kg) was from the ECT. A total of ten (five samples from MIT and five samples from ECT) mineralised samples were selected for thin section preparation and thereafter a detailed mineralogical analysis using a TESCAN integrated mineral analyser (TIMA). The analysis using TIMA was carried out at the University of the Witwatersrand in the School of Geosciences. The remaining ore samples (10 kg from each batch) were crushed and subsequently milled to pass a 75 µm sieving screen at 90% by mass. Both the jaw-crushing and milling machines were cleaned between samples to avoid cross-contamination. Milled samples were then quartered, blended (50% MIT and 50% ECT) and split to obtain representative samples for X-ray diffraction (XRD) analysis, as well as for gold fire assay. The XRD analyses were performed at the XRD Analytical & Consulting laboratory while gold fire assay was conducted at Super Laboratory Services in South Africa. Leaching experiments were conducted using milled samples with 90% by mass pass a 75 µm screens. Samples were assayed using the standard gold fire assay method to determine head feed ore grade (g/t) for hydrometallurgical work.

Experimental Methods

Six bottle roll experiment tests (Table I) were conducted using blended Elsburg reefs (50% MIT and 50% ECT layers) samples. All experiments were carried out in a hydrometallurgy laboratory at the University of the Witwatersrand. For each experimental test, 30% solids and 70% distilled water were mixed in a 2 L beaker to form a slurry. For the first six experimental tests, the dosage of glycine was varied (300 ppm, 1000 ppm and 1500 ppm), as well as potassium permanganate (600 ppm, 2000 ppm and 3000 ppm) over different leaching durations (30 and 50 hours) (Table 1). Acidity was measured using a pH meter and controlled using lime [$Ca(OH)_2$] to keep the pH value at 10 ± 0.50 after an hour of conditioning. The slurry was then transferred into 5 L bottles, which were then placed in a roller for a given leaching duration. The slurry was sampled at different time intervals to monitor gold recovery against time. Head feed and residual samples were collected, and both types of samples were dried at 60°C in an oven for at least 24 hours. Sample mass was recorded prior to gold fire-assay analysis to determine the gold grade (g/t). Atomic absorption spectrometry was used at Super Laboratory Services to determine the amount of gold in the leachate. In order to assess the reliability of gold grade results, a laboratory reference material with a gold grade of 1.560 g/t was used. The attained assayed value was 1.520 g/t, which is close to that of the reference material.

Table I. Summary of leaching parameters showing reagents dosages, pH values and leaching time. Note: parameters such as temperature and dissolved oxygen were unregulated

Tests	$C_2H_5NO_2$ [ppm]	$KMnO_4$ [ppm]	Average pH	Leaching time [hrs]
BR300A	300	600	9.99	30
BR1000A	1000	2000	9.935	30
BR1500A	1500	3000	10.005	30
BR300B	300	600	10.345	50
BR1000B	1000	2000	9.878	50
BR1500B	1500	3000	10.136	50

The results from bottle roll test experiments were used to model and predict a leaching duration to reach 85% gold recovery. Furthermore, another six experimental runs were conducted to validate the outcomes from the prediction model. For these experimental runs, glycine (~1500 ppm) was used as the principal reagent and potassium permanganate (~3000 ppm) as an oxidant. For each run, the leaching duration was set at 101 hours, with bottles rolling at 45 revolutions per minute (rpm) at ambient temperatures (~19 – 23°C). The slurry was monitored for dissolved oxygen, pH, temperature and gold contents at various time intervals for each experiment. Gold grade was calculated using equation 1.

$$\text{Recovery}(\%) = \frac{\text{head grade}\left(\frac{\text{g}}{\text{t}}\right)\times\text{head mass(g)} - \text{residue grade}\left(\frac{\text{g}}{\text{t}}\right)\times\text{residue mass(g)}}{\text{head grade}\left(\frac{\text{g}}{\text{t}}\right)\times\text{head mass(g)}} \times 100 \qquad [1]$$

Data Analytics

Data-driven modelling is a process that utilises statistical techniques to fit models to data, which could be used for inferential predictions (Bonavita *et al.*, 2021). Models capture salient relationships between input and output variables. A fitted model can be employed to predict the target gold recovery for new and/or unseen experimental data. In our study, we employed bottle-roll test experimental data to conduct a statistical analysis (including standard deviation, mean and uncertainties) at a 95% confidence interval. The confidence interval represents the range of values within which estimates can be expected to fall with a specified level of confidence, assuming the experiment is repeated (Equation 2). Subsequently, the confidence interval was transformed into a standard score, also known as the z-score. The z-score quantifies the number of standard deviations by which a raw score deviates from the mean value of the observed or measured data (Equation 3). The model incorporated the confidence interval, z-score, and a polynomial model (see Figure 4) to predict the required leaching duration for achieving 85% gold recovery. For the purpose of our model and based on understanding of the kinetics of gold recovery, we used a third-degree polynomial (Equation 4) to fit the data. This model was heuristically chosen to minimise the number of degrees of freedom of the model and to match the known behaviour of the data (Figure 3).

$$Confidence\ Interval = \mathrm{x} \pm z\frac{s}{\sqrt{n}} \qquad [2]$$

where x is the gold recovery mean, z is the confidence level value, *s* is the gold recovery standard deviation and n is the number of samples.

$$standard\ score = \frac{s-\mu}{\sigma} \qquad [3]$$

where *s* is the measured or observed gold recovery value (%), μ is the gold recovery mean and σ is the gold recovery standard deviation.

$$f(x) = \mathrm{a}x^3 + bx^2 + cx + d \quad [4]$$

where a, b, and c are coefficients and d is a constant. x represents variables.

RESULTS AND DISCUSSION

Process Mineralogy

The Witwatersrand Supergroup, specifically the Elsburg reefs, are composed of several mineral constituents (Table II). The main component is quartz, which is present as sub-angular to sub-rounded grains ranging from 0.1 to 5 mm across. Quartz grains are embedded in a fine-grained matrix that is composed of muscovite, biotite and chlorite, with minor amounts of sulphide group minerals (e.g., galena and sphalerite). Pyrite is the dominant sulphide mineral in the Elsburg reefs. It occurs in various sizes, ranging from 0.05 to 2 mm, and in different forms. Pyrite grains can be euhedral to subhedral (sub-rounded) and exhibit inclusions, porosity and fractures. Detrital pyrite grains, which resemble euhedral grains, have rounded edges and contain numerous chalcopyrite or silicate inclusions. In addition to pyrite, there are trace amounts of gersdorffite, arsenopyrite, galena and sphalerite occurring in fractures within and around pyrite crystals. Those sulphide group minerals that occur in trace amounts are referred to as 'other sulphides' (Table II). Other minerals such as zircon, rutile, biotite and muscovite are also present in Elsburg reefs. Visible gold is found in trace amounts within the Elsburg reefs. Visible gold is typically observed as inclusions in sub-rounded and porous pyrite grains, in quartz, and occasionally in euhedral pyrite, as well as at multi-mineral boundaries. Apart from visible gold, there is also invisible gold in the Elsburg reefs. This type of gold is typically associated with arsenopyrite (Cabri *et al.*, 1989; Morishita *et al.*, 2019). In Elsburg reefs gold is mainly associated with sulphide group minerals (>83%), quartz (>12%) and the remaining 5% is associated chlorite and other minerals (Table 3). Similarly, to association, gold is mainly locked in sulphide group minerals, quartz and other minerals (Table III). Free surface refers to liberated gold. There is a very small amount (<3%) of liberated gold from Elsburg reefs (Table III).

Table II. Mineralogy of the Elsburg reefs as determined by TIMA and XRD. Results given in weight percent (Wt.%)

Minerals	**TIMA**		**XRD**		
	MIT	***ECT***	***MIT***	***ECT***	***Blended***
Pyrite	14.59	8.91	2.10	0.23	1.17
Chalcopyrite	0.03	0.01	--	--	--
Pyrrhotite	0.33	0.30	--	--	--
Quartz	72.34	84.26	96.59	99.21	97.90
Chlorite	3.66	1.42	0.53	0.18	0.36
Mica	3.30	1.96	0.78	0.38	0.58
Other sulphides	0.07	0.01	--	--	--
Other minerals	5.69	3.13	--	--	--

Table III. Mineral phases that are associated or locking gold as well as liberated (free surface) gold in mass percent (mass %) as determined by TIMA

Minerals	**Association**		**Locking**	
	ECT	***MIT***	***ECT***	***MIT***
Free surface	0.00	0.00	0.18	1.13
Chlorite	1.64	0.00	1.06	3.09
Mica	0.00	0.00	1.14	4.31
Quartz	1.99	12.56	48.91	24.63
Chalcopyrite	0.00	11.60	0.00	0.44
Columbite	28.90	8.00	0.00	0.00
Pyrrhotite	13.48	27.89	0.98	1.26
Pyrite	17.51	36.82	42.34	59.72
Other sulphides	33.23	2.89	1.25	2.94
Other minerals	3.25	0.25	4.15	2.48

Effects of Leaching Parameters on Gold Recovery

Gold recovery from the composite ore deposits using glycine and potassium permanganate as leaching agents is influenced by several crucial leaching parameters as presented in Figure 2. The concentration of glycine and potassium permanganate in the leaching solution plays a critical role in enhancing the dissolution of gold grains and promoting efficient extraction. The pH level of the leaching solution is also crucial, as it influences the solubility of gold and the formation of gold complexes. Higher glycine concentrations and alkaline pH conditions generally favour better gold recovery. The leaching temperature and duration impact the kinetics of the leaching process, with higher temperatures and longer durations often leading to increased gold extraction. Additionally, geometallurgical factors such as ore particle size, poor gold liberation and the presence of reagent consuming minerals in the ore can affect the accessibility of gold to the leaching solution and consequently impact gold recovery (Oraby *et al.*, 2019). By understanding the relationships between leaching parameters and their influence on gold recovery, it becomes possible to optimise the leaching process to achieve optimal levels of gold extraction.

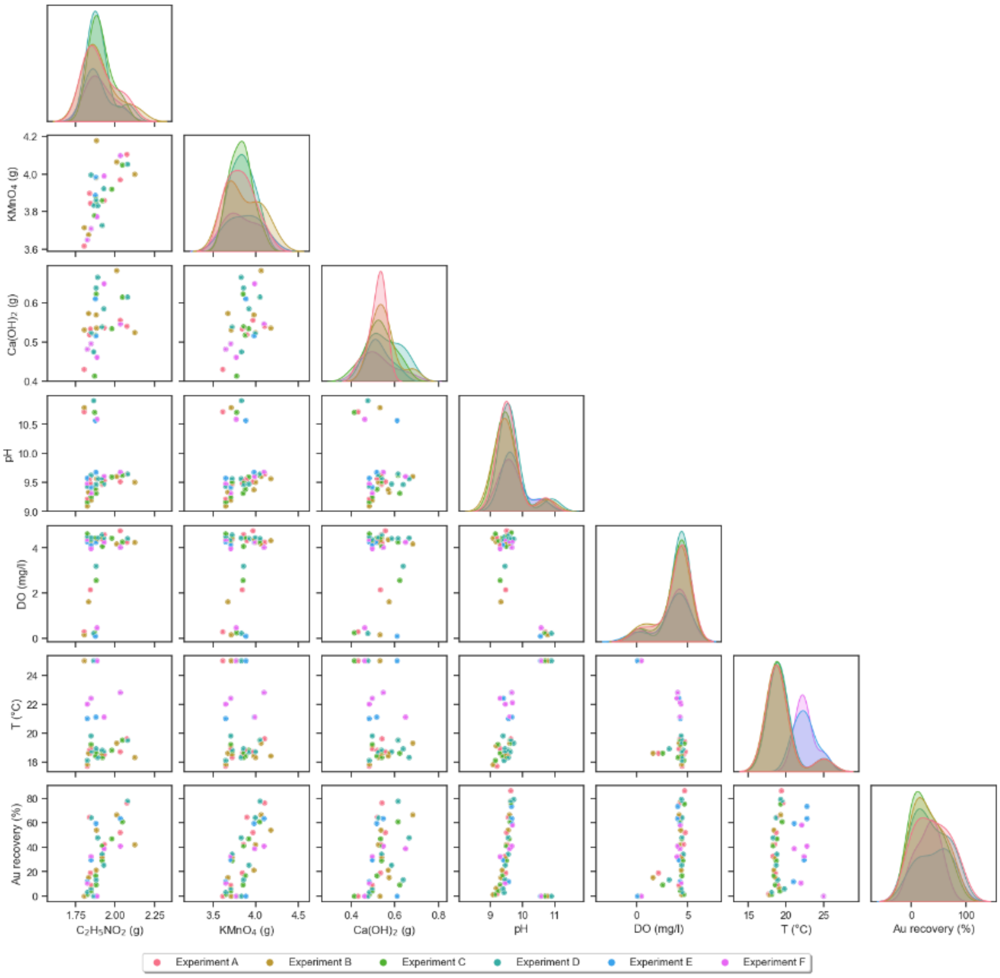

Figure 2. Scatter plot matrix illustrating the relationship between Au recovery and leaching parameters for each experimental run (A to F). DO is dissolved oxygen and T(°C) is the system temperature in degrees celsius.

Application of Predictive Geometallurgy on Gold Leaching

Bottle roll tests

The bottle roll test experiments were conducted to investigate the recovery of gold from the Elsburg reefs using a combination of glycine and potassium permanganate. The concentrations of the lixiviants, glycine and potassium permanganate, were varied during the experiments (Table I). The results of the experiments showed that the highest gold recovery achieved was 42% after 50 hours of leaching. This maximum recovery was obtained using a glycine concentration of 1500 ppm and a potassium permanganate concentration of 3000 ppm. A graphical representation of the experimental results, illustrating the relationship between gold recovery and the varying concentrations of glycine and potassium permanganate, as well as the leaching durations is shown in Figure 3. The ratio of glycine to potassium permanganate was kept at 1:2 for all experimental tests.

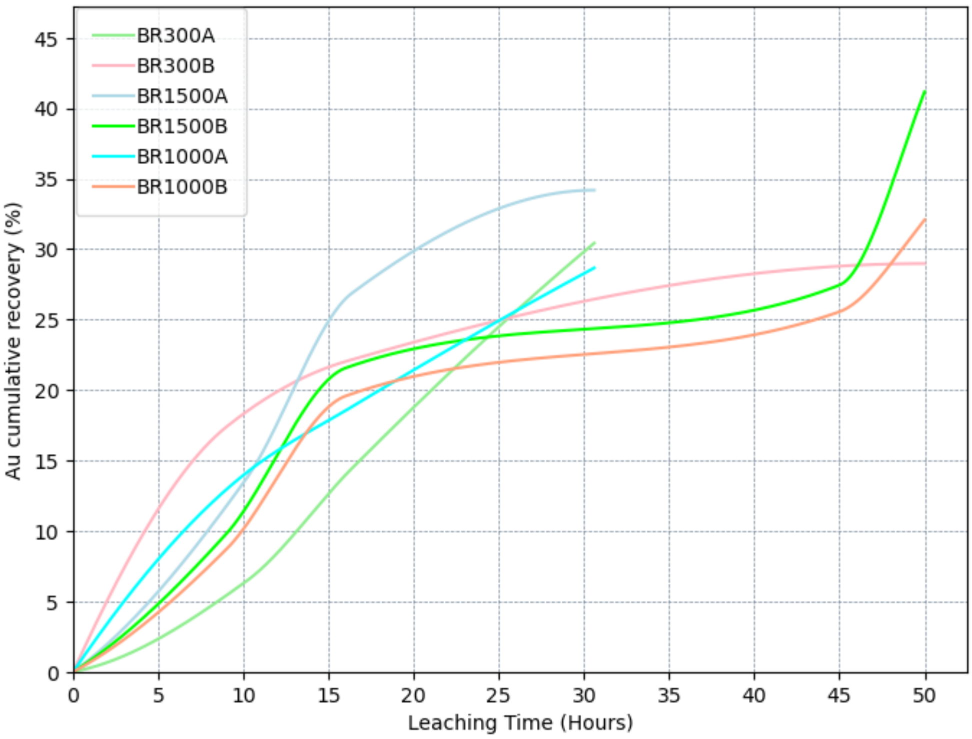

Figure 3. Bottle roll experimental test outcomes (total of six experiments) at different reagents dosages and leaching time. In 'BR300A', BR is bottle roll; 300 is glycine concentration (ppm), and A is bottle roll test 1, B is bottle roll test 2. $KMnO_4$ concentrations (ppm) is always twice that of glycine.

Modelling geometallurgical variables

Our model was fitted to the experimental data. To analyse experimental data and derive meaningful predictions, the model utilised statistical techniques to calculate the lower and upper limits (at 95% confidence interval) as well as the experimental mean. These statistical measures were determined based on the obtained experimental test work results and provided an estimate of the range within which future results were likely to fall. By considering the upper and lower limits, the model allowed for a more comprehensive understanding of the potential variability in the leaching process.

Moreover, modelling of the data was used to predict the leaching duration required to achieve an acceptable gold recovery level of approximately 85%. Based on the available data, the model suggests that, using the same leaching conditions, it is most likely that the desired recovery of 85% can be attained after 100 hours of leaching (Figure 4). The predictions generated by the model offer valuable insight into the leaching process, can guide future experiments and inform decision-making in gold recovery operations. However, it is crucial to acknowledge that these predictions are solely based on the specific data and conditions used to train the model. Factors such as variations in ore composition, temperature conditions, dissolved oxygen and solution pH can all significantly impact results. Thus, further validation and adjustment of the prediction model may be necessary to account for these factors and ensure accurate predictions in different scenarios.

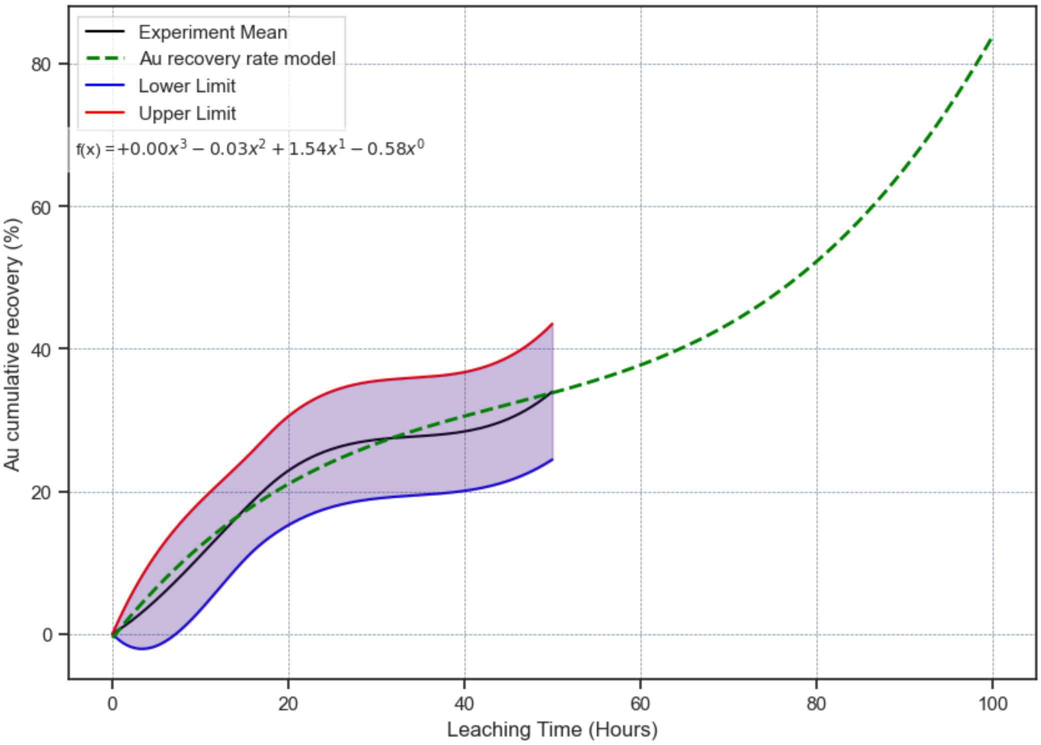

Figure 4. Statistical prediction model showing the lower and upper limits, as well as the mean from the bottle roll experimental test work data (n=6). Also shown is the 'Au recovery rate model' that estimates required time to achieve 85% gold recovery.

Validation of predictive geometallurgy model accuracy

In order to validate the prediction model, an additional series of six experiments were conducted, each lasting for a duration of 101 hours. The primary objective of these experiments was to evaluate the accuracy of the prediction model and determine whether it was indeed possible to achieve a gold recovery of at least 85% within 100 hours of leaching. The results obtained from the six experiments demonstrated that achieving and surpassing the 85% gold recovery threshold is feasible, as presented in Figure 5. In the first five experimental runs, the recovery ranges from 73% to 86%. These recoveries closely aligned with the predictions generated by the model (Figure 4), indicating that the model was accurate. However, it is noteworthy that the sixth experiment (Experiment F) yielded the lowest gold recovery, measuring at 58%. This particular outcome deviated significantly from both the model's predictions and the trend observed in the preceding experiments. The diminished recovery observed in the sixth experiment can be attributed to a deficiency of dissolved oxygen in the system. Dissolved oxygen plays a crucial role in the leaching process by facilitating the dissolution of gold particles. Insufficient levels of dissolved oxygen can impede leaching efficiency, leading to reduced gold recovery rates. Consequently, we consider it as an outlier that warrants additional investigation. The sixth experiment underscores the significance of environmental factors, such as dissolved oxygen levels, in exerting an influence on the leaching process. Validation experiments not only underscore the reliability of the data analytics-approach in predicting gold recovery rates, but also emphasise the importance of monitoring and managing processing parameters, including dissolved oxygen and duration. The tuning of leaching parameters is required to ensure consistent and optimal leaching performance.

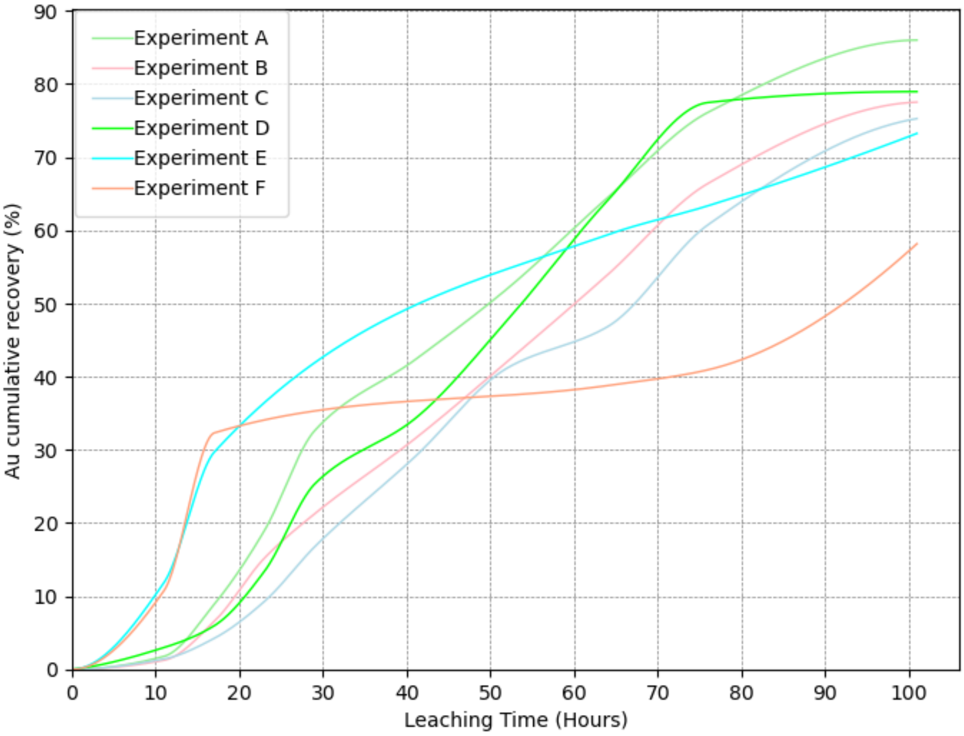

Figure 5. Validation experimental runs (total of six6 experiments) demonstrate that after 100 hours of leaching gold recoveries range between 75-86% under consistent conditions. Experimental parameters are 1500 ppm glycine as the reagent and 3000 ppm potassium permanganate as the oxidant.

CONCLUSION

The Elsburg reefs (MIT and ECT layers), and therefore by proxy the Witwatersrand Supergroup composite gold ore deposits, consist of various minerals, with quartz as the primary component and pyrite as the dominant sulphide group mineral. Gold is often found as inclusions in porous and non-porous pyrite grains as well as at multi-mineral boundaries. Results from TIMA shows that in both MIT and ECT, gold is generally associated and/or encapsulated in pyrite, quartz and other minerals (e.g., chalcopyrite, pyrrhotite, arsenopyrite, zircon and rutile) (Table 3). Invisible gold is usually associated with arsenopyrite (Cabri *et al.*, 1989; Morishita *et al.*, 2019). Gold recovery from these deposits is influenced by leaching parameters such as glycine and potassium permanganate concentrations, pH level, leaching temperature and duration, ore particle size, agitation rate and the presence of other minerals (e.g., chalcopyrite) and/or impurities (e.g., Fe, Ag, Cu etc.). Elements like Ag and Cu can form complexes with glycine, consume it (and oxygen) and reduce the overall gold recovery. Furthermore, the poor liberation (i.e., low free surface, Table 3) of the ore also negatively affects gold recovery. Optimising leaching parameters is crucial for maximising gold recovery. A total of six bottle roll experimental tests were conducted using glycine and potassium permanganate on blended ore material (50% MIT and 50% ECT) to investigate gold recovery. The highest recovery achieved was 42% after 50 hours of leaching with specific lixiviant concentrations (Figure 3). Based on our geometallurgical results (i.e., mineralogy, ore texture and metallurgical test work), we developed and validated a data-driven model, suggesting that 85% gold recovery could be attained on average after 100 hours of leaching under the same conditions (Figure 4). A total of six additional validation experiments lasting 101 hours confirmed the model's predictions, with a gold recovery of 86% obtained in the first experiment (Figure 5). However, the sixth validation experiment yielded a lower recovery rate, which was attributed to low dissolved oxygen levels as well as geometallurgical characteristics (i.e., poor gold liberation) of the ore. This highlights the importance of monitoring processing factors for consistent leaching performance. Overall, understanding geometallurgical characteristics of the ore, and optimising leaching parameters are keys to maximising gold recovery. The integration of our model with geometallurgical results provides valuable insights and predictions, but ongoing monitoring and optimisation are necessary to address mineral processing variations and maintain high recovery rates. Integrating data analytics with geometallurgy and hydrometallurgy indeed has the potential to improve gold recovery process.

REFERENCES

Altinkaya, P., Wang, Z., Korolev, I., Hamuyuni, J., Haapalainen, M., Kolehmainen, E., Yliniemi, K. and Lundström, M. (2020). Leaching and recovery of gold from ore in cyanide-free glycine media. *Minerals engineering*, 158, p.106610.

Ashiq, A., Kulkarni, J. and Vithanage, M. (2019). Hydrometallurgical recovery of metals from E-waste. *Electronic waste management and treatment technology*, 225-246.

Birloaga, I. and Vegliò, F. (2022). An innovative hybrid hydrometallurgical approach for precious metals recovery from secondary resources. *Journal of Environmental Management*, 307-114567.

Cabri, L.J., Chryssoulis, S.L., de Villiers, J.P., Laflamme, J.G. and Buseck, P.R. (1989). The nature of" invisible" gold in arsenopyrite. The Canadian Mineralogist, 27(3), pp.353-362.

da Costa, G., Hofmann, A. and Agangi, A. (2020). A revised classification scheme of pyrite in the Witwatersrand Basin and application to placer gold deposits. *Earth-Science Reviews*, 201-103064.

Dominy, S.C., O'Connor, L., Parbhakar-Fox, A., Glass, H.J. and Purevgerel, S. (2018). Geometallurgy—A route to more resilient mine operations. *Minerals*, 8-560.

Fields, G. (2012). South Deep Gold Mine Technical Short Form Report.

Fuchs, S., Williams-Jones, A.E., Jackson, S.E. and Przybylowicz, W.J. (2016). Metal distribution in pyrobitumen of the Carbon Leader Reef, Witwatersrand Supergroup, South Africa: Evidence for liquid hydrocarbon ore fluids. *Chemical Geology*, 45-59.

Frimmel, H.E., 2014. A giant Mesoarchean crustal gold-enrichment episode: Possible causes and consequences for exploration. Karen D. Kelley; Howard C. Golden, Building Exploration Capability for the 21st Century. *Society of Economic Geologists*. Littleton, Colorado.

Frimmel, H.E. (2019). The Witwatersrand Basin and its gold deposits. *The Archaean geology of the Kaapvaal craton*, southern Africa, 255-275

Frimmel, H.E., Nwaila, G.T. (2020). Geologic evidence of syngenetic gold in the Witwatersrand goldfields, South Africa, in: Sillitoe, R.H., Goldfarb, R.J., Robert, F., Simmons, S.F. (Eds.), Geology of the World's Major Gold Deposits and Provinces. *Society of Economic Geologists*, Littleton, Colorado, Special Publication, 645–668.

Kositcin, N. and Krapež, B. (2004). Relationship between detrital zircon age-spectra and the tectonic evolution of the Late Archaean Witwatersrand Basin, South Africa. *Precambrian Research*, 141-168.

Kröner, A., Hoffmann, J.E., Wong, J.M., Geng, H.Y., Schneider, K.P., Xie, H., Yang, J.H. and Nhleko, N., (2019). Archaean crystalline rocks of the Eastern Kaapvaal Craton. *The Archaean Geology of the Kaapvaal Craton*, Southern Africa,1-32.

Larrabure, G. and Rodríguez-Reyes, J.C.F. (2021). A review on the negative impact of different elements during cyanidation of gold and silver from refractory ores and strategies to optimize the leaching process. *Minerals Engineering*,107-194.

Lishchuk, V. (2016). Geometallurgical programs–critical evaluation of applied methods and techniques.

Lishchuk, V., Koch, P.H., Ghorbani, Y. and Butcher, A.R. (2020). Towards integrated geometallurgical approach: Critical review of current practices and future trends. *Minerals Engineering*, 145, p.106072.

Li, H., Deng, Z., Oraby, E. and Eksteen, J. (2022). Amino acids as lixiviants for metals extraction from natural and secondary resources with emphasis on glycine: A literature review. *Hydrometallurgy*, 10-6008.

Manzi, M.S.D., Hein, K.A.A., Durrheim, R. and King, N. (2013). Seismic attribute analysis to enhance detection of thin gold-bearing reefs: South Deep gold mine, Witwatersrand basin, South Africa. *Journal of Applied Geophysics*, 98,212-228.

Marsden, J. and House, I. (2006). *The chemistry of gold extraction.* 2nd edn. Society for Mining, Metallurgy, and Exploration Inc, Colorado.

Mokarian, P., Bakhshayeshi, I., Taghikhah, F., Boroumand, Y., Erfani, E. and Razmjou, A. (2022). The advanced design of bioleaching process for metal recovery: A machine learning approach. *Separation and Purification Technology*, 291-120919.

Morishita, Y., Hammond, N.Q., Momii, K., Konagaya, R., Sano, Y., Takahata, N. and Ueno, H. (2019). Invisible gold in pyrite from epithermal, banded-iron-formation-hosted, and sedimentary gold deposits: Evidence of hydrothermal influence. *Minerals Engineering*, 9(7), p.447.

Mngadi, S.B., Durrheim, R.J., Manzi, M.S.D., Ogasawara, H., Yabe, Y., Yilmaz, H., Wechsler, N., Van Aswegen, G., Roberts, D., Ward, A.K. and Naoi, M. (2019). Integration of underground mapping, petrology, and high-resolution microseismicity analysis to characterise weak geotechnical zones in deep South African gold mines. *International Journal of Rock Mechanics and Mining Sciences*, 79-91.

Nwaila, G.T., Ghorbani, Y., Becker, M., Frimmel, H.E., Petersen, J. and Zhang, S. (2020). Geometallurgical approach for implications of ore blending on cyanide leaching and adsorption behavior of witwatersrand gold ores, South Africa. *Natural Resources Research*, 29, pp.1007-1030.

Osburn, K., Pretorius, H., Kock, D., King, N., Pillaye, R. and Hlangwane, M. (2014). Enhanced geological modelling of the Upper Elsburg reefs and VCR to optimize mechanized mine planning at South Deep Gold Mine. *Journal of the Southern African Institute of Mining and Metallurgy*, 114(3), pp.265-273.

Oraby, E.A., Eksteen, J.J., Karrech, A. and Attar, M. (2019). Gold extraction from paleochannel ores using an aerated alkaline glycine lixiviant for consideration in heap and in-situ leaching applications. *Minerals Engineering*, *138*, pp.112-118.

Oraby, E.A., Eksteen, J.J. and O'Connor, G.M. (2020). Gold leaching from oxide ores in alkaline glycine solutions in the presence of permanganate. *Hydrometallurgy*, 198, p.105527.

Phillips, G.N. and Law, J.D. (2000). Witwatersrand gold fields: geology, genesis, and exploration.

Saldana, M., Neira, P., Gallegos, S., Salinas-Rodriguez, E., Perez-Rey, I. and Toro, N. (2022). Mineral Leaching Modeling Through Machine Learning Algorithms− A Review. *Frontiers in Earth Science*, 10, p.560.

Tanda, B.C. (2017). Glycine as a lixiviant for the leaching of low grade copper-gold ores. *Doctoral dissertation*, Curtin University, Australia.

Tucker, R.F., Viljoen, R.P. and Viljoen, M.J. (2016). A Review of the Witwatersrand Basin-The World's greatest goldfield. *Episodes Journal of International Geoscience*, 104-133.

Wills, B.A. and Finch, J. (2015). Wills' mineral processing technology: an introduction to the practical aspects of ore treatment and mineral recovery. Butterworth-Heinemann.

Wilson, A.M., Bailey, P.J., Tasker, P.A., Turkington, J.R., Grant, R.A. and Love, J.B. (2014). Solvent extraction: the coordination chemistry behind extractive metallurgy. *Chemical Society Reviews*, 123-134.

Zeh, A., Wilson, A.H. and Gerdes, A. (2020). Zircon U-Pb-Hf isotope systematics of Transvaal Supergroup–Constraints for the geodynamic evolution of the Kaapvaal Craton and its hinterland between 2.65 and 2.06 Ga. *Precambrian Research*, 345-105760.

Zhou, J. and Gu, Y. (2016). Geometallurgical characterization and automated mineralogy of gold ores. In Gold ore processing (pp. 95-111). Elsevier.

Viwe Notole

PhD Candidate in Chemical and Metallurgical Engineering
University of the Witwatersrand

Viwe Notole is a dedicated geoscientist specializing in geometallurgy, with experience in mineral characterization, mineral processing, and hydrogeology. While working as a Junior geologist at Umvoto Africa in Cape Town, Viwe engaged in fieldwork involving the collection of geological and hydrogeological data, as well as overseeing borehole drilling and test-pumping activities. As an intern mineralogist at Mintek, Viwe showcased his proficiency in mineral characterization techniques, such as XRD, SEM, and QMSCAN.

Viwe holds an M.Sc. in economic geology from the University of the Witwatersrand, where his research focused on investigating the mineral characteristics and processing behavior of the Elsburg reefs at the South Deep Gold Mine in South Africa. Prior to this, he completed a B.Sc. Honours degree in geology from the University of Johannesburg and a B.Sc. degree majoring in geology and chemistry from the University of Fort Hare. Currently, he is pursuing a Ph.D. in Chemical and Metallurgical Engineering with a keen interest in economic geology (geometallurgy), extractive metallurgy (hydrometallurgy), and machine learning. Viwe's goal is to advance the understanding and integration of these fields, contributing to sustainable and efficient resource extraction processes.