The validation of predictive geometallurgical models in concentrator process design

T. Käyhkö[a*], M.Sinche-Gonzalez[b], J. Liipo[a], and S. Khizanishvili[c]

[a]*Outotec Finland,*
[b]*Oulu Mining School/University of Oulu, Oulu, Finland*
[c]*JSC RMG Copper, Georgia*
**Corresponding author: T. Käyhkö* tomi.kayhko@outotec.com

ABSTRACT

The use of geometallurgical modelling is becoming more common in concentrator plant design and during the operational phase. Predictive modelling aims to define optimised process parameters for the concentrator plant to accommodate variability within the ore feed. The main objective of this study is to show how the metallurgical response of different types of ore blends can be simulated using kinetic models derived from experimental flotation tests with different geometallurgical end-member ore types and their blends. For these validation tests, four different end-member ore types containing different ratios of chalcopyrite, chalcocite and oxidised copper minerals from Rich Metal Group's Madneuli copper-gold mine, Georgia, were tested. Kinetic flotation tests, including both rougher and cleaner flotation tests, were carried out. The simulations were performed using HSC Chemistry software based on mineral compositions of the ores and kinetic models using rectangular distribution equations and flowsheet model. Simulated and experimental results of copper grade, copper recovery and concentrate mass pull correlated well with R2 values of >0.95. Based on these results, the metallurgical response of different ore blends can be simulated based on the flotation kinetics of end-member ore types. The use of this kind of simulation will create savings during the test work phase and increase the flexibility and predictability in the processing stage.

Keywords: Ore body characterisation, geometallurgy, process mineralogy

1. Introduction

1.1. Geometallurgy

Geometallurgy combines an understanding of the geological and mineralogical perspective of ore characteristics like throughput, recovery, concentrate quality and all characteristics related to these three. It is a modern approach to optimize the net present value of the mining project. The spatial understanding of ore characteristics and variables effecting to metallurgical performance are the basis of geometallurgy. (Andrea & Lopera, 2014)

1.1.1. *Geometallurgical models*

A geometallurgical model is defined as "organization of geological and metallurgical information into a spatial and predictive tool to be used in production planning and management in the mining industry" (Lamberg *et al*., 2013). Van den Boogaart & Tolosana-Delgado (2018), described that geometallurgy can also be seen as a mathematical geoscience because geometallurgical models are mathematical models based on geosciences like geology and mineralogy. The ideal situation would be that the operator could manage a mining process online and the plant is always optimized for processed ore before a specific ore reaches the plant. This paper considers especially simulation and modelling approaches for a concentrator plant design. Large and high-grade deposits are mostly already extracted, and it might not be feasible to build concentrator plant for small ore deposit.

1.1.2. *Validation of geometallurgical models*

HSC Sim Chemistry® software (Outotec, 2019) is used in metallurgical plant operations and during the process design stage. The main objective of this study was to evaluate how experimental flotation tests with different ore blends will correspond to the current kinetic models of HSC Sim simulations. The work included simulations with HSC Sim and lab-scale flotation tests with different ore types and their blends. The comparison was made between the results of HSC Sim modelling work and flotation test work.

Reason for this study is to validate whether the simulated blend flotation results correlates with experimental ones. Mining companies might blend different ores without necessary knowing how ore blend behave in the flotation process. Money and time can be saved using more modelling and simulation work during process design. Orientation to geometallurgy, increases knowledge of the nature of ore deposit and processing methodology will lead to better decisions to maximize the value of the mining operation Deutsch *et al.* (2016)

2. Experimental

2.1. *Experimental and simulated flotation tests*

Experimental work for this study was carried out at Outotec Research Center in Pori, Finland. The complex copper-gold ore samples for this work came from Rich Metal Group (RMG) Madneuli copper mine, from Southern Georgia (Talikka *et al*., 2018). The main points of experimental work were:

1. *The flotation test of each ore individual ore type (Madneuli XI, V, VIII-C1 and VIII-C2)*
2. *Estimation of kinetic parameters (k and R_{max}) of each mineral in each ore type*
3. *Simulation of the flotation process for different ore blends*
4. *Flotation tests of the different ore blends*
5. *Comparison of the results*

2.2. Geometallurgical ore types

Four different geometallurgical ore types (Liipo *et al*., 2019) were tested during the experimental flotation tests. All geometallurgical ore types represent different end-member ore types of complex copper-gold ores of RMG´s Madneuli mine and all ore types are being processed in the concentrator plant (Table 1). The main difference between ores is the distribution of copper between different copper minerals. Copper is carried by chalcopyrite, chalcocite-group minerals, which have the general formula $Cu_{2-x}S$ and include chalcocite, digenite anilite and geerite, oxidized copper minerals in different proportions. The distribution of copper between different copper minerals is presented in Figure 1. The main gangue minerals are quartz, muscovite, sericite, chlorite kaolinite and pyrite. Since the copper oxides are not amenable to flotation, the ratio of copper sulfides/copper oxides impacts clearly to the concentrate quality. The copper phase assays were done using four stage leaching for each sample. Ore mineralogy is simplified to five different minerals for calculations; chalcopyrite (ccp), chalcocite (cc), cuprite (cupr), pyrite (py) and non-sulfide gangue (NSG).

Table 1.

Geometallurgical ore types used in this work. (Liipo *et al*., 2019)

Madneuli XI

- Copper grade, 0,45%
- Copper mainly carried by copper sulfides, 80,5% (highest)
- Copper oxides and sulfates carry 19,5% of total copper (lowest)
- Pyrite grade, 5,42%

Madneuli V

- Copper grade, 0,52%
- Copper mainly carried by copper sulfides, 75,5% (lowest)
- Copper oxides and sulfates carry 24,5% of total copper (highest)
- Pyrite grade, 5,58%

Madneuli VIII-C1

- Copper grade, 0,31%
- Copper mainly carried by copper sulfides, 77%
- Copper oxides and sulfates carry 23% of total copper
- Pyrite grade, 9,44%

Madneuli VIII-C2

- Copper grade, 0,28%
- Copper mainly carried by copper sulfides, 76%
- Copper oxides and sulfates carry 24% of total copper
- Pyrite grade, 9,92%

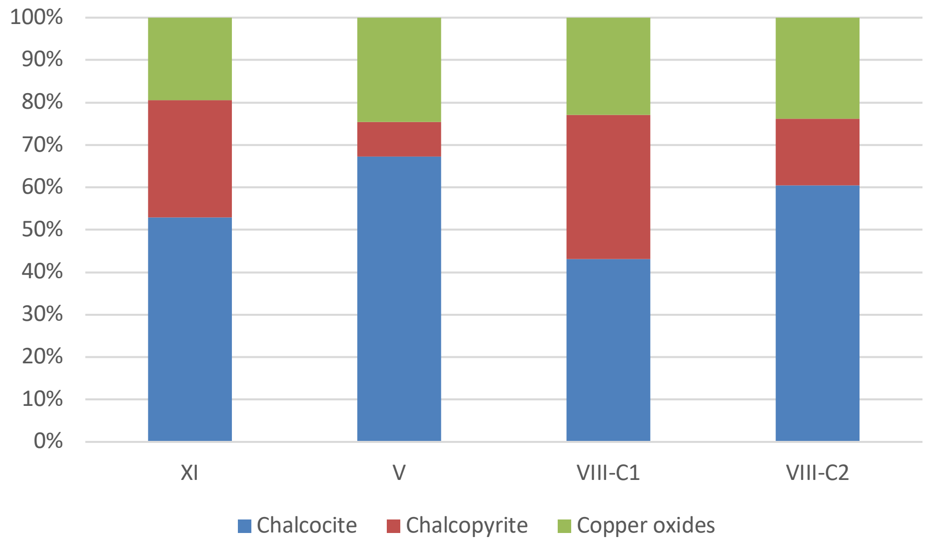

Fig. 1. The distribution of copper between copper minerals in each ore type.

2.3. Experimental conditions and procedures

Rougher flotation tests were conducted for each four ore types. First, the ore sample was ground in a laboratory ball mill with 65% solids. Calcium hydroxide was added in the grinding mill to increase the pH value before the conditioning phase. Grinding conditions of each unit were set to reach P80 value of 55µm for rougher flotation tests. During re-grinding, the concentrate was ground to reach P80 value of 25µm. Outotec-GTK laboratory flotation machine was used for flotation with 4- liter (rougher) and 2- liter (cleaner) flotation cells. Aerofloat 208 was used as a collector and Dowfroth 250 as a frother reagent. Due to the high content of pyrite (5-10%), flotation was conducted at a basis pH (12). Cleaner flotation tests were carried out with one-stage rougher and four different cleaner concentrates. Flowsheets for rougher and cleaner flotation tests are presented in Figure 2.

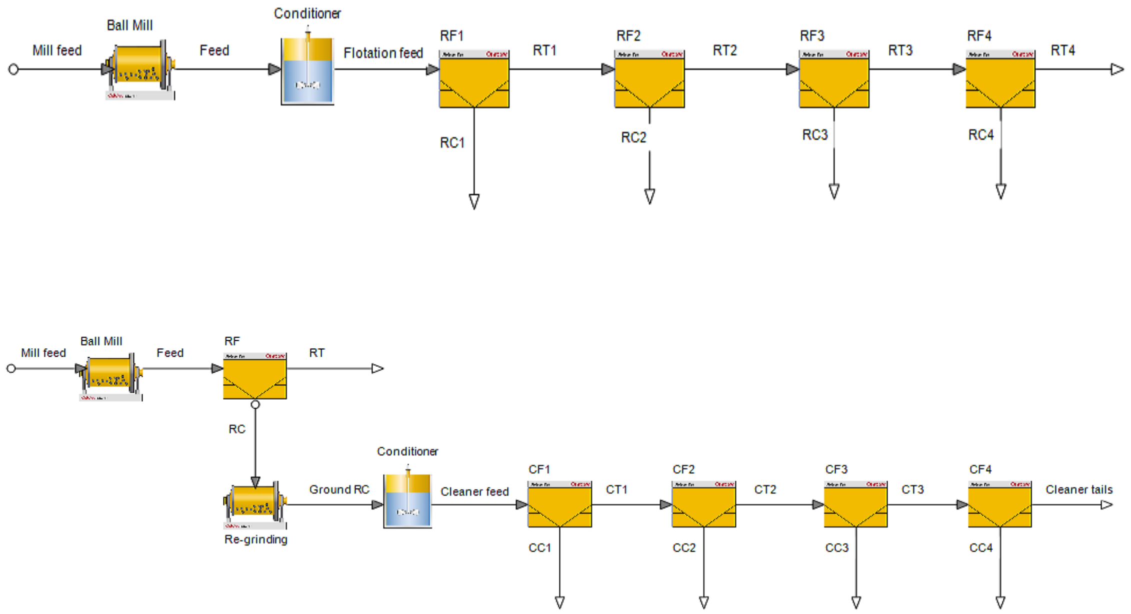

Fig. 2. Flotation flowsheet for rougher and cleaner flotation tests.

2.4. HSC Sim Modelling and simulation work

Concentrate and tails samples of each test were analyzed, and copper phase assays were used to determine copper content divided in copper sulfates, copper oxides and silicates, secondary copper sulfides and primary copper sulfides Leaching stages are water (P1), sulphuric acid (P2), cyanide (P3) and nitric acid (P4). Element to mineral conversion (EMC) from chemical assays is based on these sequential copper analyses. Mineral quantification was done using HSC Geo® module (Outotec, 2019). Copper phase assays are converted to minerals with the module, using mineral matrix found in Table 2. Cuprite represents copper oxide minerals and non-sulfide gangue includes quartz, muscovite, sericite, chlorite and kaolinite.

Table. 2.

Mineral matrix for element to mineral conversion.

	Chalcopyrite	Chalcocite	Cuprite	Pyrite	NSG
Si %					46.74
Fe %	30.43			46.55	
O %			11.18		53.26
Cu %	34.63	79.85	88.82		
S %	34.94	20.15		53.45	

After EMC and definition, mass balances were calculated including grades and recoveries for each mineral in each stream. HSC Sim® was used for mass balance, middle stream calculation and Klimpel flotation model for batch flotation to calculate kinetic parameters such as maximum recovery (R_{max}) and flotation rate constant (k). The Klimpel model (Equation 1), R_{max} showing the highest possible recovery for each mineral and the k of rectangular distribution showing how fast each mineral is floated.

$$R = R_{max}\left\{1 - \frac{1}{kt}\left[1 - e^{-kt}\right]\right\} \qquad (1.)$$

where, *t* is the cumulative residence time, and $R_{max} \leq 1$.

HSC model fit draws kinetic curves for each mineral and define value for k_{max} and R_{max}. These values were then used for flotation modelling. Next, a simplified flowsheet for a rougher and cleaner (Figure 3) flotation blend model was created. Two different ores were treated with the same flotation circuit. Kinetics for all reference ores were calculated with HSC Sim model fit tool and then added to model conditioners. This is the reason why in the simulation flowsheet cleaner bank are separated for each ore type, in the real plant this is not possible. Feed setup included the composition of minerals from reference mass balances and flotation residence times were considered similarly than in experimental flotation tests.

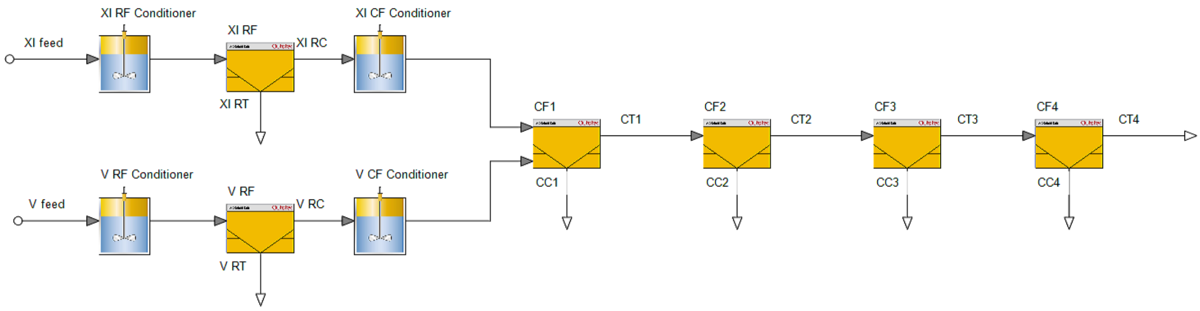

Fig. 3. Simulation model flowsheet for cleaner flotation tests.

Copper grade and recovery to concentrate and concentrate mass pull were determined using HSC Sim. Blend flotation tests were done with similar blends as in rougher phase.

3. Results and discussion

This section presents and discusses the results of correlation between simulated and experimental flotation tests.

3.1. Correlation between simulated and experimental results

There were variations in mineral recoveries and mineral grades when Madneuli XI and V ores were blended together. Chalcopyrite recoveries varied between 86-96% and chalcocite recoveries between 93-97%. Copper oxides recoveries varied between 30-54% with high effect to concentrate quality. Each mineral grade and recovery were obtained by simulation, and figures 4 and 5 present the copper grade, copper recovery and concentrate mass pull for various blending ratios of V/XI ores.

Figure 4 (A) presents simulated and experimental results of copper recovery to copper concentrate in rougher flotation tests. The coefficient of determination (R^2) value for copper recovery results was 0,97, showing a good fitting of the experimental results.

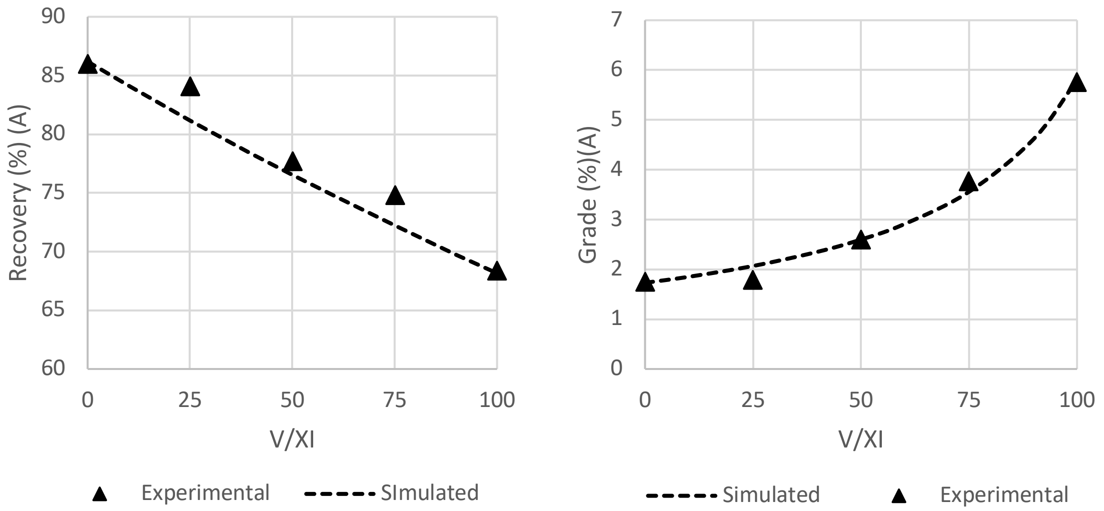

Fig. 4. Simulated and experimental copper recovery (A) and grade (B) results from rougher flotation tests for various blending ratios of V/XI ores.

Figure 4B presents simulated and experimental copper grade results in rougher concentrate. The simulated and experimental results correlate well with a R^2 value of 0,99 (Figure 4B). The copper grade (Figure 4B) shows that grades are varying exponentially, contrary to these recoveries (Figure 4A) are varying linearly. The copper grade (Figure 4B) curve steepens when blend includes more Madneuli V ore. Results show that pyrite grades follow the copper mineral grades, getting higher when the amount of Madneuli V ore is increasing. Pyrite and non-sulfide gangue recoveries go hand in hand with mass pull, so decreasing linearly when the amount of Madneuli V ore is decreasing.

The distribution of copper is divided between three copper minerals, which are chalcopyrite, chalcocite and cuprite. Grades of these three minerals in each rougher blend flotation tests are presented in Figure 5. Comparing Figure 4A and Figure 5, it can be seen that the copper grade and different copper mineral grades follow each other. This illustrates that process model is mineral based and concentrate quality can be simulated in mineral-by-mineral in each case.

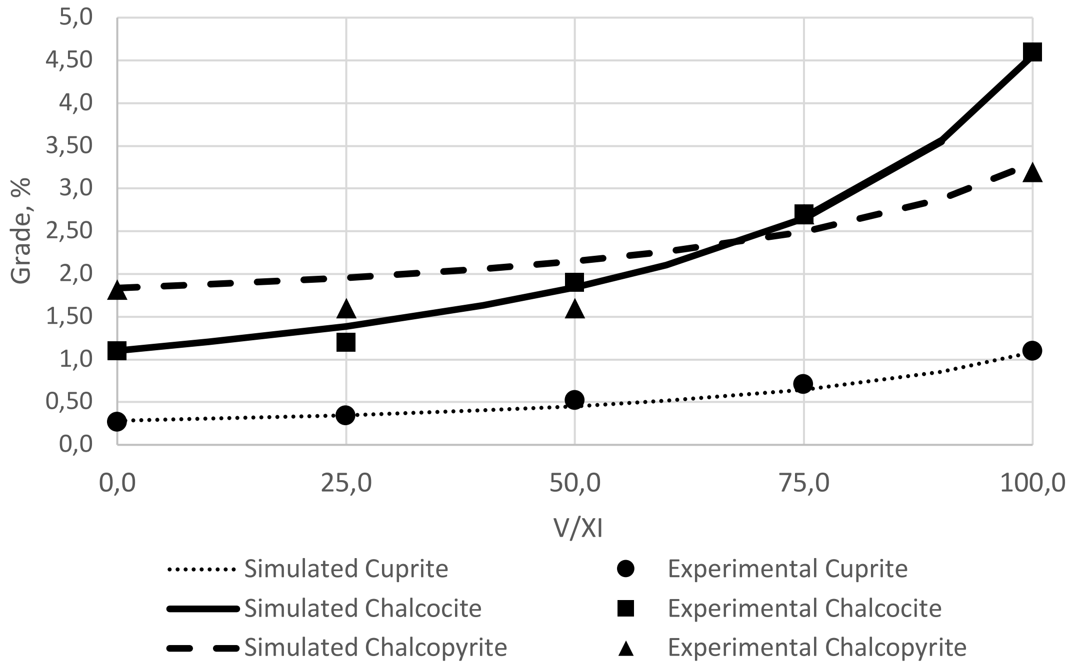

Fig. 5. Simulated and experimental copper mineral grades from rougher flotation tests for various blending ratios of V/XI ores.

Figure 6 presents simulated and experimental copper recovery and mass pull from cleaner flotation test. Experimental recoveries and concentrate mass pulls show high correlation with R^2 values of 0,97 and 0,94.

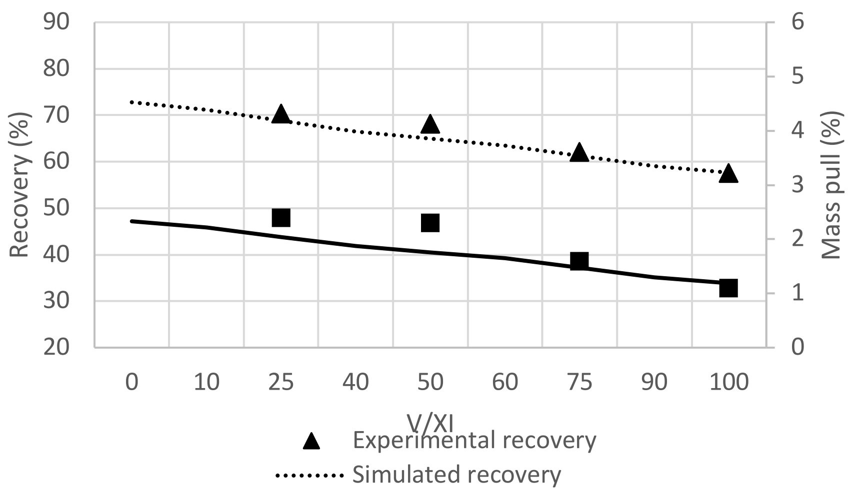

Fig. 6. Simulated and experimental copper recovery and concentrate mass pull results from cleaner flotation tests for various blending ratios of V/XI ores.

Additional flotation tests were done with three and four different ore blends. Madneuli XI, V, VIII-C1 and VIII-C2 were blended together in two different flotation tests. Used ore proportions in blends were 50/0/25/25 and 25/25/25/25 (XI/V/VIII-C1/VIII-C2). The reagent dosages and grinding times were weighed averages, particle size approximately P80=55µm. These two flotation tests were simulated, and the simulated and experimental results show a relatively good correlation (Table 3).

Table 3.
Simulated and experimental concentrate quality results for three and four different ore blends.

XI/V/VIII-C1/VIII-C2	*Cu grade*	*Cu grade*	*Cu Rec*	*Cu Rec*	*Mass pull*	*Mass pull*	*Py grade*	*Py grade*
	% Sim	% Exp	% Sim	% Exp	% Sim	% Exp	% Sim	% Exp
25/25/25/25	2,0	1,6	73,5	77,8	14,8	19,0	11,7	10,4
50/0/25/25	1,6	1,3	79,2	81,2	19,1	23,8	10,2	10,0

4. Conclusions

The validation of the ore blend flotation simulation model was studied. The conducted experiments were rougher and cleaner flotation tests for four ore types, additionally flotation tests were done blending two, three and four different ores. HSC Sim software was used for modelling and simulation, the simulations were done for similar ore proportions and results were compared then together. The simulated and experimental results of recovery, grades and concentrate mass pull correlate well and all R^2 values are between 0,94 and 0,99. Copper was carried by primary sulphide (chalcopyrite), secondary sulphide (chalcocite) and copper oxides minerals in each reference ore but with different the copper distribution between copper minerals. For further research, it is recommended to do similar testing and modelling with more different ores.

Similar studies regarding blending modelling and simulation are missing so this study was unique for that reason. It is expected this study gives ideas and causes debate during a process plant design project.

Acknowledgements

The authors would like to thank the Mineral Processing laboratory team in Outotec Research center in Pori for giving support for experimental flotation tests. Additionally, I want to thank Rich Metals Group (JSC RMG Copper, Georgia) collaboration and ore samples used in the experimental part of the study.

References

Andrea, P., & Lopera, M. (2014). *Geometallurgical Mapping and Mine Modelling - Comminution Studies : La Colosa Case Study , AMIRA P843A by*.

Deutsch, J. L., Palmer, K., Deutsch, C. V., Szymanski, J., & Etsell, T. H. (2016). Spatial Modeling of Geometallurgical Properties: Techniques and a Case Study. *Natural Resources Research*, *25*(2), 161–181. https://doi.org/10.1007/s11053-015-9276-x

Lamberg, P., Rosenkranz, J., Wanhainen, C., Lund, C., Minz, F., Mwanga, A., & Parian, M. (2013). Building a geometallurgical model in iron ores using a mineralogical approach with liberation data. *Second AusIMM International Geometallurgy Conference*, 317–324. Brisbane.

Liipo, J., Hicks, M., Takalo, V., Remes, A., Talikka, M., Khizanishvili, S., & Natsvlishvili, M. (2019). Geometallurgical characterization of South Georgian complex copper-gold ores. *Journal of the Southern African Institute of Mining and Metallurgy*, *119*.

Outotec. (2019). Outotec HSC Chemistry Software. Retrieved January 8, 2020, from http://www.outotec.com/products/digital-solutions/hsc-chemistry/

Talikka, M., Liipo, J., Hicks, M., Takalo, V., Remes, A., Khizanishvili, S., & Natsvlishvili, M. (2018). Copper ore variability – benefits of advanced simulation. *Copper Cobalt Africa Conference*, (July). Livingstone, Zambia: The Southern African Institute of Mining and Metallurgy, Johannesburg.

van den Boogaart, K. G., & Tolosana-Delgado, R. (2018). Handbook of Mathematical Geosciences. In *Handbook of Mathematical Geosciences: Fifty Years of IAMG* (pp. 673–686). https://doi.org/10.1007/978-3-319-78999-6