Copper Ore Variability – Benefits of Advanced Simulation

Matti Talikka[1]*, Antti Remes[1], Matthew Hicks[1], Jussi Liipo[1], Vesa-Pekka Takalo[1], Sandro Khizanishvili[2] and Malkhaz Natsvlishvili[2]

[1]Outotec, Espoo, Finland
[2]JSC RMG Copper, Kazreti, Georgia

**Corresponding author: matti.talikka@outotec.com*

All geological material is heterogeneous. Understanding the variability of run-of-mine material provides a base for efficient mining and minerals processing operations. The development of geometallurgical domains with relevant information, including mineralogy and processing performance, are key for the optimization of mining and minerals processing operations. Advanced simulation of the ore variability supports development, optimization, risk management and valuation of exploration and mining projects and operations. Simulation can be used to predict and compare various operational scenarios and their performance, including, but not limited to, metallurgical recovery, consumption of water, energy and chemicals, environmental footprint and economic value. In the example case, we show how copper ore variability can be studied and simulated, and how minerals processing can be optimized for various ore types. The example case demonstrates that the variations of the value generated by the geometallurgical domains can be an order of magnitude larger compared with the variations of the metal grades. This type of geometallurgical approach improves the efficiency of operation and the value of production over the whole value chain from ore to payable product.

INTRODUCTION

JSC RMG Copper (RMG) produces copper–gold concentrate from two open pit mines, Madneuli and Sakdrisi, both located in the Bolnisi mining district in South Georgia. RMG and Outotec commenced co-operation with a target to improve the recoveries and metal grades in concentrate by improving the understanding of the ore variability and developing more efficient procedures for ore blending and minerals processing (e.g., the flotation process). This type of mineralogy-led approach has already been used for other complex ores such as for iron oxide–copper–gold ores (Hunt *et al*., 2011) and for Kupferschiefer ore deposits (Rahfeld *et al*., 2018).

The co-operation started with process audits and mineralogical and chemical characterisation of process samples, and was followed by detailed chemical and mineralogical characterisation of six different ore types with simultaneous flotation test work with the very same samples. Based on these results, a preliminary geometallurgical classification of ore types was developed. To optimise the process design and improve the efficiency and value of production, the whole value chain was modelled using the *OreMet* optimizer module included in Outotec *HSC Chemistry 9* software.

GEOLOGY

According to a technical report by RMG (2016), the copper–gold mineralized domains at Madneuli and Sakdrisi are hosted by an upper Cretaceous sequence of volcano-sedimentary rocks.

The Madneuli deposit is characterised by a north–east trending dome, with the limbs of the dome dipping at between 10 to 40°. Several steeply dipping faults occur throughout the deposit. Strata are mainly composed of rhyodacitic pyroclastic rocks, with the core of the dome comprising coarse-grained and medium-grained tuffs. These rocks are overlain by a package of alternating tuffs and tuffaceous sandstones. Hydrothermal alteration of the pyroclastic host rocks of the Madneuli deposit includes silicification, chloritisation, sericitisation and sulphidisation. Alteration is typically irregularly shaped and strongest in the core of the dome, decreasing towards the marginal zones.

The Madneuli deposit displays three mineralisation styles: vein-disseminated, breccia and massive stockwork mineralisation. The majority of the copper–gold mineralisation is confined to areas of silica-rich alteration.

Mineralisation within the Sakdrisi deposit is controlled by structure and lithology comprising predominantly pod-like bodies, sheeted vein-sets and low-grade stockwork. The primary mineralisation has been overprinted by surface weathering processes, resulting in zones of sporadic supergene enrichment. Gold generally occurs as free grains, on sulphide boundaries and with silica grains to a minor degree. The mineralization style is considered to represent a transitional type between VMS and epithermal gold type.

SAMPLES AND ANALYTICAL METHODS

The ore samples from Madneuli and Sakdrisi were divided into subsamples: one subsample was used in chemical analysis and mineralogical studies and one subsample was used for flotation test work. The chemical and mineralogical characterisation tests were carried out at the laboratories of Outotec Research Centre in Finland and the locked cycle flotation tests were performed at RMG's Madneuli laboratory in Georgia.

The detailed chemical assays includes complete assays after total dissolution by inductively coupled plasma–optical emission spectrometry (ICP–OES), gold and silver assays by fire assay and sulfur and carbon contents were analysed by combustion. In addition, the copper contents was analysed after a four-stage sequential copper phase assays procedure, described by Young (1974) and further developed by Outotec. This procedure enables the chemical quantification of different copper sulfates, oxides, secondary copper sulfides and primary copper sulfides by using the element to mineral conversion (EMC) method available in the *HSC Chemistry 9 Geo* module (Lamberg *et al.,* 1997; Lund *et al.*, 2013). The main minerals and their mode of occurrence were first studied by optical microscopy (Zeiss Axioplan 2) and X-ray diffraction (Bruker D8 Focus). Scanning electron microscopy and liberation measurements were performed using a JEOL JSM-7000F field-emission scanning electron microscope (FEG SEM) equipped with an Oxford Instruments energy-dispersive spectrometer (EDS) coupled with *INCAMineral* liberation measurement software (Liipo *et al.,* 2012). The hardness of each ore type was determined according to the standard Bond grindability test (Bond, 1961).

ORE TYPES AND GEOMETALLURGICAL CLASSIFICATION

The results of mineralogical characterization and the locked cycle flotation tests data were reprocessed with the *HSC Chemistry 9 Data* module utilizing linear regression analysis and principal component analysis. This analysis of combined data revealed the occurrence of two geometallurgical endmember ore types based on mineral composition and grindability; chalcopyrite–dominant and chalcocite–

dominant types. The rest of the samples lie within these endmember types. The chalcopyrite-dominant ore type represents less altered primary zones and, with increasing alteration, the amount of chalcocite and secondary copper oxides increases. The highest concentrate grades and recoveries for both copper and gold were achieved from the chalcopyrite-dominant ore type and with increasing alteration both grades and recoveries deteriorate. The main characteristics of the three geometallurgical ore types (GMO A, B, C) and their test work results are presented in Table I.

Table I: Geometallurgical ore types and main characteristics.

Type	Copper mineralogy	Cu (%)	Au (g/t)	Bond Wi	Cu rec. (%)	Au rec. (%)
GMO A	Chalcopyrite	0.30	0.75	15.80	84.49	79.81
GMO B	Chalcopyrite–chalcocite	0.53	0.32	13.38	55.25	50.26
GMO C	Chalcocite	0.52	0.21	9.49	79.51	52.69

SIMULATION SOFTWARE AND PARAMETERS

The simulations are based on real mineralogical and flotation test work data from the Madneuli and Sakdrisi ore samples and a conceptual copper concentrator plant design. The parameters (e.g., operating costs, treatment and refining charges, etc.) used in the *OreMet Op*timizer simulation are of general nature and do not represent any specific operations (Table II).

The processing of different ore types was assessed in terms of each ore's metallurgical response and economic revenue when mined and processed in a concentrator plant. The evaluation was carried out with the *HSC Chemistry 9 Sim* module. Cost factors for each step – starting from ore block extraction continuing through all the mining and concentrator plant processing phases – were evaluated separately. The resulting concentrate value was calculated by means of the Net Smelter Return (NSR) formula. The economic revenue evaluation tool, *OreMet Optimizer* module, is available and integrated with the *HSC Sim* minerals processing flowsheet simulator. The simulator flowsheet is shown in Figure 1, and Figure 2 expands the detail of the concentrator plant model. The conceptual concentrator plant design consists of a two-stage crushing section, semi-autogenous (SAG) and ball mill grinding, rougher Cu–Au bulk flotation with subsequent re-grinding, two-stage cleaner flotation and dewatering.

The advantage of the *HSC Sim* flowsheet simulation with integrated *OreMet Optimizer* economic assessment tool is that the throughput and composition of each processing step is obtained directly according to the simulated ore metallurgical response. Operating expenses (OPEX) per throughput USD/ton of each processing stage are given, or determined according to ore processing characteristics. The value of the final concentrate is calculated using the Net Smelter Return (NSR): NSR = ∑ Product values - ∑ Penalty costs - ∑ Treatment charge - ∑ Refining charge.

The economic revenue for given size and of ore block (or blended ore) with predefined run of mine (ROM) feed rate is calculated by subtracting the total costs from the NSR, giving the operating profit for that running time period of the production.

SIMULATION RESULTS

The simulation runs included separate simulations for each geometallurgical ore type (GMO A, B, C) and for various blends [Blend A(1/3)+B(1/3)+C(1/3), Blend A(½)+B(½), Blend A(½)+C(½), Blend B(½)+C(½)]. The simulation run represents 24 h operation, totalling mining and treatment of 9000 tons of ore. The simulation results clearly demonstrate that the variability in the mill feed has significant impact on the processing performance and economics of the operations. The simulation results are summarised in Table III.

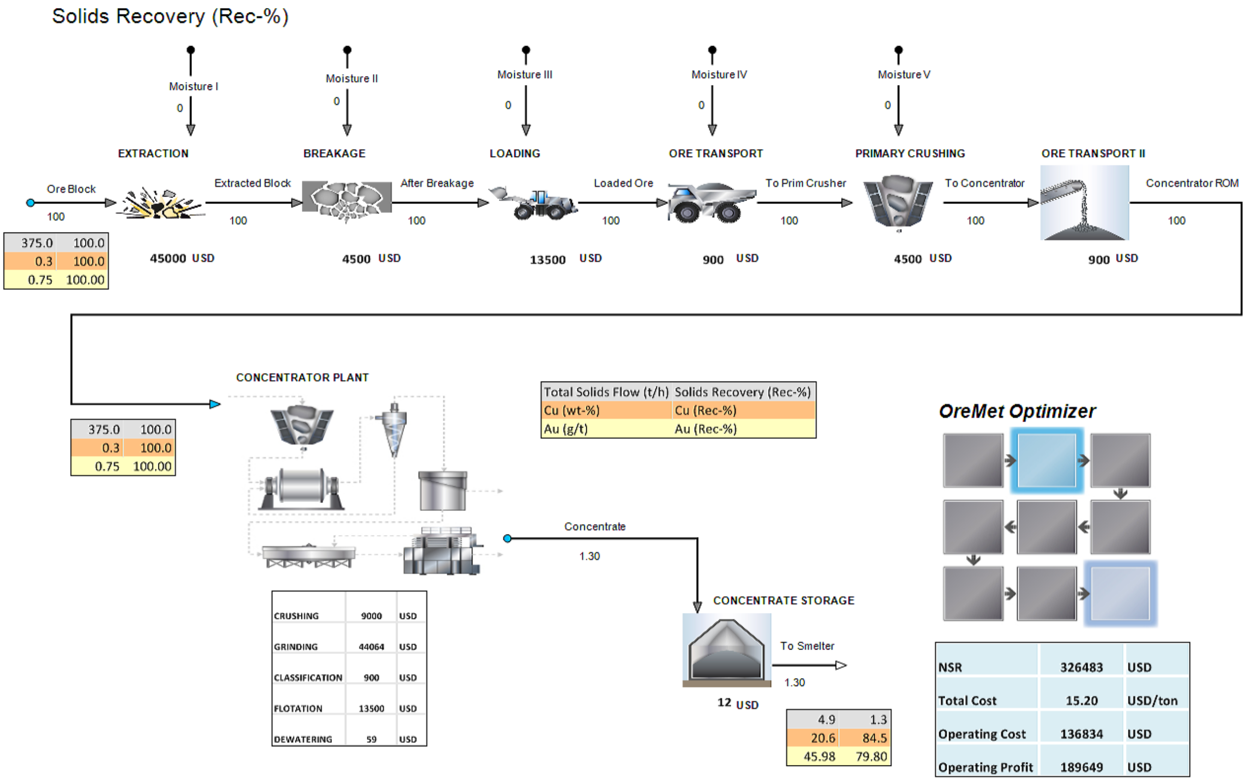

Figure 1: Ore block mining and processing flowsheet with integrated OreMet Optimizer economic assessment.

Table II: Parameters used in OreMet Optimizer simulation are of general nature.

Operating costs	Value	Unit
Extraction	5	USD/t
Breakage	0.5	USD/t
Loading	1.5	USD/t
Ore transport I	0.1	USD/t
Primary crushing	0.	USD/t
Ore transport II	0.1	USD/t
Crushing	1	USD/t
Crushed ore storage	0.1	USD/t
Grinding*	4.5–5.5	USD/t
Classification	0.1	USD/t
Beneficiation	1.5	USD/t
Dewatering	0.5	USD/t
Concentrate storage	0.1	USD/t

Simulation period	24	h
Mining and processing rate	9000	tpd
Concentrate TC**	110	USD/dmt
Cu price	6000	USD/t
Cu payable	95	%
Cu RC**	30	USD/dmt
Au price	1300	USD/oz
Au payable	90	%
Au RC	10	USD/dmt

** TC: toll treatment cost
RC: refining cost

Table III: Summary table of simulation results.

	Feed			Concentrate					Opex	NSR	Operating Profit
Simulation Run 24 hours	Cu %	Au g/t	Bond Wi kWh/t	Mass Rec %	Cu Rec %	Au Rec %	Cu %	Au g/t	USD/dmt	USD	USD
GMO A	0.32	0.75	15.8	1.3	84.5	79.8	20.6	46.0	15.2	326 483	189 649
GMO B	0.45	0.32	13.4	1.9	55.3	50.4	13.1	8.6	14.8	161 534	28 060
GMO C	0.51	0.21	9.5	1.7	79.5	52.6	23.5	6.4	14.2	225 793	97 779
Blend A+B+C	0.42	0.43	12.9	1.6	72.3	67.9	18.7	17.8	14.8	237 887	105 114
Blend A+B	0.38	0.53	14.6	1.6	67.4	70.9	16.2	23.9	15.0	243 917	108 763
Blend A+C	0.41	0.48	12.6	1.5	81.4	73.9	22.2	23.5	14.7	276 138	143 714
Blend B+C	0.48	0.27	11.4	1.8	68.2	51.3	18.1	7.6	14.5	193 696	62 952

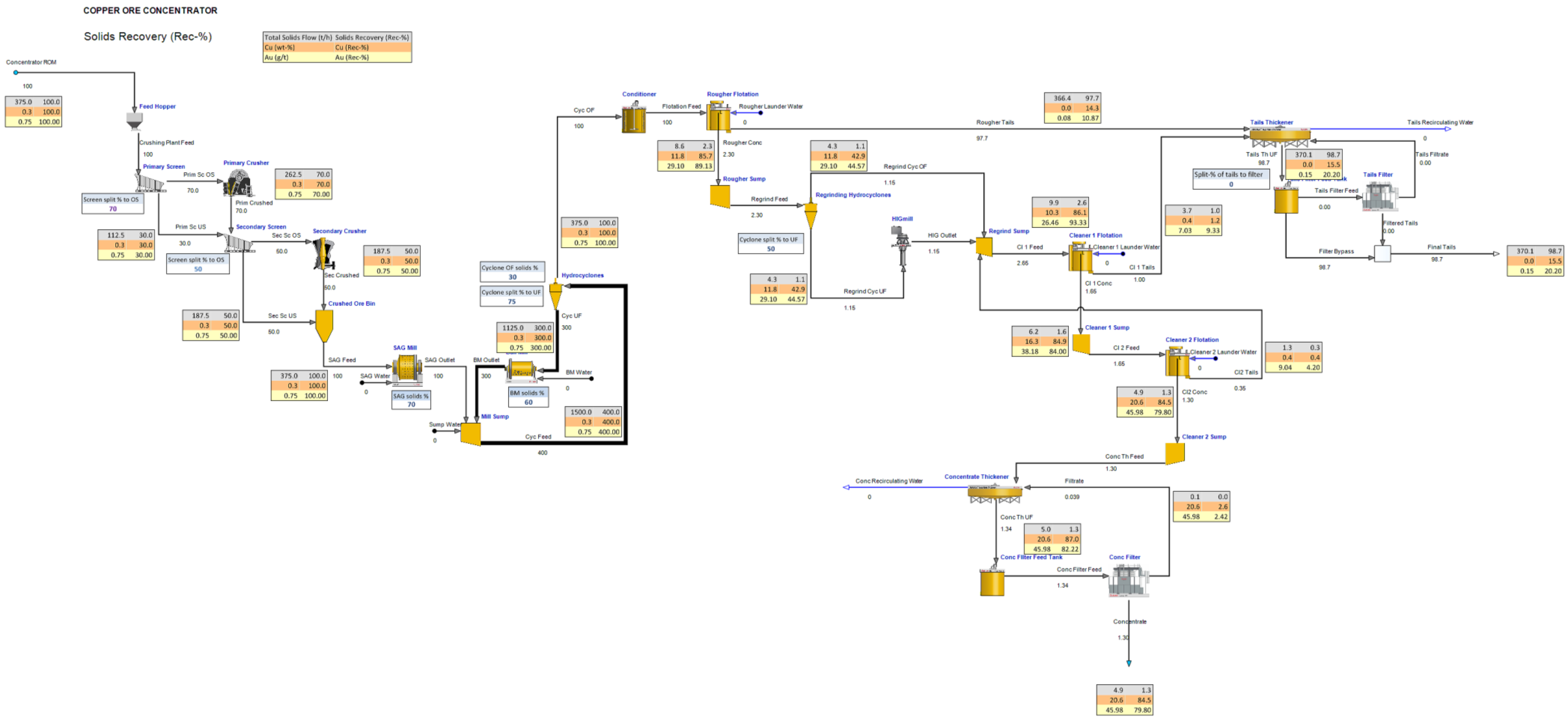

Figure 2: Minerals processing concentrator plant with Cu–Au flotation.

The operational costs for different ore types vary between 14.2 and 15.2 USD/t, mainly reflecting the variations in the Bond Wi and energy consumption in grinding. The flotation test work showed significant variations in the recoveries and concentrate grades between ore types. As a result, there are significant differences in the NSR values and operating profit for various geometallurgical ore types and blends.

The chalcopyrite-dominant ore type GMO A yields by far the highest NSR and operating profit, despite having the highest operating costs. The chalcocite-dominant ore type GMO C produces the second-highest NSR and operating profit, and the chalcopyrite–chalcocite mixed ore type GMO B provides the lowest NSR and operating profit.

The in-situ values of copper (@USD 6000/t) and gold (@USD 1300/t) contents are ~USD 50/t for GMO A, ~ SD 40/t for GMO B, and ~USD 39/t for GMO C. The differences in the NSR values between the geometallurgical ore types are far larger than the differences in the metal grades and in-situ values. This highlights the importance of the understanding of the mineralogy and processing parameters as the key value drivers.

In practice, it is not typical that various ore types are mined and processed separately. The simulated blending scenarios provide additional information for production planning.

SUMMARY

Identifying the variability within an ore deposit, and understanding the mineralogical composition and the metallurgical performance of the various ore types are key factors for efficient mining and minerals processing. The simulation of the whole value chain from extraction to payable product provides useful information on the value drivers of the deposit and operations. The example case demonstrates that the variability of the ore types, particularly on the mineralogical composition and processing performance, plays a key role in the value generation by the operations.

Project or production planning that does not take into account mineralogical composition and metallurgical performance leads to non-optimized operations. For example, the cut-off grades for the Ore Reserve estimation should consider not only the metal grades, but the mineral grades and the respective variability of the metallurgical performance.

REFERENCES

Bond, F.C. (1961). Crushing and grinding calculations. *British Chemical Engineering*, 6 (6), 378–385.

Hunt, J., Berry, R., Bradshaw, D. (2011). Characterising chalcopyrite liberation and flotation potential: Examples from an IOCG deposit, *Minerals Engineering*, 24, 1271–1276.

Lamberg, P., Hautala, P., Sotka, P., Saavalainen, S. (1997). Mineralogical balances by dissolution methodology. *Proceedings Short Course on 'Crystal Growth in Earth Sciences.* Mamede de Infesta. S. (ed.), Portugal. pp. 1–29.

JSC RMG (2016). Technical Report on the JSC RMG Copper Mine Operations: Madneuli & Sakdrisi in Georgia (unpublished).

Liipo, J., Lang, C., Burgess, S., Otterström, H., Person, H., Lamberg, P. (2012). Automated mineral liberation analysis using INCAMineral. *Proceedings Process Mineralogy '12*, Cape Town. pp. 1–7.

Lund, C., Lamberg, P., Lindberg, T. (2013). Practical way to quantify minerals from chemical assays at Malmberget iron ore operations - an important tool for the geometallurgical program. *Minerals Engineering*. 49, 7–16.

Rahfeld, A., Kleeberg, R. Möckel, R., Gutzmer, J. (2018). Quantitative mineralogical analysis of European Kupferschiefer ore. *Minerals Engineering*, 115, 21–32.

Young, R.S. (1974). *Chemical Phase Analysis*. Charles Griffin and Company Limited.