Technological innovation in Córrego do Sítio Mineração – A study of technical and economic aspects by using sensor-based sorting for refractory gold ore

http://dx.doi.org/10.1590/0370-44672020740097

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Abstract

The mining sector has a fundamental financial and economical role in the country where it practices these activities. In addition to employment creation and social-cultural development, the mining sector brings economic growth to the country. However, the sector is facing challenges due to COVID-19, incidents involving tailings dam facilities, rising energy costs, low grade ore deposits, restrictions in mining regulations and access to the available resources. Currently sensor-based sorting (SBS) is well known and applied worldwide in the food, recycling, grain separation industries, and processing of metals, such as diamond, gold, platinum, and feldspar. In the mining industry, ore sorting technology can result in significant improvement in ore quality by removing gangue, uplifting grades, reducing cost reduction and recovering minerals. In this article, we discuss the ore sorting test work and modeled cost-benefit analysis (CBA) for refractory gold ore at Córrego do Sítio Mineração, based on the test results and operating parameters.

Keywords: ore sorting; refractory ore; gold; pre-concentration; processing.

1. Introduction

Worldwide, the industry has been facing challenges due to COVID-19 (Stephany *et al*., 2020), where some operations had to make significant changes to operations or shut down and lay off employees. In parallel, power costs have been increasing yearly, the average grade in deposits is continuously declining and becoming difficult to access with available resources and technology (Li *et al*., 2019). Many problems in environmental impacts require consideration of the global mining industry (Mudd, 2007).

In response to these challenges in the mining sector, several technologies have the potential to change the sector's design and unlock new opportunities in the mining industry. Currently, sensor-based sorting is well known and applied worldwide in the food industry, recycling, grains separation, processing metals, such as diamond, gold, copper, platinum and feldspar (Cutmore *et al*., 1998; Riedel and Wotruba, 2004; Dalm *et al*., 2014).

For the mining industry, ore sorting technology can solve several issues related to capital investment by reducing the milling circuit design, addition of previously non-economical reserves, increased recovery in gold plants through blending strategies and pre-concentrate ores in remote areas for processing elsewhere (Iyakwari and Glass, 2014; Clapham and Clapham, 2015; Lessard *et al*., 2016; Dumont and Lemos, 2017).

The basics of SBS consist in contact-free detection of material properties of single particles by means of sensors, where the measurement data is analyzed and particles with specific characteristics are ejected from the material stream by an external force (Wotruba *et al*., 2014).

Many applications of ore sorting have been reported in literature: waste rock gold dumps can be exploited at good profit margins and be separated at low mass-pull to concentrate (5% to 10%) at a gold recovery rate of 70% (Von Ketelhodt *et al*., 2011). The relationship between recovery/rejection and energy savings using ore sorting for molybdenum ore suggests that at least 30% of energy reduction is possible (Lessard *et al*., 2014). Another study of laboratory-scale work using sensor-based ore sorting for lead-zinc ore presented the overall metal (lead and zinc) recoveries and grades were improved in the flotation circuit (Tong, 2012).

In this study, the same approach has been taken in order to focus on evaluating the technical and financial viability of ore sorting using refractory gold ores below cut-off grade from the underground mine at Anglogold Ashanti Córrego do Sítio Mineração.

The Córrego do Sítio gold mine is located in southeastern Brazil in the state of Minas Gerais, near the city of Belo Horizonte, belonging to AngloGold Ashanti, with the Open Pit operations having started in the 1990's. In 2008, Anglogold Ashanti purchased the former São Bento underground mine and plant from Eldorado Gold, and along with the Open Pit operation, was renamed Anglogold Ashanti Córrego do Sítio Mineração.

For this study, the ore mined from the underground was processed in an ore sorting plant to quantify the overall recovery. Thereafter bench test work was performed with ore sorting concentrate in order to evaluate the technical feasibility and predict the behavior in the Córrego do Sítio Mineração processing plant. Additionally, financial modelling was performed for the entire process.

2. Materials and methods

A stope below the cut-off grade was selected from the current mine plan. For this study, stope 539 130N in the Laranjeiras ore body, represents the mineralogical composition and grade of the geometallurgical domains at the Córrego do Sítio Mineração deposit. The stope area had a strike of 70 meters (length) and 2.22 meter (thickness) and was mined by the sublevel stope method.

The ore mined was hauled to the stockpile in the ore sorting plant. To carry out the test, the following steps were developed:

1. Crushing;
2. Screening of the material into the following size fractions:
   - + 20.00 mm – 45.00 mm.
   - + 10.00 mm – 20.00 mm.
   - – 10.00 mm.
3. For each size fraction (+ 20.00 mm – 45.00 mm and + 10.00 mm – 20.00 mm), material was processed and sorted through XRT (X-ray transmission) and Laser technology combined. The size (– 10.00 mm) was not sorted due to technological constraints;
4. Calculation of the XRT and LASER recoveries and grade uplift.

Metallurgical test work was conducted in the processing laboratory on samples of the ore sorting concentrate consisting of crushing, milling, gravity and flotation tests. The main objective was to predict and assess the behavior of the pre-concentrated material in relation to the current processing plant used for refractory gold ores.

With the results obtained previously, the last step was undertaken according to the financial viability techniques for the cost-benefit analyses. This step provides the attractiveness of the investment for decision making.

2.1 Ore mined for testing

After the mine planning sequence and mine infrastructure preparation in (Figure 1), 3,698 tons of ore was planned, blasted and hauled with a grade of 2.40 g/t gold content to the ore sorting plant. In regular operations, the ore previously mentioned would not have been mined, since the stope is below the cut-off grade.

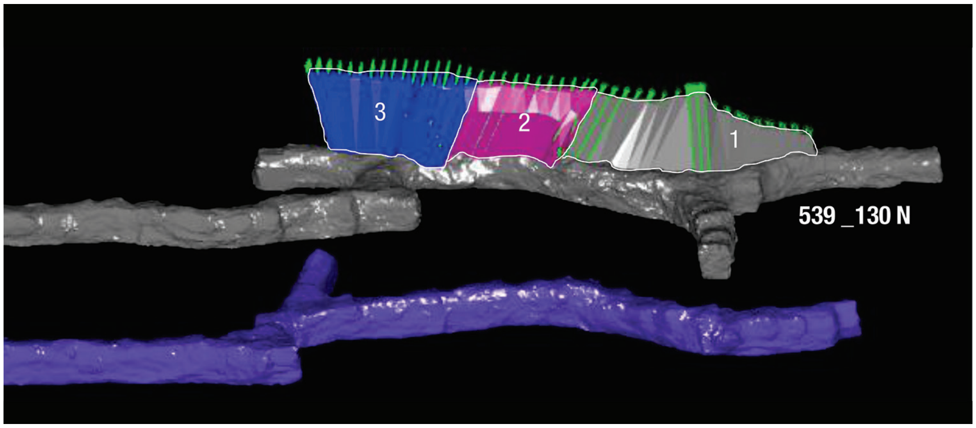

Figure 1 - Mine planning sequence. Source: AngloGold Ashanti courtesy.

Table 1, presents the mine sequence planned, which was divided into three stages.

Table 1 - Parameters related to mine sequence.

	Average thickness m	Strike m	Mass t	Grade g/t	Dilution plan %
Stage 1	1.73	34	1,040	3.35	42
Stage 2	2.64	15	936	2.10	63
Stage 3	2.30	21	1,722	1.99	65

2.2 Ore Sorting test work methodology

In the XRT machine installed in the AngloGold Ashanti Mineração, two technologies are applied in the detection stage for classification: Dual Energy X-ray transmission (DE-XRT) and single X-ray signal (for inclusion analysis). For both technologies, the basic operation consists of emission of an x-ray beam on the sample and interpretation by the detector (Robben *et al.*, 2020). This sorting principle is one of the most widely used technologies for narrow vein mining (Murphy *et al.*, 2012). In addition, to recover gold in quartz veins, within the same operation, a Laser machine operates in series, receiving XRT waste. This technology detects reflection and diffraction of laser light from the surface of crushed rocks (Robben and Wotruba, 2019).

For the tests in the ore sorting plant located at Córrego do Sitio, both XRT and Laser technology were applied, Figure 2. The aim of this phase of the work was to confirm if the ore processed was appropriately feasible for separating.

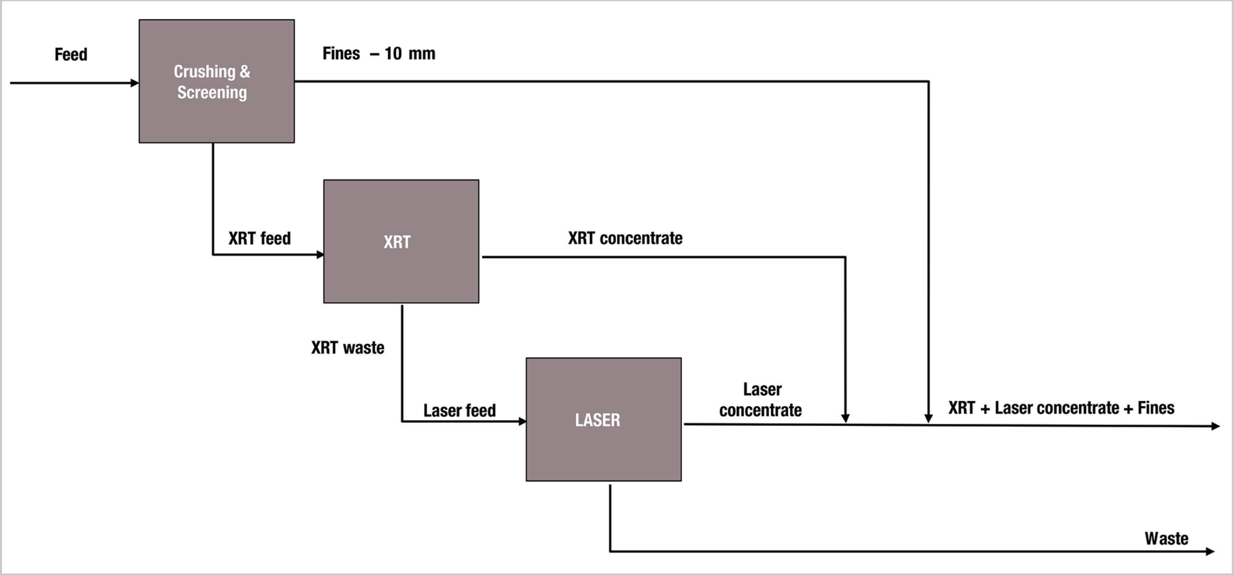

Figure 2 - Ore sorting plant flowsheet.

2.3 Metallurgical testwork

The metallurgical test work was conducted by the processing laboratory at Córrego do Sítio Mineração on the concentrated samples from the ore sorting process. Valuable information was gained in order to simulate the plant behavior, grade parameters and gold recovery. The test work program is shown in Figure 3.

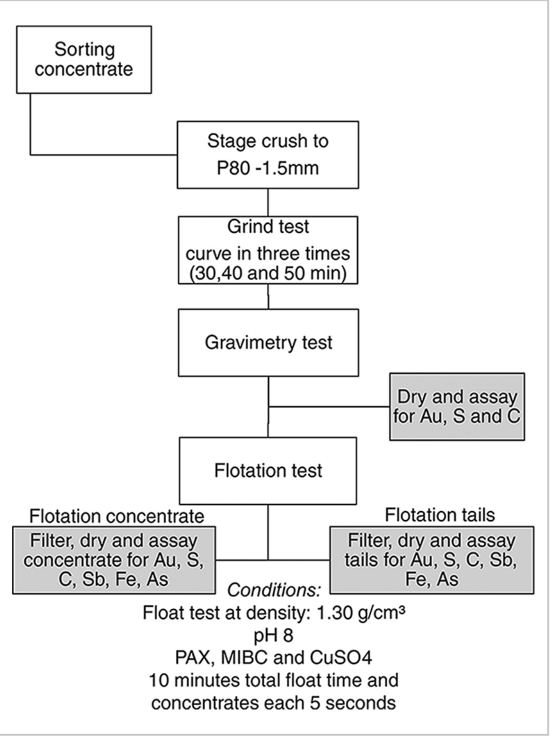

Figure 3 - Metallurgical testwork program.

2.4 Financial

The main impact of revenue from the pre-concentration process is related to metal recovery in the entire process. Metallurgical recovery is defined as the percentage of metal recovered from a metallurgical process.

Cost-benefit analysis (CBA) is a method that applies a systematic process for calculating and comparing benefits and costs. It is a widely used financial and economic approach for assessing whether the benefits of a particular action are greater than their costs.

In order to understand and guarantee if an operation is profitable or not, this step is highly essential in the overall evaluation and will provide information of project benefits versus project costs.

3. Results and discussion

3.1 Ore sorting operational results

A summary of the analyses and mass balance of the reconciliation is provided in Table 2.

Table 2 - Total mass and grade reconciliation.

	Mass t	Au g/t
Mine planned	3,698	2.40
Ore mined	3,935	3.02
Ore sorting recalculated grade	4,246	2.51

The jaw crusher operates in closed circuit with cone crushing and screening. The undersize ore (-10 mm) was transported by conveyor belt and stockpiled, this material cannot be sorted due to current technological constraints. The results are shown in Table 3.

Table 3 - Crushing and screening results.

	Mass t	Au g/t	S %
Undersize ore (-10 mm)	1,231	3.08	0.41
Oversize ore (+10 mm - 45 mm)	3,015	2.28	0.36

The metallurgical performance of the XRT sorter, Figure 4, is shown for the concentrated ore with an average gold grade of 4.07 g/t and 1.45 g/t in waste. The XRT sorter was able to recover 57% of the gold into 32% of the mass. The concentrate grade was improved by a factor of 1.8 compared to the XRT sorter feed grade and no considerable improvement factor was observed for sulfur.

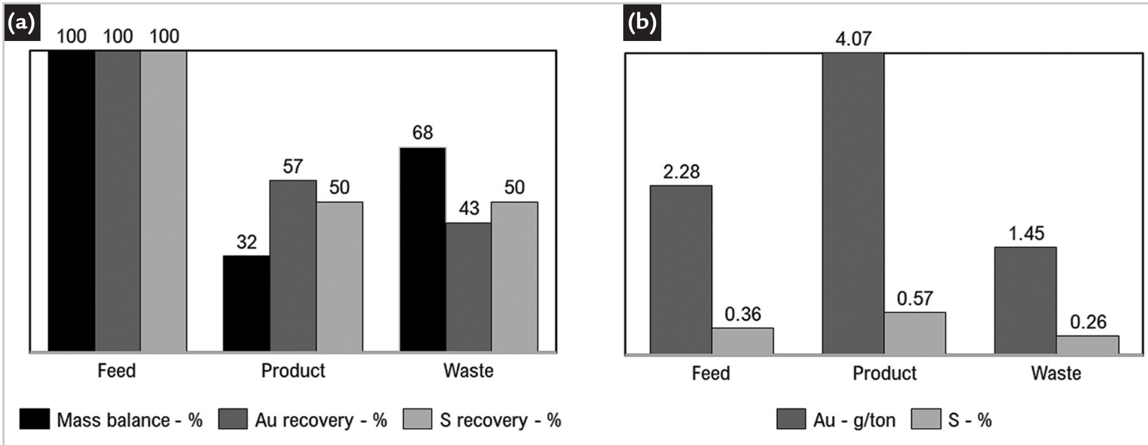

Figure 4 – (a) XRT sorter recoveries results and (b) XRT grade uplift results.

In the Laser sorter Figure 5, high gold recovery was observed with 72% of the gold concentrated into 27 % of the mass. The waste results were 73% of the mass and contained only 0.55 g/t of the gold.

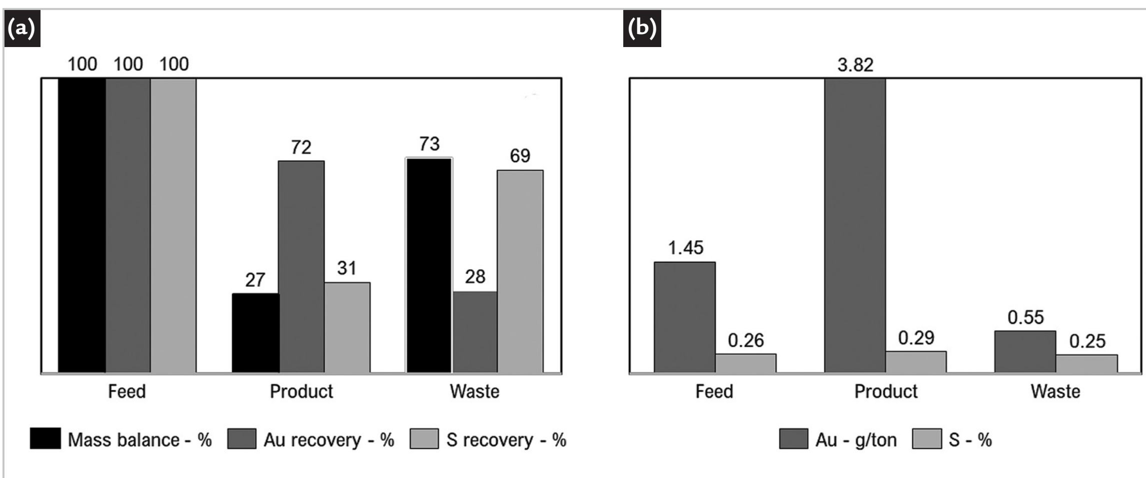

Figure 5 - (a) Laser sorter recoveries results and (b) Laser grade uplift results.

The combined XRT sorter and Laser sorter concentrate which is the final concentrate in the ore sorting plant, Figure 6, has proven to be great opportunity to combine both technologies for increasing grade in refractory gold ore deposits.

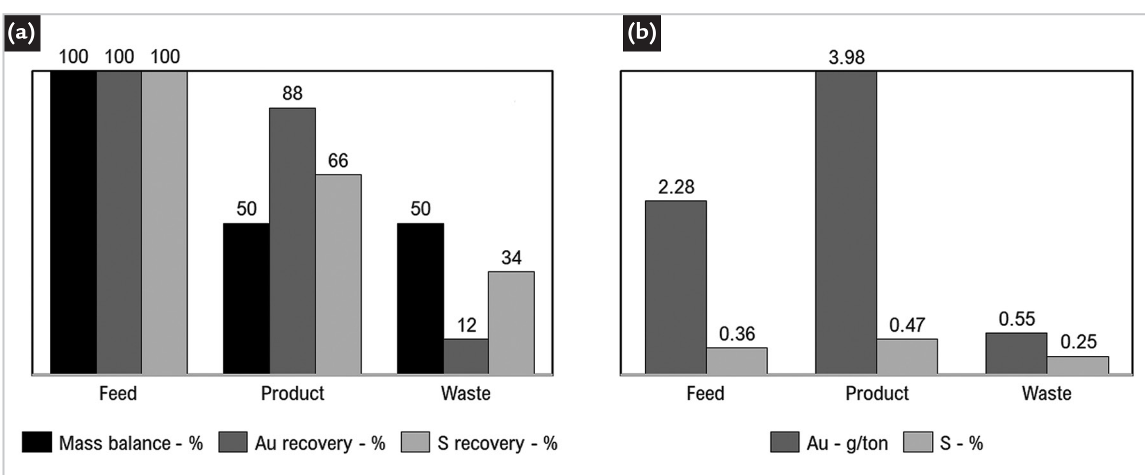

Figure 6 - (a) XRT and Laser sorter combined recoveries results and (b) XRT and Laser combined grade uplift results.

The combined operation, XRT and LASER, upgraded the feed grade of 2.28 g/t to a product of 3.98 g/t with only minimal gold content 0.55 g/t in waste. Gold recovery was 88% into 50% of the mass which leads to a significant increase for further treatment. The sulfur content of the concentrate was 0.47%. The total operation performance which including the fines screened (-10 mm) and ore sorting concentrate, reduced 35% of ore fed and upgraded the feed grade of 2.51 g/t to a final product of 3.57 g/t which represents an upgrade factor of 42%.

3.2 Metallurgical test work results

After sample preparation, the sample was crushed to a P80 of -1.5 mm. The crushed product was milled to a size P90 -74 µm and gravity concentration experiments were performed in order to identify the potential of gold recovery using a gravity circuit. Approximately 1.0 kg of material was fed into the concentrate bowl and three tests were performed. For the tests, the following variables were conducted as per Table 4.

Table 4 - Variables used for gravity concentration test.

	Force	Pressure	Flow
	G's	PSI	l/min
Feed	60	7	14

The assay results of the gravity concentration experiments are shown in Table 5.

Table 5 - Results of gravity concentration experiments for P90 -74 µm.

		Mass g	Au g/t	S %	C %	Mass pull %	Gold recovery %
Run 1	Feed	1000	2.33	0.55	1.80		
	Concentrate	55	24.70	2.82	2.32	5.52	58.46
	Tailings	945	1.03	0.42	1.77		
Run 2	Feed	1000	2.48	0.59	1.80		
	Concentrate	51	30.36	3.70	2.34	5.09	62.24
	Tailings	949	0.99	0.43	1.77		
Run 3	Feed	1000	2.43	0.61	1.81		
	Concentrate	48	30.82	3.66	2.41	4.81	61.09
	Tailings	952	0.99	0.46	1.78		
Average	Feed	1000	2.41	0.58	1.80		
	Concentrate	51	28.63	3.39	2.36	5.14	60.60
	Tailings	949	1.00	0.43	1.77		

As seen in Table 5, an average concentrate assay of 28.63 g/t Au is obtained with 60.60 % of gold recovered. The average tailings grade assayed was 1.00 g/t, showing great gravity recovery performance was achieved.

The gravity tailings was retained for flotation tests using a Denver flotation machine. Some conditions were assumed, pH was 8, speed was 1200 rpm and the air flow rate was 0.5 l/min. In a two-stage rougher and scavenger, three tests were performed for a total of 10 min each. The assay results for Au, S, C, Sb, Fe and As, are shown in Table 6 and Table 7.

Table 6 - Results of assays in flotation tests.

		Mass g	Au g/t	S %	C %	Sb %	Fe %	As %
Run 1	Feed	945	1.03	0.42	1.77	0.02	7.06	0.23
	Concentrate	132	6.46	2.38	1.83	0.06	11.16	1.10
	Tailings	812	0.14	0.10	1.76	0.01	6.39	0.09
Run 2	Feed	945	0.99	0.43	1.77	0.02	7.50	0.27
	Concentrate	132	6.33	2.49	1.83	0.07	11.73	1.29
	Tailings	813	0.12	0.09	1.76	0.01	6.81	0.10
Run 3	Feed	952	0.99	0.46	1.78	0.01	6.79	0.24
	Concentrate	134	5.93	2.44	1.86	0.05	9.72	0.88
	Tailings	817	0.18	0.13	1.77	0.01	6.31	0.14
Average	Feed	947	1.00	0.43	1.80	0.02	7.12	0.25
	Concentrate	133	6.24	2.44	2.36	0.06	10.87	1.09
	Tailings	814	0.15	0.11	1.77	0.01	6.50	0.11

Table 7 - Results of recovery in flotation tests.

	Mass %	Au %	S %	C %	Sb %	Fe %	As %
Run 1	14.00	88.26	79.49	14.48	54.98	22.14	66.56
Run 2	13.98	89.55	81.80	14.45	55.83	21.87	67.70
Run 3	14.13	84.42	75.54	14.74	50.70	20.22	50.84
Average	14.04	87.41	78.94	14.56	53.84	21.41	61.70

The flotation results show that for three tests performed, Au, S, Sb and As can be floated off into concentrate and C and Fe had a slight increase in content. Approximately 87% of gold and 79% of sulfur reported for the concentrate and mass pull was 14%.

3.3 Financial model

The financial model was based on the operational parameters in Table 8 and Table 9.

Table 8 - Base case inputs.

Input	Units	Value	Condition
Fines (10 mm) by passing sorter	per cent of total feed	29.0	tested
Sorter crushing & pre-screen upper size	mm	45	tested
Sorter crushing & pre-screen lower size	mm	10	tested
XRT sorter waste reject	%	68.3	tested
XRT sorter concentrate	%	31.7	tested
LASER sorter waste reject	%	72.7	tested
LASER sorter concentrate	%	27.3	tested
XRT+LASER sorter waste reject	%	35.3	tested
XRT+LASER sorter concentrate	%	64.7	tested
XRT+LASER overall recovery (including fines)	%	91.5	tested
Average processing plant recovery	%	89.9	tested

Table 9 - Unit operating costs.

Input	Units	Value	Condition
Underground variable costs	US$/t	29.0	assumption
Ore Sorting cost	US$/t	5.0	assumption
Sorter concentrate/rejects load & haul	US$/t	1.2	assumption
Mill plant variable cost	US$/t	30.3	assumption
Federal taxation	%	1.50	assumption

It is important to note that the financial modeling assumptions are based on a brownfield operation, which has already paid back the capital pf the ore sorting plant. The revenue calculation therefore does not account for any payback of capital. It also only incurs incremental variable costs in both the mine and the plant, as the fixed cost are deemed to be sunk by the operation. The cost benefit analysis can be calculated using the formula:

$$Benefit\ \frac{US\$}{t} = \left[(G*OSr*GP*MPr) - \left((OSc+UVc) + \left(OSm*(MPVc+CTc) - (OSr*G*GP*MPr*I)\right)\right)\right] \quad (1)$$

Where **G** is the feed grade in the ore sorting plant, **OSr** is the gold recovered in the ore sorting plant, **GP** is the gold price, **MPr** is the mill plant recovery, **OSc** is the operational cost of ore sorting, **UVc** is the underground variable costs, **OSm** is the result of ore sorting mass recovered into concentrated, **MPVc** is the mill plant variable cost, **CTc** is the concentrate transport cost and **I** is the federal income taxation.

All parameters were fixed except the gold price and the exchange rate was 4.50 R$/US$. The sensitivity of each scenario evaluated (1,400 US$/t, 1,500 US$/t, 1,600 US$/t) is demonstrated in Figure 7.

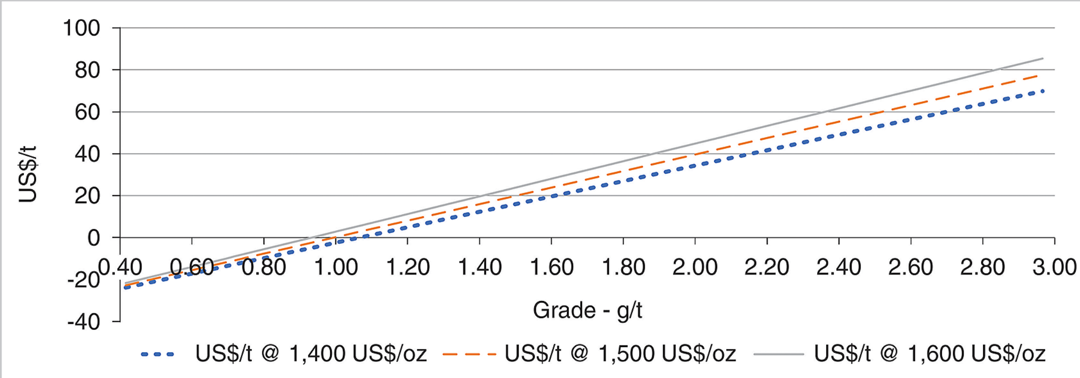

Figure 7 - Cost benefit analyses for different gold prices.

4. Conclusion

The potential of underground refractory gold ore viability using ore sorting technology has been proven technically feasible for a very specific stope application at Córrego do Sitio Mineração. From an economic perspective, based on the cost benefit analysis, for 1,400 US$/oz, 1,500 US$/oz and 1,600 US$/oz, the stope starts to be profitable after 1.07 g/t, 1.02 g/t, 0.94 g/t of gold, respectively. The combination of sensor sorting using XRT and Laser resulted in improved grade by a factor of 1.7 compared to feed grade, and 88% of gold was recovered in 50% of the mass fed into the ore sorting machine. The overall recovery (including fines) in ore sorting was 92% for 65% of the mass and based on metallurgical test work, the predicted processing plant recovery was 89.9%.

The mineralization signature of the ore, that makes it amenable for successful ore sorting, is metasedimentary sequences between mafic dyke swarms. Sulfide of the lodes are mainly arsenic-pyrite and arsenopyrite. Near the dike contacts, hydrothermal alteration is represented by chloritization and carbonatization. These contrasts between hydrothermal halos and host ricks were essential for differentiation via sensors and successful separation.

Future ore characterization of marginal and low grade areas are possible through applying the relevant mineralogical characterization and amenability tests in the ongoing mining.

Acknowledgements

The authors would like to thank Anglogold Ashanti Córrego do Sítio Mineração and CPGEM-UFMG for supporting this research.

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Received: 28 August 2020 - Accepted: 12 October 2020.