GEOMETALLURGICAL CHARACTERIZATION OF VIZCACHITAS CU/MO ORE, CHILE

Antony Amberg[1], Gonzalo Saldías[2], Romke Kuyvenhoven[3], Francisco Soto[3], Heriban Soto[4], Catherine Souza[4]

[1] Los Andes Copper, Las Condes, Chile
[2] Minera Vizcachitas, Las Condes, Chile
[3] Empirica Consultores, Providencia, Chile
[4] SGS Minerals, Pudahuel, Chile

Corresponding author: romke.kuyvenhoven@empiricaconsultores.cl

ABSTRACT

Vizcachitas is an advanced stage copper–molybdenum porphyry deposit, fully owned by Los Andes Copper and located in Central Chile. The property contains an indicated resource of 1,038 million tonnes grading 0.37% Cu and 0.012% Mo, and an inferred resource of 318 million tonnes grading 0.345% Cu and 0.013% Mo. The deposit occurs in the same geological belt as several other giant copper-molybdenum porphyry deposits including Río Blanco-Los Bronces, Los Pelambres-Pachon and El Teniente. In 2017, the original Preliminary Economic Assessment (PEA) study from 2014 was updated; this paper presents the geometallurgical testwork that was performed to support that update. The testwork focused on the metallurgical characterization of 40 DDH samples and the development of a more profound orebody knowledge by relating geological features with metallurgical performance. The scope of work included complete chemical and mineralogical QemSCAN characterization; SAG, ball mill and abrasion testing; complete rougher and cleaner kinetics including locked-cycle-test; environmental ABA and settling tests on rougher tailings. The results show that the ore can be classified as medium-hard, with a hardness that is slightly below the average for large Cu/Mo deposits in the region. A good correlation was found between lithology and breakage characteristics, implying that the specific energy consumption (kWh/t) is well correlated to rock type. The results of the flotation tests were very encouraging and did not show significant variability. An overall Cu recovery of over 90% can be expected for the flotation circuit. The use of a relatively coarse primary grind size gave good final recovery and grade for both Cu and Mo, and deserves further attention in future work, as this impacts positively both energy consumption and water recovery.

KEYWORDS

Porphyry Cu/Mo ore, geometallurgy, metallurgical testwork, process design

INTRODUCTION

Los Andes Copper Ltd. is a Canadian exploration and development company focused on the acquisition, exploration and development of advanced stage copper deposits in Latin America. The company owns 100% of the Vizcachitas project in Chile, the largest copper deposit in the Americas not controlled by the majors. Vizcachitas is a copper-molybdenum porphyry deposit, located 120 km north of Santiago, in an area of very good infrastructure.

Previous metallurgical testwork evaluated both leaching (Lakefield Research Chile, 1996; 1999 and 2000; and Fitch, 1998) and concentration (Lakefield Research Chile, 1996; 1999 and 2009) as process alternatives for the Vizcachitas ore. Based on this work, a Preliminary Economic Assessment (PEA) was published in 2014 (Los Andes Copper, 2014). Later, in 2015, Los Andes Copper decided to re-log 100% of the available cores, creating a new geological model that identified the importance of the early diorite porphyry and the later hydrothermal breccias in controlling the higher-grade mineralization. A 3,610-metre drilling program was carried during late 2015-2016 to confirm the new geological model. The results of this campaign triggered a 10,000-metre drilling campaign initiated in February 2017 to test the extensions of the new geological model, improve the understanding of sections deeper in the higher grade central core, and test extensions of the current mineralization. As part of the 2017 drilling campaign, a total of 40 metallurgical samples were selected for metallurgical characterization and development of a preliminary geometallurgical framework for the Vizcachitas orebody. With the results of the 2017 drilling campaign, un updated PEA has been prepared and published, with the objective to proceed to Pre-Feasibility in 2018.

SAMPLE DESCRIPTION

Individual samples

Individual samples were used for all grinding testwork and the rougher flotation tests.

As base criterion for the selection of individual samples it was defined that the samples should cover the different mineralizations, lithologies, alterations and Cu/Mo grades, as described in the geological model. As a result, a total of 40 samples were identified from an area that covers 676 mts (E-W) by 682 mts (N-S), with elevations between 1176 and 1994 m.a.s.l. The 40 samples, identified by sample names PVMM-01 to PVMM-040, represent the following geological features:

- Mineralization: Supergene (6 samples) and Hypogene (34 samples)
- Lithology: Andesite; Breccia; Diorite and Tonalite (8; 11; 16 and 5 samples, respectively)
- Alteration: Biotite; Chloritic; Quartz-Sericite; Sericite-Chloritic and Si-Sericite (25; 1; 9; 4 and 1 sample, respectively)

- Cu grade: between 0.19 and 1.08% Cu; with a mean of 0.48 and a median of 0.45%
- Mo grade: between 5 and 69 ppm Mo; with a mean of 22 and a median of 20 ppm

Fe content averages 3.2% for the 40 samples; Co and Ag are present as trace elements (13.5 and 1.2 ppm, respectively); As and Sb content can be considered low (30 and 225 ppm, respectively). In addition to complete chemical characterization, a BMA QemSCAN analysis was performed on each of the metallurgical samples, revealing as predominant sulphide species, chalcopyrite (CuFeS2) and pyrite (FeS2; both primarily in the hypogene samples), plus minor amounts of bornite (Cu5FeS4), covellite (CuS) and chalcocite (Cu2S; all in the supergene samples). Mo is present as molybdenite (MoS2) in the primary zone.

Composite samples

Composite samples, made up from selected individual samples, were used for the all flotation cleaner testwork including kinetic flotation tests, open cycle tests, locked cycle tests, and cleaner tests with sea water.

As base criterion for the definition of the composite samples, it was decided that these composites (I) should differ significantly as far as flotation behaviour concerns, covering the expected extremes within the orebody, and (II) would make sense from an operational point of view when looking at the mine plan. It was decided to work with three (3) composites in total, based on the following characteristics:

- Supergene/Andesite composite, representing the first few years of production with a relatively high presence of secondary sulfides and low content of molybdenum. This zone has a relatively high Cu grade but low Cu recovery, when compared to the primary ore. A total of 14 individual samples were used for this composite.
- High molybdenum composite, representing the primary zone that will get into full production after the first few years of operation, and justifying further study of a selective Mo flotation plant. A total of 10 individual samples were used for this composite.
- High pyrite composite, also representing the primary zone, with the potential to affect copper recovery and grade in the final concentrate in case of lack of control of pyrite activation. A total of 16 subsamples were used for this composite.

The final composition of the composite samples resulted as follows:

Table 1 – Description of three (3) composite samples

Composite	Average elevation	Average Cu grade %	Average Mo grade ppm	Average $FeS2/Cu_{TOT}$ ratio
Surface/andesitic	1821 m.a.s.l.	0.65	15	3.6
High FeS2 HG	1513 m.a.s.l.	0.34	24	6.8
High Mo HG	1467 m.a.s.l.	0.50	30	4.5

METALLURGICAL TESTWORK

For the 2017 metallurgical testwork program, a total of 40kg of mass was available for each individual sample. Considering this limited sample availability, combined with the overall objective to get an as complete as possible metallurgical characterization, it was decided to follow the testwork program as outlined below.

- Full chemical and mineralogical characterization
- SAG mill grindability, Bond ball mill and Abrasion tests
- Kinetic rougher flotation tests at different P80
- Settling and environmental ABA tests with rougher tailings
- Kinetic cleaner, open cycle and locked cycle flotation tests only of each composite

The testwork program is reasonably straightforward. The challenge in this specific program was to interpret the results in such a way that metallurgical results could be linked directly to specific geological features, and the potential zones of the orebody that require further attention because of its possible contribution either to value generation or capital/operational cost.

By no means the objective of the current metallurgical testwork was to provide the data for a preliminary geometallurgical model, as the amount of data available for such a model using only 40 samples would be far below industry standards. However, the geometallurgical framework as developed here should guide future sample selection and define more specifically the metallurgical testwork that is required to adequately support the plant design at the next engineering stage of the project.

DISCUSSION OF RESULTS

Grinding testwork

SAG mill grindability was determined using a test known in Chile as the “Starkey test”. This test is an earlier version of the SPI test that is widely used nowadays. One of the major advantages of the "Starkey test" is that sample requirement is low in comparison to other SAG mill grindability tests. It needs to be said though, that the use of this test generates value if and only if there is a database available that can be used to compare the specific deposit to orebodies of similar size and characteristics, which is the specific case for this project (Empirica Consultores, 2017).

The Starkey test reports the time that is required to reach a grind size of 80% minus 10 mesh Tyler, with a feed of 2kg of ore prepared at 20% +1/2 inch and 80% -1/2 inch. For the 40 samples, the SAG Mill grindability according to this test method gives an 80% percentile of 73 minutes or less, and a 50% of 66 minutes or less. This implies a SAG hardness that is considered "average" when comparing the Vizcachitas ore with other porphyry Cu deposits in Chile, as can be seen in figure 1 below.

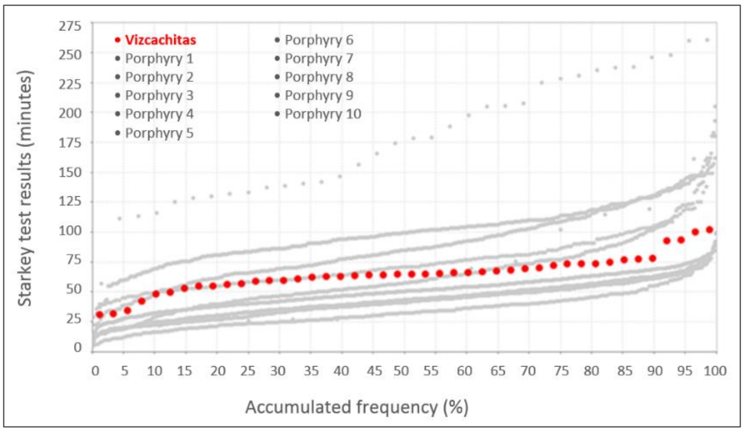

Figure 1 - Comparison of Starkey test results with similar deposits in Chile

When looking at ball mill grindability, using the standard Bond ball mill test with a feed size of 100% below 6 mesh ASTM and a final product size of 100% below 100 mesh ASTM, an 80% percentile of 12.9 kWh/st is observed, and a 50% of 11.8 kWh/st. When comparing these data with similar deposits in Chile, it can be concluded ball mill grindability requires a lower than average energy consumption than for comparable projects for the same ball mill grinding task. This is shown in figure 2 below.

The abrasion tests show a mean abrasion index of 0.248 and a median of 0.250, however the abrasion indices show significant variation between a minimum of 0.091 and a maximum of 0.364. Note that abrasion test results are reported as a dimensionless number.

With the objective of linking the grindability data to geological features, the obtained results for SAG grindability, ball mill grindability and abrasion were first organized per rock type, as can be seen in Table 2.

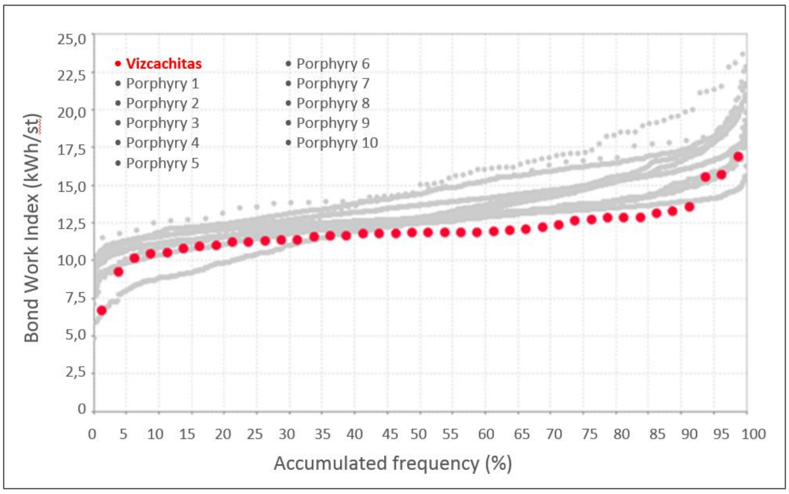

Figure 2 - Comparison of Bond ball mill test results with similar deposits in Chile

Table 2 – Average grinding results for 40 individual samples, organized per rock type

Rock Type	Counts	Starkey (min)	Bond Wi (kWh/st)	Abrasion Index
Andesite	8	*71*	13,1	0,2033
Diorite	16	*69*	13,4	0,2404
Tonalite	5	54	*12,1*	*0,3187*
Breccia	11	50	13,0	0,2607

The andesitic and dioritic ore are more competent and hence more energy consuming as far as SAG mill grindability is concerned, in comparison with the tonalitic and breccia ore types. The tonalitic ore is less competent and hence consumes less energy in ball mill grinding than the other three types of lithologies. Finally, the tonalitic ore is considerably more abrasive than any of the other three ore types.

Rougher Flotation Testwork with Individual Samples

Previous testwork with Vizcachitas samples concluded with the recommendation of performing future flotation work at a P80 between 140 and 200 microns in the rougher stage (Kelly, 2013). Despite of this relatively fine primary grind size, and to ensure continuity of the metallurgical data along the different metallurgical studies for Vizcachitas over time, it was decided to perform the tests at a P80 of 150, 180 and 210 microns. Once those results were available, a fourth P80 was added of 240 microns, as the decrease in rougher concentrate and grade was not considered significant when increasing from the fine P80 of 150 microns to the coarser 210 microns. The rougher tests were performed with fresh water, pH 10, flotation time of 1-2-5-9-14 minutes; 20 g/t 3477, 10 g/t Flomin, 20 g/t diesel and 15 g/t MIBC. All individual samples were tested under the same conditions, independent of their head grade or mineralogical composition.

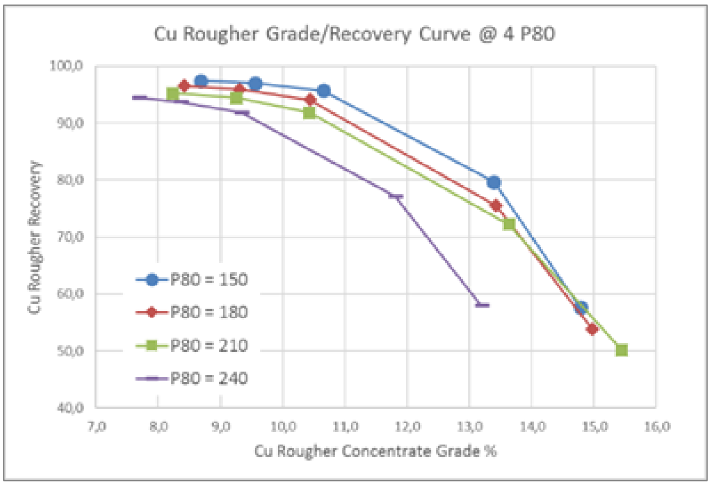

Figure 4 – Cu grade/recovery curve from rougher kinetic tests

Figure 4 shows the average grade/recovery curve for Cu, for all 40 samples, tested at a P80 of 150, 180, 210 and 240 microns. Average metallurgical values should not be used for circuit design purposes; however, they are useful to visualize trends when changing one specific operating variable (such as grind size in this case). As can be seen, even at 240 microns, results should be considered as very encouraging, and hence it is recommended to perform future work at even coarser P80 of up to 300 microns or more.

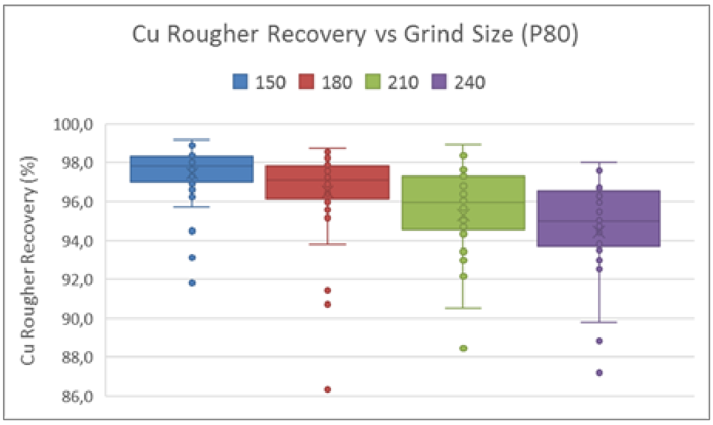

Figure 5 – Box plot Cu rougher recovery as function of primary grind size (P80)

The variability as observed in the results of the rougher tests at different P80 is shown in Figure 5. Variability in Cu rougher recovery increases in addition to the decreasing recovery, when decreasing primary grind size from P80 of 150 to 240 microns.

Cleaner flotation with Composite Samples

The kinetic cleaner tests were done with the composite samples at a regrind size of P80 = 45 microns, pH 11.5 and flotation times of 1-3-6-10-15-21-30 minutes. The same conditions were used for each of the three composites. The objective of these tests was to compare the cleaner flotation performance among the three composites and to evaluate the impact of the rougher P80 on overall Rougher-Cleaner recovery and concentrate grade. The results are shown below.

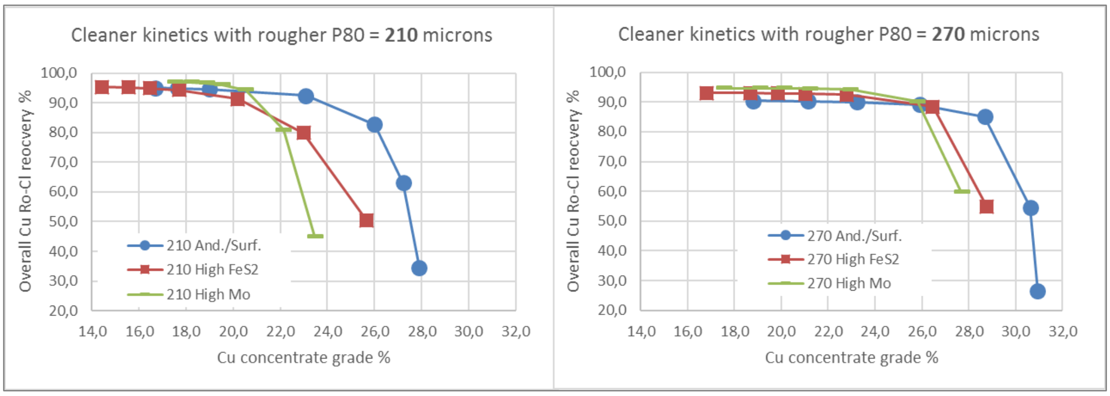

Figure 6 – Cu grade/recovery for cleaner flotation at different rougher P80

The Andesite/Surface composites shows the best grade-recovery curve, followed by the High Mo composite that shows a lower final concentrate grade but similar recovery, and finally the High FeS2 composite showing a lower final concentrate grade. When changing the primary grind size from 210 to 270 microns, overall Cu recovery decreases from a range of 95-97% to 90-95%; however, concentrate grade increases from 14-18 to 17-19% Cu. In other words, flotation becomes more selective for copper when using a coarser rougher grind size, giving slightly lower recoveries but higher final concentrate grades. This seems to indicate that species other than the Cu sulfides are primarily affected and decrease their floatability, when using a coarser grind size in the rougher stage.

Several open and locked cycle tests were performed to find the best conditions for both Cu and Mo recovery and grade, using the flowsheet as shown below.

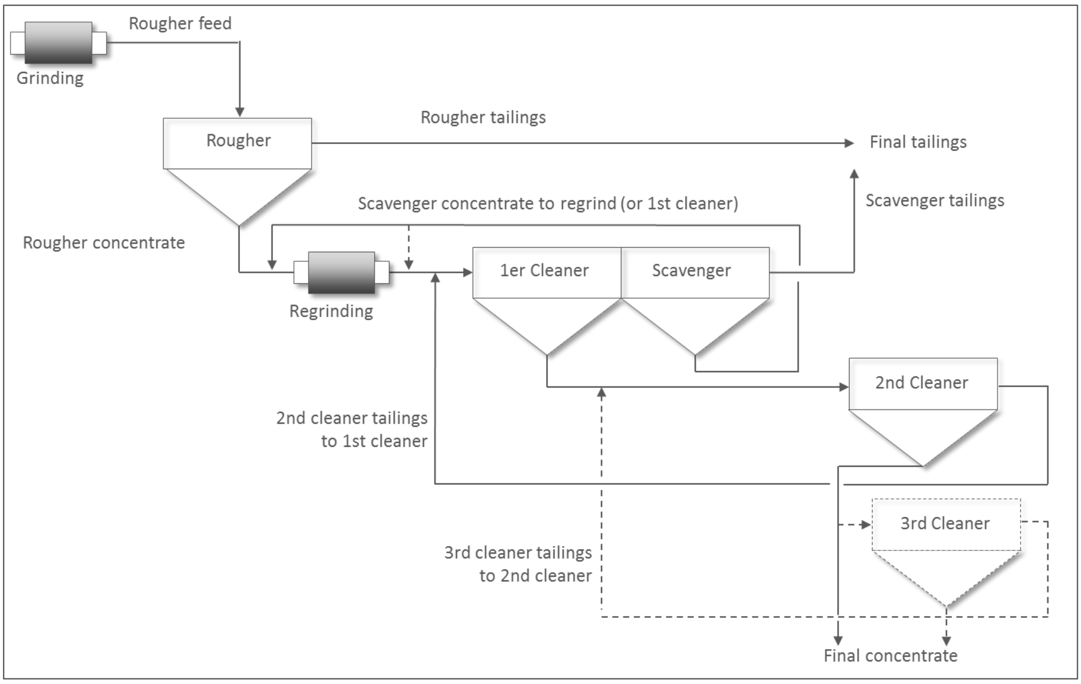

Figure 6 – Flowsheet locked cycle tests

The test conditions for the locked cycle tests are given in Table 3.

Table 3 – Conditions of locked cycle tests

Composite	Test Number	P80 rougher	P80 cleaner	pH cleaner	Cleaner time (min)	Diesel g/T	No. of cycles
Andesitic/Surface SG/HG	LCT-14	210	45	11,5	6+10+3	20	6
	LCT-15	240	45	11,5	8+10+4	20+5	6
	LCT-21	240	45	11,5	10+10+5	20+5	6
High FeS2 HG composite	LCT-16	240	45	11,5	8+10+4	20+5	6
	LCT-20	240	45	12,0	8+10+4+3	20+5	6
High Mo HG composite	LCT-19	240	45	11,5	8+10+4	20+5	9

Reagents used in all tests: 20 g/t 3477; 10 g/t Flomin; 15 g/t MIBC (all added in the rougher stage). Rougher stage flotation was at pH 10 and with 14 minutes for all tests. Only fresh water was used. In LCT-21, the scavenger concentrate was recycled to the 1st cleaner stage, not to the regrind stage. In LCT-20, a 3rd cleaner stage was added. The results of the six locked-cycle tests are shown in the Table 4 below. Those results considered optimum per composite are marked in italic.

Table 4 – Results of locked cycle tests

Test	Composite	Head Grade		Concentrate Grade		Recovery %	
		Cu %	Mo %	Cu %	Mo %	Cu	Mo
LCT-14	Andesitic/Surface	0.65	0.015	31,9	0,16	94,5	36,5
LCT-15	Andesitic/Surface	0.65	0.015	31,7	0,29	92,8	66,3
LCT-21	*Andesitic/Surface*	*0.65*	*0.015*	*27,3*	*0,47*	*92,7*	*75,0*
LCT-16	High FeS2 HG	0.34	0.024	23,8	1,40	94,8	88,3
LCT-20	*High FeS2 HG*	*0.34*	*0.024*	*28,4*	*1,33*	*94,9*	*85,3*
LCT-19	*High Mo HG*	*0.50*	*0.030*	*26,3*	*1,42*	*96,3*	*84,3*

The low Mo recovery of only 36.5% for the Andesitic/Surface composite in test LCT-14, was improved to 66.3% by increasing flotation time and diesel addition in the subsequent test (LCT-15). Mo recovery increased further in test LCT-21 to 75% by sending the scavenger concentrate to the 1st cleaner flotation and not to the regrind stage, to avoid overgrinding of molybdenite. As a result, Cu grade decreased to 27% in LCT-21, but overall grade and recovery are still very satisfactory. In case of the High FeS2 composite, Mo recovery was not a concern and emphasis was given to the potential impact of pyrite. The Cu concentrate grade of 23.8% is relatively low in the first test (LCT-16) and hence a 3rd cleaner stage was added in LCT-20 to increase Cu concentrate grade (to 28.4% Cu). Finally, only one test was done with the High Mo composite. Mo had shown throughout all cleaner testwork a consistently slower flotation kinetics than Cu, and hence in LCT-19 a total of 9 cycles was used to assure a good Mo recovery of 84.3%.

ENGINEERING DESIGN

The design of the grinding and flotation circuit for the updated PEA is beyond the scope of work presented in this paper. However, by means of reference, it can be mentioned that the 2018 PEA, developed by Tetratech Chile, considers a SAG/ball mill grinding circuit plus conventional flotation plant, for both a base case throughput of 55.000 tpd and a larger scale case of 175.000 tpd. This preliminary plant design considered the metallurgical testwork data as presented in this paper. Future engineering stages will evaluate the possible use of more innovative grinding, flotation and thickening technologies to further improve the project's feasibility and overall attractiveness. The full 2018 PEA report will be available on the public domain by the date of publication of this paper.

CONCLUSIONS AND RECOMMENDATIONS

The geometallurgical framework as presented in this paper allowed for identification of those zones of the orebody that have the potential to significantly affect the cost/benefit analysis of a future

Vizcachitas orebody exploitation, by their energy consumption in the grinding stage and Cu/Mo grade/recovery in the flotation stage. Future work should focus on assuring a statistically sound number of samples, preferably around 30, to cover those zones that have been identified as outstanding with respect to energy consumption (Andesite and Diorite rock types); high abrasion index (Tonalite rock type); lower Mo recovery (in the Andesite/Surface zones); and lower Cu concentrate grade (in those zones with relatively high pyrite content). The fact that overall flotation performance does not decrease significantly when using a coarser grind size of 240 microns in the rougher stage, justifies further research into the use a grind size up to 300 microns or more, to decrease energy consumption and improve water recovery. Further attention should be given to the presence and behaviour of Mo in the context of a possible selective Mo flotation plant. Finally, beneficial elements such as Co and Ag should be investigated considering their potential to add significant value to the project.

REFERENCES

- Lakefield Research Chile, 1996. An investigation of the recovery of copper from the Vizcachitas samples, project no. LRCSA 3109 (internal report)
- Lakefield Research Chile, 1999. Flotation testwork on eleven ore samples from Vizcachitas, project no. LRCSA 3209 (internal report)
- Fitch, R., 1998. Vizcachitas sequential leach results for copper (internal report)
- Lakefield Research Chile, 1999. Preliminary agitated leaching tests, Vizcachitas project, project no. LRCSA 3210 (internal report)
- Lakefield Research Chile, 2000. An investigation on the leaching behaviour of Vizcachitas ores, project no. LRCSA 3210 (internal report)
- SGS Minerals, 2009. Flotation and grinding testwork on samples from Vizcachitas, project no. OL-4173. (internal report)
- Kelly, R., 2013. Proposal for a testwork program on sulphide samples from the Vizcachitas project in Chile, on behalf of Compañía Minera Vizcachitas holding (internal report)
- Los Andes Copper, 2014. Preliminary Economic Assessment for the Vizcachitas Copper/Molybdenum project V Region, Chile. Document available at https://www.losandescopper.com/projects/technical-reports/
- Starkey, J., 2014. What Test Work is Required for a Bankable Feasibility Study? COMMINUTION'14, Cape Town, SA
- Empirica Consultores, 2017. Internal study of design on grinding SAG/ball mill grinding circuits of Chilean Cu porphyry deposits (internal report)