Estudio geometalúrgico del beneficio del oro en un depósito mineral en la Cordillera Oriental de los Andes Colombianos

Geometallurgical study of gold beneficiation at a mineral deposit in the Eastern Cordillera of the Colombian Andes

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RESUMEN

El estudio geometalúrgico de un depósito mineral polimetálico ubicado en las cercanías del municipio de California, Departamento de Santander, se llevó a cabo. En el estudio metalúrgico asociado, los modelos estimados mostraron una baja variabilidad promedio, lo que indica que las unidades geometalúrgicas no están definidas. En el estudio metalúrgico asociado, los procesos unitarios y las variables estimadas mostraron una baja variabilidad promedio, lo que indica que las unidades geometalúrgicas (riqueza del yacimiento, dureza de los minerales, separación de minerales particulados de acuerdo a sus propiedades físicas) inicialmente no estaban definidas. Esto sucede porque la zona presenta una formación geológica con brechas hidrotermales donde la mineralización se aloja en mayor grado asociada a los sulfuros. Del mismo modo, el modelo gaussiano de software SGeMS produce leyes estimadas de 3,126 ppm para Au, 11,5 ppm de Ag y 970,53 ppm para Cu. Durante el estudio del comportamiento mecánico, se determinó un índice de trabajo de 19,8 kWh/T, dicha dureza se deriva del alto contenido de la roca silícea presente en la caja mineral; asimismo, el tiempo de molienda calculado es de 20 minutos. El análisis de películas delgadas nos permite caracterizar la presencia de oro, que está encapsulado dentro de pirita y bornita, en tamaños de 2 a 7 micras, lo que corresponde a la concentración mediante circuitos de flotación selectiva o diferencial para obtener dos concentrados, uno de pirita y el otro de Cu.

Palabras clave: geometalurgia, minerales polimetálicos, recuperación de oro, minerales, petrografía.

ABSTRACT

The geometallurgical study of a polymetallic mineral deposit located in the vicinity of the municipality of California, Department of Santander, was carried out. In the associated metallurgical study, the estimated models showed a low average variability, which indicates that geometallurgical units are not defined. In the associated metallurgical study, the unit processes and the estimated variables showed low average variability, which indicates that the geometallurgical units (richness of the deposit, mineral hardness, separation of particulate minerals according to their physical properties) were not initially defined. This happens because the zone presents a geological formation with hydrothermal breaches on which mineralization is lodged to a greater degree associated with sulfides. Likewise, the Gaussian model of SGeMS software yields estimated laws of 3,126 ppm for Au, 11.5 ppm of Ag, and 970,53 ppm for Cu. During the study of mechanical behavior, a work index of 19,8 kWh/T was determined, said hardness is derived from the high content of the siliceous rock present in the box mineral; likewise, the calculated grinding time is 20 minutes. The analysis of thin films allows us to characterize the gold present, which is encapsulated inside pyrite and bornite, at sizes from 2 to 7 microns, which corresponds to concentration by selective or differential flotation circuits to obtain two concentrates, one of pyrite and the other of Cu.

Keywords: geometallurgy, polymetallic minerals, gold recovery, mineral, petrography.

1. INTRODUCTION

Geometallurgy is an interdisciplinary approach, which is a rapidly expanding area of ore geology integrating geological, mining, metallurgical, environmental, and economic information of ore bodies using a spatial predictive model [1, 2, 3, 4, 5]. It has become an effective tool for mitigating technical and operational risks, quantifying the material properties relevant to optimizing processing performance and resource extraction and improving economic performance in the modern mining industry [2, 5], and creates spatially-based predictive models (3D) of ore bodies that supply all relevant information for production planning and management [3, 6]. Geometallurgical models are built by identifying key geological, physical, mineralogical, and chemical properties of the ore samples and linking them to the process properties [5]. There are different kinds of geometallurgical models depending on the ore body, its quality, and the mineral processing circuit [7, 8]. Applying a geometallurgical model reduces the risks derived from exploration and improves mineral production [7] propose five important requirements to build a geometallurgic model: (1) enough and relevant samples have been identified; (2) appropriate breakage tests have been chosen to describe comminution properties of the different rock types (units) in the ore body; (3) the model(s) chosen to describe the comminution equipment in the circuit respond realistically to changes in breakage properties as described by the chosen breakage tests; (4) all of the above are integrated into an overall description of the on-line operational response of the grinding circuit that takes into account non-ore related influences and which can be easily integrated into the existing block model; (5) the final model can convincingly demonstrate its accuracy through validation using real operational data. Notwithstanding, despite the large mineral resources that lie on the subsoil of the municipality of California (Department of Santander), Colombia, mining activity has solely focused on gold extraction for more than 450 years, work that miners have learned as part of their ancestral culture by applying traditional methods that are not very environment-friendly. Thus, new alternatives should be developed for mineral beneficiation to get a polymetallic concentrate as a final product, instead of metallic gold, which would undoubtedly improve metallurgical extraction and would decrease some environmental risks so that the strategic ecosystem of this area, rich in water resources benefitting this region, is not affected. As an important component for mineral exploitation and beneficiation, the necessary mineralogical and metallurgical studies were conducted to obtain the approximation of a geometallurgical study related to the mineral species present in the ore. The importance of geologic studies on geometallurgy regards to defining the spatial variability of potential and active mining resources so that planning and scheduling can accurately predict the economic performance and environmental impact of mining in time to respond efficiently to variations in ore type [9]. All this information allows us to understand better the ore and obtain the most benefits from the mine. The mineralization of interest in this study contains gold, which is related mainly to the pyrite, which is a refractory mineral that may contain measurable concentrations of Au, Ag, Cu, Pb, Zn, Co, Ni, As, Sb, Se, Te, Hg, Tl, and Bi. Pyrite mineral chemistry can provide valuable information to assist in understanding of the genesis of mineral deposits and is formed in a later hydrothermal stage [10]. Pyrite can be an important mineral since it is a gold carrier and for this specific case represent the dominant host in this deposit [11]. The above aims at establishing the optimal variables and parameters of the unit operations and processes to verify the viability of metallurgic extraction of specific minerals, as well as to determine design characteristics and factors of the required equipment along with the flow chart of these unit operations and processes with their corresponding mass balances.

2. GEOLOGICAL FRAMEWORK AND BACKGROUND

The study area in which the project is located is known as the mining district of Vetas-California which belongs to the Massif de Santander in the Eastern Cordillera of Colombia; the project is specifically located in the geographical coordinates of latitude 7˚ 22' and longitude 72˚ 53', whose area is contained in the 110-1-C map sheet at scale 1:25000 of the Instituto Geográfico Agustín Codazzi, which is part of the H-13 Pamplona quadrangle (Fig. 1). It presents lithologies associated to Precambrian metamorphic rocks to which the Bucaramanga gneiss belong, considered the oldest unit, igneous rocks of the Triassic-Jurassic granitic composition [12, 13] are also found and an age magmatic pulse is evidenced Late Miocene due to the presence of porphyritic dikes and bodies, as well as tectono-hydrothermal gaps of Pliocene-Pleistocene age [14]. There is a strong structural control reflected by the presence of the different faults in the area of the deposit. Regionally, the main fault is the Bucaramanga fault, however, the structural control over the deposit is given by the local faults of San Juan, La Baja, Angosturas, Móngora, Paez, and Romeral-Cucutilla and other minor failures associated with these, which They play an important role in the mineralization of box rock. In the central part of the Santander Massif, between the Vetas-California and Bucaramanga block, the massif shows a particular fault pattern with predominantly NE-SW trend faults such as the Surata Fault, with dextral movement [15], which coincides with the veins of the deposit, being parallel to subparallel. The Gneiss composes the oldest unit of the igneous-metamorphic basement of the Santander massif and in the study area, it is the unit of greatest extension, as well as of greater interest since in it the gold exploitation will be carried out. This unit is composed of gneisses that vary compositionally, quartzites, amphibolites, and locally migmatites, also granulites are sporadically presented. According to [16] the regional metamorphism of this unit has reached the conditions of amphibolite facies, zone of the superior sillimanite. Geochronological studies have established a maximum protolite deposition age for this unit as Meso-Proterozoic (deposition age between ~ 1200-1300 Ma; according to U-Pb ages in detritic zircons) [17]. In the region, an intrusive body of Triassic to Jurassic age emerges, which has taken advantage of the fracturing zones to which Bucaramanga's gneiss is subjected, which acts as a box rock. Mineralization in the districts of California and Vetas occurred during a relative hiatus of arc magmatism in the Central Mountain Range [18]. According to [19], epithermal deposits are important sources of gold and silver that form at < 1.5 km depth and < 300 °C in high-temperature in different geological settings as volcanic arcs at convergent plate margins, intra-arc, back-arc and post collisional rift, and are associated with calc-alkaline to alkaline magmatism. Regarding to the Santander Massif and specifically the Vetas-California mining district host different styles of mineralization that were formed by these hot solutions and magmatic fluids and vapors, they are interpreted as hydrothermal systems which could be of high sulfidation or low sulfidation mineralization [20]. The mineralization in the mining project correspond to very variable and complex lithologies, derived from the confluence of different geological faults, related to the crystalline basement of the Santander Massif, where porphyry bodies are highlighted by the occurrence of hydrothermal veinlets with the presence of metallic sulfides [13]. The Eastern Cordillera of Colombia has been recognized for being a key region for ore mineral exploration since the geological setting, the tectonic interaction, and history of multiple subductions and orogenic events since the Proterozoic create a perfect environment for ore mineral deposits [21]. Mineralizations present in the subsoil of the area of the Soto Norte mining project in the Department of Santander correspond to very variable and complex lithologies, derived from the confluence of different geological faults, related to the Bucaramanga fault. The Santander Massif in which Precambrian rocks, igneous rocks, and porphyry bodies with hydrothermal variations are present, prevailing the presence of metallic sulfides in their veins [13]. In the first investigations for this kind of epithermal deposits, it was recognized that hot solutions were important and that wall-rocks were commonly highly altered [22]. The primary source of components in hydrothermal systems formed in volcanic arcs are represented by magmatic fluids, vapors, and hypersaline liquid, those components include metals and their ligands that become concentrated in magmas [23]. The deposit presented in the study area corresponds to a hydrothermal type whose mineralization is associated with the presence of tectonic-hydrothermal breccias formed by the evident structural control presented. There are 22 veins in the area that have been modeled, subparallel to each other, have a NE strike, and a dip between 75 and 78 degrees north. Their thickness varies from meters to centimeters, though they have a good both lateral and depth distribution [24]. The main host rock is the Precambrian Gneiss known as the Bucaramanga Gneiss unit with a compositional variety from hornblende to quartz-feldspathic gneisses, besides small amphibolite lenses that show very well-defined hydrothermal alteration halos.

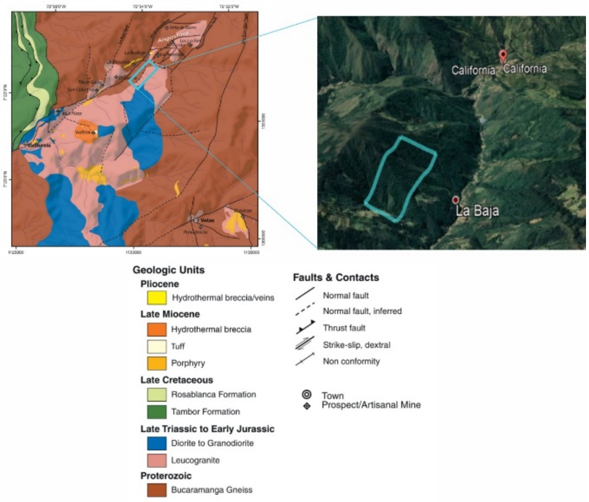

Figure 1: Geological framework and location. Taken and adapted from [25].

3. MATERIALS AND METHODS

The exploration of the deposit was performed between 2010 and 2011. Sampling for the geo-metallurgical study, laboratory tests, and processing proposal was carried out between 2018 and 2019. In the elaboration of the geometallurgical study, the evaluation was conducted on the characterization and metallurgical study of the minerals, subject to the ongoing mining extraction in the study area in the Municipality of California. The experimental work included sampling, mineralogical characterization, and metallurgical test-work (Fig. 2).

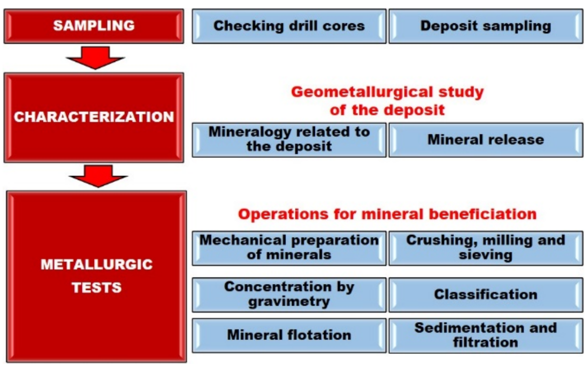

Figure 2: Flowchart of the geometallurgical study [x].

3.1. Sampling

The main objective of this sampling campaign was to assess critical metals resources, in terms of yields and chemical composition of the potential end-products through a laboratory-scale analysis. All the core sample used in this work form part of an exploratory drilling undertaken between 2010 and 2011 by Minesa, Sociedad Minera de Santander (Colombia), which allowed to collect geochemical, geomechanical, structural, and lithological information of the subsoil. According to [26], the information collected from the drilling cores was analyzed, and with the data obtained the mineral deposit was modeled using the Recmin Software. Drill core logging by geologists commonly includes a qualitative description of the lithology, mineralogy, and ore textures and it is not only a cost and time-consuming method, but it also relies on each geologist knowledge and experience [27]. Drilling cores were collected to cover the full geological variation of the deposit, selecting representative samples of the Au-Ag ore for characterization of their mineralogical composition and type of alteration. The deposit consists of 24 sub-parallel veins between them embedded in the metamorphic unit of Bucaramanga gneisses. The representative 3D model for the project is shown below in Fig. 2. In total, the area has 22 sub-parallel patterned veins with a NE heading, and a 75-85º NW dip, they are veins with a very variable thickness from meters to centimeters, but with good continuity both laterally and in-depth. The whole core samples were cut in sing a Minosecar 2 ROWRATHENO diamond wet saw until they got tablets, which were then polished in a BULHER grinding-polishing machine for SEM analyses. A PetroThin thin sectioning system was used in the preparation of thin sections for petrographic analysis.

3.2. Sample preparation

For the detailed mineralogy and metallurgy assessment, samples were crushed, ground, and screened to pass 1 mm sieve. Representative subsamples of ground samples were obtained by rotatory splitting for detailed mineralogical evaluation, bulk chemical and mineralogical analyses. Samples were wet sieved through a standard screen series to generate several size fractions.

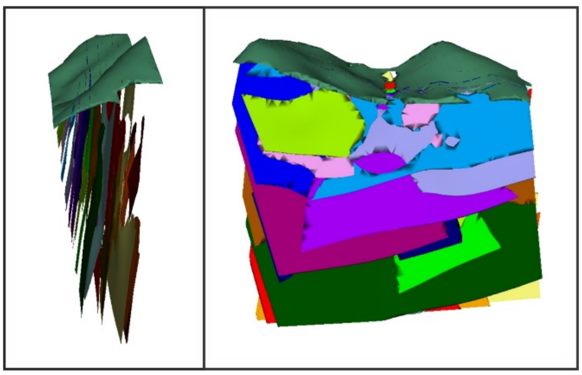

Figure 3: Model 3D showing the distribution of the 24 veins present in the project area [x].

3.3. Au-Ag liberation

Any potential proxy tool for the Au-Ag liberation prediction should be capable of a rough forecast using as little information as possible, so that additional work and costs related to the extra analysis for chemical assays or mineralogical studies will not be needed. Therefore, the calculation of mineral release and the macroscopic scale characterization of 50 samples were carried out, of which those of greatest interest were selected for analysis by conventional petrography and scanning electron microscopy (SEM). This study focused on considering fully liberated Au-Ag. Studying liberation properties of mixed particles would require a more extensive sampling campaigns, with additional metallurgical testing and mineralogical characterization.

3.4. Mineralogical characterization

The mineralogical characterization includes analysis of the hand rock samples, defining textures, percentage of minerals, and possible kind of mineral alteration, once this information is obtained is necessary prepare the thin sections from this hand rock samples to obtain deeper mineralogical information which allows the characterization of this study area. These sheets have an approximate thickness of 30 µm, which allows the microscopic description of the rocks.

Petrographic analysis was carried out by transmitted light microscopy, using a NIKON trinocular microscope, Labophot2-POL model, taking photomicrographs with the 5x objective, in order to observe the textural and microstructural features and determine and describe the constituent minerals of the rocks, their mineral associations, sequences of mineral formation, qualitative percentages, alterations and rock classification.

Mineralogical and compositional analysis was carried out in polished thin sections by scanning electron microscopy (SEM) using a FEI QUANTA FEG 650 ESEM, under the following analytical conditions: increase = 120-1000x, HFW = 2,49 mm - 298,0 µm, HV = 25 kV, WD = 10,1-10,9, signal = SE and Z Cont, detector = ETD and BSED, EDS EDAX APOLO X detector with resolution of 126,1 eV (in. Mn Kα). They were made and studied separately to determine the relationship of gangue minerals to the sulfides and localization of precious metals, as well as quantification of compositions of different ore forming minerals.

3.5. Metallurgical characterization

Taking into account the characterization analysis performed for selected samples, [28] established three alternatives with different stages for the benefit of coexistence minerals, which were schematized with the draw.io online Software program and involve 3 main stages: (1) Comminution (crushing and grinding); (2) concentration through gravimetric processes (Wilfley tables and concentrators and/or through foam flotation process; (3) drying (sedimentation and filtering of concentrates and tailings).

4. RESULTS

4.1. Main Alterations Related to the Deposit

The mineralization of interest in this study is spatially associated with Precambrian gneiss and amphibolite rocks, consisting of a sequence of quartz-feldspathic hornblende paragneisses and subordinate quantities of amphibolites, migmatites and sporadically granulites. At the rocky outcrop and core drilling scale, these rocks present banding characterized by leukosomes (quartz-feldspathic) and mesosomes (biotite-hornblende), whose thickness fluctuates between a few centimeters and various meters in some areas. Quartz-feldspathic bands (leukosomes) are generally fine-to-medium grained minerals, rich in potassium feldspar and contain plagioclase, muscovite, and quartz [29]. Mesosomes are characterized by many dark medium-sized grains with a high content of heteroblastic crystals, subidioblastic to idioblastic hornblende, and disseminated biotite and magnetite to a lesser extent. These bands are also observed on the valley of the La Baja stream, extending laterally on the right margin between 200 to 400 meters thick. Locally, banded gneisses are rich in biotite, exhibiting an augen structure with quartzes and feldspars. Intrusive rocks can be grouped into two different petrographic units: the oldest unit consists of tonalite with variations of granodiorite and quartz-monzonite, which have been related to a magmatic cycle of the Triassic-Jurassic period [30]. U-Pb dating of zircon by LA-ICPMS determined their age around 200 Ma [13].

The deposit is mainly characterized by phyllic alteration, advanced argillic alteration when closer to mineralization, argillic alteration is more distant from this and finally, propylitic alteration is present in minimal proportions. There are also some areas of overlapping supergene alteration related to the fault zones. Mineralization is mainly associated with the phyllic and advanced argillic alteration with the presence of quartz-alunite, an intermediate argillic alteration.

4.2. Geological Analysis

Fig. 4 illustrates a block model of the deposit with the Au contents, which was constructed using the 3D mining software Vulcan that allows us to determine where the main amount of Au content can be found. After determining geological limits for ore and rock types the area will be divided the geological zones into blocks and estimate the tonnage and grade of each block. The final model was built in this case with the geological information obtain and the data provided. It shows that the main content of Au is between 2-10 ppm which fits with the information obtained from the pyro analysis. The yellow color which is the main rank represents an Au ppm between 2-3 and the blue light zones between 5-10 which coincide with the cut-off grade. From the block model, a gold cut-off grade of 3,85 ppm was quantified for a 311 135,52 oz Au, with grades of 5,01 ppm Au, 15,33 ppm Ag, and 2401,00 ppm Cu. The cut-off grade for gold was established at 3,85 ppm.

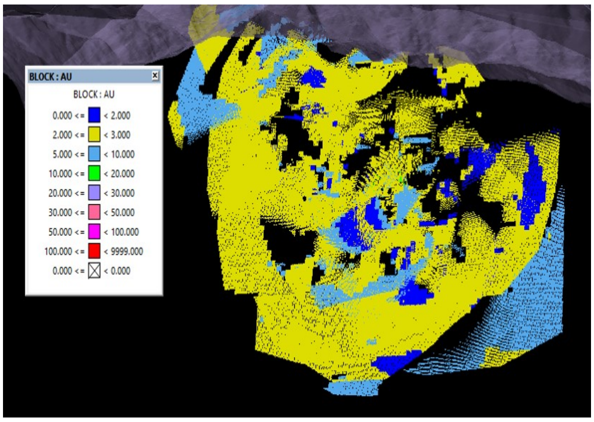

Figure 4: Block Model of Gold Mineral Deposit [x]

Total resources are displayed in Table 1, it shows the main values for the different states of resources, indicated, inferred, and both.

Table 1: Categories of Au, Ag and Cu mineral resources in the study area.

Calculation of the degree of release for mixed particles A/B/C/D/E of a given mesh	A	B	C	D	E
Sum of product area * surface exposed	584.00	0.00	102.25	6.00	188.25
Theoretical Maximum of Release (Mix particles Total: 30)	1000	1000	1000	1000	1000
Degree of release (%)	58.40	0.00	10.225	0.60	18.825

A, quartz; B,pyrite; C, Alunite; D, magnetite; E, feldspar

Results showed below were obtained from the statics software Stat Graphics. Fig. 5a illustrates a histogram of Au grades (ppm) in all veins of the study area with Mean = 4,92941 and Standard Deviation = 0,807763. The estimated Au grades (ppm) for each vein are displayed in Fig. 5b. Please note that the highest Au grade is found in Vein 17, reaching a value of 7,57 ppm, followed by veins 1, 2, 4, 7, and 16. The average is comprised between 2-4 according to the results showed before with a cut-off grade of 3,85 ppm.

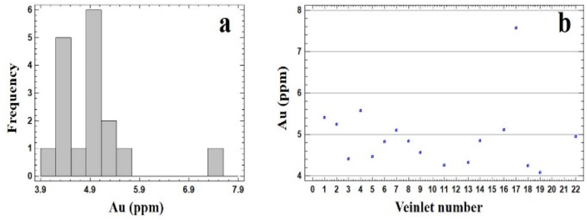

Figure 5: (a) Histogram of Au grades (ppm) in all veins of the study area. (b) Distribution of Au grades (ppm) in the study area veins [x].

4.3. Mineralogical characterization

A study of the mineralogy was performed on 6 thin sections of rocks, which show different type of textures and mineralogical alteration. Fig. 6 shows the main minerals found for each sample and in base of this first analysis is possible to define the occurrence of massive textures in most of them (Figs 6a-6c, 6e-6f). Figs. 6a-6b display pyrite veins and all of them contain pyrite as granular massive aggregates. It is possible to observe chalcanthite in Figs. 6b-6c. A brechoide texture can be seen in Fig. 6d. Oxidation is observed in many of these samples.

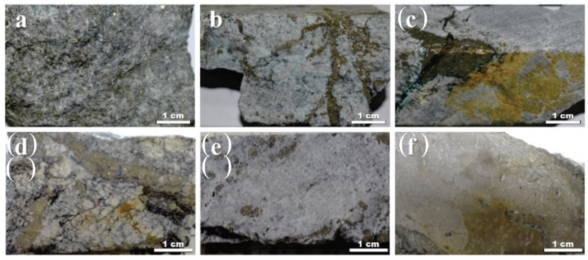

Figure 6: Hand rock samples (4, 18, 25, 24, 41, 45), mineralogy and textures [x].

4.4. Mineral alteration

The analysis of the thins sections allows us to determine with certainty the kind of mineralogical alteration present on this mineral deposit, based on the mineral composition and paragenesis, through this is seen than the most common mineralogical alteration is Phyllic for this deposit followed by argillic and advanced argillic. Phyllic alteration is typical for the assemblage quartz-sericite-pyrite. Is characterized by the complete substitution of the plagioclase feldspars by sericite and of the mafic minerals by quartz [31]. In sample 25 it is possible to observe this kind of hydrothermal alteration as seen in Figs. 7a-7b. Advanced argillic alteration in this deposit can be seen in sample 45 characterized by a high amount of clay minerals in a matrix along with quartz and pyrite, there are several veins with the same composition which is basically quartz to the edges of the veins and alunite that forms following the quartz (Figs. 7c-7d).

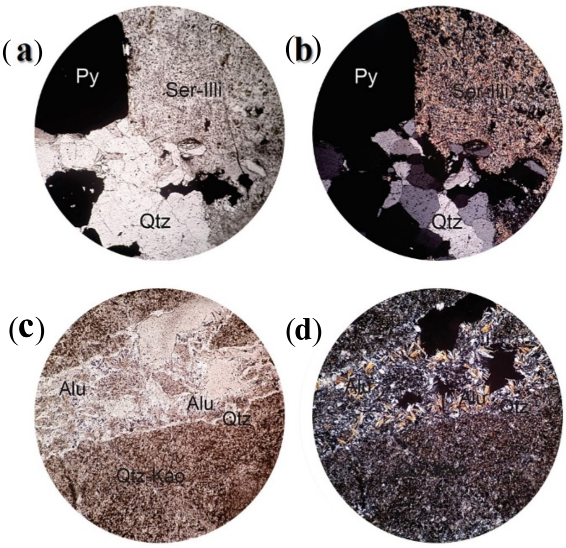

Figure 7: (a) Phyllic alteration assemblage for sample 25. (b) Argillic alteration assemblage for sample 45 [x].

Polished thin sections were studied by SEM to verify the state of the metallic minerals of interest (Au-Ag) in the ore deposit. Unlike the transmitted light microscope, the SEM analysis allows observing the petrographic characteristics of the metallic minerals of interest (Au-Ag) in the ore deposit, which being opaque, cannot be seen in transmitted light and for which it is necessary to use a reflected light microscope or other analysis techniques such as SEM, which gives an estimate of the elements present in a point that was specifically chosen for analysis. Approximately 4 areas of interest were chosen for each section in which the presence of Au and Ag was expected. The estimated time for the study of each section in the microscopy laboratory is 3 h, ensuring a correct determination of the mineral presence. This type of analysis also allows observing the relationship between minerals and mineral assemblages, referring to those minerals which are associated with Au and Ag in this deposit. Fig. 8a shows the phyllic alteration for sample 18 which presents a mineral assemblage form by pyrite, quartz and clay minerals, and the textural features of the analyzed sample. Fig.8b shows a backscattered electron (BSE) of the analyzed sample, which was chosen due to its high concentration of valuable species. Fig. 8c shows the presence of microparticles of tellurides with Au-Ag along with petzita. Fig. 8d illustrates the EDS spectrum of microparticles of tellurides with Au-Ag. The presence of refractory gold of auroargentifer pyrite is confirmed, which is related to metallic tellurium and gold encapsulated inside the pyrite. The SEM analysis allowed observing the fine particles that contain the minerals of interest associated with tellurium and included in refractory pyrite; these minerals have sizes between 4-24 micrometers. The image shows three samples that were analyzed in the scanning electron microscope and to which a carbon cover was applied.

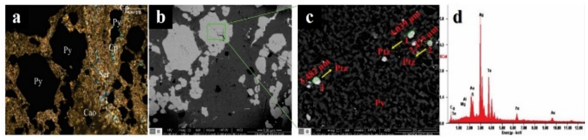

Figure 8: (a) Photomicrography of sample 18. (b)-(c) SE images of the analyzed sample. (d) EDS spectrum of microparticles of tellurides with Au-Ag [x].

4.5. Basic study of mineral release

The degree of release is a quantitative expression of the magnitude to which the mill can obtain free mineral particles. The determination of the degree of release of a given mineral is only possible by using microscopic studies and it is a parameter of decisive importance, such determination should be based on a technical and scientific sound methodology. The determination of the degree of release is not only indispensable as research prior to the design of any type of treatment process but is also very valuable to evaluate the performance of the milling or sorting equipment and to increase the efficiency of operation plants. A perfect release would be one in which all the grains of a given mineral species would be completely separated from the other associated species. That is practically impossible to obtain because mechanical stresses break more easily the body of a given mineral species than the edges between one species and another one. On the other hand, the more complex the mineralogical composition and the geometry of the intergrowths are, the more complex will be their response to the mechanical stresses of rupture. Consequently, a certain magnitude of milling will produce very different release trends between one mineral species and another, indicating that the release is a function of the mineralogical composition of each particle in the analyzed material which is different for each of the mineral species present [32].

The analysis consisted of separating and washing minerals at different mesh sizes, starting from #20 to #120. The results obtained with the duplicate are presented below (Table 2). The abbreviations used for the identified minerals are: Qtz, quartz; Pl, plagioclase, Py, pyrite; Mag, magnetite, Ftp, alkaline feldspar; Alu, alunite.

Table 2: Degree of release for the minerals deposit.

Calculation of the degree of release for mixed particles A/B/C/D/E of a given mesh					
	A	**B**	**C**	**D**	**E**
Sum of product area * surface exposed	584.00	0.00	102.25	6.00	188.25
Theoretical Maximum of Release (Mix particles Total: 30)	1000	1000	1000	1000	1000
Degree of release (%)	58.40	0.00	10.225	0.60	18.825

A, quartz; B,pyrite; C, Alunite; D, magnetite; E, feldspar

4.6. Selected alternative for mineral beneficiation circuit

4.6.1. Granulometry study

The particle size distribution obtained in two crushing cycles is shown in Fig. 9, which shows the granulometry of the head mineral (F80) of 75000 µm. The grain size corresponds to real data, and the P80 shown in Table 3 represents data calculated with the Gaudin-Schumann and Rosin-Rammler equations.

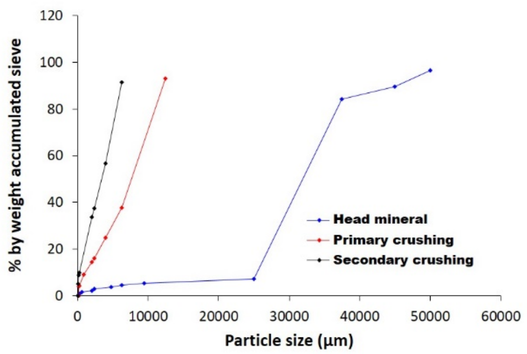

Figure 9: Granulometric distribution of the crushing products [x].

Table 3 indicates that the P80 calculations of the primary and secondary crushing are 16411.19 and 6534.77 µm according to the Gaudin-Schumann equation. Results obtained using the Rosin-Rammler equation are 19595.00 and 8199.82 µm for primary and secondary crushing, respectively. The reduction ratio of the primary crushing (6.20) and crushing (2.51) are consistent with the medium-high hardness characteristic of the mineral. The total crushing reduction corresponds to 2.51 x 6.20 = 15.562.

Table 3: P80 calculation after primary and secondary crushing and reduction ratios.

P80 calculation after primary crushing		
Model	**Granulometric distribution Equation**	**P80**
Gates-Schumann	$f(x) = 100\,(X/171376.20)^{0.9938}$	16411.19 µm Sieve 3/4" $R^2 = 0.9685$
Rosin-Rammler	$f(x) = 100\,(1\text{-}e^{(X/10961.6)^{0.9938}})$	19595.00 µm Sieve 3/4" $R^2 = 0.8986$
P80 calculation after secondary crushing		
Model	**Granulometric distribution Equation**	**P80**
Gates-Schumann	$f(x) = 100\,(X/9195.38)^{0.6533}$	6534.77 µm Sieve 1/4" $R^2 = 0.9803$
Rosin-Rammler	$f(x) = 100\,(1\text{-}e^{(X/4161.46)^{0.8168}})$	8199.82 µm Sieve 5/16" $R^2 = 0.9439$

Reduction ratio calculation			
Phase	**Supply**	**Primary trituration**	**Secondary trituration**
P80	101815.9770	19411.1914	6534.7741
Reduction ratio	NA	6.20	2.51

[x]

4.6.2. Mineral physical properties

The mineralogy associated with the mining coexistence project reveals that the main minerals are quartz (50%), sericite (15%), pyrite (12%), clay minerals (10%), feldspar (5%), bornite (4%), chalcopyrite (3%), covellite (0.99%), as well as Rare Earth Elements (REE) (0.01%).
The variables established by the metallurgical processing test were: mineral release (95% release of pyrite, size 120 µm), work index = 19.8 kWh/Tc, which corresponds to a hard mineral, specific gravity of 2.815 g/cm^3, kinetic grinding = 25 min and energy consumption for crushing 0.9 kWh/Tc and for grinding 2.5 kWh/Tc.

6.2.3. Mineral concentration tests

For the metallurgical tests, correlation of operating variables and various preliminary tests were performed, including the use of the experimental design 2^k ($k = 3$) specifically in the selective flotation tests.
Metallurgical tests (Fig. 10) were carried out to determine the most effective concentration procedure for the coexisting mineral, for which four techniques of gravimetric and flotation concentration were evaluated. The Wilfley table with a maximum Au recovery of 74%; the K-Nelson concentrator with a maximum grade obtained of 1.8 g / T, the bulk flotation with a maximum recovery of Au of 68% and Ag of 82%, and selective flotation with a recovery of Au of 95% and Ag 83%.

Figure 9: Metallurgical tests [x].

Considering the characterization analysis carried out for the sample, three alternatives in different stages have been established for the beneficiation of the minerals being studied, which are indicated in the flowsheet of Fig. 11. These were diagrammed using the online software draw.io. These flowsheets involve 3 main stages: (a) Mechanical preparation that involves the unit size reduction operations by jaw and cone crushing and ball milling, and the classification by particle sizes by industrial sieving and hydrocyclone separation; (b) Concentration of the mineral through gravimetric processes by Wilfley tables and concentrators and/or through a froth flotation process, which will have a bulk or collective flotation with subsequent flotation differences to obtain two concentrates (one of copper and one of gold pyrite); (c) Solid-liquid separation, which includes thickening in a settler and then a pressure filter, to obtain concentrates with a minimum proportion of moisture and tailings that will have their proper final disposition.
A flotation concentrator plant is proposed to be to gravimetrically concentrate the mineral and obtain Cu and pyrite concentrates, rich in Au and Ag; likewise, the drying processes of the concentrate will be through sedimentation and filtration.

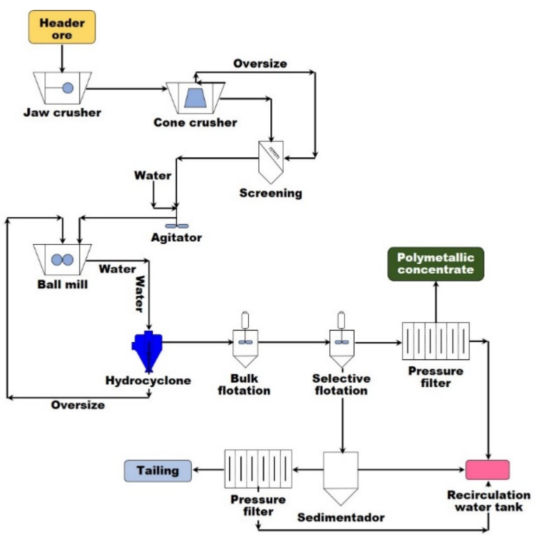

Figure 11: Alternative selected for the beneficiation of deposit mineral in the study area [x].

5. CONCLUSIONS

The analysis of geometallurgical modeling for coexistence mineral shows a gold cut-off grade of 3,85 Au ppm for a total of 311 135,52 ounces Au, grading 5,01 Au ppm, 15,33 Ag ppm, and 2401 Cu ppm. Veins 16, 1, 8, and 17 are the most representative and interesting veins of the project, adding 71% of the tonnage in gold, 73% in silver, and 74% in copper. Veins 10, 12, 15, 20, and 21 are not enough to reach the cut-off grade so they would be out of the mining coexistence project. According to the elemental characterization study carried out by fire assay, gold grades of 4,58 g/t and silver grades of 11 g/t are found. Similarly, SEM studies and thin films reveal the presence of refractory gold encapsulated in auroargentifer pyrite and bornite in sizes between 2-20 micrometers. Gold associated with tellurium is also observed. The characterization of the head ore shows a host quartzite rock on which hydrothermal alterations occur derived from the geological formation of the region. Ore mineralization is identified to a greater degree associated with sulfides, though iron oxides are also found. The presence of plagioclase, epidote, kaolinite, and potassium feldspar are also distinguished. The mineral release study shows that pyrite is 95% free but the remaining 5% is still not released using the 120 mesh. Thus, when associating gold to pyrite, we found that gold has not been totally released to that size, although it is considered the highest degree of release while considering economic costs too. The process selected for mineral beneficiation is the concentration by selective flotation through which copper and gold pyrite concentrates will be obtained, reaching global recoveries of 95% of copper, 95% of gold. and 83% of silver. Cu concentrate presents grades of 39% in Cu, 226,41 g Au/t, 850 g Ag/t, while pyrite concentrates report grades of 42,4 g Au/t and 78,6 g Ag/t.

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