Evaluation of the response of valuable and gangue minerals on a recovery, size and liberation basis for a low-grade silver ore

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A B S T R A C T

Mineralogical characterisation is typically used to assist in the development of processing strategies for ores. This paper describes the application of mineralogical characterisation techniques in the development of flotation strategies for processing an ore from a low-grade silver deposit that contains a variety of rock types that have undergone hydrothermal alteration where zinc, lead and silver sulphides are typically the primary minerals of economic interest. Comprehensive mineralogical characterisation of the feed, concentrates and tailings from batch flotation tests was undertaken using both the mineral liberation analyser (MLA) and laser ablation inductively-coupled plasma mass spectroscopy (LA-ICP-MS). The results of mineralogical characterisation of the feed (head grade, 116 ppm) indicated that the majority of the silver occurred as solid solution in pyrite which assisted in the development of the flotation strategy used for this ore which resulted in approximately 87% of the total silver being recovered to rougher concentrate at a grade of 485 ppm.

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1. Introduction

Mineral characterisation plays a key role enabling the recovery of valuable minerals through using mineral processing techniques such as hydrometallurgy, magnetic separation or flotation. It provides information on the minerals that contain the target element and the presence of any detrimental elements (such as As) or minerals that are present in trace amounts in the ore under study. There are a wide range of analytical techniques that can be used to describe and quantify both the elemental deportment and the mineral characteristics (such as grain size, liberation and association) on an unsized and size-by-size basis.

Silver in nature can be found in a wide range of Ag-bearing minerals that includes a list of more than 200 minerals that contain silver at levels that are economically viable. In many ore deposits silver is typically hosted by between five and ten silver minerals, which can make the development of an appropriate flowsheet for the extraction of silver challenging (Gasparrini, 1984). Silver minerals can be recovered by different metallurgical processes however flotation is the most adequate separation process when silver is present in both a wide range of silver minerals and in solid solution with sulphide minerals that are present in the ore.

Flotation of silver ores can be performed as bulk flotation or selective flotation (Woodcock et al., 2007). The first type of flotation is used when the ore contains between 1% and 5% of base metals and aims to recover all the sulphide minerals into a single concentrate, while selective flotation is used when the ore contains less than 1% base metals and all the silver-bearing minerals present in the ore are recovered first, with any economic base metals recovered in subsequent flotation steps. There are a number of reagent suites that can be used to selectively float silver minerals, these include:

(i) The use of a sulphidizing agent followed by flotation using a cationic collector (Pryor, 1953).
(ii) The use of an optimum amount of the sulphidizing agent followed by flotation with an anionic collector (Jones and Woodcock, 1979).
(iii) The use of a chelating collector to enhance the recovery of the oxidised silver minerals (Pryor, 1953 and Fa et al., 2005).

Sulphidizing agents are commonly used due the reactive nature of silver minerals. Some work in the use of sulphidization for silver minerals was carried out by Kim and Stanley (1988) who found that most of the silver minerals tested using sulphidization gave similar recoveries over a wide range of pH.

Mineralogical characterisation is used in the development of a flotation strategy and to understand the response of different minerals with respect to their liberation characteristics. The overall composition of composite particles, and the % surface exposure of the mineral of interest can be obtained from MLA or QEMSCAN measurements. For MLA the data may be expressed as either mineral locking or mineral liberation by free surface. Both approaches are widely used by researchers and metallurgists to identify the liberation of minerals in an ore. Mineral locking gives information on the type of particles the mineral of interest occurs in i.e. liberated, in a composite with one other mineral (binary) or in a composite with more than one other mineral (ternary and higher). No detailed information about the grade of the mineral of interest in binary or ternary classes is provided. Mineral liberation by particle composition provides information about the grade of the mineral of interest in each composition class.

Performing a mass balance on the flotation products provides recoveries and grades of the specific system under study, however to gain a deeper understanding of the behaviour of the system, particularly with respect to the nature of the losses and potential for further optimisation, size-by-size analysis is required (Greet, 2007; Johnson, 2007). Size by liberation analysis (liberation analysis on a size-by-size basis) brings further understanding of what types of particles are present in the products and how these are distributed between the concentrates and tailings. This leads to a better understanding of which minerals dilute the concentrates and their mechanism of recovery, i.e. by true flotation as liberated particles, through non-selective entrainment or as the result of being in a composite with floatable minerals (Fuerstenau, 1980; Kirjavainen, 1996).

The approach using mineral locking data from the MLA was developed to transition between traditional mineral liberation data collected from using optical microscopy techniques and that collected from automated SEM-based systems (Sutherland, 1989; Johnson, 1987). Analysis of mineral liberation by particle composition is possible using the automated SEM-based techniques and is arguably the more appropriate method to quantify liberation status of particles that are being recovered by flotation, which is reliant on the surface exposure of minerals (Vianna, 2004; Lamberg and Vianna, 2007; and Sandoval-Zambrano, 2013).

The aim of this paper is to assess the recovery of valuable minerals for a low-grade complex silver ore in a size-by-size and size by liberation analysis. The minerals that were the focus of the study concentrated on pyrite and sphalerite as the main sulphide minerals in the ore. All remaining minerals were grouped as non-sulphide gangue (NSG).

2. Experimental methodology

The experimental methodology for this work included a combination of mineralogical and flotation characterisation.

Mineralogical characterisation of the ore was initially performed on a sample that was crushed to −3.32 mm and sized with a √2 sieve series to a top size of 2.36 mm. Representative sub-samples of each size fraction were submitted for chemical assay and the −425/+300 μm size fraction, was submitted for MLA analysis to provide preliminary information on the types of minerals present and the textural features of the ore. LA-ICP-MS was performed on the −212/+106 μm fraction to determine the silver tenor for pyrite, more than 20 grains of this mineral were measured using a 35 μm spot size.

Mineralogical characterisation of the flotation feed was carried out on a sample which had been ground to a P80 of 100 μm. The sample was then sized, using a combination of wet and dry sieving and cyclosizing, into the following fractions: +106 μm, −106/+53 μm, −53/+C2 μm, −C2/+C3, −C3/+C4, −C4/+C5 and −C5. Representative sub-samples of each size fraction were submitted for

chemical assay and MLA analysis to identify the deportment of minerals of interest and quantify their degree of liberation.

Mineralogical characterisation of the flotation products was also performed; some of the concentrates (see Fig. 1) were combined to obtain the necessary mass for both MLA analysis and chemical assay on a size-by-size basis. The first concentrate of the sulphide flotation stage was kept separate and is referred to as con1; con2 represents a combination of concentrates 2 to 4; and con3 represents the combined concentrates from the non-sulphide flotation stage. Each of the combined flotation concentrates and the tailings were wet screened at +38 μm and ultrasonic micro sieving was used to obtain the following six size classes: +53 μm, −53/+38 μm, −38/+30 μm, −30/+20 μm, −20/+10 μm and −10 μm.

The flotation characterisation included the development of an appropriate flowsheet to produce the highest silver recovery and grade in a rougher concentrate. This is shown in Fig. 1, and includes a grinding stage which produces material with a P80 of 100 μm; a regrinding step was then carried out on the oversize (+75 μm) material (referred to as main stream inert grinding (MIG)) reducing the flotation feed to a P80 of 56 μm.

Following this feed preparation stage, flotation was carried out in a JKMRC 5 L bottom driven flotation machine in two separate stages. In the first stage (sulphide flotation) the combination of collectors targeted all sulphide minerals, in the second stage (non-sulphide flotation) the sulphide flotation tails were conditioned using NaHS, a sulphidizing reagent which targeted sulphide minerals which may have tarnished or oxidised surfaces. A more detailed description of the process can be found in Quinteros-Riquelme et al. (2012).

The other reagents used: were sodium silicate (1000 g/t) as dispersant added at the beginning of the sulphide flotation; copper sulphate (CuSO4) was added as an activator before the concentrates were collected (750 g/t); collectors Aero 404 (1000 g/t) and PAX (900 g/t) were added after the addition of CuSO4, allowing for the respective conditioning time; the frother MIBC was added in the cell at 180 g/t after all previous reagents; and sodium hydrosulphide (3950 g/t) was added after the sulphide flotation into the remaining pulp as a sulphidizing agent. No optimisation of reagent consumption was evaluated for this work.

3. Results

3.1. Mineralogical characterisation

A combination of MLA and LA-ICP-MS was used to determine the silver deportment in the flotation feed. These techniques showed that the majority of the silver in this sample occurs as solid solution in pyrite (with an average Ag content in pyrite of 2936 ± 686 ppm). Small quantities of silver minerals (i.e. tetrahedrite, pyrargyrite and chlorargyrite) were also observed.

Preliminary MLA analysis from one size fraction of the ore (−425/+300 μm) indicated that the major gangue minerals present were orthoclase, plagioclase and quartz. Pyrite was the dominant sulphide mineral with small quantities of sphalerite also observed. These findings were supported by MLA analysis of flotation feed (P80 of 100 microns) which indicated that the major gangue minerals were orthoclase (32.1%), plagioclase (19.4%) and quartz (26.4%), while the sulphide minerals are represented mainly by pyrite with 6.7%. Table 1, shown the mineral abundance at −425/+300 μm and flotation feed (P80 = 100 μm).

As shown in Table 2, the majority of silver in ore (−425/+300 μm fraction) is carried by pyrite. Table 3, shows the results of LA-ICP-MS and the detection limits for each element measured.

Pyrite presented different textures with colloformic layered/botryoidal concentric fabrics as can be shown in Fig. 2. The grain size had an average of 3–12 microns, which was disseminated through the non-sulphide gangue.