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Influence of mineralogy on biohydrometallurgical processing of complex sulphide ore

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Process mineralogy as a tool for improving hydrometallurgical recovery of complex sulphide ores: an overview

By

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Abstract

Process mineralogy is one of the most important and fundamental tools for obtaining optimum economic recovery, but is often overlooked. Information on process mineralogical as applied to the processing of complex sulphide ores are brought together in this paper with the view to form an integral part of the overall techniques for improving efficiency. Mineralogical characteristics affecting the processing behaviour of these ores during size reduction and recovery processes are discussed. An assessment on the need for characterization of sulphide ores are evaluated, while relevant characterization techniques for obtaining useful information that could aid effective understanding of their recovery processes are also reviewed. The paper concludes by suggesting process mineralogical steps for which optimal recovery could be obtained.

Keywords: ***Sulphide ores; Ore mineralogy; Process mineralogy; Minerals processing; Hydrometallurgy.***

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Introduction

Complex sulphide ores are natural occurring heterogeneous associations of sulphide minerals and/or non-sulphide minerals having a definite chemical composition and are commonly, but not always, crystalline. The sulphide minerals' constituents contain sulphur which is chemically bonded to one or more metals. These ores are complexes of sulphide minerals (both valuable and gangue) from which commercial values of the wanted mineral and metal can be exploited and extracted. Sulphide ores are generally semiconductors and are very important and the most abundant minerals of base metals, precious metals, and the platinum group minerals. The composition and mineralogical characteristics of sulphides ore are strongly influenced by their mode of occurrence, which therefore influences their processing behaviours.

Sulphide ores are extremely complicated mineralogical associations of the intergrown of their constituent minerals (Gomez *et al*., 1997 & 1999) comprising mainly chalcopyrite ($CuFeS_2$), sphalerite (ZnS), and galena (PbS), and many times are finely disseminated within a pyritic matrix composed usually of the minerals pyrite (FeS_2) and arsenopyrite (FeAsS). They are generally made up of fine inter-grown minerals, in which precious metals such as gold and silver often occur as interlocked refractory and finely disseminated metals in them. The precious metals are usually found in extremely low concentrations in their ore forms with fine size distributions. The manner of the associations of the constituent minerals and the degree and amount of the association determine and influence the complex nature of a particular sulphide ore deposit. The general low concentrations of precious minerals within their host base metal ores and the inherent characteristics of the host minerals usually pose difficult during processing.

As a result of result the complexities of the ores, it becomes very necessary that sound knowledge of the characteristics of the various constituent minerals forming sulphide ores be known to enable good understanding of their processing behaviour. This is because, optimum technical and economic processing and extraction route for minerals and metals requires complete knowledge of the ore, especially its chemical and mineralogical compositions, relative amounts, and grain size distribution (Olubambi *et al.*, 2006).

Mineralogical characteristics of sulphide Ores

There are quite a number of sulphidic minerals and non-sulphidic minerals associating together to form complex sulphide ores. Mineralogical characteristics of the major sulphide minerals in which principal base metals (copper, zinc, and lead) occur are discussed here. According to Craig and Vaughan (1994), the sulphide ore minerals sphalerite, galena and chalcopyrite provide the major sources of the world's base metals (Zn, Pb, Cu), whereas pyrite is virtually ubiquitous as a metalliferous mineral in sulphide ore deposits.

Mineralogy of sphalerite

Sphalerite is a mineral of particular hydrometallurgical interest (da Silva *et al.*, 2003) and is the major source of zinc, which occurs in a wide range of hydrothermal environments mostly with galena in various types. In many cases, sphalerite occurs with pyrite and chalcopyrite, as well as quartz, carbonates, and sulphates. Its cleavage is perfect in six directions forming dodecahedrons but it fractures on an uneven - flat surface which makes it fractures only along the flat surface during grinding. It has a hardness of 3.5 to 4 on the Moh's scale. It has the chemical formula ZnS, and according to Beaudoin (2000), sphalerite can incorporate a diverse suite of chemical elements in its structure. Fe, Cd, and Cu commonly substitute for Zn in sphalerite, whereas Pb, Hg, Ga, Sn, Mn and other elements occur more sporadically (Dini *et al.*, 1995; Kuhlemann and Zeeh 1995; Ueno *et al.*, 1996). Dold (2000) noted that Fe may in many cases significantly substitute for Zn, up to 15 mole %. It is generally a non-acid producing mineral when oxidized by oxygen as shown in Equation 1.

$$ZnS + 2O_2 \rightarrow Zn^{2+} + SO_4^{2-} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

Plumlee and Nash (1995) found that a sulphide-rich mineral assemblage with high percentage of sulphide minerals having iron as a constituent (such as iron-rich sphalerite) will generate significantly more acidic water than sphalerite-rich assemblages that lack iron sulphide minerals. The acid generation power of iron-rich sphalerite could be attributed to the hydrolysis of ferric phases (Walder and Schuster, 1998), while wet oxidation of sphalerite results in a leached solution rich in sulphate and dissolved zinc.

Mineralogy of galena

Galena (PbS) is the major source of lead, and it is mostly found in veins with sphalerite and chalcopyrite in hydrothermal igneous, sedimentary and metamorphic rocks. With other sulphides, it is often found with quartz and carbonates, and may also contain silver. It is very brittle and has a characteristic cubic structure with distinctive cleavage and fracture, which makes it easy to break along its cleavages into cubes. According to Equation 2, it does not generate acid (Plumlee and Nash, 1995) when oxidized with oxygen.

$$PbS + 2O_2 \rightarrow Pb^{2+} + SO_4^{2-} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

Wet oxidation of galena results in secondary anglesite ($PbSO_4$) in equilibrium with a Pb^{2+} and SO_4^{2-} solution. Jambor and Blowes (1998) noted that the secondary anglesite coating on galena may increase the apparent resistance to leaching because anglesite has a low solubility and protects the sulphides from direct contact with oxidizing reagents.

Mineralogy of chalcopyrite

Chalcopyrite is the most abundant primary copper mineral (Lu *et al*., 2000a&b) and is consequently extremely important to the copper industry (Dutrizac, 1981). It has a chemical formula of ($CuFeS_2$) and is found in a wide range of hydrothermal environments. Its structure is derived from the sphalerite structure by the orderly substitution of Cu and Fe for Zn. Its composition lies centrally within the Cu-Fe-S system; hence it co-exists with many of the common iron salts and copper sulphides. It is often associated with sphalerite and galena, and commonly massive and intergrown with pyrite and sphalerite. Complete oxidation of chalcopyrite (Equation 3) is non-acid producing (Walder and Schuster, 1998), but its oxidation with the combination of ferrous iron oxidation and ferrihydrate hydrolysis results in an acid producing process (Dold, 2000) shown in Equation 4. The oxidation rate of chalcopyrite increases with ferric iron concentration, but with an oxidation rate of 1-2 orders of magnitude less than pyrite (Rimstidt *et al*., 1994).

$$CuFeS_2 + 4O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2SO_4^{2-} \ldots\ldots\ldots\ldots\ldots\ldots \quad 3$$

$$2CuFeS_2 + 17/2O_2 + 5\ H_2O \rightarrow 2Cu^{2+} + 2Fe(OH)_3 + 4SO_4^{2-} + 4H^+ \quad \text{.....} \quad 4$$

Mineralogy of pyrite

Pyrite (FeS_2) is the most common sulphide mineral and is typically an abundant component of both relatively simple and complex sulphide ore assemblages with significant concentrations of valuable metals within its matrix (Abraitis *et al*., 2004). Although pyrite is not the most reactive sulphide mineral (Jambor, 1994), it is of significant interest in the hydrometallurgical process due to its oxidation which results in generation of acid. Its oxidation takes place in several steps: the formation of the metastable secondary products ferrihydrite ($5Fe_2O_3 \cdot 9H_2O$), schwertmannite (between $Fe_8O_8(OH)_6SO_4$ and $Fe_{16}O_{16}(OH)_{10}(SO_4)_3$), and goethite ($FeO(OH)$), as well the more stable secondary jarosite ($KFe_3(SO_4)_2(OH)_6$), and at times hematite (Fe_2O_3) depending on the geochemical conditions (Schwertmann *et al*., 1995; Bigham *et al*., 1996). According to Dold (2000), pyrite oxidation may be considered to take place in three major steps: oxidation of sulphur (Equation 5); oxidation of ferrous iron (Equation 6); and hydrolysis and precipitation of ferric complexes and minerals (Equation 7).

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad \text{.....} \quad 5$$

$$Fe^{2} + 1/4O_2 + H^+ \rightarrow Fe^{3+} + 1/2H_2O \quad \text{.....} \quad 6$$

$$Fe^{3+} + 3\ H_2O \rightarrow Fe(OH)_3(s) + 3H^+ \quad \text{.....} \quad 7$$

Mineralogy of precious and platinum group minerals

Platinum group elements (PGEs) occur either as discrete PGMs or as solid solution impurities. They are usually highly disseminated in sulphide ores, especially chalcopyrite, pentlandite, pyrrhotite, and in most times in chromites and silicates. These metals not only occur at low concentrations in their host minerals, but are commonly very inhomogeneously distributed, which often lead to a "nugget" effect, where most of the precious metals are hosted by a small number of scattered mineral grains (Totland *et al.,* 1995). Their distribution within the host ores, low concentration, and the multi-diversity in their associations largely determine and influence the complexities of their mineralogical characteristics.

According to Xiao and Laplante (2004), the range of minerals present, their relative densities, shape, particle size, and associations present a challenge to the metallurgist in designing and optimizing the extraction process, and the various ore types of typical ore bodies each with its own metallurgical response will heighten this challenge. Considering the high value of precious and PGEs and their very low concentrations in ores, their mineralization and the overall effectiveness of their processing is therefore very important. Because of their low concentration levels and the inhomogeneous distribution of these elements in rocks, a large sample size is commonly taken for preconcentration before instrumental determination (Juvonen *et al*., 2002). The mineralogical associations of the precious minerals within the host ores where they are distributed presume that the precious metals values could be prevented from being chemically attacked during leaching.

The need for characterization of sulphide ores

The existence of mineral deposits in any area is not enough to justify the hope of mere adopting any exploitation and processing techniques relevant to such ore for its recovery, but involves a number of mineralogical considerations. This is because, different ore deposits have typical and different mineralogical properties resulting from their mode of formation. The differences and the variation in the complexities in the mineralogical association of different sulphide ores from different origin necessitate a detailed mineralogical characterization of each deposit to determine optimal processing route for its constituent minerals and metals. This is due to the fact that the identification and characterization of minerals is of fundamental importance in the development and operation of mining and mineral processing systems (Hope *et al.,* 2001), and it is very important in choosing a suitable flowsheet for recovering the constituent metals.

In order to exploit any mineral deposit, it is necessary to provide comprehensive data on all minerals present and their respective proportions in the ore as well as in waste and concentrate products, in addition to the spatial distributions of those minerals on the scale of the deposit (Cook, 2000). Not only does the ore mineralogy play a critical role on the recovery method chosen but also dictate the process flowsheet for different ore types and for plant flowsheet optimization for improving the performance (Xiao

and Laplante, 2004). Comprehensive data on all the minerals present obtained through process mineralogy provide information about such characteristics as the chemical composition, the level of trace impurities, or the physical structure or appearance of the sampled region. Such information is of importance to researchers or processors in order to understand recovery process, verify a theory, and/or develop a better process.

In the hydrometallurgical process for treating and extracting metals from these sulphide ores, it is observed that these ores do not allow the recovery of metal by direct chemical leaching (Hiskey and Wadsworth, 1975; Dutrizac, 1989) because the sulphides are insoluble in nearly all reagents. For the metal content to be leached either through the chemical or even the bioprocess, the reagent/organism must come into direct contact with metal atoms or metal containing compounds within the mineral ore. An approach to achieving this is to thoroughly liberate all the mineral phases so as to enable them to be exposed to chemical attack. A limitation to grinding many sulphide ores is that, they cannot practically be ground down fine enough to expose the metals. For instance, chalcopyrite and sphalerite are frequently intergrown, with micro-size grains of 10-20µm being dispersed within the pyrite (Gomez *et al.,* 1999). Therefore, due to these specific mineralogical characteristics, it is necessary to finely grind and concentrate the ore prior to the solubilization of the valuable metals (Barbery *et al,* 1980).

Crushing and grinding of ore are however, a significant capital and operational cost in many mineral processing plants. Considering these factors, a small gain in comminution efficiency can have a large impact on the operating cost of a plant, while conserving resources as well (Fuerstenau *et al.,* 1999). In the case of precious minerals, especially the PGMs, very fine particles are difficult to recover, especially during flotation process which is one of the main recovery routes. As a mean to therefore minimize bubble-particle detachment due to ore fineness, platinum concentrators usually operate their agitation cells with power intensities higher than the typical industrial range. These agitators are usually operated at intensities of about 10 kW/m^3 due to the general philosophy in the platinum industry; that increasing power intensity increases the rate of flotation fine particles through improved particle–bubble contacting (Deglon, 2005). The overall increase in power intensities however

becomes an economic nightmare. It is therefore of major importance to fully determine the comminution parameters for obtaining optimum size fraction for effective recoveries and that are relevant to the crushing and milling of an ore to enable complete plant design to take place. Since ore mineralogy is very crucial for both the fineness of grinding required for liberation and the optimal flotation conditions, it is believed that process mineralogical studies would be beneficial in predicting optimal communition and processing routes and improving processing efficiencies.

Characterization techniques applied to sulphide ores

A number of characterization techniques are available for quantitative and qualitative analyses of sulphide ores. Besides the quantitative and qualitative analyses of their chemical composition, other mineral parameters of interest for effective recovery processing include mineral morphology and association, mineral size, and degree of mineral liberation. Although the traditional microscopic studies, thin-section petrography and geochemical analysis are useful and essential in providing fundamental mineralogical information, the very complex nature of sulphide ores and the low concentration of precious and PGMs in host ores requires modern and sophisticated characterization techniques for certainty. Many techniques for process mineralogical studies have been developed and applied to sulphide ores since the last century. The use of these modern techniques including X-ray diffraction analysis (XRD), scanning electron microscopy coupled with energy dispersive X-ray analysis (SEM/EDX), X-Ray Fluorescence Spectroscopy (XRF), quantitative electron probe microanalysis (EPMA), image analysis, laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS), automated mineral liberation analyzer (MLA), QEMSCAN, inductively coupled plasma-mass spectrometry (ICP-MS), inductively coupled plasma-optical emission spectrometry (ICP-OES), etc, have been extensively applied to acquire relevant mineralogical information on these ores.

Although all these arrays of available techniques co-exist for process mineralogical studies, not all of them are however suitable for analyses at high accuracy. According to Xiao and Laplante (2004), there is a distinct problem when characterizing the precious minerals in an ore, which is from their extremely low grade (often less than

1–2 g/t). Since the goal of every mineral processing operation is to effectively separate the valuable material from the gangue with minimum metal loss in tailings, the need to have a full understanding of mineralogical knowledge of the ore deposit, feed material and material flow during processing is imperative to develop and employ a sustainable, effective and relatively economical recovering route, and to improve recovery of the existing process. However, no single characterization technique can satisfy all the goals and requirements for achieving the absolute aims during sulphide ore processing and recovery. In contrast, it is of little use and uneconomical to adopt all characterization techniques for mere comparison of results and effectiveness. It is therefore very necessary that a combination of those techniques suitable for improving and optimising base and precious minerals recovery process be selected and adopted. In this paper, relevant techniques amongst the various types of analyses suitable for sulphide ores processing and for obtaining useful information that could aid effective understanding of their recovery processes are briefly discussed below.

The scanning electron microscope

The scanning electron microscope (SEM) is one of the most versatile and widely used tools of modern science as it allows the study of both the morphology and composition of materials (Xiao and Laplante, 2004). It has been extensively applied in mineralogical studies of sulphide ores and their residues (Hey, 1999; Power *et al*., 2000; Gornostayev and Mutanen, 2003; Dai *et al*., 2003, Kayanuma *et al*., 2004; Cabri *et al*., 2005; Grieco *et al*., 2006). It resolves both chemical and structural features at high resolution. It is essentially a high magnification microscope, which uses a focused beam of electrons instead of light to ‘‘image’’ the sample, both top-down, and gain the necessary information. Different detectors within the electron microscope can be used to provide alternative information, e.g., a backscattered electron detector will provide average atomic number information, while an auxiliary energy dispersive X-ray (EDX) detector provides elemental identification analyses. The primary electron beam interacts with the sample through generation of energy secondary electrons which tend to emphasize the topographic nature of the specimen, backscattering by producing images with high degree of atomic number, and ionization of atoms.

When equipped with an energy dispersive X-ray analyzer (EDX), it is used in applied/ process mineralogy to analyse the polished and/or thin sections of samples, as well as

un-mounted pieces of material (Petruk, 2000). The SEM provides information on the physical properties of the minerals while EDX provide information on their chemistry. During the backscattering, the differential production rate causes higher average atomic number minerals to appear brighter than lower average atomic number ones (Xiao and Laplante, 2004). This makes a mineral with lower average atomic number (e.g silicate mineral) appear dark grey and minerals with higher average atomic number (the PGMs) appear white in a back scattered electron image. Since atomic number contrast from backscattered electrons (BSE) signal are primarily used for phase discrimination, when phases with a very similar average atomic number are present, X-ray information from a X-ray analyser is used to differentiate between them (Kahn *et al.,* 2002)

SEM also provides an optical image that can be processed and treated by image analysis techniques, permitting characterisation of size, morphology, habit and association (Cook, 2000), and also finds application in the study of the degree of mineral liberation. According to Gu (2003), very stable back-scattered electron (BSE) signals from a modern SEM can be used to generate quality sample images, from which the most important minerals can be differentiated using modern image analysis methods. Each mineral grain delineated from a BSE image can be positively identified with single x-ray analysis well positioned inside the grain, and minerals of similar BSE intensities can be discriminated using simple x-ray mapping.

Mineral liberation analyzer

Precious minerals that are usually hoisted in sulphides ores are typically very fine oftentimes less than 20 µm, and therefore represent a challenge during processing. It is therefore very important that useful mineralogical information about them are adequately known before and during processing. SEM equipped with high resolution BSE imaging and EDX analysis and image analysis gives precise analysis of very fine particles. However, PGMs with finer particles less than 1 micron need imaging at very high resolution to identify them through the mineral liberation analyzer (MLA). MLA reveals essential mineralogical data for mineral processing in the sense that it shows the relative amount of individual particle obtainable from the valuable mineral phase available for physical concentration. Its operation involves the measurement of geometrical and volumnetric features of mineral grains and their relationship. The

application of MLA is becoming a well accepted technique in the processing of PGMs especially in Anglo Platinum where about five has been acquired as at 2005 (de Vaux, 2005).

The mineral liberation analyzer was developed to provide an automatic, off-line, size-by-size good quantitative mineralogy and liberation data for mineralogists and processors to fully assess the orebody, improve the plant recovery, and maintain the quality of product (Xiao and Laplante, 2004). MLA is equipped with backscatter electron imaging and EDX system, and combined with the MLA software package, which enables liberation measurement, data analysis and presentation. According to Gu (2003), there are seven basic MLA measurement modes to handle different sample types and to meet different mineralogical information requirements. These include; standard BSE liberation analysis (BSE), extended BSE liberation analysis (XBSE), sparse phase liberation (SPL) analysis, particle X-ray mapping (PXMAP) analysis, selected particle X-ray mapping (SXMAP) analysis, X-ray modal (XMOD) analysis, and rare phase search (RPS) methods.

Quantitative evaluation of minerals by scanning electron microscope (QEMScan)

Information about the mineral assemblages, association and its distribution is imperative in determining how an ore will behave during processing, to determine whether an ore is refractory or free milling, and in establishing an efficient processing route for an ore. The QEMScan, formerly known as QEM*SEM, is one of such effective technique that was developed by CSIRO Minerals. It is equipped with one to four X-ray detectors and is one of the fastest and most accurate mineral analysis and identification technique. It provides a rapid, accurate, precise, automatic, off-line, size by- size and particle-by-particle chemical and mineralogical analysis of an ore. Currently, the QEMScan is used for ore characterization, comminution, liberation analysis, process optimization (efficient fine grained ore processing, particularly improved feed preparation and grinding optimization), process modeling and plant problem solving (Xiao and Laplante, 2004). It has now become a successful commercial instrument with 19 instruments in operation around the world at companies such as Rio Tinto, BHP Billiton, Phelps Dodge, Falconbridge and Anglo Platinum (Pirrie *et al*., 2004).

It uses a combination of BSE images and EDX analysis to create digital mineral images with corresponding mineral identification occurring online. X-ray is acquired based on the images and individual minerals or groups of similar composition are identified by comparison to a comprehensive mineral database incorporated into the QEMScan software (Goodall *et al*., 2005). It is highly automated; performing quantitative analysis more easily and automatically with high magnification searches at detailed point spacing, and can identify mineral particles as small as 0.5 to 1 µm. According to Xiao and Laplante (2004), the QEMScan has three basic modes of operation:

1. Point scan, this is the most basic mode of QEMScan operation, and is similar to a mineralogical point count. EDX analyses are performed on a grid pattern with equidistant points. Only modal abundance information can be determined from this image.
2. Line scan, the scan grid is set up so that points are closely spaced in the X-direction and widely spaced in the Y -direction.
3. Area scan, points are closely spaced in both X and Y directions, this mode is used to determine grind size for liberation in feed samples, diluents in concentrates and losses in tailing samples.

X-Ray diffractometry (XRD)

Diffraction of X-rays or neutrons by polycrystalline samples is one of the most important, powerful and widely used analytical techniques available to materials scientists (Langfordy and Louerz, 1996). According to Cook (2000), it is a mineralogical identification method that permits semi- to full-quantitative assessment of the minerals present in a given sample and in what relative proportions they occur. It is especially suitable for the study of material containing significant small-scale variations in mineralogy, or in mineral chemistry of component minerals or an exceptionally coarse-grained sample, which could inhibit the reliability of image analysis studies of thin-sections. However, XRD analysis does not hold much application for characterising PGMs, and its uses have not been well documented. This might be as a result of the low concentrations of PGMs in ores, which XRD may not effectively detect. Nevertheless, XRD provides basis for other characterization techniques (Penberthy *et al*., 2000). It is very reliable and has been applied for

analysing the major minerals of the ores where PGMs are disseminated (Newell *et al*., 2006).

X-ray fluorescence spectroscopy (XRF)

Sulphide ores consist of an assemblage of its constituent minerals, which as a result of the preponderance of low atomic numbered elements in a variable mineralogical and elemental matrix, often pose difficulties in phase identification and sometimes present problems during quantification. Since SEM, XRD, MLA and QEMScan are mostly suitable for mineral phases, it becomes very important that determination of constituent elements within bulk ore be made. An approach to achieve this is the use of XRF. It is an excellent technique for the qualitative and quantitative determination of the major and important trace elements in sulphide ores (Yuan *et al*., 1992) in solid form, but also sometimes in liquid samples for bulk ores. According to Brewer and Harvey (2005), X-ray fluorescence spectroscopy has the capability of providing precise analysis for a wide spectrum of elements at much reduced lower limits of detection down to sub-ppm levels. Although it is not an excellent technique for the qualitative and quantitative analysis of precious minerals and PGMs, it serves as an effective tool for determining the major and important base metals contents of sulphide ores. It has been used and applied for base metals analysis during the mineralogical studies of PGMs (Tarkian and Stribrny, 1999; Song *et al*., 2003; Ely and Neal, 2003).

Its operating principle is based on scattering, emission and absorption properties of X-ray radiation. When a sample of material is bombarded with energetic radiation (X-rays, g-rays, electrons, protons, etc.) vacancies may arise from the removal of inner orbital electrons, and there will be transference of electrons from outer to inner electron shells for the atom to regain stability (Jenkins, 2000). These transitions are accompanied by the emission of an X-ray photon having energy equal to the energy difference between the two states, and cause the element present in the sample to emit their characteristic fluorescence lines. The intensity of the emitted X-ray which is influenced by absorption from elemental interactions and physical effects resulting from variation in particle size and surface, allows the determination of the elemental concentrations in the sample.

Inductively coupled plasma

The complexities in complex sulphide ores leading to high variability in the composition and structure within bulk ore, usually affects the performance of the X-ray fluorescence method for detecting and quantifying light and trace elements in sulphide ore. These affect the behaviour of X-rays in highly complex ways, such as spectral overlap effects, absorption/enhancement effects and the matrix effects (La Tour, 1989). Moreover, as the amount of heavier elements increases in the bulk ore matrix, the fluorescent energy from light elements decreases thereby reducing the sensitivity of XRF for light and trace elements (Hewit,1997). Hence, the results of the XRF-method are always too low for the light elements (e.g. K, Na, Ca, Al, and Mg) and cannot be recommended for the analysis of these elements (Wehausen, 1995). In order to completely determine all the elements within bulk ores, sample analysis in aqueous form using the Inductively Coupled Plasma (ICP) technique is preferred above other alternative analytical methods.

ICP provides fast multi-element analysis of metals and non-metals, high dynamic linear range, and high sensitivity with superior detection limits, and simultaneous determination of the elements (Heitland, 2004). The most frequently used ICP technique which have found effective application for sulphide ores analyses are the mass spectrometer (ICP-MS) and the optical emission spectrometer (ICP-OES) (Wemyss, 1978; Rampazzi and Dossi, 2001; Juvonen *et al*., 2002; Pasava *et al*., 2003; Dai *et al*., 2003). The ICP-MS utilizes inductively coupled plasma as the ionization source and a mass spectrometer (MS) analyzer to detect the ions produced. ICP-OES is on the other hand, base on the principle of emission spectroscopy which makes use of the fact that the atoms of elements can take up energy from inductively coupled plasma, are thereby excited, and fall back into their ground state again emitting a characteristic radiation.

Process mineralogy for improving sulphide ores

The variations in the complexities in the mineralogical association and assemblages of sulphide ores together with the low concentrations of precious and PGMs present challenges to process engineer in improving the recovery of the constituents metals. Whichever form the different minerals and elements occur within sulphide ores, they are usually very difficult to process (Deveci *et al.*, 2004; Rubio and Frutos, 2002).

This may be due to the close similarities and complexities in the mineralogical associations and properties of complex these ores, which often pose difficulties during their various recovery processes. They have to be ground to fines in order to liberate all the mineral phases, prior to processing.

Mineralogical data on the various types of sulphide ores and the processing techniques for the base metal contents are well documented and available. The PGMs being process across the globe and their recovery efficiencies are also well documented (Cole and Ferron, 2002; Kozyrev *et al*., 2002; Dai *et al*., 2003; Xiao and Laplante, 2004). For examples, comprehensive flowsheets from various PGMs processing plants including South African MF2, Northam South African, Noril'sk USSR, Stillwater Montana, and Lac des Iles North America are presented in Cole and Ferron (2002). The flowsheets were designed based on the different mineralogical characteristics of the ores being processed. It is however observed that most of these processes have not been very efficient, as recoveries have not been more than 85% in most of the precious metal processing plants. Much of the valuable metals are therefore lost in tailings, leading to reduction in profit. As a result of these, it is imperative to mitigate these losses and to improve recoveries.

Improving the effectiveness of recovery process requires accurate understanding of the underlying principles governing the behaviour of these minerals prior and during processing. Several research studies reporting hydrometallurgical recoveries of sulphide ore are available globally. However, process mineralogy which is an important area in hydrometallurgy and is critical to the behaviour of ores during dissolution is observed not to have been adequately taken into consideration.

Mineralogical analyses are usually done on the feed materials, which in most times, are not repeated on constant basis in many mineral processing plants. This might have led to incorrect assumptions in understanding recovery processes, interpreting data and solving problems that were being encountered during processing. Therefore, to avoid some of these wrong assumptions and provide adequate information on recovery process for improving efficiencies, relevant mineralogical data about feedstock and its subsequent deportment during processing is therefore necessary on

routine basis. In an effort to reduce losses and improve recovery processes, relevant mineralogical questions amongst others that are pertinent include;

How do these host minerals behave in each stage of the processing route?

Does a particular mineral(s) favour or inhibit the deportment and recovery of another mineral(s) under the same conditions?

What influencing factors/parameters promote the recovery of some minerals and the rejection of others?

Which process modifications conducive for improving recovery can be made?

Process mineralogy, which involves detailed mineralogical characterization of the feed and products at different stages of beneficiation processes, provides suitable and best answers to the above questions. It is a fundamental key for the planning, optimization and monitoring of recovery processes. According to Márquez *et al*. (2006), characteristics like chemical composition, relative proportions, distribution, texture, types of intergrowths, size distribution, liberation degree and habits of different ore minerals and its products in the different stages of the process are very important to the understanding of the different stages of the system, which allows to optimize the performance of processes, to improve the recovery, and/or to mitigate environmental problems.

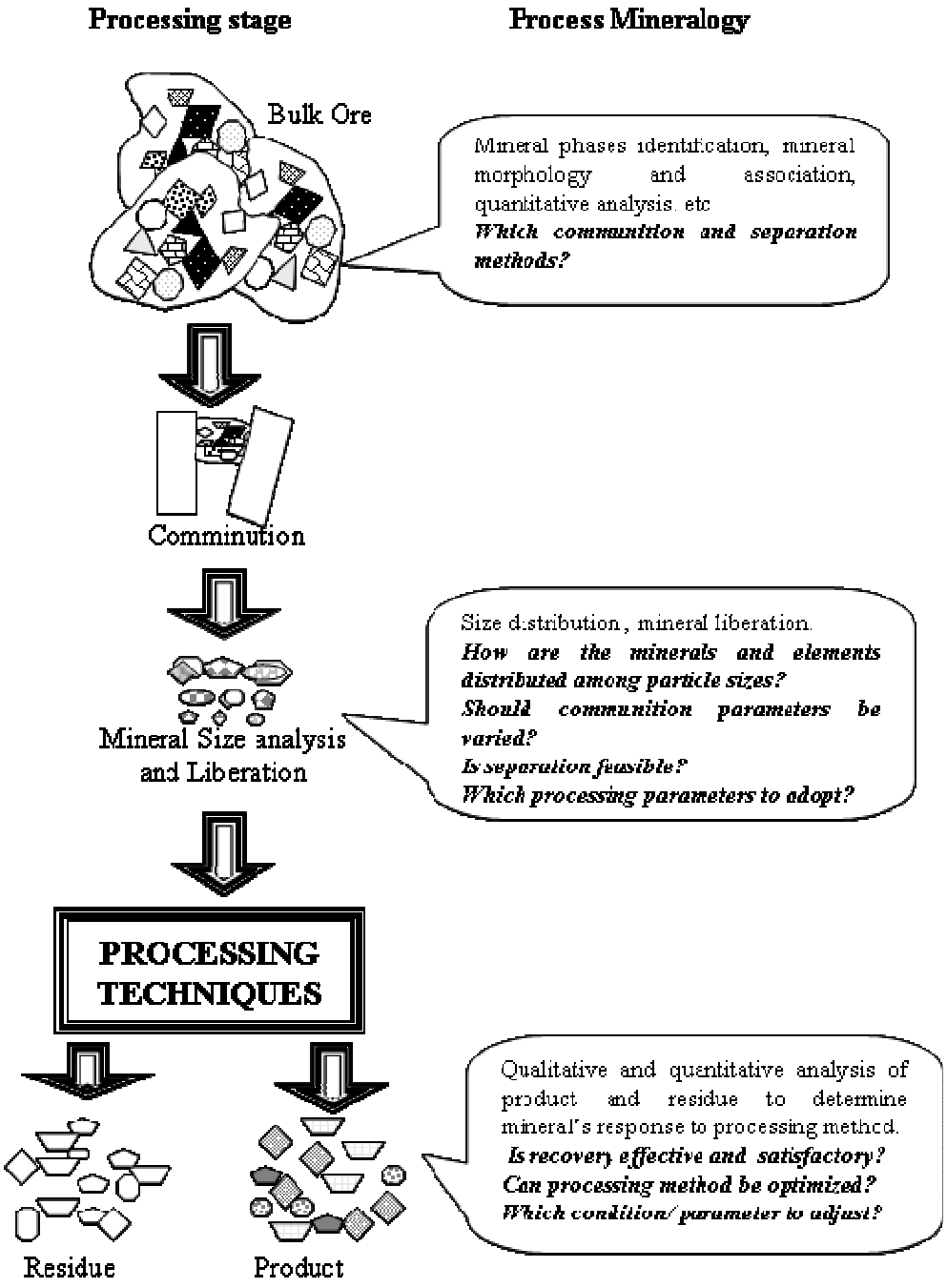


Figure 1: Typical process mineralogical steps for improving sulphide ore processing

A diagrammatic representation of a typical routinely process mineralogical analysis that could aid the improvement of recovery process is given in Figure 1. Typical information on the type and amounts of elements present in the ore, the different mineral phases in which they occur, their associations, morphology, grain size and

growth, etc help the processor to determine which crushing and grinding media to adopt. This would also help in predicting the cumminution parameters to be varied. Mineralogical studies on comminuted product reveal information on size distribution and mineral liberation. At a glance, relevant information on liberated mineral, mineral associated and locked in host minerals, and minerals occurring on host mineral grain boundaries would be revealed. These would assist the processor to measure the extent of the liberation of the valuable minerals from the gangue at various particle sizes. It will also help in the determination of the optimum size of feed to the process for maximum efficiency, as well as the size range at which any losses occurring in the plant might be reduced.

An important process mineralogical approach is the determination of the distribution of the constituent minerals and elements within the various particle size fractions. Although the effect of particle size on hydrometallurgical processing has been widely studied, it is observed that these studies were centered on the physico-chemical factors relating to particle size. The overall effect of these factors in obtaining optimum particle size and in understanding oxidation behaviour is yet to be fully known to optimally predict recovery performance. Dissolution process and trend will be best understood from a mineralogical perspective as dissolution of minerals depends mostly on their chemical and mineralogical compositions (Olubambi *et al*., 2007). Owing to the differences in the mineralogical compositions at different particle sizes, there exists variations ore reactivity which often leads to differences in dissolutions at varying particle sizes. This might result from the differences in the electrochemical galvanic interactions, as galvanic interactions depend on the mineralogical association between the phases present (Cruz *et al.* (2005).

Since the effectiveness of practically all mineral processing and hydrometallurgical operations is a function of the size of the particle treated, detail mineralogical study would help to ascertain the degree of the reduction of specified minerals and reveal the breakage characteristics of the different minerals within the comminution system. This would help in measuring the extent of the liberation of the value from the gangue at various particle size fractions, to determine the optimum size of feed to the process for maximum efficiency and to determine the size range at which losses occurs in the plant, so that they may be reduced. It would also provide mineralogical basis for

which the recovery at any given particle size could be determined and to ascertain relative recovery of the specified metal. Mineralogical information on production within each of the separation stages and on the concentrates and tailings would assist in the determination of separation efficiencies. Should separation prove not to be satisfactory, the processor would decide on means for which process could be optimized. This might include making some adjustments on process conditions, physical parameters, and the physico-chemical parameter affecting recoveries.

Conclusion

This study has overviewed the usefulness of process mineralogy and how it could be applied in improving the recovery of sulphide ores. Mineralogical studies prove to be very important in choosing suitable flowsheet and for optimizing and improving plant performance. Improving recovery must therefore involve interaction and communication between the mineral processor and the mineralogist at each stage of the recovery processes in understanding feed response and product behaviour. For effective communication of information between the mineralogist and the processor for subsequent process optimization, two major issues should be reconciled according to de Vaux (2005): the mineral processor needs to know more about mineralogy, so that the correct question can be asked thereby the mineralogist to providing answers that are of use; the mineralogist needs to learn more about mineral processing so that the efforts can be directed to looking for information that is relevant and not just throw the mineralogical book at a problem. Since ore deposits are heterogeneous in nature and their mineralogy vary within the deposit at different locations and as it undergoes successive exploitation, process mineralogy should be done on constant basis.

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