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Understanding interaction mechanisms between pentlandite and gangue minerals by zeta potential and surface force measurements

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ABSTRACT

Understanding the interaction between valuable and gangue minerals is of both fundamental and practical importance in the field of flotation. In this study, we investigated the interactions between valuable (i.e. pentlandite) and gangue minerals (i.e. serpentine, olivine, and magnesite) in an aqueous solution by directly measuring the zeta potential distributions. In addition, interaction force measurements using an atomic force microscope (AFM) were performed between a silicon nitride tip and gangue mineral surfaces, and the classical Derjaguin–Landau–Verwey–Overbeek (DLVO) theory was used to fit the interaction force between the silicon nitride tip and gangue mineral surfaces. In the case of serpentine and pentlandite mixture system at pH 10.1, only a single zeta potential distribution was obtained, as compared to two distinct distributions for the two individual minerals, indicating an attractive interaction is present between the two minerals. For olivine and pentlandite mixture system, a single distribution with two distinct spikes was obtained in the zeta potential distribution of the mixture, indicating repulsive interaction between the two minerals. Similarly, a single distribution with two distinct spikes was also observed in the zeta potential distribution of magnesite and pentlandite mixture system, indicating repulsive interaction between the two minerals. Repulsive interaction between silicon nitride tip and olivine surface, and slight attractive interaction between silicon nitride tip and magnesite surface, were observed and consistent with the DLVO model. The zeta potential and AFM force measurements show good agreement regarding the surface charge properties and interactions of the minerals, and provide complementary information and new insights into the interaction mechanism of valuable and gangue minerals.

1. Introduction

Nickel has been widely used in many engineering applications (e.g. stainless steel, shape memory alloys) and plays an important role in the production of wear and corrosion resistant materials (Minowa et al., 1989; Rahilly and Price, 2003; Zhang et al., 2005). Due to the declining reserve of high-grade nickel ores, the low-grade ultramafic nickel ores (e.g. Thompson Pipe deposit, Manitoba, Canada) have been revisited and are becoming important resources of nickel mineral (Dai et al., 2009; Merve Genc et al., 2012). However, most of these ultramafic nickel ores have low nickel grade and high magnesia (MgO) content, leading to challenging issues during the flotation process.

The MgO-containing minerals in the low-grade nickel ores mainly include serpentine and olivine. Serpentine has a layered structure which is comprised of 1:1 layering of one silica (SiO_4) tetrahedral layer bonded to a brucite (Mg–O) octahedral layer (Mookherjee and Stixrude, 2009). The tetrahedral and octahedral layers are held together by van der Waals forces (Alvarez-Silva et al., 2010). Serpentine group consists of three common polymorphs: chrysotile, antigorite, and lizardite. Chrysotile is a fibrous, tubular mineral and classified as asbestos (Zussman, 1978). In contrast, lizardite has a flat-layered and platy structure while antigorite has a curved, corrugated sheet structure (Zussman, 1978). As opposed to serpentine, olivine is an orthosilicate mineral consisting of isolated SiO_4 tetrahedral connected via divalent cations (i.e. magnesium and iron) in six fold coordination and it has no layered structure (Gualtieri et al., 2003).

The challenging issues during the processing of such low-grade ores mainly include the high pulp viscosity and slime coating on the valuable nickel bearing mineral (i.e. pentlandite), which significantly reduce nickel recovery and grade concentrate during flotation (Feng et al., 2012b, 2013). The high pulp viscosity is attributed to the high-serpentine content in the low-grade ultramafic nickel ore (Dai et al., 2009). Hence, the flotation and

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grinding can only be done at low percent solids, which largely increase the operation cost. The presence of fibrous minerals (e.g. chrysotile) is responsible for the formation of air bubble-macro fibers aggregates, which easily report to the flotation concentrate and lead to the recovery of MgO-containing minerals (Xu et al., 2010).

The slime coating on pentlandite surface is mainly due to the presence of serpentine. The interaction between serpentine and pentlandite has been discussed in previous studies (Bremmel et al., 2005; Edwards et al., 1980). The occurrence of slime coating is directly related to the surface potentials of pentlandite and serpentine. The formation of slime coating is mainly attributed to the attractive interaction between a positively charged serpentine and a negatively charged pentlandite. Partial slime coating normally leads to the dilution of the flotation concentrate, while the loss of nickel recovery occurs when heavily coated pentlandite becomes hydrophilic (Alvarez-Silva, 2011). In addition, the presence of serpentine in the nickel concentrate results in the imposition of smelter penalties for mineral processing companies due to higher slag melting point (Alvarez-Silva, 2011; Feng et al., 2012b, 2013).

Thermal pretreatment of the ultramafic nickel ores is being investigated as a way to improve flotation by reducing or eliminating the negative effects of serpentine (Bobicki et al., 2014). It is known that serpentine transforms into olivine at above the dehydroxylation temperature (Gualtieri et al., 2012; Huang et al., 2013; Leonelli et al., 2006). In another aspect of flotation, sodium carbonate is also widely used in nickel ore processing to control the precipitation of magnesium hydroxide by sequestering magnesium to form magnesite (Alvarez-Silva, 2011).

Therefore, a better understanding of the interaction between valuable nickel mineral (i.e. pentlandite) with gangue minerals (i.e. serpentine, olivine, and magnesite) has a practical importance for the flotation of low-grade ultramafic nickel ores. Zeta potential distribution measurement proves to be a powerful technique to study slime coating in a colloidal system, which has been shown for bitumen-clay and coal-clay interactions (Liu et al., 2002, 2004a, 2004b, 2005; Xu et al., 2003). The interaction in a binary mixture can be inferred based on the shift of the zeta potential distribution of the mixture with respect to that of each individual component. AFM has also been used to directly measure surface forces between an AFM tip and the surfaces of clay minerals (Gupta and Miller, 2010; Yan et al., 2011). Surface properties of the minerals (e.g. surface charges, surface potential) could be inferred from the force-distance profiles. In this study, the interaction between pentlandite and gangue minerals such as serpentine, olivine, and magnesite has been investigated using zeta potential distribution measurements. In addition, direct surface force measurement has been conducted on serpentine, olivine, and magnesite surfaces using a silicon nitride AFM tip. This study provides new insights into the interaction between pentlandite and gangue minerals in the flotation of low-grade ultramafic nickel ores.

2. Experimental

2.1. Materials and reagents

Serpentine and olivine rocks were obtained from Ward's Natural Science Establishment. Magnesium carbonate powder (Fisher Scientific), magnesite rock (Minerals Unlimited, USA), and Min-u-sil 5 silica (US Silica, USA) were used as received. Pentlandite was obtained from Vale Base Metals Technology Development (Mississauga, Ontario, Canada). Serpentine and olivine were crushed and pulverized to obtain the −200 μm size fraction. Serpentine, olivine, and pentlandite samples were then sieved to obtain the −38 μm size fraction to be used for the zeta potential distribution measurement. Some of the serpentine, olivine, and magnesite rocks were kept for the AFM force measurement. Pentlandite was washed using 0.1 M hydrochloric acid and deionized water, followed by freeze drying and stored in the −20 °C freezer before zeta potential experiments.

Hydrochloric acid (HCl) and potassium hydroxide (KOH) from Fisher Scientific were used as pH modifiers. Potassium chloride (KCl) from Fisher Scientific was used for the preparation of supporting electrolyte solution. All the reagents used were of ACS reagent grade. Deionized water (Milli-Q water) with a resistivity of 18.2 MΩ cm prepared with Millipore Elix 5 purification system was used throughout this study.

2.2. Zeta potential distribution measurements

2.2.1. Suspension preparation

For the zeta potential measurement of single mineral system, the suspension was prepared by adding the mineral particles into the supporting electrolyte solution (10 mM KCl). The suspensions of serpentine, olivine, and magnesite were stirred for 24 h prior to the measurement to enhance the suspension stability. Pentlandite suspension was prepared fresh prior to the measurement to limit possible oxidation. Prior to the measurement, the pH of the suspension was adjusted to a desired value and the suspension was then sonicated for 5 min.

In the case of a binary mineral mixture suspension, the prepared mineral suspensions were mixed at a 1:1 solid weight ratio. Prior to the measurement, the pH of the suspension was adjusted to 10.1 and the suspension was then sonicated for 5 min. The pH 10.1 was selected based on the operational conditions at the Thompson Mill (Dai et al., 2009).

2.2.2. Zeta potential distribution measurement technique

The zeta potential distribution measurements were performed on the single and the mixed mineral systems. The zeta potential distributions were measured based on an electrophoretic method using a Zetaphoremeter IV CAD Instruments equipped with a rectangular electrophoresis cell, a pair of hydrogenated palladium electrodes, a laser illuminator, and a CCD camera. The system allows for an accurate positioning of the stationary layer, where the electrophoretic mobility can be measured accurately. The built-in imaging processing software traces the movement of 50–100 particles in the stationary layer, 5 times in each direction by alternating positive and negative electrode potentials. The electrophoretic mobility distribution is then converted to zeta potential distribution by using Smoluchowski equation (Masliyah et al., 2011).

2.3. AFM force measurements

2.3.1. Preparation of mineral surfaces

The rock pieces of serpentine, olivine, and magnesite minerals were mounted in an epoxy resin (West System Inc., Bay City, MI, USA). The samples were then polished to obtain flat mineral surface. A wet grinding using 45 μm grinding paper was performed, followed by series of polishing using diamond slurry (9 μm and 3 μm) and alumina slurry (0.05 μm). The samples were then washed and sonicated in Milli-Q water to remove the slurry suspension residue. For AFM measurements, the samples were rinsed with Milli-Q water, and then subjected to a high-pressure nitrogen gas blow before immersed in a desired electrolyte solution.

2.3.2. AFM force measurements

A MFP-3D atomic force microscope (Asylum Research, Santa Barbara, CA, USA) was used in this study. Silicon nitride tip (PNP, Nano World AG, Switzerland, 17 kHz resonant frequency, 20 nm tip radius) was used for both imaging and force measurements. The tip geometry was examined using a field emission scanning