



Bioleaching of six nickel sulphide ores with differing mineralogies in stirred-tank reactors at 30 °C



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ABSTRACT

A bioleaching study was conducted with six nickel sulphide ores from different geographical locations across Canada. Mineralogical and chemical examination revealed considerable variability between the samples, particularly in the silicate phases. The ores contain 0.3–1% nickel, primarily in pentlandite and secondarily in pyrrhotite. Copper is present primarily in chalcopyrite, and cobalt in pentlandite. The ores were subjected to the same crushing and grinding procedure, and bioleached under the same conditions for 3 weeks with a mixed culture of iron- and sulphur-oxidizing bacteria. Stirred-tank experiments with finely ground ore ($-147\ \mu\text{m}$) at 30 °C were conducted to assess the effect of pH (2–5) and the impact of the bacteria. Nickel extraction from pentlandite and pyrrhotite during bioleaching at pH 2 and 3 was generally good (49–86% after 3 weeks), and cobalt extraction tracked nickel extraction over most conditions. All six ores showed a similar response to a change in pH; an increase in pH from 2 to 3 resulted in approximately the same nickel and cobalt extraction (within statistical error), and a statistically significant reduction in sulphuric acid consumption, dissolved iron, and magnesium extraction.

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1. Introduction

The discovery of new high grade base-metal deposits is diminishing in frequency; consequently, mining companies are processing low-grade deposits in order to maintain production levels. Heap bioleaching practices can potentially enable the development of some low-grade deposits that are not currently economically viable with conventional processing technologies. Since 1977, over 20 commercial heap/dump (bio)leaching operations have been commissioned for processing copper oxide and secondary copper sulphide ores (Watling, 2006). There have been heap bioleaching pilot trials with nickel sulphide ores in Australia (Hunter, 2002), Finland (Riekkola-Vanhanen, 2007), and China (Wen et al., 2006; Qin et al., 2009). The first commercial application of nickel sulphide heap bioleaching began production at Talvivaara, Finland in October 2008 (Talvivaara, 2009).

The primary objective of this study was to assess the amenability of several different nickel sulphide ores to bioleaching, and to identify broad trends with respect to mineralogical content; particularly with regard to the bioleaching of the primary nickel-bearing

phases, pentlandite and pyrrhotite. The ores were subjected to the same crushing and grinding procedure, and subjected to the same stirred-tank bioleaching tests with bacteria that were enriched from the same source. Several of the ores were determined to contain appreciable amounts of copper and cobalt; however, an emphasis was placed on the extraction of nickel as it is the most-economically significant element in all the ores studied.

Six ore samples were acquired from different geographic locations across Canada in order to study the bioleaching of nickel sulphide ores that contain a variety of mineralogical assemblages. The ore samples were subjected to a thorough mineralogical and chemical characterisation. Ores 1, 2, and 4 are from different deposits in Ontario; Ore 3 is from Manitoba; Ore 5 is from Quebec; and Ore 6 is from Newfoundland.

All the experiments discussed in this paper were conducted at 30 °C, with pH as the only variable. Solution pH was selected as the only variable because a review of the technical literature indicated that pentlandite and pyrrhotite are amenable to bioleaching at pH levels higher than what is generally considered to be optimum for bioleaching of copper-containing sulphides (i.e. pH \sim 1.6–2). This point was verified during shake flask experiments with Ores 1 and 2, during which nickel extraction showed limited dependency on pH in the range of pH 2–3 (Cameron, 2011). In the same experiments, the extraction of both iron and magnesium (considered to be nuisance elements) showed a greater dependence

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on pH, with lower pH resulting in a substantial increase in both dissolved iron and magnesium. It was then considered that operating at higher pH levels may result in cost savings from reduced sulphuric acid consumption, waste disposal, and solution management.

2. Materials and methods

A total of 53 stirred-tank experiments were conducted at 30 °C, including 40 bioleaching experiments and 13 abiotic experiments. The materials and methods were the same as in the previously reported stirred-tank reactor experiments conducted with Ore 3 (Cameron et al., 2009a,b), unless otherwise noted. There were some minor differences in the experimental procedures due to slightly different experimental objectives. These differences were in the preparation of the inocula, the duration of the experiments, and the sampling frequency. With each ore, bioleaching experiments were conducted at pH 2, 3, and 5; and abiotic experiments were conducted at pH 2 and 3. The bioleaching experiments were conducted in at least duplicate, with the exception of Ore 3 at pH 2,

which was conducted without a replicate. The abiotic experiments were conducted without replicates, with the exception of Ore 3 at pH 3, which was conducted in triplicate.

2.1. Characterisation of the nickel sulphide ores

The ores were received in bulk samples ranging in size from 100 to 2000 kg. Each bulk sample was crushed to -12.7 mm, and after thorough mixing, a sub-sample of several kilograms was crushed to -6.35 mm. For each ore, a portion of the -6.35 mm sub-sample was used for mineralogical characterisation, and a portion was pulverized to -147 μm (100 Tyler mesh) and used for stirred-tank (bio)leaching experiments and bacterial culture maintenance. Lastra et al. (2007a,b, 2008, 2009a,b, 2010) reported on the mineralogical characterisation of Ores 1–6 (summarized in Tables 1 and 2).

As seen in Table 1, all the ores contain the same sulphide minerals, mainly pentlandite, pyrrhotite, and chalcopyrite. Pyrrhotite is the most abundant sulphide mineral in all the ores (33% of Ore 1). Nickel is present primarily in pentlandite and secondarily in pyrrhotite, whereas copper is present primarily in chalcopyrite. There are significant differences in the silicate minerals, which are the main constituents of the ores. Ores 1, 2 and 4 are from different deposits in Ontario and contain similar silicate minerals, with major amounts of feldspars, amphiboles, and pyroxenes. Ore 3 (from Manitoba) and Ore 5 (from Quebec) contain major amounts of serpentine ($\sim 60\%$ and 40% respectively), whereas Ore 6 (from Newfoundland) contains $>50\%$ feldspars.

Electron probe X-ray microanalysis (EPMA) was used to determine the chemical composition of the pentlandite, pyrrhotite, and pyrite in each ore (Table 2). The nickel content of the pentlandite ranged from $\sim 32\%$ in Ore 5 to $\sim 39\%$ in Ore 3. The nickel content of the pyrrhotite exhibited considerable variability, ranging from $\sim 0.2\%$ in Ore 5 to $\sim 0.8\%$ in Ore 2. Pentlandite is the primary nickel-bearing phase in all six ores, ranging from $\sim 97\%$ of the nickel in Ore 3, to $\sim 78\%$ of the nickel in Ore 2. Pyrrhotite is the second most significant nickel-bearing phase in all the ores, and contains 22% of the nickel in Ore 2. Pyrite was determined to be a significant nickel-bearing phase only in Ore 4 ($\sim 12\%$). None of the other phases contained a significant quantity of nickel. Cobalt is primarily present in pentlandite in all the ores.

The chemical compositions listed in Table 3 are the averages of at least three replicates taken from different sub-samples. The

Table 1
Mineralogical composition of the nickel sulphide ores.

Mineral or mineral group	Ore 1	Ore 2	Ore 3	Ore 4	Ore 5	Ore 6
Amphibole/pyroxene	19.6	36.4	6.2	32.6	17.4	11.6
Carbonates (calcite, dolomite, ankerite)	0.1	0.3	2.1	0.2	tr	nd
Chalcopyrite	0.7	1.9	tr	2.0	2.7	1.8 ^a
Chlorite	1.7	1.5	9.1	1.1	16.9	nd
Oxides (magnetite, hematite, ilmenite, chromite)	9.0	2.5	12.2	1.0	4.1	6.2
Feldspars	23.2	19.3	0.1	21.8	0.2	51.7
Pentlandite	3.0	2.0	0.7	1.2	2.5	2.9
Pyrrhotite	33	25.2	0.9	13	15.7	15.3
Pyrite	0.1	0.1	0.5	2.5	tr	0.6
Quartz	7	4.7	0.1	13.2	0.1	0.5
Serpentine	nd	nd	64.4	3.9	39.9	nd
Sphalerite	tr	tr	tr	tr	0.2	tr
Talc	0.5	0.1	3.3	nd	nd	nd
Others (apatite, danalite, epidote, mica, titanite)	2.1	6.0	0.5	7.5	0.1	9.6

All values quoted in %mass; tr: trace; nd: not detected.

^a Plus trace of cubanite.

Table 2
Chemical composition of the primary nickel-bearing phases and distribution of nickel.

Mineral		Ore 1	Ore 2	Ore 3	Ore 4	Ore 5	Ore 6
Pentlandite	Ni (%)	36.3 \pm 0.7	36.2 \pm 0.7	39 \pm 2	36.1 \pm 0.8	31.9 \pm 0.4	33 \pm 1
	Co (%)	0.8 \pm 0.2	1.4 \pm 0.3	1.1 \pm 0.4	1.2 \pm 0.3	1.63 \pm 0.09	1.6 \pm 0.2
Pyrrhotite	Ni (%)	0.7 \pm 0.1	0.8 \pm 0.2	0.7 \pm 0.2	0.7 \pm 0.2	0.19 \pm 0.06	0.30 \pm 0.09
Pyrite	Ni (%)	\sim 0	\sim 0	0.03 \pm 0.01	3 \pm 2	\sim 0	\sim 0
Proportion of nickel reporting to pentlandite (%)		83	78	97	72	96	95
Proportion of nickel reporting to pyrrhotite (%)		16	22	2	15	3	5
Proportion of nickel reporting to pyrite (%)		\sim 0	\sim 0	\sim 0	12	\sim 0	\sim 0

All values quoted in %mass \pm 1 standard deviation.

Table 3
Chemical composition of the nickel sulphide ores.

Element	Ore 1	Ore 2	Ore 3	Ore 4	Ore 5	Ore 6
Ni (%)	0.79 \pm 0.02	0.68 \pm 0.03	0.305 \pm 0.005	0.59 \pm 0.01	0.95 \pm 0.01	0.99 \pm 0.02
Mg (%)	2.74 \pm 0.02	3.76 \pm 0.02	21.2 \pm 0.1	3.39 \pm 0.04	13.2 \pm 0.3	3.20 \pm 0.006
Cu (%)	0.224 \pm 0.003	0.63 \pm 0.01	0.016 \pm 0.002	0.721 \pm 0.004	0.965 \pm 0.006	0.602 \pm 0.004
Co (%)	0.0274 \pm 0.0001	0.0289 \pm 0.0003	0.013 \pm 0.0004	0.0252 \pm 0.0007	0.042 \pm 0.002	0.0439 \pm 0.0008
Fe (%)	14.0 \pm 0.2	16.1 \pm 0.1	7.2 \pm 0.1	14.13 \pm 0.04	20.5 \pm 0.4	21.5 \pm 0.2

All values quoted in %mass \pm 1 standard deviation.

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