HOKKAIDO UNIVERSITY

Title	On the Use of Magnetite for Gold Recovery From Chloride Solution
Author(s)	Alorro, Richard Diaz; Hiroyoshi, Naoki; Kijitani, Hajime et al.
Citation	Mineral Processing and Extractive Metallurgy Review, 31(4), 201-213 https://doi.org/10.1080/08827508.2010.483359
Issue Date	2010-10
Doc URL	https://hdl.handle.net/2115/47187
Rights	This is an electronic version of an article published in Mineral Processing and Extractive Metallurgy Review, 31(4) Oct. 2010, 201-213. Mineral Processing and Extractive Metallurgy Review is available online at: http://www.informaworld.com/openurl?genre=article&issn=0882-7508&volume=31&issue=4&spage=201
Type	journal article
File Information	MPEMR31-4_201-213.pdf



Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

ON THE USE OF MAGNETITE FOR GOLD RECOVERY FROM CHLORIDE SOLUTION

RICHARD DIAZ ALORRO
NAOKI HIROYOSHI
HAJIME KIJITANI
MAYUMI ITO
MASAMI TSUNEKAWA

Division of Solid Waste, Resources and Geo-Environmental Engineering, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo, 060-8628 Japan

ABSTRACT

The sorption of $AuCl_4^-$ from chloride solution on synthetic and natural magnetite powders was investigated by batch-sorption experiments. The effects of different parameters on the recovery were studied. The results showed that Au uptake by magnetite was influenced by pH, contact time, chloride concentration, and initial Au concentration. Gold (Au) uptake by synthetic and natural magnetite was at a maximum at pH 6-7 with sorption amounts of 4.4 µmol/g and 5.0 µmol/g, respectively, after 24 hours at an initial Au concentration of 0.05 mol/m^3. The SEM-EDX and BSE analyses of the magnetite particles after treatment confirmed the presence of Au precipitates on the Fe_3O_4 surface.

Corresponding author: Richard Diaz Alorro, Division of Solid Waste, Resources and Geo-Environmental Engineering, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo, 060-8628 Japan.
E-mail: richard@eng.hokudai.ac.jp

Keywords: gold, magnetite, iron oxide, hydrometallurgy, sorbent, reductive precipitation

INTRODUCTION

Gold is one of the most useful metals and has been used as a unit of exchange and store of wealth for over a long period of time. Nowadays, apart from the traditional uses, gold has found new applications in electronics, chemical and environmental catalyses, medicine and life sciences, aerospace engineering, and other industrial applications (Lam et al 2007; Ishikawa et al 2002). Considering this growing demand, coupled with the declining resources

available, the recovery of gold from secondary sources (i.e. electronic scraps and waste electroplating solutions) and primary sources, such as leach liquors, has become a very important technology.

The hydrometallurgical technique still remains the a standard method for gold extraction from ores, and is substantially considered in many metal recycling processes where metal contents are usually present in minimum amounts, due to its simpler operation, lower cost requirement, and relatively well-purified products with minimal loss of target metals (Lam et al 2007; Wiraseranee et al 2008). To extract gold from different ores, cyanide has been widely used worldwide. However, due to the environmental hazards posed by cyanide's toxicity, a restriction or ban on its use has been pursued. Due to this, safer and more environmental-friendly leaching agents, such as chloride and thiosulfate solutions, have been examined and introduced as alternatives to the toxic cyanide (Aylmore 2005). Separation and recovery of the dissolved precious metals from these solutions, however, still remains a problem and poses a real challenge. Several methods were proposed to recover the extracted metals from the solution phase and these include precipitation, solvent extraction and sorption. Among these methods, sorption offers a number of advantages, such as easy operation, low energy consumption, simple maintenance and large capacity (Lam et al 2007; Aktas et al 2009).

The search for potential sorbents to recover gold from solution has acquired significant attention in recent years. Since gold is usually present at very low concentrations (1-100 ppm) in solutions, especially in waste liquors, employment of a sorbent with the following characteristics is desirable: high efficacy, low environmental impact, cost-effectiveness due to relatively simple method of synthesis and chemical processing, ease of phase separation, and is readily available.

Iron oxides and hydroxides, such as hematite (Fe_2O_3), magnetite (Fe_3O_4) and goethite (FeOOH), are ubiquitous both in surface and subsurface environments. These metal oxides are benign and are easy to synthesize in laboratory-scale using common chemical reagents. Several authors (Machesky et al 1991; Uchida et al, 2002; Enzweiler and Joekes, 1991; Schoonen et al 1992; and Ran et al, 2002), reported that synthesized goethite and hematite can uptake gold from chloride solutions and explained the roles played by these metal oxides in geochemical mobilization and mineralization of gold in the subsurface environment and the association of gold in iron oxide deposits. The implication on the use of these iron oxides to separate dissolved gold from the extractive metallurgical point of view was not presented. Moreover, no literature exists detailing the use of synthetic or natural magnetite as sorbents to recover gold from solution.

Motivated by the geochemical findings presented above, this study explored the mineral processing and hydrometallurgical application of using magnetite to recover gold from aqueous solution. Magnetite (Fe_3O_4) is one of the most common Fe^{2+}-containing oxide minerals in the Earth's crust. Magnetite oxidation (Equation 1) most commonly produces maghemite (γFe_2O_3), an Fe-deficient, metastable spinel polymorph of hematite (White et al 1994).

$$2[Fe^{2+}Fe_2^{3+}]O_{4(\text{magnetite})} + H_2O \leftrightarrow 3\gamma[Fe_2^{3+}]O_{3(\text{maghemite})} + 2H^+ + 2e^- \quad (1)$$

Magnetite is a semiconductor. Therefore, the oxidation of magnetite transfers electrons both within the solid phase and across the solid-aqueous interface. The electrical conductivity in magnetite is responsible for heterogeneous electron transfer between the solid state and redox sensitive species in solution (White et al 1994). White and Peterson (1996) confirmed that the surface of magnetite effectively reduces Fe^{3+}, Cu^{2+}, Cr^{4+}, and V^{5+} in solution. Metal reduction occurs via several reaction pathways, the most direct being heterogeneous electron exchange

between structural Fe and aqueous transition metals at the oxide-fluid interface (White and Peterson, 1996).

The premise of the present paper is that Au is a redox sensitive species in solution and can be reduced to a metallic state on the surfaces of magnetite. Gold in chloride solutions can be reduced to metallic state according to the following reaction (Equation 2),

$$AuCl_4^- + 3e^- \leftrightarrow Au^o + 4Cl^- \quad (2)$$

Magnetite can be harnessed as a potential sorbent to recover Au from solution. In addition, since magnetite exhibits a strong magnetic property, physical separation of magnetite particles from the solution can be carried out easily. Based on this perspective, the sorption of $AuCl_4^-$ from NaCl solution on synthetic and natural magnetite powders was investigated by batch-sorption experiments. Different recovery parameters, such pH, contact time, chloride concentration, and Au concentration, were examined.

MATERIALS AND METHODS

Reagent grade gold ($HAuCl_4$ in 1 kmol/m^3 HCl) standard solution (Wako Chemicals, Japan) was used as the source of Au ions. The commercial grade synthetic magnetite powder was purchased from Wako Chemicals Japan. The natural magnetite sample, crushed and sieved to the desired particle sizes, was obtained from Iron County, Utah, USA. The magnetite samples were characterized using X-ray Fluorescence Spectroscopy (XRF, JEOL Element Analyzer, JSX-3201A, Japan), Scanning Electron Microscopy-Energy Dispersive X-ray (SEM-EDX, SSX-550 Shimadzu, Japan), Nova 2200e Surface Area and Pore Size Analyzer (Yuasa Ionics, Japan), and Microtrac Size Analyzer (MT3300SX, USA) to determine their chemical composition, surface area, and particle sizes. The rest of the chemicals involved in this experiment, such as sodium chloride (NaCl), hydrochloric acid (HCl), sodium hydroxide (NaOH), were all reagent grade.

Batch sorption experiments were performed to demonstrate the ability of Fe_3O_4 to recover Au from chloride solution. The experiments were carried out by adding 0.1 gram of Fe_3O_4 powder to a 50 cm^3 Erlenmeyer flask containing 10 cm^3 of NaCl solution (0.001-1.0 M) with $HAuCl_4$ at varied concentrations. The pH of the solution was adjusted by adding HCl or NaOH solutions. The mixture was shaken for 0.5-72 h in a water bath shaker (ML-10F, Taitec, Japan) at a rate of 120 strokes per minute and a temperature of 25^oC. After shaking, the mixture was centrifuged and then membrane filtered using a 0.20 µm nitro-cellulose membrane filter (Sartorius, Germany)**.** The Au content in the aqueous phase was determined by Inductively Coupled Plasma-Atomic Emission Spectrometer (SPS 7800, Seiko Instruments, Japan). The magnetite particles after the treatment were examined under the Scanning Electron Microscope (EDX) equipped with an Electron Dispersive X-ray Spectrometer to check the presence of Au on its surface.

The amount of adsorbed Au was calculated according to the mass balance equation

$$\text{Metal Uptake, µmol/g} = (C_i - C_f) \times V/W \quad (3)$$

where C_i is the initial metal concentration, C_f is the remaining metal concentration in the aqueous phase, V is the volume of the aqueous solution, and W is the weight of the sorbent.

RESULTS AND DISCUSSION

The following results outline our findings on the potential of magnetite as a sorbent to recover gold from chloride solution. Two types of magnetite powders were used and compared in terms of their ability to uptake Au from solution. Different parameter studies were conducted to evaluate and determine the optimum condition for the recovery. The effects of contact time, pH, chloride concentration, and initial Au concentration were investigated.

Magnetite Characterization

Two types of magnetite were utilized as sorbents in this study: synthetic and natural. The chemical composition, surface area, and particle size of the magnetite samples were determined by various analytical techniques. Table 1 shows the elemental composition of the two magnetite samples as measured by XRF. The synthetic magnetite used in this study has a purity of 98.3% with MnO_2 as the major impurity. The natural magnetite sample, on the other hand, has a purity of 82.2% with major impurities consisting of Mg, Al, Si, Ca, and P. The X-ray Diffraction (XRD) analysis (not shown) suggests that these impurities in natural magnetite are in the form of sillimanite (Al_2SiO_5), apatite-carbonate-fluoroapatite [$Ca_{10}(PO_4)_5CO_3F_{1.5}(OH)_{0.5}$], and apatite-fluoroapatite [$Ca(PO_4)_3F$].

The surface area of synthetic and natural magnetite was measured by N_2-BET method using a Nova 2200e Surface Area and Pore Size Analyzer. The analysis showed that the synthetic magnetite sample has a surface area of 116 m^2/g, 27 times larger than that of the natural magnetite powder used in this study (4.3 m^2/g). The average particle size of the synthetic magnetite powder dispersed in distilled water, as determined by Microtrac size analyzer, was 5.3 µm, while that of the natural magnetite was 44 µm. However, the SEM analysis of the synthetic Fe_3O_4 particles revealed that its particle size was of nanometric scale, reasonable enough to account for a large surface area. The reason for this discrepancy was reported by Pang, Chin and Anderson (2007) and they explained that nanosized magnetite particles are inherently unstable with a high tendency to aggregate in order to minimize their high surface energies.

Sorption of different metal ions on magnetite

The behavior of Au ions, other precious metal ions, and some base metal ions towards synthetic and natural magnetite was investigated through single-component batch sorption experiments using reagent grade metal solutions as sources of metal ions, and 24 h contact

time. The initial metal concentration was 0.05 mol/m^3 and the amount of magnetite added was fixed at 0.1 g. The pH was adjusted at a range of 4-5 to avoid precipitation of metal species. The results are shown in Figure 1.

In the case of synthetic magnetite, about 3.2 μmol/g of Au (86%) was recovered; followed closely by Cu with an uptake amount of about 2.6 μmol/g. The synthetic magnetite can also recover Pt, Pd, Ni and Co at varying degrees. Other metals, such as Zn and Mn, were not recovered by the synthetic magnetite. On the other hand, natural magnetite exhibited strong selective sorption ability towards Au only. A 100% gold recovery or an uptake amount of 5.0 μmol/g was obtained after the treatment. No recoveries were noted for Pt, Pd, Cu, Ni, Co, Zn and Mn under similar experimental conditions.

Selectivity, from an engineering point of view, is an important consideration in the recovery of gold ions from leach liquors, especially in recycling where various metal species usually co-exist with gold. Recently, there has been increasing activities in selective recovery of gold from solution. The results presented above suggest that magnetite has a great potential as a selective sorbent for Au recovery from solution. If the electro-conductive property of magnetite is considered, a possible explanation for this selective ability can be deduced. Figure 2 shows the standard potentials of different half-cell reactions involving precious metals and some base metals in comparison with the Fe_2O_3/Fe_3O_4 redox pair. Precious metals, such as Au and Pt, have standard potentials higher than that of magnetite; hence, these metals can be reduced on the surface of magnetite. Metals which have standard potentials lower than that of the Fe_2O_3/Fe_3O_4 redox pair, such as Zn and Mn, cannot be reduced by magnetite. The results presented in Figure 1 conform to the standard potential differences of the metal species involved.

Aside from the selectivity experiments, different parameters were studied to evaluate the recovery of Au from chloride solution by synthetic and natural magnetite powders. The results are presented in the succeeding sections.

Effect of solution pH

The pH of the solution plays an important role in the sorption of metal ions onto oxide surfaces, such as the magnetite surface. The influence of pH on the sorption of gold ions has been studied under the initial Au concentration of 0.05 mol/m^3 and 0.1 g Fe_3O_4. Figure 3 shows the pH dependence of Au uptake by synthetic and natural magnetite. The effect of pH was clearly seen, and the uptake behavior against pH was very similar for both types of magnetite. At acidic pH ranges (0-4), about 1.3 µmol/g (26%) and 1.6 µmol/g (32%) Au was recovered by synthetic and natural magnetite, respectively. The uptake amount increased significantly as pH increased from 3 to 6, and showed a maximum at pH around 6.5. At pH greater than 6.5, the uptake amounts decreased gradually. At pH 6-7, 100% recovery or an uptake amount of 5.0 µmol/g Au was obtained when natural magnetite was used as sorbent and 4.4 µmol/g (86%) when synthetic magnetite was utilized. Similar pH behavior was also observed by Uchida et al (2002), when they investigated the pH dependence of the recovery of Au(III) complexes by Fe(III) and aluminum hydroxide.

Control experiments for the pH dependence of Au uptake by magnetite were conducted to determine if precipitation of gold occurs. At each pH range considered, the same conditions with that of the batch sorption experiments were followed except for the addition of Fe_3O_4. The results of the control experiments confirmed that no Au precipitation occurred at all pH ranges. This implied that the difference in the initial and the final Au concentrations was due to the sorption of the gold ions onto magnetite.

The zeta potential of the synthetic and natural magnetite particles at 0.1 kmol/m^3 NaCl concentration was measured using a Zeta Potential Analyzer (Brookhaven Instruments

Corporation, USA) and the results were evaluated against the pH dependence shown in Figure 3. The zeta potential results in Figure 5 show that the surface charge of synthetic magnetite is positive at pH < 4, while that of the natural magnetite at pH < 3, and decreases with increasing pH. From this figure, the iso-electric point of synthetic and natural magnetite at 0.1 kmol/m^3 NaCl can be estimated and the values fall around 4.4 and 3.2, respectively. In Figure 3, the Au uptake by both types of magnetite gradually decreased above pH 6.5. The $AuCl_4^-$ ion is negatively charged, while the surface charge of magnetite varies with pH in aqueous solution with constant ionic strength. In electrostatic adsorption, negatively charged species is not easily attracted to the surface of a sorbent with negative charge (Uchida et. al, 2002). This implies that the recovery of $AuCl_4^-$ by magnetite is not only due to electrostatic adsorption.

Effect of contact time

The effect of contact time on the sorption of gold chloride ions on synthetic and natural magnetite was investigated under the initial Au concentration of 0.05 mol/m^3, 0.1 g Fe_3O_4, and NaCl concentration of 0.1 kmol/m^3. Since the result of the pH dependence experiments showed that Au recovery was at maximum at pH 6-7, this pH range was used in the subsequent investigations. The results are shown in Figure 5. Both types of magnetite shared a similar pattern of Au uptake against contact time; rapid initial increase followed by a slower increase in Au uptake. Around 58% of Au was recovered by the synthetic magnetite after 3 h contact time. However, longer time was required to advance the uptake of the remaining Au ions in the solution. A 100% gold recovery was obtained after 72 h.

The Au uptake against contact time plot for natural magnetite showed a similar pattern with that of the synthetic magnetite. At 3 h contact time, 64% Au recovery was achieved and was completed at 24 h with 100% recovery. The kinetic comparison of gold recovery by the two types of magnetite indicates that the natural magnetite exhibited a faster

kinetics than the synthetic magnetite. It should be noted that the surface area of natural magnetite used in this study was 27 times less than the surface area of the synthetic magnetite. In physical adsorption, faster kinetics and higher recovery should favor the Au uptake by synthetic magnetite but the results indicated the opposite. Considering this, the results suggest that the Au uptake by magnetite is not simply governed by a typical electrostatic adsorption mechanism. The reason as to why natural magnetite offers a high Au uptake capacity at a faster rate is still unknown to the authors and yet to be confirmed in a separate investigation.

Effect of chloride concentration

Figure 6 illustrates the effect of chloride concentration on the uptake of Au by synthetic and natural magnetite particles. As a source of chloride ions, NaCl solution was used and the concentration was varied from 0.001 to 1.0 kmol/m^3. The Au concentration, Fe_3O_4 amount, contact time and pH were fixed at 0.05 mol/m^3, 0.1 g, 24 h and pH 6-7, respectively. The increase in the NaCl concentration from 0.001 to 0.1 kmol/m^3 did not affect the Au recovery by magnetite. At these NaCl concentrations, more than 99% Au was recovered by the natural magnetite and about 86% for the synthetic magnetite. However, as the NaCl concentration was increased to 1.0 kmol/m^3, the Au uptake on synthetic and natural magnetite decreased significantly. The Au recovery decreased to 70% for synthetic magnetite and to about 88% for natural magnetite at very high chloride concentration. The sorption capacity decreases as the concentration of chloride ions in the aqueous solution increases. These results indicate that very high chloride concentration has a negative effect and is detrimental to the sorption of Au onto magnetite.

Effect of Au concentration

The effect of the gold concentration on Au sorption on synthetic and natural magnetite was examined by varying the initial Au concentration in the range of 0.01-0.50 mol/m^3. The amount of magnetite powder added was 0.1 g. The residual Au concentration was determined by ICP-AES after treatment. The results are shown in Figure 7 as a plot of the Au concentration after 24 h against gold uptake. At an initial Au concentration of 0.5 mol/m^3, the synthetic magnetite recovered about 18 µmol/g Au, leaving behind 0.32 mol/m^3 of Au in the solution phase. At the same initial Au concentration, natural magnetite recovered 30.5 µmol/g Au, with only 0.16 mol/m^3 residual gold ions in the aqueous phase. The gold uptake by natural magnetite was almost double than that of the synthetic magnetite at higher initial Au concentrations.

The plots in Figure 7, which are both represented by straight lines, clearly shows that gold uptake by both types of magnetite increased with increasing residual Au concentration in the aqueous phase. However, the Au uptake against residual Au plot for natural magnetite is characterized by a steeper slope compared to that of the synthetic magnetite. This signifies that for natural magnetite, the increase in the Au uptake amount was proportional to the increase in the residual Au ions in the solution. In addition, at increasing Au concentration, natural magnetite recovers more Au than synthetic magnetite. Figure 7 also conveys that the Au uptake by synthetic and natural magnetite did not approach a constant value, which could mean that the maximum sorption capacity of both types of magnetite was not reached yet and the magnetite powders can still recover more Au from the solution.

The magnetite particles used to recover Au from a solution containing 0.5 mol/m^3 $AuCl_4^-$ at 24 h, pH 6-7, and 0.1 $kmol/m^3$ NaCl concentration, were collected, washed with distilled water and dried in a vacuum oven for one day. The dried magnetite powders were examined under Scanning Electron Microscopy-Energy Dispersive X-ray Spectrometer

(SEM-EDX) and Back Scattering Electron (BSE) analyses. The results of the spectrometric analyses are displayed in Figures 8 and 9 for synthetic magnetite and natural magnetite, respectively. The presence of gold on the surface of synthetic magnetite was detected by SEM-EDX and BSE as shown in Figure 8. Gold was observed as the glittering white part in the midst of nanosized synthetic magnetite particles under the BSE image. The elemental mapping and point analysis by EDX confirmed that the shiny component was indeed gold. The EDX spectra identified different peaks of Au, the highest of which was Au-Mα.

Figure 9 shows the SEM-EDX and BSE results for the natural magnetite containing Au. Unlike that of the synthetic magnetite, gold on the surface of natural magnetite was more visible under the microscope; many shiny and bright white components were observed under BSE. This could be due to the higher amount of Au recovered by the natural magnetite from the solution. The SEM elemental mapping and the EDX spectra generated by point analysis, verified the occurrence of gold on the magnetite surface. It was also observed that the gold on the magnetite surface was not uniformly distributed throughout the surfaces of the magnetite particles, but instead, appeared to be cemented or agglomerated on some areas of the magnetite surface. This condition was also noted in the case of the synthetic magnetite. Due to this observation, it can be perceived that the detected gold was not of the physically adsorbed or ionic form. A closer look at the morphology of the magnetite surface, specifically the bright white part under BSE, revealed a cluster of gold precipitates (Figure 10). The presence of gold cements or precipitates on the magnetite surface would signify the reduction of $AuCl_4^-$ complex to metallic gold.

All of these results demonstrate that Fe_3O_4 can uptake gold and can be used as a potential selective sorbent to recover gold from chloride solution or chloride leach liquors. Since magnetite is a magnetic material, the problem of phase separation associated with conventional separation techniques can be resolved.

CONCLUSION

Gold chloride complexes are redox sensitive species in solution and can be reduced to metallic state on the surface of an electro-conductive material. The sorption of Au from chloride solution on magnetite, an iron oxide capable of reducing redox-sensitive species on its surface, was studied under various conditions. Single-component batch sorption experiments were performed using synthetic and natural magnetite and the effects of different parameters, such as pH, contact time, Cl^- concentration and initial Au concentration, were investigated.

Sorption experiments involving various metal ions demonstrated that synthetic magnetite exhibited selectivity towards Au, Pt, Pd, Cu and Ni at varying degrees, while the natural magnetite towards Au only. The pH dependence of Au sorption on both types of magnetite showed similar patterns with maximum peaks at pH 6-7. At this pH range, maximum gold uptake values of 4.4 µmol/g and 5.0 µmol/g were obtained for synthetic and natural magnetite, respectively. Investigation on the effects of contact time and residual Au concentration on Au recovery revealed that natural magnetite can uptake more gold at 24 h contact time compared to the synthetic magnetite. Moreover, the results also conveyed that the Au uptake by synthetic and natural magnetite did not approach a constant value, which could mean that the maximum capacity of both types of magnetite was still not reached at 24 h and the magnetite powders can still recover more Au from the solution; a phenomenon not common in a typical electrostatic adsorption process. High chloride concentration decreased the Au uptake capacity of both types of magnetite. The SEM-EDX and BSE analyses confirmed the presence of gold concentrated on some areas of the synthetic and natural magnetite's surfaces. The detected gold appeared as a cluster of Au cements or precipitates suggesting the reduction of $AuCl_4^-$ to metallic Au on the surface of magnetite.

REFERENCES

Aktas, S., Gozuak, B., Acma, H., Ozalp, M.R., Acma, E., 2009, Gold recovery from chloride solutions using fallen leaves, Environmental Chemistry Letters, DOI: 10.1007/s10311-009-0245-7.

Aylmore, M.G., 2005, Alternative lixiviants to cyanide for leaching gold ores, in *Developments in Mineral Processing* (ed: Adams, MD), Vol. 15, pp 501-539, The Netherlands: Elsevier.

Einzweiler, J., Joekes, I., 1991, Adsorption of colloidal gold on colloidal iron oxides, Journal of Geochemical Exploration, 40, pp 133-142.

Koyanaka, H, Takeuchi, K, Loong, C-K, 2005. Gold recovery frpm parts-per-trillion-level aqueous solutions by a nanostructured Mn_2O_3 adsorbent, Separation and Purification Technology, 43, pp 9-15 (Elsevier: The Netherlands).

Lam, K.F., Fong, C.M., Yeung, K.L., 2007, Separation of precious metals using selective mesoporous adsorbents, Gold Bulletin, 40/3, pp 192-198.

Machesky, M.L., Andrade, W.O., Rose, A.W., 1991, Adsorption of gold (III)-chloride and gold (I)-thiosulfate anions by goethite, Geochimica et Cosmochimica Acta, Vol. 55, pp 769-776.

Parinayok, P., Yonezu, K., Yokoyama, T., Watanabe, K., Leepowpanth, Q., Wiwattanadate, D., 2008, Recovery of platinum from spent automobile catalytic converters, in *Proceedings of*

the 2nd International Workshop and Conference on Earth Resources Technology (ed: Pinyo, M. et al), pp 36-41.

Ran, Y., Fu, J., Rate, A.W., Gilkes, R.J., 2002, Adsorption of Au(I, III) complexes on Fe, Mn oxides and humic acid, Chemical geology, 185, pp 33-49.

Schoonen, M.A.A., Fisher, N.S., Wente, M., 1992, Gold adsorption onto pyrite and goethite: a radiotracer study, Geochimica et Cosmochimica Acta, Vol. 56, pp 1801-1814.

Uchida, A., Yokoyama, T., Motomura, Y., Miyazaki, A., Okaue, Y., Watanabe, K., Izawa, E., 2002, Role of iron (III) and aluminum hydroxides in concentration/reduction of Au (III) complexes, Resource Geology, Vol. 52, No. 3, pp 223-230.

Uheida, A., Iglesias, M., Fontas, C., Hidalgo, M., Salvado, V., Zhang, Y., Muhammed, M., 2006, Sorption of palladium(II), rhodium(III), and platinum(IV) on Fe_3O_4 nanoparticles, Journal of Colloid and Interface Science, 301, pp 402-408.

White, A.F., Peterson, M.L., 1996, Reduction of aqueous transition metal species on the surfaces of Fe(II)-containing oxides, Geochimica et Cosmochimica Acta, Vol. 60, No. 20, pp 3799-3814.

White, A.F., Peterson, M.L., Hochella, M.F. Jr., 1994, Electrochemistry and dissolution kinetics of magnetite and ilmenite, Geochimica et Cosmochimica Acta, Vol. 58, No. 8, pp 1859-1875.

Wiraseranee, C., Yonezu, K., Yokoyama, T., Wiwattanadate, D., Leepawpanth, Q., Watanabe, K., 2008, Selective recovery of gold and platinum by coprecipitation with manganese (II) hydroxide, in *Proceedings of the 2nd International Workshop and Conference on Earth Resources Technology (ed: Pinyo, M. et al)*, pp 143-150.

Table 1. Composition (weight %) of natural and synthetic magnetite as determined by X-ray Fluorescence Spectrometer (XRF).

Components	Weight %	
	Synthetic Magnetite	Natural Magnetite
Fe_3O_4	98.3	82.2
MnO_2	1.7	-
MgO	-	0.7
Al_2O_3	-	0.9
SiO_2	-	5.4
CaO	-	4.8
P_2O_5	-	5.9

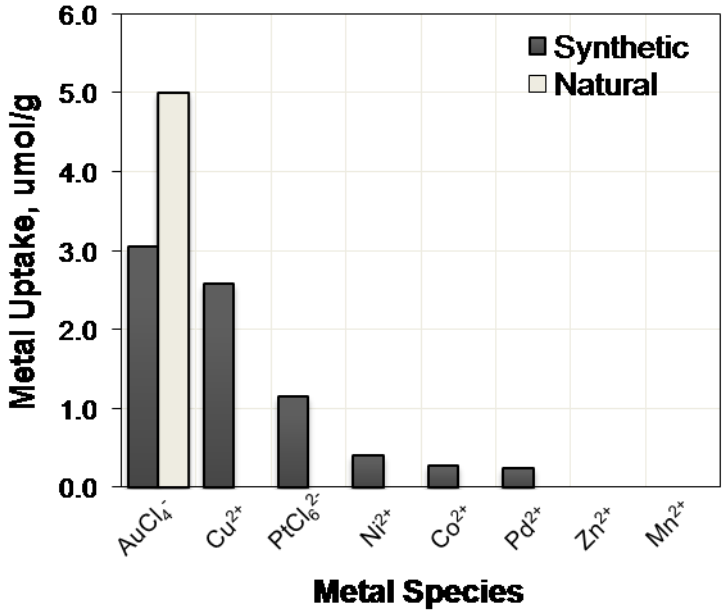


Figure 1. Sorption of different metal species on synthetic and natural magnetite. Initial metal concentration: 0.05 mol/m^3; contact time: 24 h; pH: 4-5; NaCl concentration: 0.1 kmol/m^3; Fe_3O_4 amount: 0.1 g; temperature: 298K.

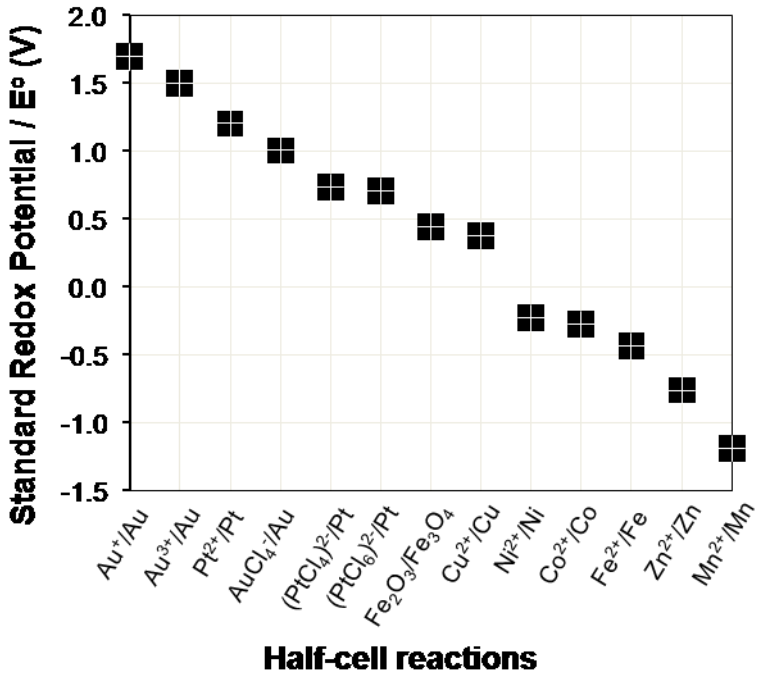


Figure 2. Standard potentials of Au, Pt and some base metals' half-cell reactions and Fe_2O_3/Fe_3O_4 redox pair.

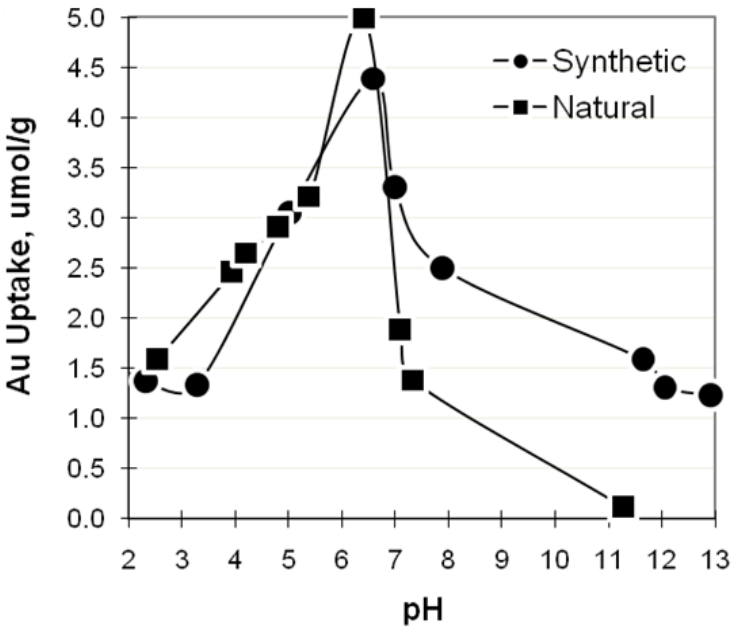


Figure 3. Effect of solution pH on Au uptake by synthetic and natural magnetite. Initial Au concentration: 0.05 mol/m^3; contact time: 24 h; NaCl concentration: 0.1 $kmol/m^3$; Fe_3O_4 amount: 0.1 g; temperature: 298K.

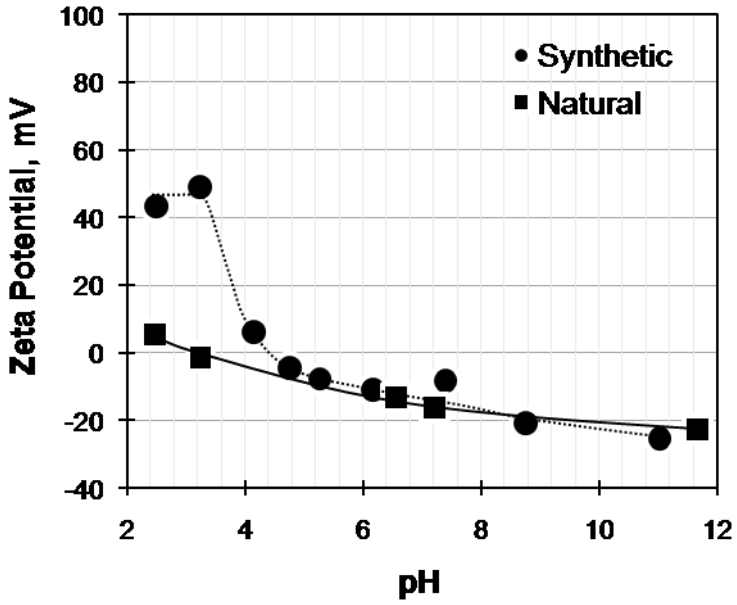


Figure 4. Zeta potential of the synthetic and natural magnetite at 0.1 kmol/m^3 NaCl concentration.

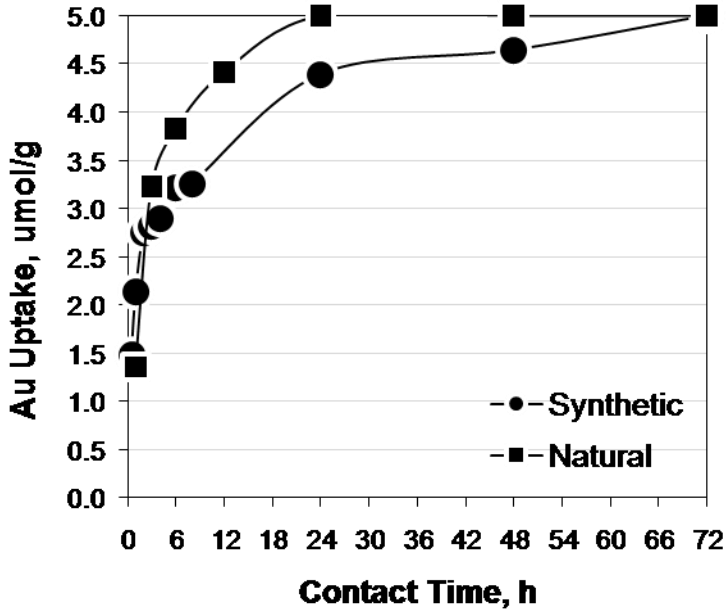


Figure 5. Effect of contact time on Au uptake by synthetic and natural magnetite. Initial Au concentration: 0.05 mol/m^3; pH: 6-7; NaCl concentration: 0.1 kmol/m^3; Fe_3O_4 amount: 0.1 g; temperature: 298K.

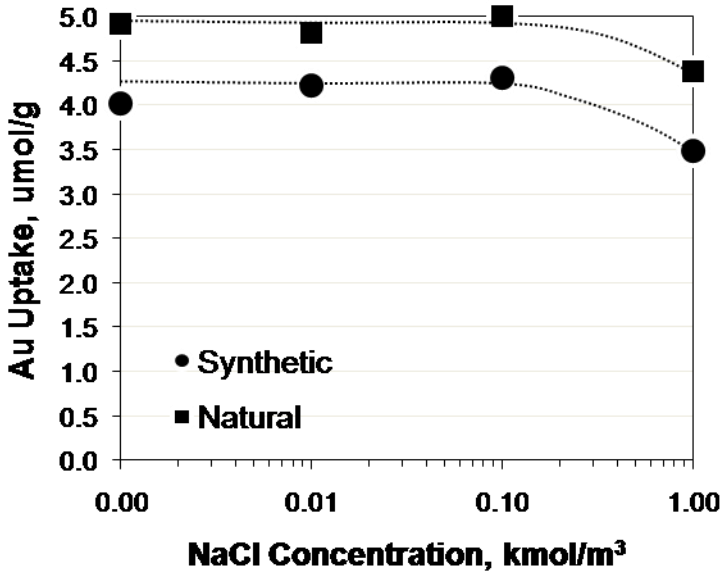


Figure 6. Effect of NaCl concentration on Au uptake by synthetic and natural magnetite. Initial Au concentration: 0.05 mol/m^3; pH: 6-7; contact time: 24 h; Fe_3O_4 amount: 0.1 g; temperature: 298K.

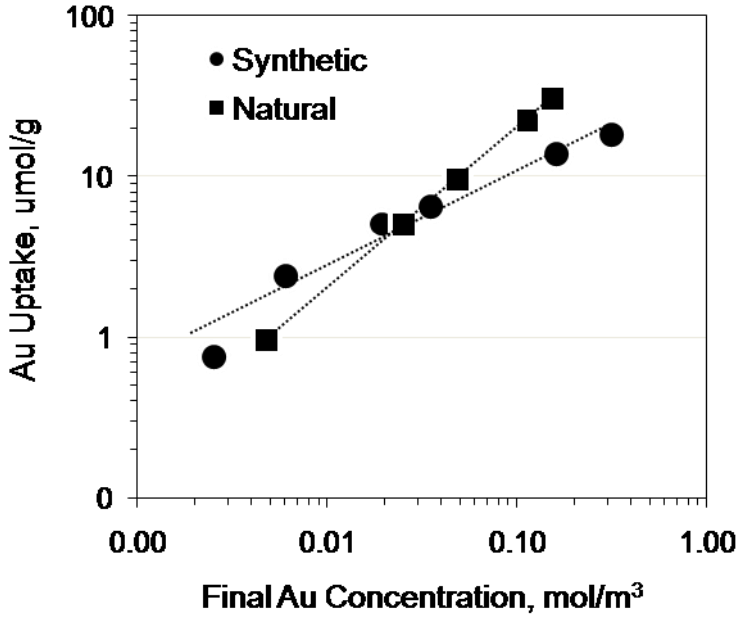


Figure 7. Effect of residual Au concentration on Au uptake by synthetic and natural magnetite. NaCl concentration: 0.1 kmol/m^3; pH: 6-7; contact time: 24 h; Fe_3O_4 amount: 0.1 g; temperature: 298K.

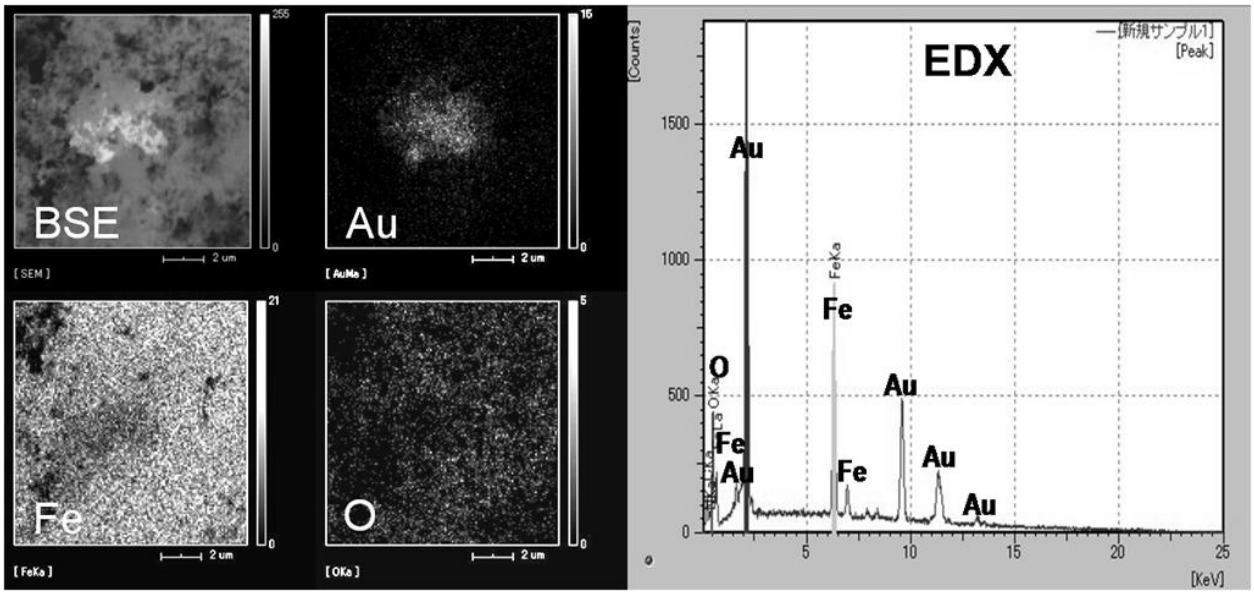


Figure 8. SEM-EDX and BSE image, mapping and spectra for synthetic magnetite containing Au (6000x magnification).

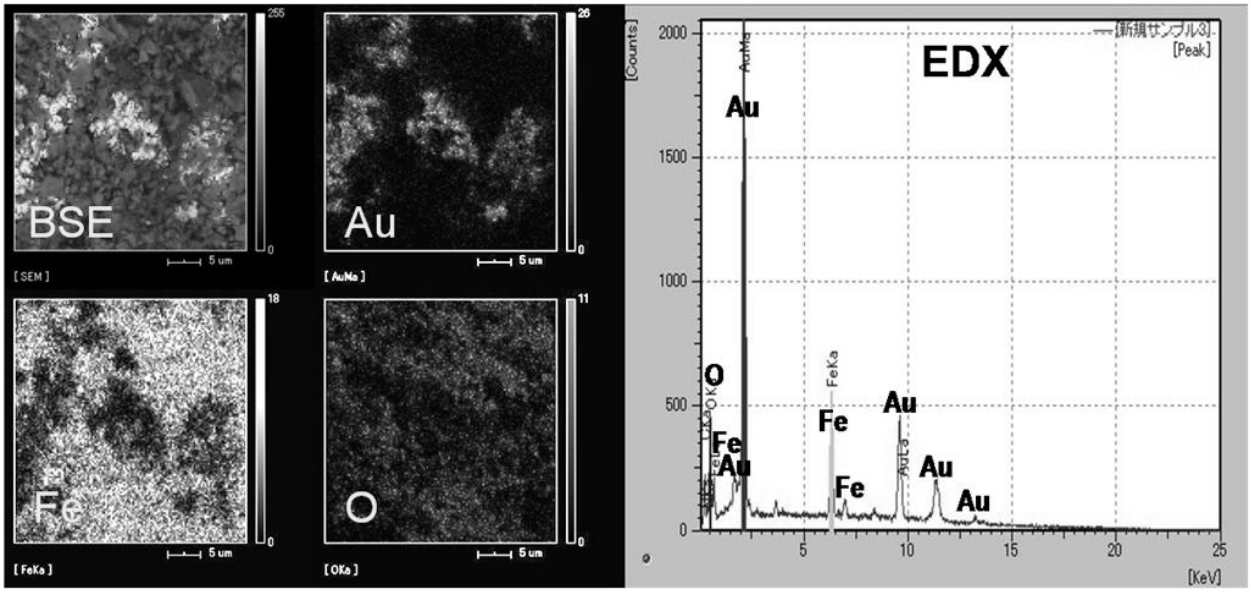


Figure 9. SEM-EDX and BSE image, mapping and spectra for natural magnetite containing Au (2000x magnification).

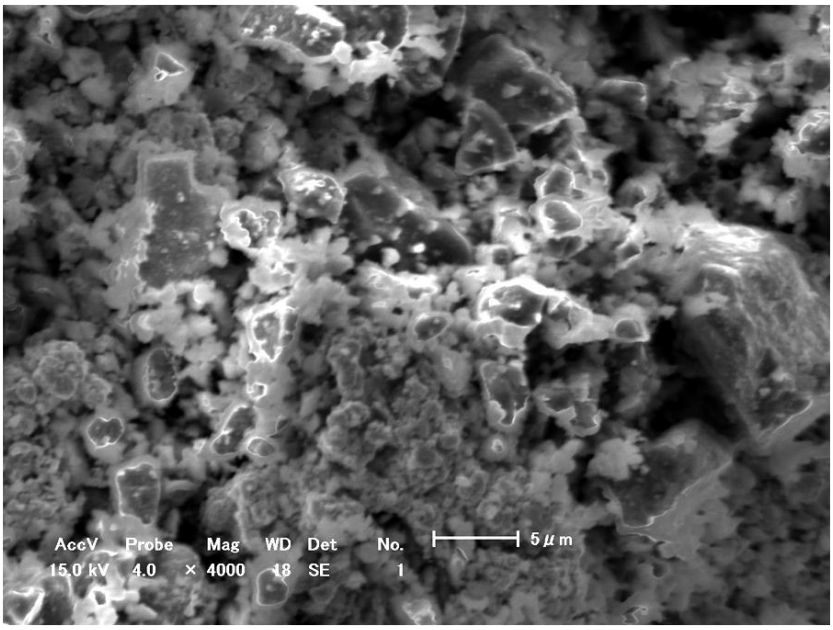


Figure 10. SEM image of the natural magnetite showing clusters of gold cements/precipitates (white part) on magnetite surface (4000x magnification).