PHYSICOCHEMICAL CHARACTERISTICS OF ACID MINE DRAINAGES (AMD) AND AMD-RECEIVING RIVER WATERS IN RANAU, SABAH

LIM KAH LING

DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF SCIENCE WITH HONOURS

INDUSTRIAL CHEMISTRY PROGRAMME
SCHOOL OF SCIENCE AND TECHNOLOGY
UNIVERSITI MALAYSIA SABAH

APRIL, 2007

PUMS 99:1

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS@

JUDUL: PHYSICOCHEMICAL CHARACTERISTICS OF ACID MINE DRAINAGES (AMD) AND AMD-RECEIVING RIVER WATERS IN RANAU, SABAH

Ijazah: Sarjana Muda Sains Dengan Kepujian BSc (Hons)

SESI PENGAJIAN: 2004 - 2007

Saya LIM KAH LING

(HURUF BESAR)

mengaku membenarkan tesis (LPS/Sarjana/Doktor Falsafah)* ini disimpan di Perpustakaan Universiti Malaysia Sabah dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Malaysia Sabah.
2. Perpustakaan Universiti Malaysia Sabah dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (/)

[ ]	SULIT	(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)
[ ]	TERHAD	(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)
[√]	TIDAK TERHAD	

Disahkan oleh

(TANDATANGAN PENULIS)

(TANDATANGAN PUSTAKAWAN)

Alamat Tetap: 01-16-03, Jalan San Peng, Flat SRI Selangor 55200 Kuala Lumpur.

Assoc. Prof. Dr. Marcus Jopony
School of Science and Technology
Universiti Malaysia Sabah
Nama Penyelia

Tarikh: 13/4/07

Tarikh: 13/4/07.

CATATAN: * Potong yang tidak berkenaan.

** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh tesis ini perlu dikelaskan sebagai SULIT dan TERHAD.

@ Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (LPSM).

DECLARATION

I hereby declare that this dissertation is based on my original work, except for quotations and summaries each of which have been fully acknowledged

APRIL, 2007

LIM KAH LING
HS2004-4651

VERIFICATION

Name: Lim Kah Ling

Title: Physicochemical Characteristics of Acid Mine Drainages (AMD) and AMD-receiving River Waters in Ranau, Sabah

ASSOC. PROF. DR. MARCUS JOPONY

DR. NOUMI SURUGAU

MR. MOH PAK YAN

DEAN

APRIL, 2007

ACKNOWLEDGEMENT

First and foremost, my heartiest gratitude and thanks to my supervisor, Assoc. Professor Dr. Marcus Jopony for his valuable advice, guidance, perseverance, motivation, support and help throughout the dissertation. Special thanks to all lecturers of Industrial Chemistry course for their guidance and support. I also would put into words of appreciation to Mr. Sani Gorudin, the lab assistant for the help with the fieldwork as well as providing all the necessary apparatus. My appreciation also goes out to all other members and personnel at the Industrial Chemistry Lab for their kind help and advices especially Miss Stella Ho Yen Ling. Many thanks are to all my supportive friends for their endless cooperation and providing help whenever I need them. I also would like to thank my family members for their undying love and emotional support. I am also grateful to those who are not mention but have helped making this dissertation a successful one. Lastly, not forgetting my sincere thanks are to the School of Science and Technology for providing me the opportunity and amenities to enable this research carried out successfully.

ABSTRACT

Selected physicochemical characteristics of AMD and river water samples from Ranau, Sabah were analyzed according to APHA methods. The results showed that the AMDs at the Mamut Copper Mine have low pH (pH 2.77 – 4.26), high total acidity (50.0 – 1557.5 mgL^{-1} $CaCO_3$), high TDS (0.16 – 2.42 gL^{-1}), high E_c (0.32 – 4.86 $mScm^{-1}$), high concentration of dissolved sulphate (202.94 – 5147.06 mgL^{-1}), and elevated concentration of dissolved Cu (0.82 – 27.34 mg mL^{-1}), Zn (0.29 -7.59 mg mL^{-1}) and Fe (0.03 – 12.51 mg mL^{-1}). The total acidity of the AMD samples is strongly correlated with dissolved metals concentration, TDS and E_c, but there is no apparent relationship with pH. The higher the total acidity, the greater the acid buffering ability of the AMD samples. Except for Mamut-Langanan River, which is highly impacted by AMD from the mine, the water of other main rivers in the area have high pH (pH 7.21 – 7.58), high alkalinity (22.67 – 59.33 mgL^{-1} $CaCO_3$), low TDS (0.03 – 0.33 gL^{-1}), low E_c (0.07 – 0.66 $mScm^{-1}$), low dissolved sulphate (4.0 – 244 mgL^{-1}), and low dissolved Cu (0.001 -0.014 mg mL^{-1}), Zn (0.000 – 0.026 mg mL^{-1}), and Fe (0.000 – 0.012 mg mL^{-1}). Comparatively, the pH, alkalinity, TDS, Ec, dissolved sulphate, Cu, Zn, and Fe of Mamut-Langanan River is 4.78, 1.17 mgL^{-1} $CaCO_3$, 0.29gL^{-1}, 0.59 $mScm^{-1}$, 258 mgL^{-1}, 0.734 mg mL^{-1}, 0.473 mg mL^{-1}, and 0.014 mg mL^{-1}, respectively. The impact of AMD, however, was less apparent downstream of this river.

CIRI-CIRI FIZIKOKIMIA SALIRAN ASID LOMBONG (AMD) DAN AIR SUNGAI YANG MENERIMA AMD DI RANAU, SABAH

ABSTRAK

Ciri-ciri fizikokimia terpilih bagi sampel-sampel AMD dan air sungai dari Ranau, Sabah telah dianalisis mengikut kaedah APHA. Hasil kajian menunjukkan AMD di Lombong Tembaga Mamut mempunyai nilai pH (pH 2.77 – 4.26) yang rendah, jumlah keasidan (50.0 – 1557.5 mgL^{-1} $CaCO_3$) yang tinggi, TDS (0.16 – 2.42 gL^{-1}) yang tinggi, E_c (0.32 – 4.86 mScm^{-1}) yang tinggi, kepekatan sulfat terlarut (202.94 – 5147.06 mgL^{-1}) yang tinggi, dan kepekatan Cu (0.82 – 27.34 mg mL^{-1}), Zn (0.29 -7.59 mg mL^{-1}) dan Fe terlarut (0.03 – 12.51 mg mL^{-1}) yang tinggi. Jumlah keasidan sampel AMD berkorelasi baik dengan jumlah kepekatan logam terlarut, nilai TDS dan nilai E_c tetapi tiada hubungan nyata dengan nilai pH. Semakin tinggi jumlah keasidan, semakin tinggi sifat penimbalan asid oleh sampel AMD. Melainkan Sungai Mamut-Langanan, yang nyata dipengaruhi oleh AMD dari kawasan lombong, air sungai lain di lokasi kajian mempunyai nilai pH (pH 7.21 – 7.58) yang tinggi, nilai kealkalian (22.67 – 59.33 mgL^{-1} $CaCO_3$) yang tinggi, dan nilai TDS (0.03 – 0.33 gL^{-1}), E_c (0.07 – 0.66 mScm^{-1}), kepekatan sulfat (4.0 – 244 mgL^{-1}), Cu (0.001 -0.014 mg mL^{-1}), Zn (0.000 – 0.026 mg mL^{-1}), dan Fe (0.000 – 0.012 mg mL^{-1}) yang rendah. Sebaliknya, nilai pH, kealkalian, TDS, E_c, sulfat terlarut, Cu, Zn, dan Fe bagi Sungai Mamut-Langanan ialah masing-masing 4.78, 1.17 mgL^{-1} $CaCO_3$, 0.29gL^{-1}, 0.59 mScm^{-1}, 258 mgL^{-1}, 0.734 mg mL^{-1}, 0.473 mg mL^{-1}, dan 0.014 mg mL^{-1}. Kesan input AMD, walau bagaimanapun, menjadi tidak ketara di bahagian hilir sungai ini.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOS

LIST OF ABBREVIATIONS AND SYMBOLS

%	Percent
°C	Degree Celsius
λ	Wavelength
$\mu g\ mL^{-1}$	Microgram per millilitre
µm	Micrometre
$\mu S\ cm^{-1}$	Microsiemens per centimetre
AMD	Acid mine drainage
H^+	Hydrogen ions
i.e.	For example; that is (in Latin term)
km	Kilometre
m	Metre
$mg\ L^{-1}$	Milligram per litre
mL	Millilitre
mm	Millimetre
NaOH	Sodium Hydroxide
nm	Nanometre
OH^{-1}	Hydroxyl ion
R.	River
Temp.	Temperature

CHAPTER 1

INTRODUCTION

1.1 Mining and Acid Mine Drainage

Mining activity is a major cause of environmental pollution (Down & Stocks, 1977; Salomons, 1995). By general consensus, acid mine drainage (AMD), which is more apparent in abandoned or closed mines, is the most critical environmental problem created by mining. AMD is known to adversely affect both surface and ground waters worldwide (Kalin *et al.*, 2005; Gray, 1998; Banks *et al.*, 1997). The problem of AMD is basically due to its acidic pH (i.e. pH ~ 3.0), high acidity and high concentration of dissolved heavy metals. Inputs of AMD can degrade receiving water quality besides adversely affecting aquatic life (Akcil & Koldas, 2006; Banks *et al.*, 1997).

Various treatment methods are used to remedy or mitigate AMD problem. One of the purposes for the treatment is to reduce or neutralize the acidity of the AMD. The acidity, quantified as total acidity, is contributed by free H^+ in solution (i.e. proton acidity) and dissolved metal ions (i.e. mineral acidity). The neutralization process can be complicated by the mineral acidity. Neutralization of proton acidity leads to increase in pH. However, as the pH increases, the metals (namely Fe^{3+} and Al^{3+}) can undergo hydrolysis, releasing H^+ into the solution. This causes pH buffering effect and thereby ineffective neutralization. Consequently, the total acidity value and not the pH value is a better reference during AMD treatment (Jopony *et al.*, 2002; Evangelou, 1995; Singer & Stumm, 1970).

In order to better understand the impact of acid drainage and to provide a basis for assessing a long-term management options and strategic research needs, it is important to determine and characterize the acidity of AMD.

1.2 Mamut Copper Mine

Mamut Copper Mine near Ranau in Sabah was the largest mining project in Malaysia and was one of the biggest mining operations in South East Asia. Mamut is situated 60 km due east of Kota Kinabalu, at 1300 m above sea level on the southeastern slope of Mount Kinabalu. The mining lease covers an area of 4800 acres of rugged mountains and steep valley. The annual rainfall is 4000 mm and the climate is sub-tropical (Ramli *et al.*, 1994).

During its operation, the mine produced metal concentrates at the rate of 120 000 tonnes per year, which were sold to smelters overseas for refining. The metal output of the mine was about 30 000 tonnes of copper, 16 tonnes of silver and 2.4 tonnes of gold per year, which is equivalent to almost 25 % of Malaysia's annual mineral export revenue.

The mine was operated during the period of 1975 - 1999. During that time, some 250 million tones of overburdens were stored in waste rock dumps while over 105 million tones of tailings from the mineral process were deposited at Lohan Tailings Dam. Also, the mining activity left behind a mine pit which is about 1200 m in diameter and a depth of 500 m (Photo 1.1). Currently, there are evidences of AMD pollution at the mine area and the surrounding rivers (Shin, 2000).

Photo 1.1 Mamut copper mine pit currently filled up with AMD.

1.3 Objectives of Study

The objectives of this study are as follows:

(a) to determine and compare the physicochemical characteristics of AMD and AMD-receiving waters.

(b) to determine and compare the acidity of AMD samples at Mamut Copper Mine.

(c) to evaluate the relationship between acidity and other characteristics of AMD , including dissolved metals concentration.

(d) to determine and compare the buffering characteristics of the AMD.

1.4 Scope of Study

In this study, AMD samples were collected from the abandoned Mamut Copper Mine in Ranau, Sabah. The samples will be analyzed for selected water quality parameters, including pH, total acidity and total dissolved metals. Each sample will also be titrated potentiometrically with an alkaline solution to evaluate it's buffering characteristic. A similar study will be extended to water samples of AMD-receiving rivers in the area.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Mining

Mining is the first operation in the commercial exploitation of a mineral resource. It can be defined as the act of tunnelling and digging out of the ground in order to recover one or more mined material (Dunster, 1996). A typical mining operation is shown in Figure 2.1.

Mining can be broadly categorized into two types, namely surface and underground mining. Surface mining is dominated by open pit (e.g. base and precious metal ore extraction) or open cast (e.g. coal operations). Surface and underground mining usually occur independently of one another, although open pit mining does occasionally occur in areas already partly worked by underground methods. Similarly, underground methods are sometimes used to extract ore from beneath or in the vicinity of pits, where further extension of the pit itself is not economic or technically feasible (Warhurst & Noronha, 1999).

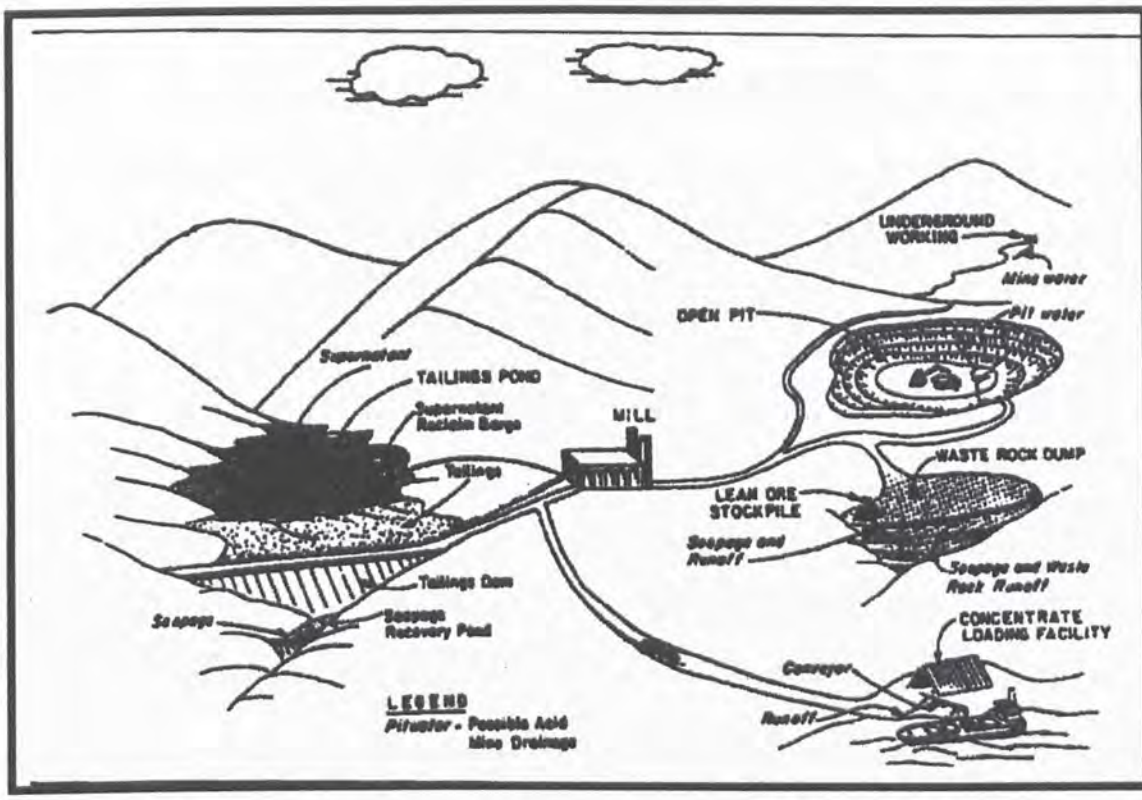

Figure 2.1 A typical mining operation (Source: Ferguson & Erickson, 1988)

Mining operation at the Mamut Copper Mine was undertaken by the open pit method, utilising drilling and blasting to fragment the overburden and mineral ore followed by loading using loaders then hauling by heavy dump trucks. The overburden was stored in waste rock dumps whilst the ore was hauled to the crushing and milling plants for grinding and processing. After processing, the valuable metallic mineral component was sold as concentrate whilst the tailings were deposited in the Lohan Tailings Dam (Ramli *et al.*, 1994).

Extraction or mining of coal or metal ore deposits produces large volume of solid wastes including overburdens, waste rocks, and tailings which are usually dumped in the vicinity of the mine. Since sulphide minerals tend to be present as impurities in coal and metal ores, these mine wastes are generally enriched with the sulphides (Skousen, *et al.*, 2000). The dominant sulphide mineral in mine wastes is pyrite, FeS_2 (Kalin *et al.*, 2005; Kim & Chon, 2001; Hawley, 1977). Other minor sulphide minerals are as listed in Table 2.1.

Pyrite's metallic luster and pale-to-normal brass-yellow colour, as shown in Photo 2.1, have earned it the nickname of "fool's gold" (Morrison, 1992). It is relatively stable in its natural anoxic environment. However, when exposed to water, oxygen, and bacteria, pyrite can readily undergo oxidation to form sulphuric acid, and subsequently leads to the formation of AMD (Akcil & Koldas, 2006; Kalin *et al.*, 2005; Kim & Chon, 2001).

Photo 2.1 Pyrite mineral
(Source: Friedman, 2006)

REFERENCES

Akcil, A. and Koldas, S., 2006. Acid Mine Drainage (AMD): causes, treatment and case studies. *Journal of Cleaner Production* **14,** 1139-1145.

Alpers, C. N. and Blowes, D. W., 1994. *Environmental geochemistry of sulphide oxidation*. American Chemical Society Symposium Series 550.

American Public Health Association (APHA), 1995. *Standard Methods for the Examination of Water and Wastewater*. 19th Ed. American Public Health Association, Washington, DC.

Arnesen, R. T., 1993. *Water pollution from sulphide ore mines with discharge to freshwater (in Norwegian)*. Norsk Institutt for Vannforskning (NIVA) Report No. O-67084/O-92204, NIVA, Oslo, Norway.

Aykol, A., Budakoglu, M., Kumral, M., Gultekin, A. H., Turhan, M., Esenli, V., Yavuz, F. and Orgun, Y., 2003. Heavy metal pollution and acid drainage from the abandoned Balya Pb-Zn sulfide Mine, NW Anatolia, Turkey. *Environmental Geology* **45,** 198-208.

Azcue, J. M. (Ed.)., 1999. *Environmental Impacts of Mining Activities*. Springer-Verlag Berlin Heidelberg, Berlin, Germany.

Ball, J. W. and Nordstrom, D. K., 1991. *User's manual for WATEQ4F with revised data base*. U.S. Geological Survey Open-File Report 91-183, 189.

Banks, D., Younger, P. L., Arnesen, R., Iversen, E. R., Banks, S. B., 1997. Mine-water chemistry: the good, the bad and the ugly. *Environmental Geology* **32** (3), 157-169.

Barton, P., 1978. *The Acid Mine Drainage*. Wiley-interscience, New York. 313-358.

Berner, R. A. and Morse, J. W., 1974. Dissolution kinetics of calcium carbonate in seawater. *American Journal of Science* **274,** 10-134.

Black, A. and Craw, D., 2001. Arsenic, copper and zinc occurrence at the Wangaloa coal mine, southeast Otago, New Zealand. *International Journal of Coal Geology* **45,** 181-193.

Blowes, D. W. and Ptacek, C. J., 1994. Acid-neutralization mechanisms in inactive mine tailings. In: Jambor, J. L. and Blowes, D. W. (Eds.). *Environmental Geochemistry of Sulfide Mine-wastes: Mineralogical Association of Canada, Short Course Handbook* **22,** 271-292.

Brake, S. S., Connors, K. A. and Romberger, S. B., 2001. A river runs through it: impact of acid mine drainage on the geochemistry of West Little Sugar Creek pre- and post- reclamation at the Green Valley coal mine, Indiana, USA. *Environmental Geology* **40,** 1471-1481.

Cánovas, C. R., Olías, M., Nieto, J. M., Sarmiento, A. M. and Cerón, J. C., 2007. Hydrogeochemical characteristics of the Tinto and Odiel Rivers (SW Spain). Factors controlling metal contents. *Science of the Total Environment* **373,** 363-382.

Castro, J. M. and Moore, J. N., 2000. Pit lakes: their characteristics and the potential for their remediation. *Environmental Geology* **39,** 1254-1260.

Chon, H. T. and Hwang, J. H., 2000. Geochemical characteristics of the acid mine drainage in the water system in the vicinity of the Dogye coal mine in Korea. *Environmental Geochemistry and Health* **22,** 155-172.

Costello, C., 2003. *Acid mine dranage: innovative treatment technologies*. Washington, D.C.: US EPA Office of Solid Waste and Emergency Response Technology Innovation Office, 52.

Cravotta III, C. A., Brady, K. B. C., Rose, A. W., Douds, J. B., 1999. Frequency distribution of the pH of coal-mine drainage in Pennsylvania. In: Morganwalp, D. W., Buxton, H. (Eds). *US Geological Survey Toxic Substances Hydrology Program – Proceeding of the Technical Meeting*. US Geology Survey Water-Resources Inv. Rep. 99-4018A, 313-324.

Cravotta III, C. A., Dugas, D. L., Brady, K. B. C., Kovalchuk, T. E., 1994. *Effects of selective handling of pyritic, acid-forming materials on the chemistry of pore gas and ground water at a reclaimed surface coal mine in Clarion County, PA, USA.*US Bur. Mines Spec. Publ. SP 06A, 365-374.

Cravotta III, C. A. and Traham, M. K., 1999. Limestone drains to increase pH and remove dissolved metals from acidic mine drainage. *Appl. Geochem* 14 (5), 581-606.

Dean, J. G., Bosqui, F. L. and Lanouette, K. H., 1972. Environmental Science and Technology. *Journal of Environ. Sci. Technol.* **6** (6), 17-23.

Dinelli, E. and Tateo, F., 2002. Different types of fine-grained sediments associated with acid mine drainage in the Libiola Fe-Cu mine area (Ligurian Apennines, Italy). *Applied Geochemistry* **17**, 1081-1092.

Down, C. G. and Stocks, J., 1977. *Environmental Impact of Mining*. Applied Science Publishers, London. 371.

Dunster, J. and Dunster, K., 1996. *Dictionary of Natural Resource Management*. CAB International: Wallingford, U.K.

Edwards, P. J., Bolton, C. P., Ranson, C. M. and Smith, A. C., 1997. The river Pelenna minewater treatment project. In: Younger, P. L. (ed.). Minewater Treatment Using Wetlands. *Proc of a National Conf, University of Newcastle, UK*. Chartered Institution of Water and Environmental Management, London, 17-32.

Eger, P. and Lapakko, K. 1988. Nickel and copper removal from mine drainage by a natural wetland. U.S. *Bureau of Mines Circulalr 9183*. 301-309.

España, J. S., Pamo, E. L., Santofimia, E., Aduvire, O., Reyes, J. and Barettino, D., 2005. Acid mine drainage in the Iberian Pyrite Belt (Odiel river watershed, Huelva, SW Spain): Geochemistry, mineralogy and environmental implications. *Applied Geochemistry* **20,** 1320-1356.

Evangelou, R. P., 1995. *Pyrite Oxidation and its Control*. Boca Raton, Florida: CRC/Lewis Press.

Ferguson, K. D. and Erickson, P. M., 1988. Pre-mine prediction of acid mine drainage. In: Salomons, W. and Forstner, U. (ed). *Environmental Management of Solid Waste – Dredged Material and Mine Tailings*. Springer-Verlag Berlin Heidelberg.

Filipek, L. H., Nordstrom, D. K. and Ficklin, W. H., 1987. Interaction of Acid Mine Drainage with Waters and Sediments of West Squaw Creek in the West Shasta Mining District, California. *Environmental Science Technology* **4,** 388-396.

Friedman, H., 2006. Department of Earth Sciences. Geology and Environmental Geoscience, University of Bristol, UK. http://www.gly.bris.ac.uk/.../images/ pyriteP00024.jpg

Gray, N. F., 1998. Acid mine drainage composition and the implications for its impact on lotic systems. *Water Research* **32,** 2122-2134.

Hardesty, D., 2005. *Environmental Contaminants*; Status and Trends of the Nations Biological Resources, USGS Columbia Environmental Research Center. http://en.wikipedia.org/wiki/Image:Iron_hydroxide_precipitate_in_stream.jpg

Hawley, J. R., 1977. The problem of acid mine drainage in the province of Ontario. *Ontario Minist Environ*. 338.

Hedin, R. S., Watzlaf, G. R. and Nairn, R. W., 1994. Passive treatment of acid mine drainage with limestone. *Journal of Environment Quality* **23**, 1338-1345.

Hyman, D. M., Watzlaf, G. R., 1997. Metals and other components of coal mine drainage as related to aquatic life standards. In: *Proceedings of 1997 National Meeting of American Society for Surface Mining and Reclamation*, May 10-15, Austin, TX. American Society for Surface Mining and Reclamation, 531-545.

Jage, C. R., Zipper, C. E. and Noble, R., 2001. Factors Affecting Alkalinity Generation by Successive Alkalinity-Producing Systems: Regression Analysis. *Journal of Environ. Qual.* **30**, 1015-1022.

Jönsson[1], J., Jönsson, J. and Lövgren, L., 2006. Precipitation of secondary Fe(III) minerals from acid mine drainage. *Applied Geochemistry* **21**, 437-445.

Jopony, M., Tongkul, F., Atong, M., Surugau, N., Juin, E. and Gabriel, J., 2002. Assessment and Management of residual impacts of Mamut Copper Mine in Sabah, Malaysia. Paper presented at *International Conference on Environmental and Public health Management*. 12-15 March, 2002. Hong Kong.

Kalin, M., Fyson, A. and Wheeler, W. N., 2005. The Chemistry of Conventional and Alternative Treatment Systems for the Neutralization of Acid Mine Drainage. Paper presented at *the 2005 National Meeting of the American Society of Mining and Reclamation*. 19-23 June, 2005. United States of America.

Kelly, M. G., 1988. *Mining and the freshwater environment*. Elsevier, London.

Kepler, D. A., McCleary, E. C., 1994. Successive Alkalinity Producing Systems (SAPS) for the Treatment of Acidic Mine Drainage. *Proceedings of the International Land Reclamation and Mine Drainage Conf and the 3rd International Conf on the Abatement of Acidic Drainage*. Tittsburgh, P. A. **11,** 195-204.

Kim, J. Y. and Chon, H. T., 2001. Pollution of a water course impacted by acid mine drainage in the Imgok creek of the Gangreung coal field, Korea. *Applied Geochemistry* **16,** 1387-1396.

Kirby, C. S., 2006. Acid Mine Drainage Treatmet – passive or semi-passive treatment. http://www.facstaff.bucknell.edu/kirby/AMDtrmt.html

Kirby, C. S. and Cravotta III, C. A., 2005a. Net alkalinity and net acidity 1: Theoretical considerations. *Applied Geochemistry* **20,** 1920-1940.

Kirby, C. S. and Cravotta III, C. A., 2005b. Net alkalinity and net acidity 2: Practical considerations. *Applied Geochemistry* **20,** 1941-1964.

Kleinmann, R. L. P., Crerar, D. A. and Pacelli, R. R., 1981. Biogeochemistry of acid mine drainage and a method to control acid formation. *Mining Engineering* **33,** 300-303.

Kuyucak, N., Mikula, R. J., Whelland, K. G., 1991. Evaluation of improved lime neutralization process: Part 3. Interpretation of properties of lime sludge generated by different processes. *Proceedings of the Second Int. Conf. on the Abatement of Acidic Drainage*, Setember 16-18 1991, Montreal, Canada, MEND, vol. 2. Ottawa, Canada: CANMET, 31-33.

Laine, D. M., 1997. The treatment of the pumped minewater discharge at Woolley Colliery, West Yorkshire. In: Younger, P. L. (ed.). Minewater Treatment Using Wetlands. *Proceedings of* a *National Conf, University of Newcastle, UK.* Chartered Institution of Water and Environmental Management, London, 83-103.

Langmuir, D. and Whittemore, D. O., 1971. Variations in the stability of precipitated ferric oxyhydroxides. In: Hem, J.D. (ed). *Non-equilibrium systems in natural water chemistry.* American Chemical Society, Advances in Chemistry Series.

Lee, C. H., Lee, H. K. and Lee, J. C., 2001. Hydrogeochemistry of mine, surface and groundwaters from the Sanggok mine creek in the upper Chungju lake, Republic of Korea. *Environmental Geology* **40** (4-5), 482-494.

Lee, J. S. and Chon, H. T., 2006. Hydrogeochemical characteristics of acid mine drainage in the vicinity of an abandoned mine, Daduk Creek, Korea. *Journal of Geochemical Exploration* **88,** 37-40.

Lettermen, R. D. and Mitsch, W. J., 1978. Impact of mine drainage on a mountain stream in Pennsylvania. *Environmental Pollution* **17,** 53-73.

Mello, J. W. V. D., Dias, L. E., Daninel, A. M., Abrahão, W. A. P., Deschamps, E. And Schaefer, C. E. G. R., 2006. Preliminary Evaluation of Acid Mine Drainage in Minas Gerais State, Brazil. *Recebido para publicação em janeiro and Department de Solos* **30,** 365-375.

Morrison, T., 1992. *Hardrock gold: A miner's tale.* USA: University of Oklahoma Press.

Nordstrom, D. K., 1982. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. In: Kittrick, J. A., Fanning, D. S. and Hossner, L. R. (ed). *Acid sulphate weathering.* Soil Science Society of America.

Nordstrom, D. K. and Alpers, C. N., 1999. Negative pH, efflorescent mineralogy, and consequences for environmental restoration at the Iron Mountain Superfund site, California. *Proc. Natl. Acad. Sci. (PNAS)* **96,** 3455-3462.

Nordstrom, D. K., Alpers, C. N., Ptacek, C. J. and Blowes, D. W., 2000. Negative pH and extremely acidic mine waters from Iron Mountain, California. *Environ. Sci. Technol* **34,** 254-258.

Nuttall, C. A. and Younger, P. L., 1999. Reconnaissance hydrogeochemical evaluation of an abandoned Pb-Zn orefield, Nent Valley, Cumbria, UK. Proc of *the Yorkshire Geological Society* **52,** 395-405.

Ott, A. N., 1988. Dual acidity titration curves – Fingerprint, indicator of redox state, and estimator of iron and aluminum content of acid mine drainage and related waters. *US Geological Survey Water Supply Paper 2330*, 19-33.

Parsons, J. D., 1977. Effects of acid mine wastes on aquatic ecosystems. *Water Air and Soil Pollution* **7,** 333-354.

Payne, D. A., Yeates, T. E., 1970. The effects of magnesium on acidity odetermination of mine drainage. In: *Proceedings of 3rd Symposium on Coal Mine Drainage Research.* Carnegie Mellon University, Pittsburgh, PA, 200-226.

Petterson, C., Hakansson, K., Karlsson, S. and Allard, B., 1993. Metal speciation in humic surface water system polluted by acidic leachates from a mine deposit in Sweden. *Water Resources* **27,** 863-871.

Ramli, H., Yangin, J., Anselmus, W. and Birrell, J., 1994. Pollution Control and Mitigation at Mamut Copper Mine, Sabah, Malaysia. Paper presented at a *Workshop on Control of Water Pollution Caused by Mining Activities in South East Asia.* 28th March, 1994. Perkasa Hotel, Kundasang, Sabah.

Rose, A. W., Cravotta III, C. A., 1998. Geochemistry of coal-mine drainage. In: Brady, K. B. C., Smith, M. W., Schueck, J. (Eds.). *Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania*. Harrisburg, PA, Pennsylvania Department of Environmental Protection, 5600-BK-DEP2256, 1.1-1.22.

Salomons, W., 1995. Environmental impact of metals derived from mining activities: Processes, predictions, prevention. *Journal of Geochemical Exploration* **52,** 5-23.

Shin, Y. F., 2000. Mamut Copper Mine – The untold story. Paper presented at the *National Seminar on the Malaysian Mineral Industry*. 22-24 June 2000. Kota Kinabalu, Sabah, Malaysia.

Singer, P. C. and Stumm, W., 1970. Acid mine drainage : The rate-determining step. *Science* **167,** 1121-1123.

Singh., Gurdeep and Rawat, N. S., 1985. Removal of trace elements from acid mine drainage. *International Journal of Mine Water* **4** (1), 17-23.

Skousen, J. G., Rose, A. W., Geidel, G., Foreman, J., Evans, R., Hellier, W., 1998. *Handbook of Technologies for Avoidance and Remediation of Acid Mine Drainage*. National Mine Land Reclamation Center, Morgantown, WV.

Skousen, J. G., Sexstone, A. and Ziemkiewicz, P. F., 2000. Acid mine drainage control and treatment. In: Barnhisel, R. I., Darmody, R. G. and Daniels, W. L. (Ed.). *Reclamation of Drastically Disturbed Lands*. America Society of Agronomy, 131-168.

Smuda, J., Dold, B., Friese, K., Morgenstern, P. and Glaesser, W., 2007. Mineralogical and geochemical study of element mobility at the sulfide-rich Excelsior waste rock dump from the polymetallic Zn-Pb-(Ag-Bi-Cu) deposit, Cerro de Pasco, Peru. *Journal of Geochemical Exploration* **92,** 97-110.

Stromberg, B. and Banwart, S. A., 1999. Experimental study of acidity-consuming processes in mining waste rock: some influences of mineralogy and particle size. *Applied Geochemistry* **14,** 1-16.

Stumm, W. and Morgan, J. J., 1981. *Aquatic chemistry*. J. Wiley and Sons, New York.

Stumm, W. and Morgan, J. J., 1996. *Aquatic chemistry – chemical equilibria and rates in natural waters*. 3rd Ed. Wiley-International science, New York.

Sullivan, A. B. and Drever, J. I., 2001. Spatiotemporal variability in stream chemistry in a high-elevation catchment affected by mine drainage. *Journal of Hydrology* **252,** 237-250.

Sullivan, P. J. and Yelton, J. L., 1988. An evaluation of trace element release associated with acid mine drainage. *Environ. Geol. Water Sci.* **12,** 181-186.

Ulrich, M., 1999. Non-metallic carbonous minerals in the passive treatment of mining wastewater in Slovenia. *Chemicals Engineering and Processing* **38,** 249-258.

U.S. Environmental Protection Agency (U.S. EPA), 1994. *Technical document: Acid Mine Drainage Prediction (EPA530-R-94-036)*. Washington: Office of Solid Waste Special Waste.

Warhurst, A. and Noronha, L., 1999. *Environmental Policy in Mining – Corporate Strategy and Planning for Closure*. Lewis Publishers, United States of America.