# A hydrogeochemical review of riverine mine tailings deposition at Freeport Indonesia

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## ABSTRACT

This study is carried out at PT Freeport Indonesia (PTFI), one of the world's largest copper-gold mines. Due to steep terrain, high intensity rainfall and seismic activity, and after exhaustive studies, years of planning and engagement with government and other stakeholders, a controlled river tailings management system has been adopted to transport the tailings as the only feasible system. The tailings are transported to an engineered deposition area in the lowlands and coastal zones called the Modified Deposition Area (ModADA). Understanding the long-term geochemical stability of the deposited tailings is critical for tailings management. As such, the study aims to evaluate the performance of a geochemically managed discharge approach under tropical climatic conditions by studying the relationships between geomorphic setting, geochemical processes and fate of carbonate-rich sulphidic mine tailings transported via the river. The result of this study indicates that the ore-feed blending strategy applied by PTFI has achieved the objective of ensuring that there will be no or minimal acid generation resulted from tailings deposition in ModADA.

## INTRODUCTION

Riverine tailings deposition is still practiced today by mining companies in some parts of the world, particularly in areas of high rainfall, high seismic activity condition, steep terrain, and frequent natural hazards that make other tailings management options were considered unsuitable and potentially dangerous (IIED and WBCSD 2002a,b,c). Common environmental impacts may arise due to the physical transport of tailings and prolonged residence time of heavy metals in sulphidic tailings deposited within river sediments. The geochemistry of tailings may have implications for the water quality in river and aquatic life in the longer-term (Hettler et al., 1997; IIED and WBCSD, 2002d; Extractive Industries Review, 2003), hence emphasising that the long-term fate and geochemical stability of the deposited tailings is a critical and important aspect of the tailings management.

PTFI is one of the world's largest copper-gold mines and is located in the high equatorial mountains of the Indonesian province of Papua (Figure 1). The climate is alpine/sub-alpine with little seasonal variation in temperature or rainfall in the highland and tropical climate in the lowland. Annual rainfall at the mine site is about 4000 mm to 5000 mm, and in the lowland ranges between 5000 mm to 10,000 mm with humidity ranges between 65% to 100%.

The PTFI ore bodies are porphyry gold-copper deposits. Mining of the Grasberg open pit will be completed within the next six years, at which time ore production will be exclusively from underground operations. The remaining underground ore bodies will be developed between now and the end of the 'Contract of Work' in 2041. Copper ore is primarily in the form of chalcopyrite with some bornite, chalcocite and covellite. Pyrite is less abundant than copper sulphides in most ore zones. Some ore bodies in the area are hosted in copper skarns where pyrite is subordinate to copper sulphides and there is abundant carbonate mineral present.

PTFI uses a controlled river tailings management system to transport the ~225 K t/d of tailings to a designated area in the lowlands and coastal zone, called the Modified Deposition Area (ModADA). The deposition area is an engineered managed system for the deposition and control of tailings and natural sediment in the floodplain of Otomana River. This system includes lateral containment structures, or levees, of approximately 55 km in length on both sides along the deposition area. In addition to the levee construction, an equally important component of the controlled riverine tailing management system is the design of the mill feed blending at the concentrator facilities so that the final tailings have a desirable Acid Neutralising Capacity (ANC)/Maximum Potential Acidity (MPA) ratio when transported by the river. The sediment monitoring determines an additional limestone requirement to the mill feed to ensure that there is sufficient alkaline material to neutralise at least 50% more acid than the maximum amount potentially generated by the tailings.

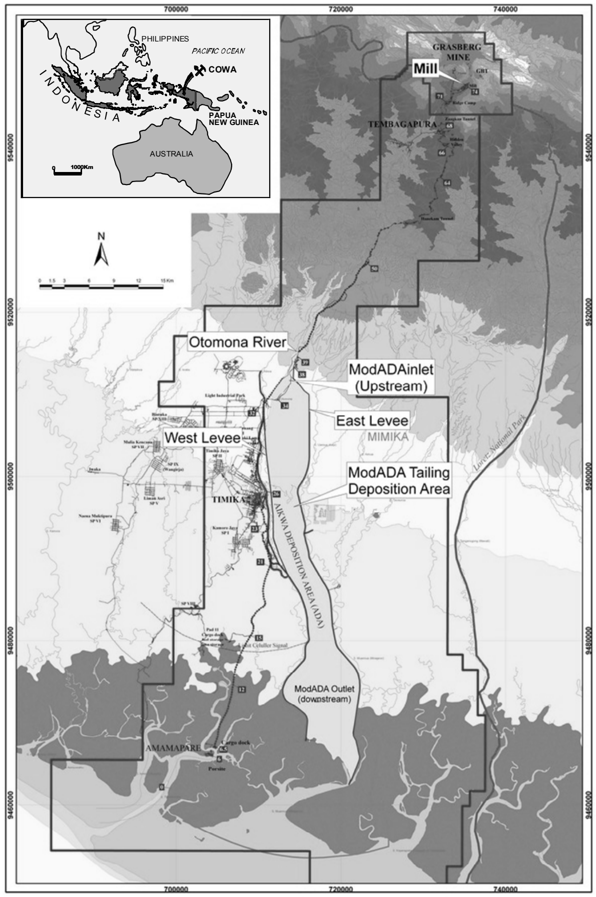


**Figure 1** Map of PTFI tailing deposition area (ModADA) at floodplain of Otomona River, Papua

PT FI tailings management includes an extensive tailing geochemical monitoring programme consists of collection of daily tailing samples from mill and at inlet and outlet points of ModADA. Approximately 800 tailing samples were collected annually along 40 transects from the North to the South of ModADA. Static and kinetic tests for tailing geochemical monitoring and investigation were carried out. The geochemical investigations of tailings using static and kinetic tests have been widely used (e.g. sulphidic mine tailings the Copperbelt Zambia (Sracek et al., 2009), tailings of the La Andina, El Teniente, and El Salvador porphyry copper deposits and Punta del Cobre belt in Chile (Dold & Fontbonte, 2001; 2002), tailings solids of the Greens Creek Mine, Juneau, Alaska (Lindsay et al., 2009), mining tailings of Black Swan Nickel Mine, Kalgoorlie, Western Australia (Lei & Watkins, 2005), and tailings collected at the concentrator at the Kidd Creek metallurgical site in Ontario, Canada (Ardau et al., 2009)). Static test is used to predict whether a tailing sample will be acid producing after exposure to weathering applied at one time of determination, while the kinetic test used repeated cycles in which dosages of humidity or aqueous solutions are applied over a period of time (Blowes et al., 2003). The kinetic tests allow the materials to react on a real time basis, therefore, this has been used as one of most common approach to refining the acid release prediction. The kinetic tests can provide information on weathering rates and the leachate water chemistry which are not obtainable from a static test (Blowes et al., 2003).

The aim of this paper is to review the performance of PTFI's tailing geochemistry management strategy. The review will provide a basis for evaluating the effectiveness of current ore-type and blends of sulphidic ore containing high carbonates, and development of an investigation plan for the potential distribution and their geochemical stability of downstream tailings under tropical climatic conditions.

## METHODOLOGY

Currently, tailings samples are collected on a daily basis at the mill and at the entrance and exit of the ModADA. Sampling transects are also conducted on a semi-annual basis across the ModADA. Approximately 400 profile tailing sampling locations have been sampled annually since 1998 along 40 transects from the north to the south of ModADA. Depth profile samples of tailings solids have been collected at each site down to a maximum depth of 500 mm.

The geochemical methods of tailing sediment analysis include pH, electrical conductivity (EC), total copper and sulphur, Maximum Potential Acidity (MPA) and Acid Neutralising Capacity (ANC) (Sobek, 1978), Net Acid Producing Potential (NAPP) and Net Acid Generation (NAG).

A series of column leach testing of tailings have been carried out during the past 18 years, each designed with specific aim to investigate the ANC/MPA ratio that will be required to ensure that tailings depositing within the ModADA remain Non Acid Forming (NAF). The study was also designed to assess the benefits of limestone addition to Potentially Acid Forming (PAF) tailings, and to investigate whether grain-size significantly changes the effectiveness of added limestone. The columns included a sample of Ajkwa sand as a control, tailings from Upper and Middle ModADA, mill tailings discharge, and pilot plant samples representing future tailings.

## RESULTS AND DISCUSSION

### Particle size distribution

The sediments sampled largely (85% to 100%) comprised of material size fraction of smaller than 0.3 μm with the remaining portion fraction between 0.3 μm to 0.6 μm (Figure 2). A natural segregation of the different particle sizes and also specific densities are observed as tailings are transported along the river from the mill to the lowlands. The coarser particles tend to settle upstream of the ModADA, whereas the finer particles remain suspended in the river.

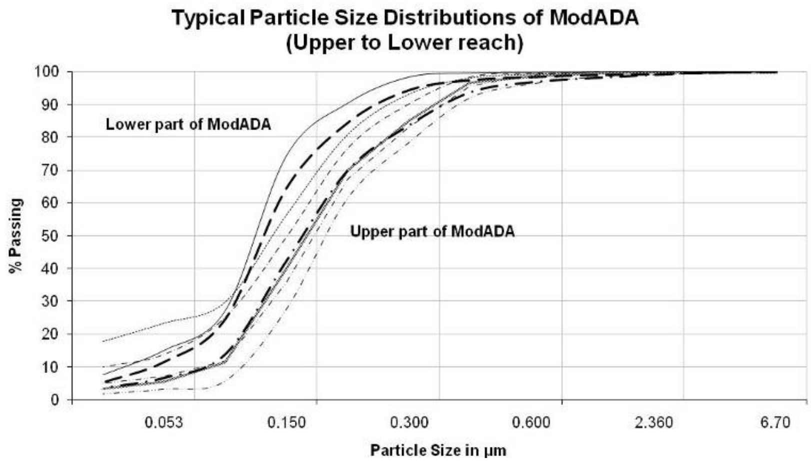


**Figure 2** Typical particle size distribution of tailings deposited in ModADA (ASTM D 421/ D 422 method)

## Mineralogy and geochemistry

The tailings from the plant on average contain 33% quartz, 19% carbonate, 13% feldspar, 7% sulphate, 7% mica, 3% iron oxide, and typically less than 5% sulphide (Cu-sulphide, Zn-sulphide, and Fe-sulphide) with the balance of other ferromagnesian minerals and clay. The sulphur content at the upper reach is generally higher than those for the rest of ModADA due to the high specific gravity of sulphides (Figure 3). Consequently, this can result in small, localised areas of tailings in the upper ModADA that are potentially acid forming, even when ModADA inlet and outlet tailings are non-acid forming. Unlike sulphur, the ANCs of suspended tailings at the ModADA outlet is comparable to the results for ModADA inlet, hence there appears to be no preferential settling of carbonate mineralogy (Figure 4). The combined effect is that ModADA outlet tailings have an ANC/MPA ratio that is higher than ModADA inlet tailings. This may imply a favourable condition for material that discharges into the estuary, but can be a concern for the sediment captured within the ModADA in that the acid potential will be slightly higher. It is important to note that although the survey shows the potential for preferential segregation in the upper ModADA, the upper ModADA also contains sufficient carbonate buffering, which prevents short term acid formation. Furthermore, the upper ModADA is a high energy reach of the river system which is regularly re-mobilised by high flows and thus unlikely to be a concern during operation.

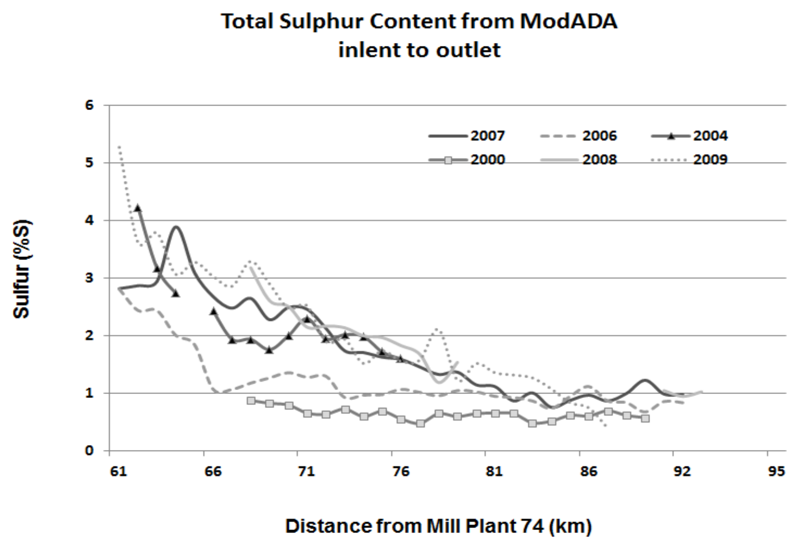


**Figure 3** Preferential deposition of the sulphur due to the high specific gravity

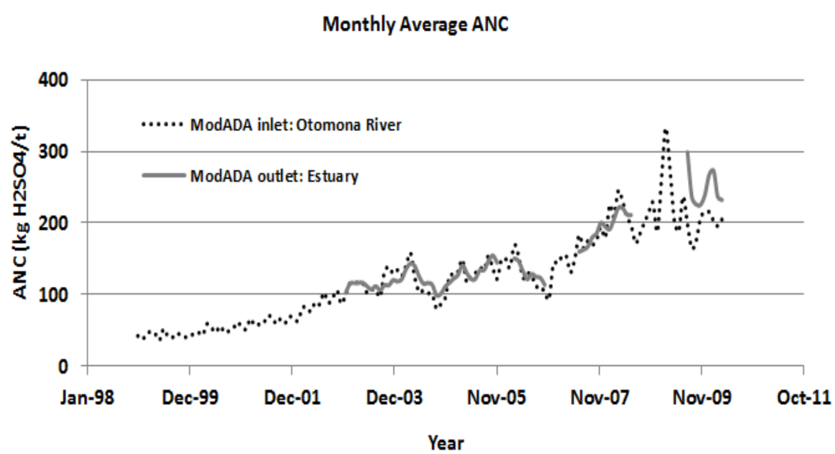


**Figure 4** Monthly ANC (carbonate) of the ModADA inlet and outlet

## Element mobility

The NAGpH trends for the mill plant station at the high land, ModADA inlet (Otomona bridge) and ModADA outlet (estuary) are presented in Figure 5. The increasing trend shows that the pH is generally alkaline, thus maintaining limited potential for release of soluble copper. Figure 6 shows an increasing ratio of Cu to sulphur from highland to estuary. The increase is associated with a slight decrease in pH from the mill down to the ModADA discharge outlets at Pandan and Kelapa lima areas primarily due to dilution along the course of tailings river.

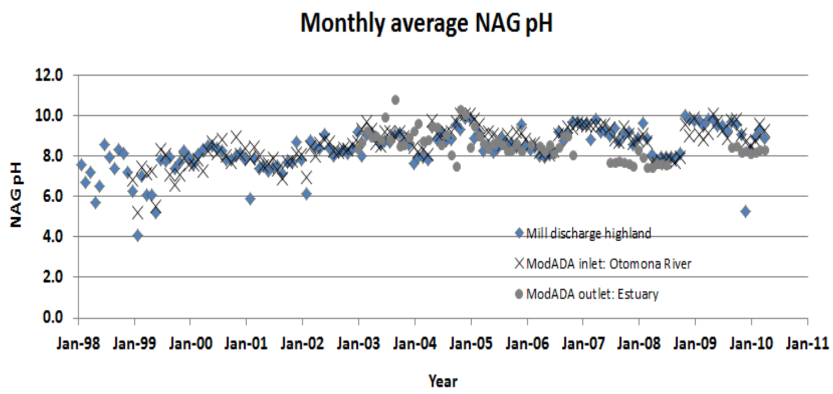


**Figure 5** Monthly average NAG pH of the ModADA inlet (Otomona River)

However, as the pH remains within alkaline range, such an increase does not significantly change the solubility of copper. The solubility of copper under alkaline conditions is low as copper will be complexed with hydroxide. Most of the copper that could potentially be released from sulphides following oxidation is likely to re-precipitate as carbonates or hydrous oxides within the tailings mass.

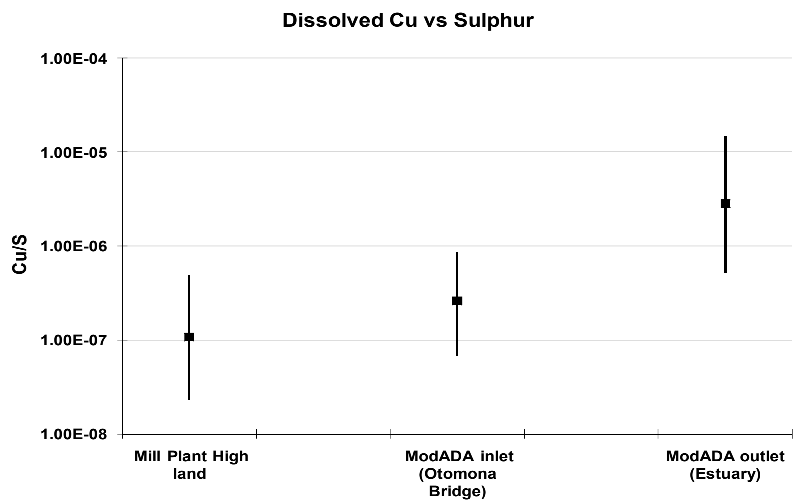


**Figure 6** Dissolved Cu/S ratios from highland to estuary

The results of the column tests have provided the understanding of the reactivity and leaching behaviour of the samples, neutralising potential and the required ANC/MPA ratio to ensure tailings depositing within the ModADA remain non-acid forming. The test also provided insight into the benefits of limestone addition to potential acid forming tailings, and to investigate whether grain-size significantly changes the effectiveness of added limestone. Limestone was amended on the Upper ModADA tailings as varying amounts of crushed limestone to produce tailings with target ANC/MPA ratios of 1.5, 2.0 and 2.5. The addition of crushed lime to experimental leach column tests has increased the ANC/MPA ratio of the Upper ModADA tailings to a minimum of 1.3 and a maximum of 2.6 (i.e., column 18 and 10 respectively). Column 24 (ex-tails sample with an

ANC/MPA value of 1.15) is the only sample (of 38 columns) to acidify within the test period of 9 years. The pH trend for this sample is presented in Figure 7 along with all other column results and shows a 3-year lag before the pH begins to decrease, reaching pH 4 after 4 years. Figure 7 also shows that all other samples have maintained circum-neutral pH throughout the test period.

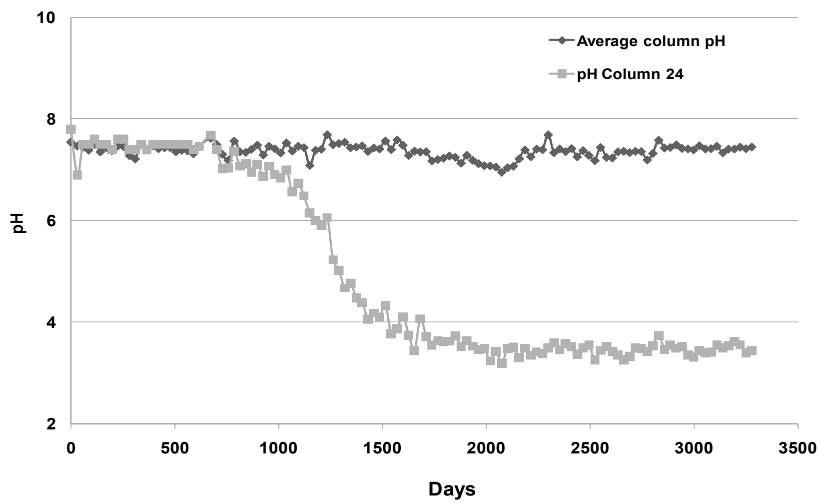


**Figure 7** pH trends for tailings column

The acid-base accounting and NAG test results indicate that all the limestone amended columns are non-acid forming (NAF). Leachate quality data confirm the NAF nature of the limestone amended tailings with leachates typically averaging a pH of around 7.0 to 8.0. Results also indicate that sulphide oxidation is occurring with average $SO_4$ concentrations of about 400 mg/l to 600 mg/l (Figure 8), and average alkalinity between 20 mg and 30 mg $CaCO_3$/l. There are no discernable differences between columns containing different limestone grinds (fine, medium and coarse), and the sulphur release trends suggest that at the current rates of oxidation and release, all sulphur would be removed before depletion of ANC, confirming that these samples are non-acid forming and will not generate ARD. However, different pyrite content in future ore bodies may potentially require adjustments in the tailing geochemistry management.

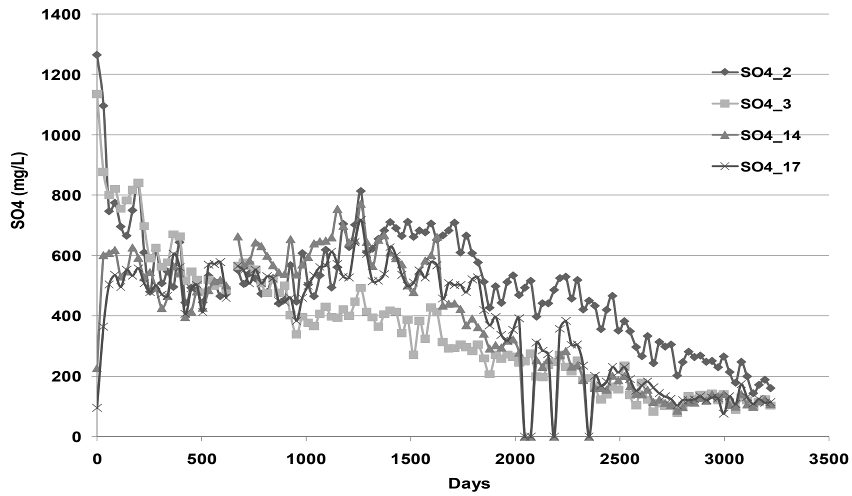


**Figure 8** $SO_4$ trends for selected columns

## CONCLUSION

The review confirms that current ore-feed blending has resulted in the tailings of almost net neutralising. Small areas with lower than target ANC/MPA ratios are observed towards the upper reach of the ModADA as a result of preferential segregation of heavier density sulphide minerals. However, most areas still contain significant ANC and would require a long period of exposure to atmospheric conditions before onset of acid conditions as indicated by the transect sampling and columns leach tests results. Underground ore containing high buffering capacity has been the primary reason that compensates for the increasing trend of sulphur and produces, almost, non-acid forming tailings. This result suggests that the ore-feed blending strategy has achieved the objective of ensuring that there will be no or minimal acid generation resulting from tailings deposition in ModADA. Consistent results were also obtained from leach columns tests which indicate that all columns amended with varying amounts of lime have maintained circum-neutral pH throughout the test period with the exception of one sample to acidify within the test period of 9 years. This indicates that current ore-feed blending with the set criteria ANC/MPA ratio of 1.5 provides an adequate factor of safety to prevent long-term generation of acid and metal leaching of the tailings deposited in ModADA. Furthermore, it is expected that given the tailings are non-acid forming and alkaline conditions prevail within the deposition area, there will be only limited potential for release of soluble copper due to oxidation of pyrite in tailings.

The increased Cu/S ratio downstream of ModADA/estuary suggests that dilution of the transported tailings along the course of the river has lowered initial tailings pH exiting the mill. This alkaline condition will be maintained by consistent implementation and evaluation of current blending strategy on current and future mine development. Model to predict future tailings geochemistry based upon the relative contributions of ore from each ore body will be updated periodically to accommodate potential changes in the mine plan and understanding. Thus, this will ensure a low level of metal solubility within the transported tailings, hence deposited tailings.

## ACKNOWLEDGEMENT

The authors would like to thank the management of Freeport Indonesia for their review and approval of an early version of this paper.

## REFERENCES

**Ardau, C., Blowes, D.W. & Ptacek, C.J.** (2009) 'Comparison of laboratory testing protocols to field observations of the weathering of sulfide-bearing mine tailings', *Journal of Geochemical Exploration*, vol. 100, pp. 182–191

**Blowes, D.W., Ptacek, C.J., Jambor, J.L., Weisener, C.G., Heinrich, D.H. & Karl, K.T.** (2003) 'The Geochemistry of Acid Mine Drainage', *Treatise on Geochemistry*, Oxford, Pergamon.

**Dold, B. & Fontbonte, L.** (2001) 'Element Cycling and secondary mineralogy in porphyry copper tailings as a function of climate, primary mineralogy, and mineral processing', *Journal of Geochemical Exploration*, vol. 74, pp. 3-55, 74, 53.

**Dold, B. & Fontbote, L.** (2002) 'A mineralogical and geochemical study of element mobility in sulphide mine tailings of Fe oxide Cu-Au deposits from the Punta del Cobre belt, northern Chile', *Chemical Geology*, vol. 189, pp. 135-163.

**Extractive Industries Review** (2003) 'Striking a better balance', *Vol.I. The World Bank Group and Extractive Industries*, pp. 31, 36.

**Hettler, J., Irion, G. & Lehmann, J.** (1997) 'Environmental impact of mining waste disposal on a tropical lowland river system: a case study on the Ok Tedi Mine, Papua New Guinea', *Mineralium Deposita,* vol. 32, pp. 280-291.

**International Institute for Environment and Development** (IIED) and World Business Council for Sustainable Development (WBCSD) (2002a) Mining for the future, Appendix H: Ok Tedi Riverine Disposal Case Study, International Institute for Environment and Development, pp. H-7-H-8.

**International Institute for Environment and Development** (IIED) and World Business Council for Sustainable Development (WBCSD) (2002b) Mining for the future Appendix I: Porgera Riverine Disposal Case Study, International Institute for Environment and Development, pp. I-6 – I-8.

**International Institute for Environment and Development** (IIED) and World Business Council for Sustainable Development (WBCSD) (2002c) Mining for the future Appendix J: Grasberg Riverine Disposal Case Study, International Institute for Environment and Development, J-5 – J-7.

**International Institute for Environment and Development** (IIED) and World Business Council for Sustainable Development (WBCSD) (2002d) 'Breaking new ground: the report of the mining, minerals, and sustainable development project', *Earthscan*, pp. 242-243.

**Lei, L. and Watkins, R.** (2005) 'Acid drainage reassessment of mining tailings, Black Swan Nickel Mine, Kalgoorlie, Western Australia', *Applied Geochemistry*, vol. 20, pp. 661–667.

**Lindsay, M.B.J., Condon, P.D., Jambor, J.L., Lear, K.G., Blowes, D.W. & Ptacek, C.J** (2009) 'Mineralogical, geochemical and microbial investigation of a sulfide-rich tailings deposit characterized by neutral drainage', *Applied Geochemistry*, vol. 24(12), pp. 2212-2221.

**Sobek, A.A., Schuller, W.A., Freeman, J.R. & Smith, R.M**. (1978a) *Field and laboratory methods applicable to overburden and minesoils*, EPA 600/2-78-054, Environmental Protection Agency, Washington, D.C.