Management of Pyrrhotite Tailings at Savannah Nickel Mine: A decade of Experience and Learning

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ABSTRACT

Savannah Nickel Mine is an underground mine located in the Kimberley region of Western Australia and is owned and operated by Panoramic Resources Limited (Panoramic). The open cut mine commenced in 2005 and rapidly progressed to an underground operation. Tailings generated from processing ore are stored at an above-ground valley fill Tailings Storage Facility (TSF). The initial mine approval was based upon a number of studies, which incorporated preliminary geochemical data, and included a requirement to tranfer the tailings from the TSF to the open cut void at the end of mine life. Recent exploration success has demonstrated that the open cut void has insufficient storage capacity to store the volume of tailings predicted to be generated over the life of mine.

Over the past decade, a substantial body of geochemical and mineralogical information has demonstrated that the geochemical behaviour of the tailings in the TSF is much more benign than initially predicted. Despite containing almost 30% pyrrhotite, the tailings generate only a fraction of the acidity predicted by classical static geochemical test techniques, and the rate of acidity generation is more than compensated by the inherent non-carbonate acid neutralizing capacity available from specific silicate minerals within the tailings matrix. These studies have shown that leaving the tailings in situ at mine closure and using a cover system will produce a sustainable environmental outcome, and the mine operator has recently received regulatory approval to increase the storage capacity of the TSF and implement this closure strategy.

The mine operator now has a very good understanding of the geochemistry of the tailings, although geochemical, mineralogical and a broad range of other related studies are continuing, moving towards mine closure.

Keywords: Tailings, Pyrrhotite, Geochemistry, Mineralogy, Mine Closure

INTRODUCTION

In order for mining companies to obtain approval and finance for mining and mineral processing projects, a broad range of technical studies need to be completed, including the geochemical and mineralogical assessment of mine waste materials. These studies should commence during exploration and ultimately continue throughout the various phases of the life of the operation through to closure. Successful completion of these studies can lead to the development and implementation of appropriate environmental management strategies, which can significantly reduce the risk of the development of Acid Rock Drainage (ARD) and Metal Leaching (ML).

Acquisition of timely geochemical and mineralogical information on the characteristics of waste materials can be used to develop innovative design solutions, limit the potential for environmental impacts, and promote sustainable closure (Miller, 2014). During the mine planning and regulatory approvals stage, there may be a limited amount of information available on the long-term geochemical behaviour of waste materials. This can lead to the development of impractical mine waste management solutions and prescriptive approval conditions, which may not result in the best environmental outcome. Some flexibility should remain during the mine operational phase to improve mine waste management strategies, based on additional knowledge and experience gained during the mine life.

Geochemical and Mineralogical Studies

Whilst technical guidelines for the geochemical and mineralogical assessment of mine and mineral process waste materials have been developed in Australia (DITR, 2007) and internationally (INAP, 2009), it is important to consider the individual characteristics of sites and waste material types when selecting the best test methods to use. Classical geochemical characterisation techniques can sometimes produce inconclusive and unexpected results. In such cases, further study using more specialised geochemical and mineralogical tests can be warranted, particularly where some uncertainty remains over the long-term geochemical behaviour of waste materials.

The information acquired from geochemical and mineralogical tests on mine waste materials can assist with predicting the level of environmental risk and potential impacts. However, due to scale-up and other factors such as the heterogeneity of the mine waste materials and the redox conditions experienced by mine waste materials in the field, simplistic direct comparison of leachate chemistry with existing water quality guidelines should be treated with caution. Where uncertainty exists, modelling is often used to assess the complex behaviour of mine waste materials and potential impacts from mine waste storage facilities (Mayer *et al*., 2003).

Focus of Paper

This paper presents a case study from Savannah Nickel Mine located in the Kimberley region of Western Australia, which illustrates the benefits of ongoing geochemical and mineralogical characterisation and assessment studies on mine tailings materials throughout mine life and in planning for closure. These studies form an integral part of broader operational and closure planning studies completed for the site Tailings Storage Facility (TSF), such as geotechnical stability, cover design, geomorphology, solute transport modelling, ecotoxicology and ecological assessment of downstream aquatic fauna.

Classical geochemical classification techniques completed at the mine planning stage of the project produced results that were not replicated in the field and led to regulatory conditions of consent, which not produce the most effective long-term environmental outcome at the site. Geochemical, mineralogical and other related studies completed over the past ten years show that leaving the tailings *in situ* at mine closure and using a store and release cover system will produce a more sustainable environmental outcome. Whilst some researchers have had some success with reactive alkaline cover systems, the use of such a cover system is not required st this site (Quispe *et al*., 2013) The mine operator has now received regulatory approval to increase the capacity of the TSF and implement this closure strategy.

CASE STUDY

Project Background

Savannah Nickel Mine is owned by Panoramic Resources Limited (Panoramic) and is located in a semi-arid to sub-tropical part of Australia with an average annual rainfall of approximately 557 mm (ranges from 280 to 1,310 mm) and an average annual evaporation of approximately 3,200 mm. Most rainfall occurs in the hot summer months between December and March.

Commencing in 2005 as an open pit operation, the mine is now an underground operation, and tailings are currently disposed of as a cement-based backfill underground or stored at an above-ground valley fill TSF. The original mine approval required the mine operator to remove the tailings from the TSF back into the underground workings and open pit at the end of mine life. Approximately six million tonnes of tailings had been placed at the TSF by the end of 2014.

Additional mineral resources were identified at the project resulting in an extension of the mine life and a requirement for additional capacity to accommodate additional tailings generated from mineral processing. In 2007, Panoramic began assessing options for the long-term management of tailings at the operation to match revised life of mine ore reserve estimates. The preferred option was to increase the capacity of the TSF in a series of embankment raises and leave the tailings *in situ* at mine closure before covering with a suitable cover system. The high evaporation to rainfall rate at the site (over 5:1) essentially precludes the use of a permanent water cover system for the tailings.

Geochemical information presented in the original approvals documentation (Notice of Intent) in 2002 predicted that the tailings would be Potentially Acid Forming (PAF) and could pose a significant long-term risk to the environment from potential seepage of ARD and ML. However in 2008, an independent peer review found that removing tailings from the TSF and returning them to the open pit was unlikely to produce the best environmental outcome at closure. A broad range of technical studies were recommended to assess the tailings at the TSF and the merits of vairous mine closure options. These studies included geochemistry, mineralogy, surface water and groundwater hydrology, cover design, geomorphology, solute transport modelling, ecotoxicology and ecological assessment of downstream aquatic fauna. A network of surface and groundwater monitoring infrastructure was already in place at the site.

The additional technical studies outlined above were commissioned in 2008 and completed in 2013, and included consultation with relevant stakeholders, including State Government agencies. Site visits and risk workshops were held to communicate the ongoing findings of the technical studies and demonstrate a transparent process for seeking approval for the preferred operational and post-closure tailings storage option. In 2013, Panoramic received approval from the WA State Government to increase the capacity of the existing TSF and implement the preferred long-term tailings storage option at closure. Panoramic has continued to fund long-term geochemical and mineralogical studies on tailings, and some of the latest findings are included in this paper.

RESULTS AND DISCUSSION

Tailings Characteristics

Geochemical studies completed on a simulated tailings sample in 2002 concluded that pyrite was present as the main sulfide species and classified the tailings as PAF. Subsequent geochemical and mineralogical studies completed over the past ten years have found that 'actual' tailings generated at the project and deposited in the TSF contain pyrrhotite rather than pyrite and react in a very different way to that originally assumed in 2002. Whilst the 'actual' tailings are still classified as PAF using static geochemical classification methods, the bulk tailings continue to generate very little acidity, and contain sufficient neutralising capacity to produce circumneutral pH leachate with excess alkalinity and low metal concentrations (Robertson *et al*, 2012). At the TSF surface, the tailings form a trafficable hardpan surface about 3 cm thick and the oxidation front has not progressed below the hardpan layer. Below the surface hardpan, the tailings remain relatively fresh/unoxidised and do not generate acid conditions after a storage period of up to ten years (Robertson *et al.*, 2012) as evidenced by:

- The visual appearance of the tailings at the TSF,
- *In situ* geochemical and mineralogical data for tailings in and below the hardpan surface;
- The findings of a "tailings-at-depth" geochemical assessment down to 20m;
- Water quality seepage data at the downstream Water Storage Facility;
- Groundwater monitoring data downstream of the TSF; and
- Geochemical and mineralogical studies completed over the past ten years.

Water quality monitoring downstream of the TSF indicates that seepage water is typically pH-neutral, with excess alkalinity and elevated conductivity, mostly attributable to dissolved sulfate, calcium and magnesium, whereas the concentration of dissolved iron is low. The elevated sulfate is attributable to a number of factors including the oxidation of near-surface tailings stored in the TSF (*i.e.* hardpan formation) and recycling of sulfate rich water from dewatering of the water storage facility seepage and underground workings at the mine.

Geochemical and mineralogical studies of *in situ* bulk tailings at the TSF demonstrate that below the hardpan surface, bulk tailings remain pH neutral (due to the neutralizing capacity of magnesium silicates) are slightly brackish, and containing low concentrations of trace metals suggesting limited oxygen diffusion into the bulk tailing material (possibly through a combination of surface hardpan formation, elevated tailings saturation levels, and maintenance of reducing/anoxic conditions at depth in the TSF). The results of ongoing kinetic leach column (KLC) studies on tailings over the past seven year mirror these findings. A key finding is that under anoxic conditions, the tailings pore water contains very low concentrations of soluble reduced iron and sulfate sulfur species indicating limited potential for any latent acidity in TSF seepage. However, this does not entirely explain the geochemical behaviour of the *in situ* bulk tailing materials at the TSF. A significant amount of elemental sulfur was also found to be present in both the bulk tailings at depth and the oxidised hardpan, which suggests that alternative pyrrhotite reaction mechanisms are occurring in the bulk tailings.

Tailings Hardpan

The relatively benign geochemical nature of the tailings solids at the TSF is unusual as this material can contain up to 30 wt. % pyrrhotite. A review of the available literature over the past 15 years suggests that pyrrhotite is less well studied that pyrite, but is commonly associated with nickel sulfide deposits (Schippers *et al.*, 2007, Heikkinen and Räisänen, 2008; Robertson *et al.*, 2012).

The rate of pyrrhotite oxidation slows when a hardpan layer is present on tailings under both dry and saturated cover conditions (Gilbert *et al*., 2003). McGregor and Blowes (2002) suggested that a TSF hardpan layer could act as a hydraulic and diffusive barrier against the migration of rainfall infiltration and oxygen. The authors presented a case study for uncovered pyrrhotite tailings at a TSF in Canada (Fault Lake), and highlighted that the hardpan layer had grown to 20 cm and the oxidation front had migrated only an additional 18 cm after 25 years of exposure to atmospheric conditions. Further numerical simulations of the Fault Lake tailings concluded that, over a time period of 1,000 years, only the top three metres of tailings would become oxidised (Romano *et al.*, 2006), which aligns with earlier tailing modelling work which indicated that the overall rate of oxidation of the near surface tailings was eventually controlled by the diffusion of oxygen into the tailings mass rather than by the reaction kinetics in the tailing (Elberling *et al.*, 1994). No information on water quality was presented in either of these references. These references illustrate the characteristics of a tailings surface hardpan and clarify the expected rate of progression of the oxidation front into the bulk tailings material over time.

At Savannah Nickel Mine TSF, the tailings form a surface hardpan, which also appears to limit oxygen diffusion or at least maintain a high level of saturation in the bulk tailings and generally retains the bulk tailings in a mostly reducing/anoxic environment. This has been confirmed by recent work completed on the tailings (Schumann *et al*, 2015), which indicates a slow and comparable rate of progression of the hardpan layer and oxidation front into the tailings (1cm per year if tailings are maintained above 75 % saturation). Another attribute of the tailings is that they contain significant amounts of potentially acid-neutralising gangue silicate minerals (*e.g*. enstatite), which can provide both short- and long-term neutralisation of acid generated through pyrrhotite oxidation (Ciccarelli *et al*, 2008).

Soil-atmosphere modelling results associated with the proposed final cover design for the TSF prepared by O'Kane Consultants demonstrate that a saturation level of 75 % in the tailings below the cover material is likely at depths of 5m or greater below the tailing-cover interface (Panoramic, 2012). At shallower depths in the tailings profile, a reduced level of saturation is expected, although at a depth of 1 m, a saturation level in the range 62 to 68% is still likely. This modelling takes no account of the surface hardpan maintaining higher levels of saturation in the bulk tailings. Hence the predicted level of saturation, together with the surface hardpan, will serve to significantly slow the pyrrhotite oxidation rate at the TSF to a rate that is likely to be matched by the silicate dissolution rate within the bulk tailings.

Reaction Pathways

In order to explain the relatively benign nature of the project tailings, the reaction mechanisms of pyrrhotite should be considered. The dissolution behaviour of pyrrhotite is less studied than that of pyrite; however a number of studies from both laboratory and field investigations have been published (*e.g.* Nicholson and Scharer, 1994; Thomas *et al*., 1998, 2000; and Belize *et al*., 2004). Pyrrhotite can follow a number of reaction pathways that can be acid forming or non-acid forming (Thomas *et al*., 2001). The non-acid forming reaction pathway involves the generation of goethite and elemental sulfur. Another potential pathway for pyrrhotite oxidation is where iron is converted to goethite and in this situation sulfur is fully oxidised to produce sulfuric acid. The two main reaction pathways which are considered to potentially operate within the tailings are provided below.

<u>**Reaction Pathway 1**</u>

$$Fe_{(1-x)}S + 3(1-x)/4O_2 + (1-x)/2H_2O \rightarrow (1-x)FeOOH + S^0 \qquad [1]$$

Pyrrhotite + Oxygen + Water → Goethite + Elemental Sulfur

<u>**Reaction Pathway 2**</u>

$$Fe_{(1-x}\ S + 3(3-x)/4O_2 + (3-x)/2H_2O \rightarrow (1-x)FeOOH + H_2SO_4 \qquad [2]$$

Pyrrhotite + Oxygen + Water → Goethite + Sulfuric Acid

Both acid forming and non-acid forming reactions could be occurring in the tailings at the TSF. However, the KLC test results, "tailings at depth" assessment, and seepage and groundwater quality observations downstream of the TSF suggest that, although pyrrhotite may be acid generating to some extent in the hardpan tailing material, it is generally non-acid forming or acid neutral in the bulk tailing material. The presence of elemental sulfur in the bulk tailings hardpan and at depth, and the lack of oxygen below the tailing hardpan surface (dissolved oxygen was measured in the tailing porewater during a drilling and sampling program at the TSF) suggests that a non-acid forming pathway is likely to be favoured. It is noted that no reduced sulfur species (such as sulfite) were found in the bulk tailings pore water at depth and iron concentrations were very low suggesting that the potential for latent acidity to occur in seepage from the TSF is low.

Any acid generated according to an acid generating reaction pathway in the tailings is likely to be neutralised by alkalinity from residual lime from the tailings and/or from mineral dissolution reactions. Recent mineralogical assessment work has established that the tailings contain enstatite, a magnesium silicate with a dissolution rate comparable to the measured oxidation rate of pyrrhotite in near saturated tailings and which provides a source of alkalinity at a rate comparable to the acid generation rate from pyrrhotite oxidation. This results in pH neutral drainage with excess alkalinity and low levels of dissolved metals as well as elevated salinity from sulfate, calcium and magnesium. These results are consistent with observations reported in the literature regarding other pyrrhotite-bearing tailings wastes (Schumann *et al.*, 2015).

KLC Tests

Long-term KLC tests have been operated for bulk (25 kg) tailings samples from the project over the past seven years to investigate the likely quality of seepage from tailings stored at the TSF. When operated under anoxic, saturated conditions the leachate chemistry closely resembles that of groundwater monitoring data for seepage from the TSF (*i.e.* pH neutral, excess alkalinity and low concentrations of trace metals). The KLC data has been used in other study components (*e.g.* post-closure TSF seepage modelling and potential groundwater impacts), to facilitate prediction of the likely quality of any long-term TSF seepage and potential for environmental impact.

More recently, three KLC tests have been established to determine the oxidative dissolution behaviour of pyrrhotite in the tailings as a function of water content and in the absence of additional alkalinity inputs (**Figure 1**). The three KLC tests have been operated with average levels of saturation of 50 %, 75 % and 100 % to investigate what geochemical processes are likely to occur in the tailings stored in the TSF in the post-operational period, during which saturation levels and alkalinity inputs may be less than those which currently occur during operations.

The tailings used in the more recent KLC tests were fully characterised prior to commencement of the tests. The pyrrhotite content of the tailings is around 29 wt. %, and no pyrite was found. The tailings contain no carbonate minerals, but contain magnesium silicates such as enstatite and anthophyllite, which are likely to provide some neutralising capacity. After eighteen months "weathering" of the tailings under KLC test conditions, the following conclusions can be drawn:

For fully saturated conditions –

- Leachates from the column are pH neutral with no acidity;
- Leachates are composed essentially of calcium and sulfate with most metals being non-detectable;
- There is little evidence of pyrrhotite oxidation (approximately 6 % estimated oxidation);
- The main geochemical process occurring in the tailings under fully saturated conditions is dissolution of gypsum which is present in the tailings as a precipitated phase when the tailings are deposited in the TSF.

At 75 % saturation –

- Leachate pH dropped to around pH 4.5 after eighteen months with low levels of acidity;
- Leachates are composed essentially of calcium, magnesium and sulfate with low levels of metals;
- Around 15 % of the pyrrhotite in the tailings has undergone oxidative dissolution;
- The main geochemical processes occurring in the tailings at approximately 75 % saturation are oxidative dissolution of pyrrhotite to produce goethite and elemental sulfur as the major reaction (64 %) and goethite and sulfate as the minor reaction pathway (36 %). Less than 2 % of the oxidised sulfur is leached from the column as soluble sulfate; the majority of sulfate remaining within the tailings as partially soluble sulfates (e.g. gypsum, epsomite, melanterite) or less soluble salts such as jarosite or schwertmannite. Dissolution of magnesium silicates (enstatite and anthopyllite) is also occurring.

Figure 1 KLC test setup.

At 50 % saturation –

- Leachate pH dropped to around pH 4 after eighteen months with acidity around 10 times higher than that in leachate from the tailings weathered at 75% saturation;
- Leachates are composed essentially of magnesium, iron, calcium and sulfate with the concentrations of other metals being low;
- Around 57 % of the pyrrhotite in the tailings has undergone oxidative dissolution over the 18 months of leaching;
- The main geochemical process occurring in the tailings at approximately 50 % saturation are essentially the same as those occurring at 75 % saturation, except that the rates are increased in the tailings with lower water content.

These results confirm that even under unsaturated conditions, the dominant reaction pathway for pyrrhotite oxidative dissolution in tailings produces elemental sulfur which, in the absence of further oxidation, is a non-acid producing reaction (Robertson *et al*, 2012). Of the pyrrhotite, which is fully oxidised to sulfate, the majority appears to precipitate as poorly soluble sulfate salts which contain stored acidity. This stored acidity in compounds such as jarosite is likely to redissolve at a sufficiently slow rate such that dissolution of magnesium silicates in the tailings will match that of acid production eliminating or greatly reducing acidity.

The low amount of acidity generated during weathering of the tailings can clearly be seen from the data shown in **Table 1**. Even under conditions of 50% saturation where nearly 60% of the pyrrhotite in the tailings has oxidised, the acidity measured in leachate is only 0.2% of the expected acidity based on ABA analysis. Therefore it is likely that even if fully saturated conditions cannot be maintained post operation, oxidation of pyrrhotite will result in a significantly reduced acidity load than is predicted by classical static geochemical tests.

Table 1 Measured versus expected acidity during eighteen months of tailings KLC testing

Saturation (%)	Amount pyrrhotite oxidised (%)	Expected acidity[A] (kg H_2SO_4/t)	Measured acidity (kg H_2SO_4/t)	Measured acidity as a percentage of expected acidity
50	57	145	0.34	0.23
75	16	41	0.039	0.10
100	6	15	0.035	0.23

A. Expected acidity calculated by multiplying the measured net acid producing potential (NAPP) (255 kg H_2SO_4/t) by the percentage of pyrrhotite oxidised.

The results of these KLC tests also demonstrate that there is an inverse correlation between the moisture content of the tailings and the rate of pyrrhotite oxidation, indicative of oxygen diffusion as the rate controlling process. These results suggest that at saturation levels likely to occur in the TSF following closure, the oxidation rate of pyrrhotite is likely to be sufficiently slow to be matched by the dissolution rate of magnesium silicates in these tailings resulting in pH neutral or low acidity leachate. Further testing is continuing to verify whether this situation is maintained.

CONCLUSIONS

A case study has been used to illustrate the complexity of the geochemical and mineralogical processes associated with tailings material at a nickel mining operation in Australia. Whilst detailed and targeted geochemical studies in the early stages of mine feasibility and planning can provide important information of the characteristics of mine waste materials, this paper illustrates that ongoing study and flexibility are required throughout the life of mine to ensure that the most appropriate operational and closure options are developed and implemented for tailings storage.

The results of this case study indicate that there is now a very good understanding of the geochemistry and mineralogy of tailings material at the mining operation based on a number of studies by recognised experts and peer reviews, where field evidence at the TSF matches predicted geochemical behaviour over time. The downward movement of the surface hardpan and oxidation front into the bulk tailings at the TSF is very slow and predicted to remain so even without a cover system in place. The final cover design for the TSF predicts a high level of saturation in the bulk tailings below the cover material, but does not take into account the positive effects of the surface hardpan on maintaining the elevated tailings saturation level. Mineralogical and kinetic geochemical studies show that the rate of pyrrhotite oxidation and acid generation in the tailings is likely to be matched by the magnesium silicate dissolution rate. At the TSF, this results in pH neutral drainage with excess alkalinity and low levels of dissolved metals as well as elevated salinity from sulfate, calcium and magnesium. Further testing is continuing to confirm that this situation is maintained in the longer term.

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