Acid mine drainage investigations at the Reddale Coal Mine, Reefton, New Zealand

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Abstract

The Reddale Coal Mine, near Reefton, commenced operations in early 2012. Acid-base accounting techniques applied to drillcore combined with assumptions carried forward from mining similar lithologies in other areas (where acid neutralisation capacity (ANC) is assumed to be 0 kg H₂SO₄/t equivalent) resulted in what proved to be an overly conservative waste rock management strategy that assumed the site would produce acid mine drainage (AMD) immediately. This has not occurred. The lack of ANC data meant that, prior to mining, the time lag to acid onset derived from ANC was not identified. After 12 months of operation the drainage waters remain near neutral and, as a result, the water treatment plant has yet to be used, even after the removal of 494,000 tonnes of BCM overburden.

15mm (19kg CaCO₃/m²) of aglime (AP < 2.5mm CaCO₃) was applied to each 4m lift of the Ferndale engineered landform (ELF) such that the overall NAPP of the overburden within the ELF was 19.4 kg H₂SO₄/t. This indicates that the site may eventually produce AMD, in the absence of neutralising materials. Subsequent, geotechnical assessment of the ELF demonstrated that the permeability of the dump on the uncompacted tipheads was 1 x 10⁻⁶.6 m/s, whilst on the traffic-compacted lifts it was 1 x 10⁻⁷.1 to 1 x 10⁻⁸.0 m/s, sufficient to retard significant oxygen ingress into the dump core and thus limit pyrite oxidation and AMD generation rates. Oxygen probes confirmed that only the outer 4-8m of the ELF is oxidising.

Paste pH testing of waste rock on the surface of the ELF indicated significant pyrite oxidation, acid generation, and a decreasing pH with time as would be expected throughout a zone where oxygen is freely available. Within the ELF pH values > 6 are still being recorded indicating a zone of slower oxidation kinetics and neutralisation of acidity associated with unreacted carbonates. Although the geochemistry of the ELF will provide a time lag to acid onset, it is likely that the geotechnical properties of the ELF will extend this time lag significantly.

Keywords: Acid mine drainage, acid base accounting, geochemistry, geotechnical.

Introduction

Acid mine drainage (AMD) is the result of sulfide mineral oxidation, typically pyrite in coal measures, where the pyrite reacts with oxygen and water during the mining process to produce acidity and metal precipitates such as Fe oxyhydroxides (Equation 1). This can lead to depressed pH (< pH 3) in streams impacted by acid mine drainage. The acidity generated by pyrite oxidation can be neutralised by materials such as limestone (CaCO₃) as shown in Equation 2.

\[
\begin{align*}
\text{FeS}_2(s) + 7/2\text{H}_2\text{O} + 15/4\text{O}_2 & \rightarrow \text{Fe(OH)}_3 + 2\text{H}_2\text{SO}_4 \quad (1) \\
2\text{CaCO}_3(s) + 2\text{H}_2\text{SO}_4 & \rightarrow 2\text{Ca}^{2+} + 2\text{H}_2\text{O} + 2\text{CO}_2(g) + 2\text{SO}_4^{2-} \quad (2)
\end{align*}
\]

Rocks can contain both pyrite and carbonate minerals, which means that although pyrite may be present, if the carbonate content is sufficient and readily available, depressed pH (< 3) may not occur. At the Stockton coal mine, near Westport, South Island, New Zealand, the Brunner
Coal Measures (BCM) are often deficient in carbonate minerals such that the oxidation of pyrite typically leads to the formation of AMD.

To obtain regulatory consent for a mining project to proceed there is a requirement for geochemical characterisation of the overburden potential to produce AMD or circum-neutral drainage enriched in metals. If overburden characterisation identifies the potential for AMD at a project during development work, this triggers a cascade of prevention, minimisation, treatment and the scoping of works to manage the associated risks, including detailed overburden characterisation, overburden scheduling and AMD-prevention engineering strategies (to minimise pyrite oxidation). In addition, AMD treatment system evaluation and design, as well as a final closure plan to minimise any long-term liability associated with the effects of AMD on the local ecosystem may be required.

Geochemical characterisation of waste rock overburden involves a variety of acid-base accounting (ABA) techniques. The industry standard approach is to determine the net acid production potential (NAPP) of the sample. This is the difference between the acid neutralisation capacity (ANC), which typically represents carbonates (Equation 2), and can be determined by titration methods (expressed in kg H$_2$SO$_4$/t equivalent), and the maximum potential acidity (MPA) where $\text{MPA} = \text{wt}\% \text{total S} \times 30.6$ (in kg H$_2$SO$_4$/t equivalent): note this is a conservative approach as it assumes that the total sulphur determination is present as pyrite. The 30.6 factor is determined by the stoichiometry and molar mass of components in Equation 1. A negative NAPP indicates that the sample has a net neutralising capacity and a positive NAPP indicates the sample has a net acid-generating capacity:

$$\text{NAPP} = \text{MPA} – \text{ANC}$$

Previously the mine owner, Solid Energy New Zealand Ltd, has assumed that the BCM at Stockton Coal Mine has an ANC of 0 kg H$_2$SO$_4$/t based on results for 131 BCM samples that indicates the mean ANC is 1.7 kg H$_2$SO$_4$/t (Weber et al., 2006a). This is a conservative approach and was seen as suitably cautious. For several years this was universally applied to new projects, without additional quantification. However, recent work at the proposed Escarpment mine, on the Denniston plateau, about 10 km south of Stockton coal mine has indicated that the BCM can contain higher ANC values up to 12 kg H$_2$SO$_4$/t (Pope et al., 2011). It has been shown that this level of ANC can provide a time lag to acid onset (AMD) for rocks classified as NAPP positive, which has implications for the timing, and expense, of AMD management (Weber et al., 2006b). For example, if the potentially acid forming (PAF) overburden is eventually going to be flooded by a water cover to prevent AMD, then any time lag to acid onset may mean that a treatment system may not be required as long as saturation occurs before significant AMD develops.

An acceptable approach to managing incorrect geochemical classification of mine waste rock is to use comparative testing of samples to determine both the NAPP acidity and the net acid generation (NAG) acidity of the sample (e.g. IWRI and EGi, 2002) to provide two methods to assess whether the sample is PAF or NAF (non-acid forming). The NAG analysis method also provides a robust basis for data interrogation and validation, as well as a schematic classification which makes it simple to identify anomalous samples and potential errors.

A number of other tests are commonly used for AMD geochemical characterisation, including paste pH, column leach tests, humidity cell trials, and a variety of field trials (from kilogram scale to thousands of tonnes) to help confirm classification processes. These tests can
determine the time lag to acid onset for rocks that have sufficient acid neutralisation capacity (ANC) to neutralise the acidity generated by pyrite oxidation (or other acid generating sulphide minerals) in the short term but insufficient capacity to neutralise all the acidity generated by pyrite oxidation in the long term (e.g. Miller et al., 1997; IWRI and EGi, 2002; Weber et al., 2006b).

Part of the management plan for AMD minimisation at Reddale Coal Mine was the construction of the Ferndale ELF that contains the overburden in 4m lifts. ELF construction using lifts reduces chimney effects, which are prevalent in overburden disposal areas that utilise end tipping (where the end tip > 4-6 metres). Significant chimney effects develop in tipheads (> 4-6m) when the coarse and fine materials separate producing coarse grained layers (chimneys) for oxygen ingress and fine grained layers for water ingress with a high permeability rubble layer at the dump base (e.g. Fala et al., 2003; Wilson, 2008). Furthermore, to provide initial acid buffering capacity, and mitigate the initial effects of AMD every 4m lift had 15mm (19kg/m²) of aglime (AP < 2.5mm limestone) applied to prevent the onset of acid mine drainage. An application rate of 19kg/m² equates to 2.5kg of aglime per tonne (or ~ 2.5 kg CaCO₃/tonne) (based on a cubic metre density of 1.9).

The overall financial viability of the mining project relies on accurate forecasting of the quantity and duration of acid mine drainage because this impacts the net present value (NPV) of the project. Over estimation of the severity of AMD may prevent projects from starting due to high capex and opex costs for treatment; underestimation may result in unanticipated AMD management costs and legacy issues for the project. It is important that the correct estimation is provided so that mining companies can design and approve engineered landforms and treatment systems with greater confidence that will be acceptable and approved by regulators.

The time lag to acid onset in full scale dumps is dependent on complex scale-up factors that include dump construction (e.g. end tipping, end tip height, paddock dumping), hydrologic processes (e.g. saturated dumps and the effects of unsaturated flow), oxygen diffusion into the dump (influenced by waste rock dump permeability, geometry, and thermal regime), temperature (e.g. climate), mineral weathering rates (which are a function of the above and grainsize of the waste rock), and microbial activity. Most of these factors are not considered in laboratory based trials and researchers are looking at scale-up of lab results to large scale field trials to evaluate the expected diminishment in acid loads at site.

A significant amount of work has been conducted at the Grasberg mine, Indonesia into scale-up of laboratory tests to operational waste rock dumps (Miller et al., 2003; Andrina et al., 2012). Geochemical results for lab columns, 500 tonne field trials (where oxygen would be freely available) and full scale trial dumps (480m x 80m x 20m high) demonstrate that columns and 500 tonne field trials are comparable producing, for that site, 50-65 kg of sulfate per tonne, whereas the trial dump generated only 3-8 kg of sulfate per tonne (Andrina et al., 2012). The calculated intrinsic oxidation rate for the waste rock was an order of magnitude lower in the trial dump compared to the 500 tonne trial and the lab columns (Andrina et al., 2012). Thus site specific physical factors need to be considered to determine the time lag to acid onset in full scale waste rock structures.

A number of monitoring systems are used to understand the physical factors affecting the geochemical processes in the field, including lysimeters and leachate monitoring of field trials; monitoring of oxygen concentrations; and temperature (e.g. Ritchie, 1994; Miller et al.,
2003; Andrina et al., 2012). Our paper uses these diverse datasets to understand the physical factors that are contributing to much slower geochemical reactions in the field.

Materials and methods

Site description

The Reddale Coal Mine is located approximately 1.5 km north east of Reefton within the Brunner Coal Measures (BCM) that is associated with the Reefton Coalfield and is overlain in the area by recent alluvial gravels. The mine commenced operations in early January 2012. Current plans are that 1.3 million bank cubic metres of overburden (920,000 m³ of BCM; 364,000 m³ of alluvial gravels) will be excavated over the current planned mine life (3 years) within a total disturbance area of 29.1 ha.

Sampling

Two drillholes were used to assess the acid generating potential of rock from the Reddale Coal Mine (Drillholes 662 and 663) and were drilled in April 2005 prior to mining. A total of 36 samples were gathered from these drillholes for ABA testing (Table 1). These samples were used to characterise the site and develop the AMD management strategy. Another 6 samples were obtained from drillholes DH697, DH699, and DH703, ~325 – 800 m from the Reddale Coal Mine and are considered representative of the area and were obtained in early 2012 after mining at Reddale Coal Mine had started. Two alluvial gravel samples were also tested.

During the first six months of mining a further 50 samples were obtained from the active tip-head of the Ferndale ELF to validate the ABA data and develop a greater understanding of the AMD potential in the ELF. Grab samples were obtained from the outer ELF surface on a regular basis.

Paste pH

Paste pH testing (e.g. IWRI and EGi, 2002) was conducted to determine the pH of the samples after the addition of water. The method adopted for paste pH involved mixing the sample with water at a solid to water ratio of 1:2 (50g: 100ml) with the pH measured on the slurry after 5 minutes.

Acid base accounting techniques

The ANC test conducted as part of this work is based on the methodology of IWRI and EGi (2002). ANC was not conducted as part of the pre-mining investigations for samples obtained from Drillholes 662 and 663. Total sulfur was determined by LECO analysis (Crock et al., 1999) whereby the sample is combusted in an O² atmosphere at 1370°C (V₂O₅ catalyst) to oxidize sulfide and SO₄ to SO₂ and then the S content is measure by a calibrated solid state infrared detector. Forms of sulfur were determined by method AS 1038.11-1993. Sulfate sulfur was determined directly as a sulfate in a hydrochloric acid extract of the sample; pyritic sulfur is calculated from the determination of iron soluble in nitric acid following removal of non-pyritic iron by hydrochloric acid; and organic S is determined by difference. MPA was determined by calculation as discussed (Equation 3) based on either total S or pyritic S (which is discussed).
The NAG test used and reported here was refined by IWRI and EGi (2002) and is based on earlier similar procedures. This test involves the addition of 250 ml 15 vol.\% (unstabilised) hydrogen peroxide (with a measured pH of 4.5) to 2.5 g of pulverised sample (< 75 \mu m), to encourage the rapid oxidation of reactive sulfides.

**Column leach testing**

Two column leach tests were undertaken on samples derived from the drill core composites using the methodology developed by IWRI and EGi (2002). Testing commenced 6 months after drilling was completed and operated for 2 years starting in December 2005 and finishing in December 2007. 1.5 kg of BCM material (MPA = 32 kg H₂SO₄/t; ANC not determined) and 1.5 kg of alluvial gravels (ANC = 1 kg H₂SO₄/t; MPA = 12 kg H₂SO₄/t; NAPP = 11 kg H₂SO₄/t) were assessed.

Other columns were set up using the six samples that were obtained from the Burkes Creek Expansion project from drillholes DH697, DH699, and DH703, ~325 - 800 m from the Reddale Coal Mine as the most suitable unweathered representative samples to rerun column leach tests. These columns started within 1 month of drilling and operated for three months.

**Oxygen probes**

Oxygen probes were installed in the Ferndale ELF upon completion of every second 4 m lift of overburden. The 30 m long, 0.5 m wide trenches were constructed perpendicular from the ELF face. At intervals of 4, 8, 15, 20, and 30 m along the trench, a 0.5 m³ sample collection pit (~0.5 m x 1.6 m x 0.6 m deep) was excavated below the base of the trench. These sample pits were backfilled with large (> 40 mm) rounded gravels and the oxygen probe terminus was within this chamber. The trench was then backfilled and track rolled to compact. A Teledyne Analytical Instruments portable oxygen analyser with built in vacuum pump was used to extract pore water samples from the five sample collection pits.

The pump was run for up to two minutes to purge the conduit before a stable oxygen content was reported by the meter. Between measurements, the oxygen meter was re-calibrated to an atmospheric oxygen content of 20.6%.

**Lysimeters**

Lysimeters were installed in trenches that ran parallel to the oxygen probes but were separated by 5 m. Two lysimeters were installed in every second lift at a distance of 10 and 15 m into the ELF. Sample collection from lysimeters is gravity driven. The lysimeters consisted of three components; a leachate collection drum, a conduit and a sample collection bucket.

**Falling head permeability**

Four falling head permeability tests were carried out on the Ferndale ELF to determine the permeability of different materials under different compaction conditions. Two tests were completed on a machine compacted bench (dozer and dump truck). One test was done on uncompacted overburden which had been pushed up into a windrow. One test was done on compacted gravels. Permeability testing involved driving a 1.7 m long, 300 mm diameter cylinder made of 6 mm steel 300 mm into the material using a digger bucket. The PAF columns were then completely filled with water (~ 1.4 m head) and left to saturate the underlying material overnight. The following day the columns were topped up and the
permeability test was started, with daily water level recordings made over several days. The gravel columns drained almost immediately so water level recordings were made over a 90 second period to determine permeability.

**Monitoring of the Ferndale ELF**

Thirty random representative samples were collected from the Ferndale ELF on 4 separate occasions 1-4 months apart. Sufficient sample was obtained to undertake a paste pH test at a ratio 1 part rock to 2 parts water. Paste pH can provide an indication of the amount of sulfide oxidation in a sample and the presence of any subsequent highly soluble stored acidic salts. The method adopted for paste pH involved mixing the sample with water at a solid to water ratio of 1:2 (50g : 100ml) with the pH measured on the slurry after 5 minutes.

**Results and discussion**

The ABA results presented (Figure 1) indicate that the majority of samples, are PAF as determined by NAG testing. For the samples obtained from Drillholes 662 and 663 no ANC was measured so NAPP data is biased towards PAF or Uncertain classification. Even a small amount of ANC can result in a time lag to onset of acidity for PAF samples and this can be predicted from NAG pH versus paste pH testing (Weber et al., 2006b). Figure 2 indicates that the majority of samples obtained from early drillhole samples at Reddale Coal Mine will have a time lag to acid onset.

![Figure 1. NAPP versus NAG pH Plot. NAPP in kg H₂SO₄/t equivalent. DH 662 and 663 ABA data obtained prior to mining and NAPP is based on the assumption that ANC = 0 kg H₂SO₄/t equivalent. Column data was obtained from nearby drill holes and NAPP includes ANC for these samples. There is a good correlation except for the three samples circled, due to there being no ANC data being considered for these samples in the NAPP calculation.](image)

To confirm the new expected geochemical trend (Figure 2) a total of fifty representative grab samples were collected from the Ferndale ELF during the placement of the overburden and were assessed for ABA characteristics. Results indicated that a small quantity of ANC was present in both overlying gravels that became the base of the Ferndale ELF ($\bar{X} = 4.2$ kg H₂SO₄/t equivalent) and for the BCM PAF rock ($\bar{X} = 5.9$ kg H₂SO₄/t equivalent), indicating there is more ANC available in the PAF BCM than the alluvial gravels.

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Sulfur speciation work indicated that the majority of the S was present as pyrite in both the alluvial gravels and the PAF BCM overburden. However, the results indicated that the non-acid forming organic S fraction is significant, reducing the MPA determination for the BCM PAF overburden from a mean of 33.3 kg H$_2$SO$_4$/t equivalent (based on total S) to a mean of 27.8 kg H$_2$SO$_4$/t equivalent (based on pyritic S). All of the 20 samples tested for NAG pH data and paste pH data indicates they would fall into the lag PAF category.

**Summary of ABA interpretation**

Neither ANC nor sulfur speciation was considered during the pre-mining ABA characterisation of the Reddale mine site. The mean ANC for the PAF BCM is 5.9 kg H$_2$SO$_4$/t equivalent and MPA calculated from total S is 5.5 kgH$_2$SO$_4$/t higher than the MPA calculated from pyritic S. If the NAPP was calculated for this tiphead dataset using only MPA based on total S (and assuming ANC = 0 kg H$_2$SO$_4$/t equivalent) then the NAPP would be 33.3 kg H$_2$SO$_4$/t equivalent for the BCM. Taking into account ANC and using MPA based on pyritic S indicates the more correct NAPP is 21.9 kg H$_2$SO$_4$/t equivalent. The conservatisms associated with assuming ANC = 0 kg H$_2$SO$_4$/t equivalent for BCM and using total S rather than pyritic S at Reddale alters the acid base accounting balance by about a third and are therefore very significant.

**Column leach test results**

Two columns were established in December 2005 and were operated for 2 years finishing in December 2007, however the columns were not started until 6 months after drilling and the core was not stored appropriately enabling oxidation processes to occur prior to testing. Acidity and pH results indicated low pH and elevated acidity from the first month and no time lag to acid onset could be determined. In total, 8.8 kg H$_2$SO$_4$/tonne equivalent acidity was leached from the BCM column over the 2 years of operation. The column BCM rock sample had a measured MPA (based on total S) of 32 kg H$_2$SO$_4$/t acidity thus more than a third of the acid load had leached from the remaining sulfides after two years confirming the potential for significant acid mine drainage from the BCM at Reddale.

In total 0.01 kg H$_2$SO$_4$/t equivalent acidity was leached from the alluvial gravels, which is negligible. However, leachate from the alluvial gravels column had near neutral pH and it is
likely substantial alkalinity could have been leached from the gravels over the two years of testing, which would help offset any AMD formation. Alas the alkalinity was not quantified in these lab trials.

To understand whether any time lag to acid onset is possible for rocks obtained from the Reddale site, a number of fresh drill core samples (<1 month old) from the nearby Burkes Creek site were tested by column leach testing. The samples tested have ANC from 3.7 to 13.7 kg H$_2$SO$_4$/tonne equivalent and have paste pH values greater than 6. This indicates that there would be a time lag to acid onset based on the NAG pH – paste pH classification process. In addition compared to earlier columns there is a time lag to acid onset in these column leach tests.

Oxygen probe monitoring

Oxygen probe monitoring was carried out monthly (Figure 3) and shows the oxygen content data collected from the two sets of oxygen probes. This data demonstrates that the oxygen content in pore space gas in the dump decreases rapidly from 20.6% (atmospheric) outside the dump to less than 5% at depths greater than 8 m into the dump. The oxygen content of the outer 8 m skin varies between 1 and 9%. The higher oxygen content readings were recorded in the initial monitoring periods, 3 to 44 days after oxygen probe installation. This suggests that initially atmospheric oxygen penetrates the dump to a depth of up to 8 m. After 44 days the oxygen content of the 4 m probes became similar to that of the deeper probes. Over the preceding 44 days, additional material was dumped over the oxygen probes and compacted by heavy vehicle traffic, resulting in a reduction in permeability of overlying material. Following this compaction and stabilisation period, the reactive skin of the dump thins to less than 4 m.

![Figure 3: Ferndale ELF Oxygen content at RL 248 and 256. Data from obtained from 4-5-12 to 24-1-13.](image-url)
Lysimeters

Leachate water samples did not report through the lysimeters until the 24th January 2013. The low permeability of overlying material limits percolation through the dump, delaying capture of any drainage. Only a few samples were obtained. Results indicated that pH remains near neutral (pH 6.6) at 10m horizontally into the ELF. This is beyond the limit of significant oxygen ingress and indicates the core of the ELF is not producing significant acidity.

Permeability

The four permeability tests were carried out from the 6th to the 14th November 2011. Results indicated the permeability of the heavy vehicle compacted PAF (10^-7.1 – 10^-8.0 m.s^-1) was significantly lower than the permeability of the un-compacted PAF rocks (10^-6.6 m.s^-1). Thus, vehicle compaction of the PAF materials decreases permeability by an order of magnitude.

Paste pH monitoring

The outer surface of the ELF was sampled four times over a period of 9 months and tested for paste pH. A clear trend is identified of decreasing paste pH from 5.2 (6 months after mining started) to 3.0 demonstrating that the outer surface of the dump is becoming more acidic with time and producing acid runoff (Figure 4).

![Figure 4. Paste pH values from the Ferndale ELD surface.](image)

pH has been monitored on a daily basis at a monitoring location downstream of the Reddale Coal Mine site within Burkes Creek. Results indicate the pH has remained fairly consistent, and is comparable to pre-mining conditions of pH ~ 6-7. It may therefore be concluded the onset of significant depressed pH associated with significant AMD has not eventuated, as predicted by the pre-mining geochemistry analysis.

Conclusions

At this site, the assumption that the Brunner Coal Measures do not have significant ANC is incorrect. As shown here at Reddale there may be sufficient ANC (~5.9 kg H2SO4/t equivalent) to provide a time lag to acid onset. Omission of this ANC is conservative and conservatism can lead to over-engineering and greater project costs. Similarly, use of total S
for MPA determinations of the Brunner Coal Measures is conservative and MPA can be significantly lower if pyritic S is used. At Reddale the use of pyritic S reduces MPA by ~5.5 kg H\textsubscript{2}SO\textsubscript{4}/t equivalent compared to using total S content for the MPA calculation. Thus, original ABA data suggested that acid potential could be ~ 33.3 kg H\textsubscript{2}SO\textsubscript{4}/t equivalent, whereas the inclusion of ANC and MPA based on pyritic S results in a NAPP of 21.9 kg H\textsubscript{2}SO\textsubscript{4}/t equivalent; close to a 30% decrease in acid potential. Approximately 2.5 kg CaCO\textsubscript{3}/tonne has been added to each 4m lift within the Ferndale ELF thereby increasing the total ANC within the dump to ~8.4 kg CaCO\textsubscript{3}/tonne. This will further contribute to acid neutralisation within the dump and again extend the time lag to acid onset.

The significant oxygen gradient to < 5wt% oxygen within the first 4-8m indicates that diffusion is the dominant gas transport mechanism. Paste pH results of the ELF surface indicate that significant acid generation is occurring on the surface of the ELF where oxygen is freely available; yet at depth, 10m into the ELF, near neutral drainage is still being observed.

The work presented here indicates that the Ferndale ELF can be divided into two geochemical zones, an outer oxidising skin where oxygen is freely available (>5%) and where the dominant sulfide oxidation reactions are occurring, producing significant acidity; and an inner core that has reduced oxygen content (< 5%) and sulfide oxidation rates are much lower and percolation remains near neutral. It should be noted that the oxidising skin model proposed here is specific to the site. In some waste rock dumps this oxidising skin may encompass the whole dump (Ritchie, 1994).

The ABA testing indicated that there is likely to be a general delay to significant AMD onset due to inherent ANC of the PAF overburden, combined with the application of aglime to the ELF. In conjunction with reduced oxygen ingress there is likely to be a greater delay to significant AMD generation. In retrospect, the upfront installation of a Ca(OH)\textsubscript{2} water treatment plant was thus unnecessary and a better option could have been the design of a low cost passive treatment system.

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