

Long-term geochemistry prediction and implications for closure of the Doornpoort tailings storage facility, South Deep Gold Mine, South Africa

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Abstract

Long-term predictions of tailings geochemistry are of fundamental importance when developing closure plans. SLR developed a long-term prediction strategy for the Doornpoort (DPT) tailings storage facility (TSF) at the South Deep Gold Mine. Mineral scaling was identified in the underdrainage network of the DPT TSF which could result in the drainage system becoming non-operational over time. A comprehensive geochemical characterisation of the fresh and mature DPT tailings materials, assessment of all related water chemistries and a kinetic humidity cell (HC) study were developed to understand the scaling mechanisms and predict the geochemical behaviour after closure to inform engineered solutions.

Earlier geochemical studies and SLR's acid-base accounting results predicted the tailings materials to be potentially acid generating. Operational drainage waters, conversely, display variable pH values and supersaturation with carbonate minerals (calcite and aragonite). The same dominant mineral phases are found in the underdrainage scale. A 20-week HC experiment undertaken on composite tailings and plant slurry samples reported initial acidic values for the most recent tailings deposited in the TSF, increasing to circumneutral ranges. However, the youngest sample generated an acidic leachate over the last three weeks of the experiment. The plant slurry sample produced leachate with the highest sustained total alkalinity during the first weeks of leaching compared to the youngest tailings sample, which produced the lowest alkalinity. This difference in alkalinity was not reflected in the samples' mineralogy. Therefore, short-term alkalinity is likely being introduced to the system by the underground ore beneficiation process.

The carbonate molar ratios indicate that, except for the plant slurry sample, the DPT tailings materials' neutralisation potential will not be sufficient to neutralise the acidity produced by pyrite oxidation over time. However, the study has shown that aluminosilicate minerals provide secondary neutralisation capacity in the interim, with acid-generating conditions expected to dominate after closure.

Keywords: *mineral scaling, underdrainage network operation, kinetic humidity cell experiment, geochemical behaviour prediction, engineered closure solutions*

1 Introduction

Scaling has been identified within the Doornpoort (DPT) tailings storage facility (TSF) underdrainage network at South Deep Gold Mine (SDGM). The concern is that potential blockages within the underdrainage pipes, toe and blanket underdrains could cause the TSF drainage system to become non-operational. This, in turn, may create a raised phreatic surface within the body of the tailings and future instability issues. The blockages within the underdrainage network would require that elevated drains (and/or other measures) be installed within the body of the tailings to increase drainage and manage the phreatic surface.

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The DPT TSF is the main waste repository for SDGM and has been operating since 2012. Phase 1 storage ran up to June/July 2022, followed by the construction and completion of Phase 2 for tailings deposition from June/July 2022 to the present. The tailings reporting to the DPT TSF are mainly sourced from underground ore but since 2015 they have been mixed with reclaimed tailings from the old TSF complex. Although previous geochemical investigations undertaken on the Old TSF 1 and 2 and the DPT TSF surface and subsurface tailings materials by Metago Environmental Engineer (2008) and Golder Associates (2020) predicted the DPT tailings materials to be potentially acid generating (PAG), seepage water from the DPT TSF is alkaline and scaling/calcification is occurring in some of the underdrainage pipes and filter underdrains.

2 Methodology

2.1 Sampling

The SLR geotechnical team conducted the DPT tailings sampling between Q3 2023 and Q1 2024. Core samples were collected from various depths and at various locations across the TSF. Grab samples were collected at the surface of the TSF, and fresh slurry samples were collected directly from the processing plant. Selected discrete tailing samples were constituted into composites that represent fresh slurry mix, youngest to oldest tailings, according to depth horizons (Table 1).

Table 1 Doornpoort tailings and slurry material composites

Composite ID	Materials	Sample ID	Depth of sample (m)	Proportion of composite (%)
DPT-Top Comp 1 (young tailings)	Tailings	DTPA-1TC	0.5	25
		DTPB-1TC	0.5	25
		DTPC-1TC	0.5	25
		DTPF-1TC	0.5	25
DPT-Middle Comp 2 (mature tailings)	Tailings	DBHF3-1/S1	2.00-2.55	25
		DBHB3-1/S2	6.00-6.55	25
		DBHE3-1/S2	7.00-7.55	25
DPT-Bottom Comp 3 (old tailings)	Tailings	DBHD3-1/S3	9.00-9.55	25
		DBHA1-1/S3	10.95-11.50	25
		DBHF1-2/S3	13.50-14.05	25
		DBHB1-1/S5	17.50-19.00	25
DPT-Concentrator plant Comp 4 (fresh slurry)	Plant slurry	24-1370	Underground ore	61
		24-1369	Reclaimed tails	39

2.2 Laboratory testing

The DPT materials underwent the following comprehensive geochemical analysis:

- pre- and post-humidity cell (HC) X-ray diffraction (XRD) mineralogy
- pre- and post-HC acid-base accounting (ABA), paste pH and total sulphur

- 20-week kinetic HC testing
- weekly leach analysis of pH, electronic conductivity, total dissolved salts, total alkalinity and major ions
- inductively coupled plasma mass spectrometry and optical emission spectroscopy analysis of >40 metals.

3 Results and discussion

3.1 X-ray diffraction mineralogy

The main mineralogical composition of the DPT tailings composites prior to and post the 20-week kinetic leaching procedure is summarised in Table 2.

Table 2 Mineralogy of Doornpoort (DPT) tailings composite samples (pre- and post-) humidity cell leaching

Mineral	Formula	DPT-Top Comp 1	DPT-Middle Comp 2	DPT-Bottom Comp 3	DPT-CP Comp 4
Quartz	SiO ₂	87.39 (90.62)	89.55 (91.92)	74.05 (87.69)	84.68 (89.16)
Pyrite	FeS ₂	1.84 (0.96)	1.45 (0.75)	0.93 (0.86)	1.72 (1.21)
Clinocllore	(Mg,Fe) ₅ Al(AlSi ₃ O ₁₀)(OH) ₈	3.17 (3.27)	2.79 (2.59)	5.06 (6.26)	3.10 (3.60)
Pyrophyllite	Al(Si ₂ O ₅)(OH)	1.48 (3.10)	1.25 (2.87)	2.37 (1.47)	3.23 (3.01)
Muscovite	KAl ₂ ((OH) ₂ AlSi ₃ O ₁₀)	3.94 (2.05)	3.52 (1.87)	6.73 (1.80)	6.70 (3.02)
Gypsum	Ca(SO ₄)(H ₂ O) ₂	1.19	0.85	0.78	0.58
Dolomite	CaMg(CO ₃) ₂	0.21	0.30	1.09	–
Calcite	CaCO ₃	0.79	0.29	0.33	–
Plagioclase	(Na,Ca)(Si,Al) ₄ O ₈	–	–	1.82 (1.92)	–
Microcline	KAlSi ₃ O ₈	–	–	1.28	–
Monticellite	CaMgSiO ₄	–	–	0.24	–
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	–	–	4.46	–
Smectite	CaMg ₂ AlSi ₄ (OH) ₂ ·H ₂ O	–	–	0.88	–

After 20 weeks of leaching, the fast-reacting carbonate and sulphate minerals (calcite/dolomite and gypsum) were depleted, resulting in any remaining neutralising potential (NP) shifting to the slower-weathering aluminosilicate minerals (chlorite, pyrophyllite and plagioclase). The pyrite proportions decreased by 39% on average, however, relatively elevated proportions remained (>0.3%), suggesting that the DPT tailings materials' acid potential (AP) could overwhelm any long-term aluminosilicate neutralisation potential.

3.2 Acid-based accounting

The pre-HC paste pH values (Table 3) recorded circumneutral values of between 6.70 and 7.53 for DPT tailings composite samples. On the other hand, the post-HC paste pH displayed acidic to circumneutral values of between 4.74 and 6.71.

The neutralisation potential ratio values for all the DPT composite samples, pre- and post-HC, recorded values <1, indicating that they are all PAG. This is attributed to the elevated total sulphide (>0.3) and greater AP versus NP values.

Table 3 Doornpoort (DPT) tailings storage facility composite acid-base accounting pre- and post-humidity cell testing

Sample	Paste (pH)	Total S (%)	Sulphide acid potential (kg/t CaCO ₃)	Neutralisation potential (kg/t CaCO ₃)	Neutralisation potential ratio	Net neutralisation potential (kg/t CaCO ₃)	Classification
Non-potential acid generating (PAG)	>6	<0.3			>2	>20	
Intermediate					1–2	–20 to 20	
PAG/AG	<6	>0.3			<1	<20	
Pre-humidity cell testing							
DPT-Top Comp 1	6.70	1.18	53.60	2.42	0.05	–61.18	PAG
DPT-Middle Comp 2	7.53	1.19	37.97	4.61	0.12	–33.36	PAG
DPT-Bottom Comp 3	7.15	0.93	29.14	6.70	0.23	–22.44	PAG
DPT-CP Comp 4	7.40	1.25	39.06	4.21	0.11	–34.85	PAG
Post-humidity cell testing							
DPT-Top Comp 1	4.74	1.28	40.00	0.05	0.001	–39.50	AG
DPT-Middle Comp 2	5.03	1.43	44.69	1.77	0.04	–42.92	AG
DPT-Bottom Comp 3	5.98	0.89	27.88	4.30	0.15	–23.58	AG
DPT-CP Comp 4	6.71	1.18	36.88	1.77	0.05	–35.21	PAG

Similarly, all samples pre- and post-HC returned NNP values in the PAG range <20, reinforcing their status as PAG materials. The overall lower paste pH in all the post-HC tailings samples (<6) infers that the DPT tailings will display long-term acid-generating (AG) potential.

When comparing the DPT pre- and post-HC ABA results, the 20-week leaching resulted in all composite samples displaying a general reduction in total sulphur but a shift to a majority sulphide percentage due to the dissolution of gypsum. At the same time, the paste pH decreased to circumneutral to acidic values. These results were expected as the XRD results showed that the larger concentration of AG pyrite would consume the potential short-term neutralising capacity from the carbonate minerals. These findings infer that the DPT tailings material will, over time, become AG.

3.3 Humidity cell experiment

Kinetic testing has been undertaken using HC over 20 weeks. Composite samples were selected to improve the understanding of potential acid generation and neutralisation availability in the DPT tailings. Kinetic testing is used to evaluate the reaction rates and depletion times for minerals that are present within the tailings waste following the approaches laid out in Table. The key aspect relates to (a) understanding the presence and availability of NP detected in the static ABA analyses, (b) the pH buffering afforded by the minerals and (c) assessment of the metal leaching rates.

The last three weeks of kinetic testing have been averaged and used to demonstrate the final sequence of parameters in relation to their leachate generation. In circumstances where Simpson's paradox might have applied ("averaging averages"), the last data point was adopted as representative.

Table 4 Approaches to the interpretation of kinetic results (Price 2009)

Humidity cell interpretations
<p><u>Acid generation</u></p> <p>Sulphate production rate (mg/kg/week) = sulphate (mg/L) × mass of extraction fluid recovered/1,000</p> <p><u>Neutralisation potential (NP) molar ratios</u></p> <p>Carbonate molar ratio = [(Ca (mg/L)/40.08) + (Mg (mg/L)/24.31)]/(SO₄ (mg/L)/96.06)</p> <p>Feldspar molar ratio (FMR) = [(Ca (mg/L)/40.08) + (K (mg/L)/2*39.1) + Na (mg/L)/(2*22.99)]/(SO₄(mg/L)/96.06)</p> <p><u>Acid neutralisation and NP consumption</u></p> <p>Carbonate ratio NP consumption (mg CaCO₃/kg/wk) = carbon molar ratio (CMR) × theoretical NP consumption (mg/kg/week):</p> <p>$2H^+ + SO_4^{2-} + (Ca_zMg_{1-z})CO_3 \rightarrow zCa^{2+} + (1-z)Mg^{2+} + SO_4^{2-} + H_2CO_3^0$ or</p> <p>$2H^+ + SO_4^{2-} + 2(Ca_zMg_{1-z})CO_3 \rightarrow 2zCa^{2+} + (2-2z)Mg^{2+} + SO_4^{2-} + 2HCO_3^-$</p> <p><u>Theoretical NP consumption at pH6 (mg CaCO₃/kg/wk)</u></p> <p>Sulphate production rate (mg SO₄/kg/wk) x100.09/96.06:</p> <p>$2H^+ + SO_4^{2-} + CaCO_3 \rightarrow Ca^{2+} + SO_4^{2-} + H_2CO_3^0$</p> <p><u>Remaining NP (% of original)</u></p> <p>{[Initial NP (t CaCO₃/1,000 t) – (cumulative NP depletion rate (mg/kg)/1,000)]/initial NP (t/1,000 t)} × 100</p> <p><u>Feldspar molar ratio NP consumption (mg CaCO₃/kg/wk)</u></p> <p>FMR*theoretical NP consumption (mg/kg/week) based on:</p> <p>$2H^+ + SO_4^{2-} + H_2O + CaAl_2Si_2O_8 \rightarrow Ca^{2+} + SO_4^{2-} + 2Al(OH)_3 + 2H_4SiO_4$</p> <p>$2H^+ + SO_4^{2-} + H_2O + 2KA_{12}Si_2O_8 \rightarrow 2K^+ + SO_4^{2-} + 2Al(OH)_3 + 4H_4SiO_4$</p> <p>$2H^+ + SO_4^{2-} + H_2O + 2NaAl_2Si_2O_8 \rightarrow 2Na^+ + SO_4^{2-} + 2Al(OH)_3 + 4H_4SiO_4$</p>

3.3.1 Assessment of pH and alkalinity leaching

The temporal trends for leachate pH and alkalinity for the DPT tailings composite samples are plotted in Figures 1 and 2.

The Comp 1 (young) and Comp 2 (mature) samples exhibited first flush acidic pH values of 2.63 and 3.04, respectively, increasing to a circumneutral range (>6) by week four of leaching. Over the remaining weeks of leaching, the pH fluctuated within the circumneutral range except for Comp 1, where pH decreased to acidic values in the last three weeks of leaching (<6). Comp 3 (old) and CP Comp 4 (fresh slurry) reported relatively stable circumneutral pH values throughout the leach experiment (6.47–7.65), with an overall trend to decreasing pH at the end of the 20-week leaching experiment.

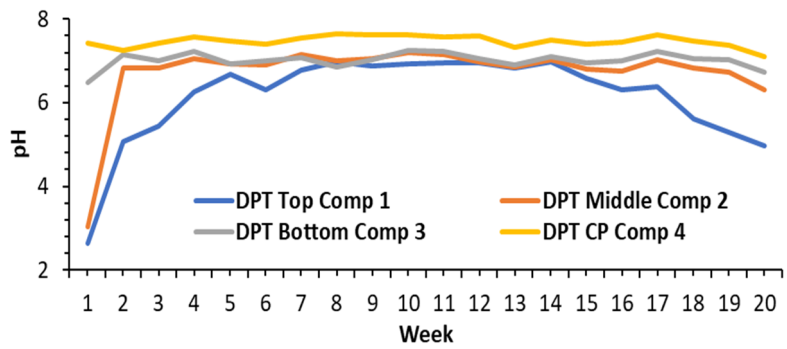


Figure 1 pH profile for Doornpoort tailings composite samples over a 20-week leaching experiment

The results of the alkalinity leaching rate assessment indicate that the Comp 4 plant slurry sample produced the most alkalinity (111 mg/kg/week) during the first week of leaching, compared to Comp 1 top tailings which produced the least alkalinity (2.5 mg/kg/week), corresponding to the cumulative alkalinity profile. This significant difference in alkalinity between the plant slurry (Comp 4) and young 0.5 m deposited tailings material (Comp 1) should be explained by the XRD mineralogy of the samples. However, the plant slurry does not report any carbonates while the top composite reported small proportions of calcite (0.79%) and dolomite (0.21%). These results suggest short-term alkalinity is being introduced to the TSF by the ~60% volume of underground ore slurry reporting to the facility, which controls the underdrainage water chemistry quality. This relative alkalinity production persists through to the last three weeks of the leaching experiment, with the Comp 1 averaging the lowest alkalinity production (3.67 mg/kg/week) compared to the Comp 4 plant slurry final three-week average alkalinity of 26 mg/kg/week.

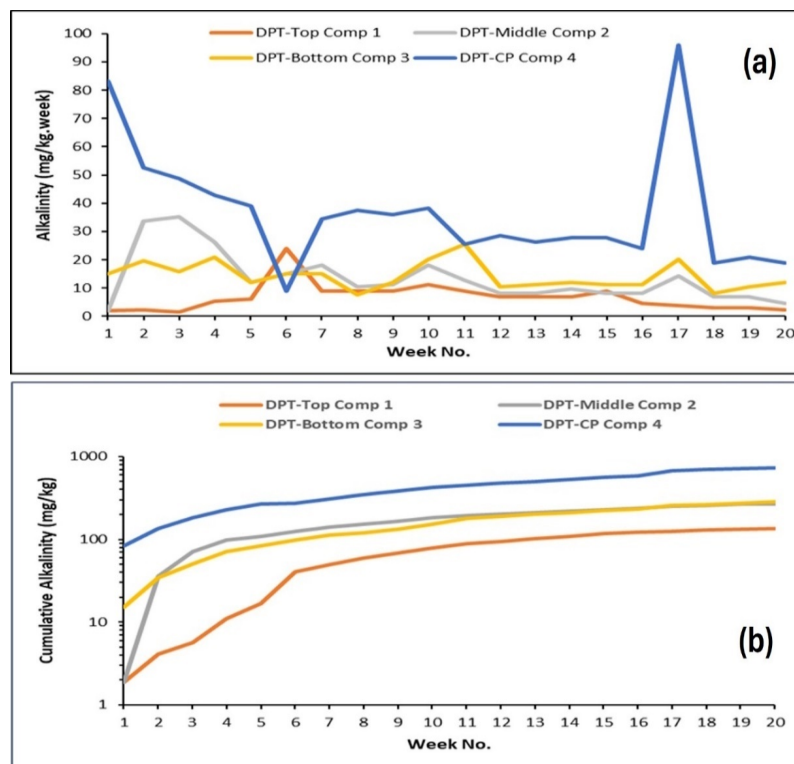
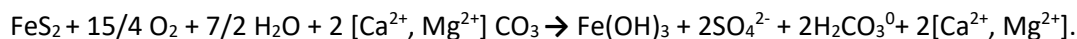


Figure 2 Alkalinity profile for Doornpoort tailings composites over a 20-week leaching experiment: (a) Weekly alkalinity production (mg/kg/week); (b) Cumulative alkalinity (mg/kg)

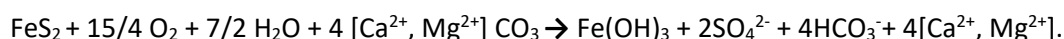
3.3.2 Sulphate production and neutralisation potential

The HC tests determine the rate of sulphide mineral oxidation by the presence of sulphate in weekly samples of leachate analysed. It is also important to note that sulphate can also be detected through the dissolution of sulphate minerals such as barite, anhydrite and gypsum, and this needs to be included in any interpretation of sulphate generation. Sulphide oxidation is the major source of acid production in mine drainage as the associated reduction in pH causes the release of metal ions. When sulphide is being oxidised the dominant NP consumption reaction is that of acid neutralisation. When carbonates are present the neutralisation reaction is pH-dependent (assuming no calcium and sulphate are lost to secondary mineral precipitation, indicated by the saturation indices for CaSO₄) and there are two main reactions (using pyrite as the sulphide).

At pH < 6.3:



At pH 6.3 – pH < 10.3:



Therefore, at pH < 6.3 neutralisation will produce one mole of calcium/magnesium and sulphate which gives a 1:1 carbonate molar ratio (CMR). Due to factors such as carbon dioxide evolving out of solution and the contribution of calcium and magnesium from non-carbonate minerals, this equation is theoretical.

At pH values around 8, carbonic acid is not stable and bicarbonate dominates. In such circumstances, carbonates are less efficient at neutralising acidity where a 2:1 calcium/magnesium ratio is realised. Weekly leachate concentrations of calcium, magnesium and sulphate are used to calculate the CMR (see Table 4 for the equation). The CMR indicates the actual carbonate dissolution rate (NP consumption) and thus can be used to estimate the time to the onset of acid generation. The values of the CMR should be between 1 and 2 in carbonate-bearing rock that is actively and effectively neutralising acidity caused by sulphide oxidation (Morin & Hutt 2000). The CMR can fall below 1.0 when effective neutralisation falters and the rinse pH decreases to between 5 and 6. This is because the effective and fast-neutralising carbonate has been exhausted. Where there is a low rate of in situ acid generation from sulphide oxidation, the predominant form of acidity is associated with the residual acidity of the deionised water (pH 5.5) introduced into the HCs. The carbonate minerals react with this water and give large values for the CMR, significantly greater than two. Further, the CMR values do not accurately reflect the relative rates of sulphide oxidation and NP depletion when the sulphate concentration in the HC leachate is less than 20 mg/kg (Mattson 2005). The mean results of the calculated CMR for weeks 18–20 are shown in Table 5. These results indicate that, except for the Comp 4 plant slurry sample, the DPT tailings materials NP is not keeping pace with the oxidation of pyrite, which will result in net acid generation potential (CMR < 1). Although the dissolution of the moderate proportions of gypsum reported in the pre-XRD analysis could influence the CMR results, no gypsum was reported in the post-XRD analysis, and therefore it is unlikely to have consumed NP towards the end of the test. The mean CMR for Comp 4 indicates that the introduced alkalinity still plays a role in neutralising any acid produced by pyrite oxidation after 20 weeks of leaching.

Table 5 Mean Doornpoort tailings carbonate molar ratio (CMR) results for weeks 18–20

Sample ID	Weeks 18 to 20 average CMR
DPT-Top Comp 1	0.99
DPT-Middle Comp 2	0.73
DPT-Bottom Comp 3	0.86
DPT-CP Comp 4	1.15

3.3.3 Sulphide oxidation rates/sulphide production

The rate of sulphide oxidation in mine waste is estimated from the sulphate analyses of the HC leachate. To obtain sulphide oxidation rates, weekly sulphate concentrations are normalised to the mass of sample in the HC. The results of the ABA determined that measurable NP was present. Kinetic tests are used to evaluate if the measured NP effectively buffers pH at the rate of acid generation produced by the oxidising sulphide minerals. The amount of carbonate NP leached from the HC samples is calculated by conducting a mass balance of the cation leach rates. The depletion rate assumes all calcium and magnesium come from dissolving calcite/dolomite. Given the nature of the host rock, the major ions can also be generated from the host rock material. Therefore, feldspar major ions and silica ratios are also used to assess secondary neutralisation.

These methods give conservative (worst case) projections because of the potential inaccuracies in determining sulphide and NP depletion rates. In samples where the rate of sulphide oxidation is slow, neither of the methods will give a reliable indication of depletion. In addition, the time to the depletion of the NP, the remaining concentration of the NP (as a %) and the time remaining for the NP have been calculated using the cumulative calcium and magnesium leached and the theoretical NP consumption rate at pH 6. Upon completion of the kinetic testing and using geochemical theory, the rock samples are analysed for total sulphur to validate the calculations of total sulphur remaining.

Samples Comp 1 (young) and Comp 2 (mature) reported the highest initial sulphate production rates of 4,746.75 mg/kg/week and 4,030.50 mg/kg/week, respectively, reinforced by both samples displaying elevated pyrite and gypsum mineralogy compared to Comp 3 (old) and Comp 4 fresh slurry samples. The cumulative sulphate trends reinforce the initial higher sulphate production rates in Comp 1 and Comp 2 samples, with both samples displaying elevated trends (Figure 3) throughout the 20-week leach period.

The remaining total sulphur percentage for all four composites correlates with post-HC static analysis results, confirming the validity of the sulphate kinetic calculations (Tables 3 and 6). According to these calculations, the NP is exhausted for all composites within the first leaching week, confirming that the DPT tailings materials and slurry are long-term net AG materials. This is reinforced by the comparison of the NP/AP ratio and inverse CMR for the last three weeks for each composite (Table 7) that predicts the long-term pH to be acidic (NP/AP < inverse CMR values). The fact that the leachate pH values reported circumneutral ranges for Comp 3 and Comp 4 throughout the 20-week leaching and through the mid-leach weeks for Comp 1 and Comp 2 suggests that secondary neutralisation capacity is available via slower-reacting aluminosilicate minerals.

3.3.4 Non-carbonate (aluminosilicate) neutralisation potential

The presence of primary minerals and secondary phyllosilicates and aluminosilicates indicates that additional sources of NP may be available to offer pH buffering capacity. The method to assess the dissolution of these minerals involves calculating the feldspar molar ratio (FMR).

Understanding the reactivity of silicate minerals is important when evaluating the long-term availability of NP in mine waste materials to ensure that silicate dissolution rates are sufficiently rapid to offset the acidity produced from sulphide oxidation. The ratios of the cations (Ca, K and Na) to sulphate for the above reactions are shown in Table 8. These reactions are incongruent and typically release cations from the silicate mineral structure, generating residual secondary and possibly tertiary minerals that are stable under the geochemical weathering environment.

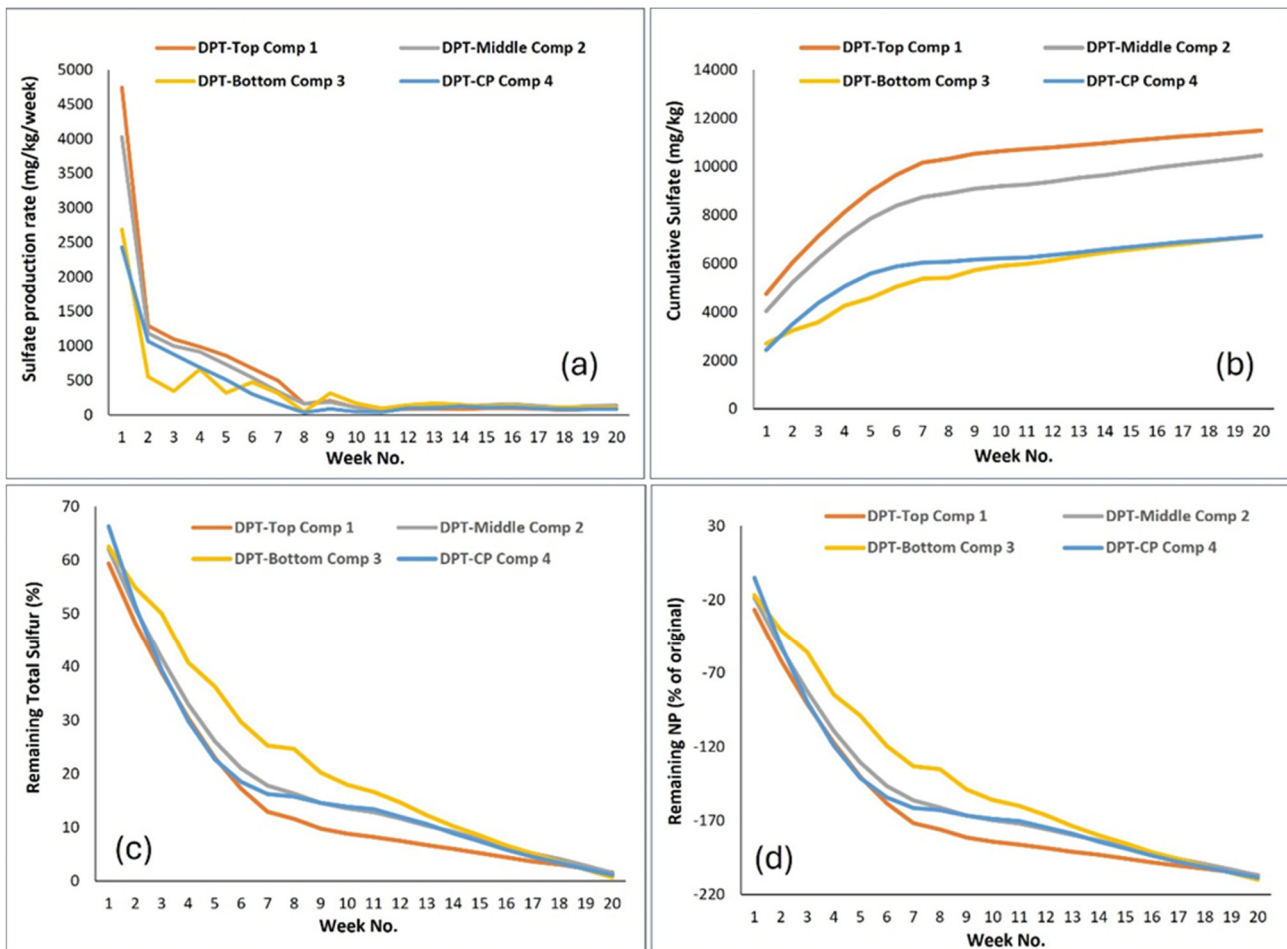


Figure 3 Doornpoort tailings materials: (a) Sulphate production; (b) Cumulative sulphate; (c) Remaining total sulphur; (d) Remaining neutralisation potential (% of origin)

Table 6 Summary of sulphate calculation results for 20-week leach experiment

Sample ID	Mean sulphate production rate (mg/kg/week) last 3 weeks	Cumulative sulphate production (mg/kg) at week 20	Average sulphate depletion time in weeks at week 20	Remaining total sulphur at week 20
DPT-Top Comp 1	79.50	11,488	212	1.68
DPT-Middle Comp 2	126.25	10,466	88	1.60
DPT-Bottom Comp 3	108.50	7,141	87	0.68
DPT-CP Comp 4	82.00	7,136	154	1.16

Table 7 Predicted long-term pH based on inverse carbonate molar ratio (CMR) compared to neutralisation potential/acid potential (NP/AP) ratio for the last three weeks of leaching

Sample ID	NP/AP	Inverse CMR week 18	Inverse CMR week 19	Inverse CMR week 20	Predicted long-term pH*
DPT-Top Comp 1	0.013	0.993	1.153	0.922	Acidic
DPT-Middle Comp 2	0.040	1.232	1.434	1.441	Acidic
DPT-Bottom Comp 3	0.154	1.168	1.120	1.221	Acidic
DPT-CP Comp 4	0.048	0.838	0.925	0.845	Acidic

* If the inverse of CMR < NP/AP ratio, sample pH will remain circumneutral. If CMR > NP/AP ratio, sample pH will potentially become acidic

Table 8 Ratio of cations (Ca, K, Na) to sulphate during selective neutralisation reactions (Morin & Hutt 1994)

Mineral	pH7	pH4
Calcite	2	1
Anorthite (Ca feldspar)	1	0.25
Albite (Na feldspar)	2	0.5
K-feldspar (various)	2	0.5

The results suggest that non-carbonate neutralisation is available or has occurred, more so in the Comp 4 plant slurry sample. The minerals that may contribute to the NP are shown in Table 9, with main molar ratios included.

Table 9 Molar ratio of major ions in potential secondary neutralisation minerals

Mineral	Formula	Al/Si	Mg/Si	Al/K
Chlorite	(Mg,Fe) ₅ Al(Si ₃ Al)O ₁₀ (OH) ₈	0.32	1.4	–
Muscovite	KAl ₂ ((Si,Al) ₄) ₁₀ (OH) ₂	1.4	–	4.1

A review of the molar ratios of major ions over the full leaching period is shown in Figure 4. The results suggest that mostly Ca-dominant minerals react during the first half of the leaching period, while Mg, Na, and Al are liberated during the first few weeks of leaching but drastically decline thereafter. This is further explored by comparing the sulphate release with major ions (Figure 5). When comparing Figures 4 and 5, the major ion ratio trends indicate that secondary NP may have been generated because of magnesium and calcium dissolution. The latter would partly be explained by calcite dissolution, with magnesium being generated from chlorite or dolomite dissolution. These secondary NP minerals are likely assisting with buffering the pH after the depletion of carbonates, as suggested by the circumneutral pH values for Comp 2–4 in the last three weeks of leaching.

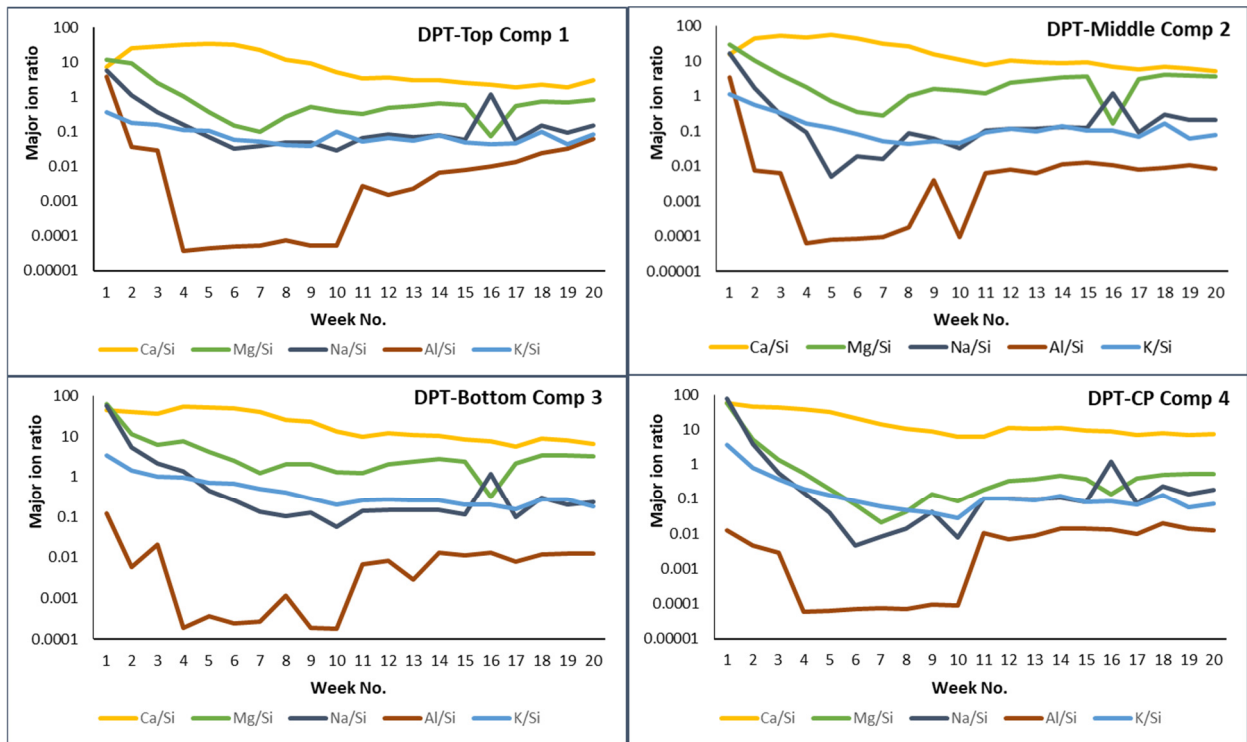


Figure 4 Leached major ion ratios for Doornpoort (DPT) tailings and plant slurry composites

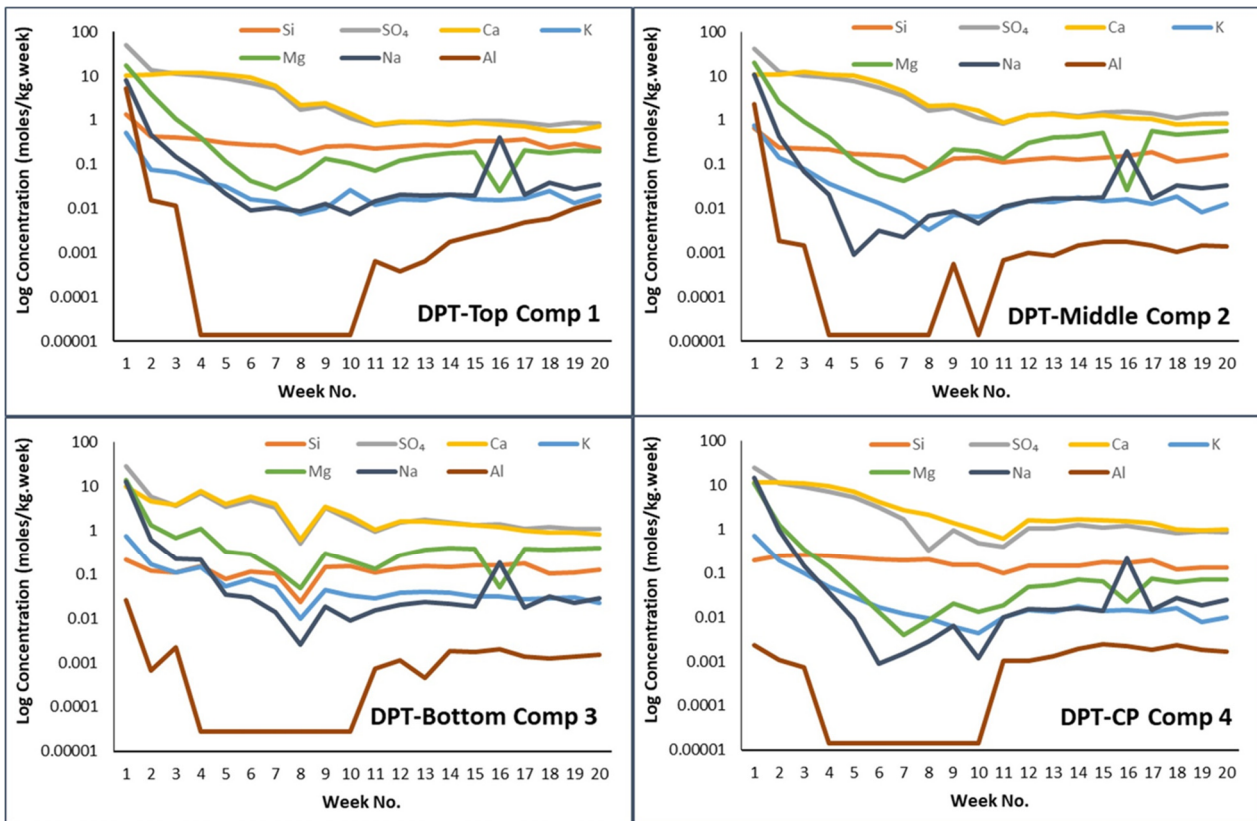


Figure 5 Leached major ion and sulphate leachate quality for Doornpoort (DPT) tailings and plant slurry composites

3.3.5 Scaling kinetic testing results

Over several years, a concerted effort has been made to understand how the results of various laboratory-based geochemical testing can be used to predict drainage water generated from mine waste as part of extension or closure planning. However, no established methodology exists to scale up laboratory results generated at a micro scale to predict drainage quality for larger-scale structures in the field.

Notwithstanding this, there is ongoing research to establish the correlation between laboratory testing results and the measured drainage quality in the field. There are two trains of thought regarding developing appropriate scaling factors. These are typified by the approach adopted by Stromberg & Banwart (1999) which applies scaling factors for individual mechanistic phenomena to account for differences such as rock composition, reaction environment and solute transport by reviewing many studies in this area. The second approach calculates a scaling factor by comparing the results of field studies with those from laboratory-based procedures. When selecting the appropriate scaling factor, the literature has been searched to establish if similar correlation efforts have been made for sites such as the SDGM. The research has not identified the exact scale up for kinetic results for the pyritic gold mine setting.

However, the available information suggests that for the similar total sulphur and mineralogy at the SDGM it is likely that a scale factor of 0.3–0.6 is appropriate for adjusting the HC testing results, based on the mechanistic approach by Kempton (2012) and the empirical approach by Hanna & Lapakko (2012). If we use the average concentrations of the constituents of potential concern reported in the site monitoring boreholes as a calibration, added to SLR's experience with gold ore mine settings, we suggest a scaling factor of 0.4 be applied to the humidity cell results.

3.3.6 Calcite saturation index and pH predictions

Previous analyses of the water quality using AqQA (RockWare®) and scaling geochemistry from the DPT TSF drains had identified that the scaling was predominantly calcite. The major ion chemistry of the fresh plant slurry (Comp 4) sample throughout the HC study was analysed through AqQA to understand calcite saturation during that time. Calcite (i.e. calcium carbonate) saturation is calculated using the ion activity product (i.e. the solubility of sparingly soluble) of dissolved calcium and dissolved carbonate, divided by the solubility product (K_{sp}) constant. The more soluble a substance is, the higher the K_{sp}. The solubility product of a mineral is temperature- and pressure-dependent.

Positive saturation index (SI) values indicate the mineral is supersaturated, while negative values indicate the dissolved concentrations are not high enough to precipitate the mineral and, if the mineral is present, it could be dissolved. Zero indicates the mineral is in equilibrium: i.e. there is no net precipitation or dissolution.

The equation for the SI of calcite is shown below. It is important to note that the SI does not account for the kinetics of any precipitation or dissolution (i.e. how quickly mineral phases will precipitate).

$$SI_{\text{calcite}} = \log \frac{[Ca^{2+}][CO_3^{2-}]}{K_{sp} \text{ Calcite}} \quad (1)$$

where:

- SI > 0 = supersaturated mineral
- SI = 0 = equilibrium
- SI < 0 = undersaturated.

Because any new drains will most likely be subjected to deposition associated with the freshest tailings geochemistry, the calculated saturation of calcite for Comp 4 has been plotted alongside pH in Figure 6. The saturation of calcite is strongly positive up to week 7 (excluding the outlier at week 6), which indicates that during this period the precipitation of calcite is favourable. Between weeks 7 and 17, the calcite saturation approaches equilibrium and fluctuates around it, being weakly negative from week 10. The SI of calcite then drops to negative/undersaturated from week 16 (except for the outlier at week 17).

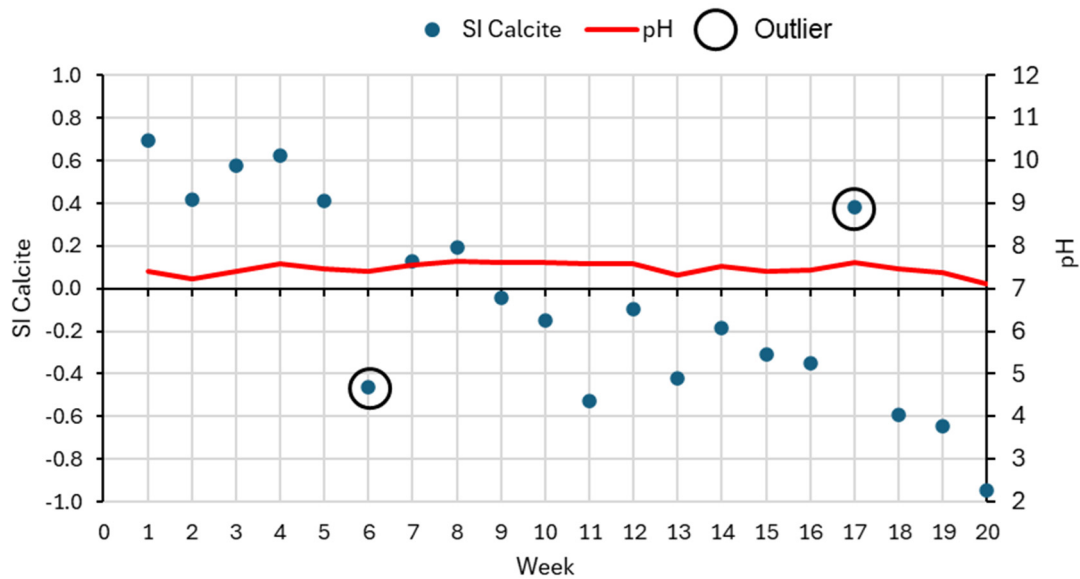


Figure 6 Saturation index (SI) of calcite and pH during a humidity cell test for Comp 4

The change in calcite saturation to undersaturated aligns with the depletion of NP for Comp 4 at week 17 (as indicated by the HC testing), which has been calculated by comparing the starting concentration of sulphide, the production rate of sulphate and the NP from ABA results. At the same time calcite becomes undersaturated in Comp 4, the pH in Comp 4 and deeper tailings materials also begins to become more acidic.

3.3.6.1 Impact on drain design and operations

The times at which calcite becomes undersaturated and NP is depleted need to be scaled to the rate of sulphate production to account for the lag time in these events. For this, SLR used a scaling factor of 0.4 (explained in Section 3.3.5). This suggests that calcite would become undersaturated and NP would become depleted after 56 weeks (over one year) after the final deposition of material.

It is important to understand that the kinetic study results and SI of calcite presented are a conservative measure of the tailings leachability. The deposition of material will be several orders of magnitude larger than samples of 1 kg, and the exposure to oxygenated water will be reduced through deposition and the cover of new material. In addition, the partial pressure of carbon dioxide may increase in the drain, which can also cause scaling by differential pressure release kinetics.

In addition, the geochemical consistency of material deposited over the life of the mine will influence the leachate quality. Deeper (older) tailings samples exhibited a secondary NP that buffered pH in their respective humidity cells for several weeks before it turned acidic. Therefore, even with scaling the outputs, the estimate of one year+ for calcite scaling to cease and leachate to become acidic is likely an underestimate of the actual time frame in which scaling will stop and pH will begin to become acidic.

4 Conclusion

The pre- and post-XRD analysis showed that over the 20-week leaching period, any remaining NP shifted to the slower-weathering aluminosilicate minerals and that relatively elevated proportions of pyrite remained (>0.3%), suggesting that the Doornpoort (DPT) tailings acid potential (AP) would overwhelm any aluminosilicate NP in the long-term. Both pre- and post-HC samples were classified as potentially acid generating (PAG) due to elevated sulphide levels and unfavourable AP versus NP values. Post-HC samples showed a shift to full AG status over the long-term. The kinetic results reported that both the young and mature tailings exhibited initial acidic pH values. Thereafter, these were in the circumneutral range, except for the young tailings sample decreasing to acidic values in the last three weeks of leaching. The old (deep DPT) and plant slurry samples reported relatively stable circumneutral pH values throughout the leach

experiment, dipping towards the end of the 20-week leaching. The plant slurry sample produced the most alkalinity during the first week of leaching compared to the tailings of the top (near surface), which produced the least alkalinity. This difference in alkalinity is not explained by XRD mineralogy of the samples. Therefore, it is inferred that alkalinity is being introduced during the beneficiation of the underground ore, which is affecting the underdrainage water chemistry.

The CMR results indicate that, except for the Comp 4 plant slurry sample, the DPT tailings materials' NP is not keeping pace with the oxidation of pyrite, which will result in long-term net acid generation occurring (CMR < 1). Although the FMR values confirm that secondary neutralisation capacity is available via slower-reacting aluminosilicate minerals, due to their slow reaction rates, this secondary neutralisation will be overwhelmed by the acidity generated by long-term pyrite oxidation. When considering the different parameters listed by field scaling research and calibrating the leached metal concentrations with the groundwater data, it is suggested that a scaling factor of 0.4 be applied to the HC results which estimate that, except for manganese, all determinants are either non-detected or are below national and international effluent water guideline limits.

By plotting the evolving SI of calcite and pH of the fresh tailings sample over the 20-week leaching experiment, and using the 0.4 scaling factor, we predict that it will take approximately 56 weeks for calcite to become undersaturated and NP to be depleted. However, this is a conservative estimate owing to the amount and consistency of the tailings materials deposited, the reduction in oxygen exposure once buried and the possible change in the partial pressure of carbon dioxide, which can alter the estimated time frame for the calcite to become undersaturated. Additionally, the deeper (older) tailings exhibited secondary NP which could buffer the pH for several additional weeks before the solution turns acidic. To increase the drainage efficiency within the facility it is suggested to look at the feasibility of installing an elevated drainage system that includes a reaction barrier with a minimum of three years' reactivity life to prevent initial calcite scaling in the new drains.

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References

- Golder Associates Africa 2020, *Post Closure Water Management Plan (Phase 2). Gold Fields: South Deep Gold Mine*, Midrand.
- Hanna, B & Lapakko, K 2012, 'Waste rock sulfate release rates from a former taconite mine, laboratory and field-scale studies', *Proceedings of the 9th International Conference on Acid Rock Drainage*, Mine Environment Neutral Drainage.
- Kempton, H 2012, 'A review of scale factors', *Proceedings of the 9th International Conference on Acid Rock Drainage*, Mine Environment Neutral Drainage.
- Mattson, BH 2005, 'Evaluating depletion of carbonate neutralisation potential in sulfidic mine wastes from laboratory kinetic tests', *Proceedings of Securing the Future: International Conference on Mining and the Environmental Metals and Energy Recovery*, SveMin, Stockholm.
- Metago Environmental Engineer 2008, *Geochemical Waste Characterisation for the Proposed Tailings Storage Facility at South Deep Mine*, Johannesburg.
- Morin, KA & Hutt, NM 1994, 'Observed preferential depletion of neutralization potential over sulfide minerals in kinetic tests: site-specific criteria for safe NP/AP ratios', *International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acid Drainage*, Canadian Land Reclamation Association, Edmonton.
- Morin, KA & Hutt, NM 2000, 'Lessons learned from long term and large batch humidity cells', *Proceedings from the Fifth International Conference on Acid Rock Drainage*, Society of Mining Metallurgy and Exploration Inc., Englewood.
- Price, WA 2009, *Prediction Manual for Drainage Chemistry from Sulfidic Geologic Materials*, report 1.20.1, Mine Environment Neutral Drainage.
- Stromberg, B & Banwart, S 1999, 'Weathering kinetics of waste rock from the Aitik copper mine, Sweden: scale dependent rate factors and pH controls in large column experiments', *Journal of Contaminant Hydrology*, vol. 39, issue 1, pp. 59–89.