Acid Mine Drainage Risk Assessment Utilizing Drill-Hole Data and Geological Modelling Tools

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ABSTRACT

For an Australian iron ore operation in the Pilbara region of Western Australia, an acid and metalliferous drainage (AMD) study has considered available drill-hole data (chemical assays and geological logging information) combined with mine planning information to conduct a high level assessment of the potential for AMD from mined waste storage facilities and within the pit void.

Geological modelling tools (Vulcan, Leapfrog) were used to generate 3D visualisations of the distribution of sulfur (a key parameter indicative of AMD risk) within the mined volume. The final sulfur model was aligned with the existing block model to aid future mine planning. Small volumes representing sulfur-bearing 'hot-spots' were identified and pit void maps were generated to determine the location of these hot spots on exposed pit walls. Similarly, volumetric quantities of sulfur-bearing material that would report to waste rock dumps and ore stockpiles were estimated.

Outcomes from the assessment were used to focus ongoing geochemical characterisation activities, and can be used as a basis for scoping calculations to predict the possible quality of drainage waters from mined waste storage facilities and pit walls. This paper describes the overall assessment approach and summarises outcomes from the AMD risk assessment.

Keywords: acid mine drainage, sulfur distribution, geological modelling

INTRODUCTION

There are numerous iron ore mines within the Pilbara, Western Australia. In many, mineralized ore is located within the Dales Gorge Member of the Brockman Iron Formation which is part of the Early Proterozoic Hamersley Group. The Brockman Iron Formation is stratigraphically underlain by the Mount McRae Shale, which is known to contain sulfidic mineralization. Due to the possible exposure of sulfidic materials during mining it is necessary to assess the potential for acidic and/or metalliferous drainage (AMD) at the site from mined materials placed above ground and also exposed on walls within the pit void (Figure 1).

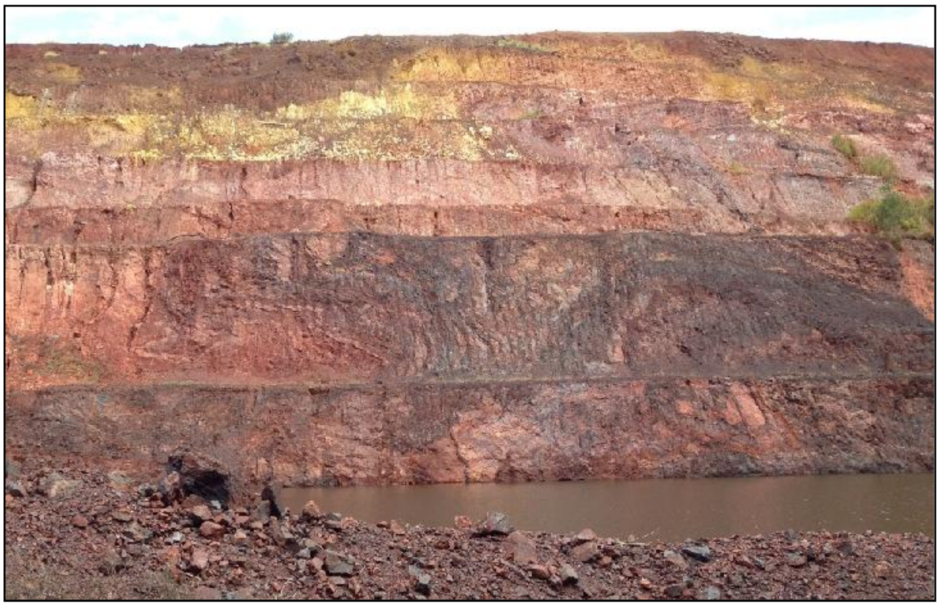

Figure 1 Photograph of exposed Mount McRae Shale (dark colored rock) on pit walls

This paper describes how sulfur data (a key parameter indicative of AMD risk) have been used to develop an approach to assess the risk of AMD. Geological modelling tools were utilized to build an understanding of the spatial distribution of sulfur within the mined void, helping to inform assessment of risk. Outcomes have been used to focus ongoing geochemical characterization activities, as a basis for scoping calculations to predict the possible quality of drainage waters, and as a foundation for closure planning.

APPROACH

The propensity for mined materials to generate acid is a balance between the abundance of acid forming minerals (i.e. sulfides) and acid neutralizing minerals (e.g. carbonates). In the current work, the geochemical characteristics of mined lithologies were assessed principally on the basis of geochemical data within the drill-hole database. These data comprised XRF results for the following parameters: Al_2O_3, CaO, Fe, K_2O, MgO, MnO, P, S, SiO_2, TiO_2.

Sulfur (S), was used to infer maximum acid potential (AP) based on the assumption that all sulfur present is in the form of reactive sulfide. This is a conservative approach, as some proportion of the sulfur may be present as sulfate in the form of gypsum or other non-acid forming minerals. CaO and MgO were assessed as possible surrogates for carbonate-based neutralization potential (NP) but were found to over-estimate NP when compared to available acid-base accounting data – probably due the presence of Ca- and Mg-bearing silicates in the materials.

Because CaO and MgO were found to be unreliable surrogates for NP, the most conservative approach was to assume no NP and to classify materials on the basis of a sulfur cut-off threshold. Additionally, materials are flagged as 'pyritic' in the drill-hole database if they had been logged as un-oxidized Mount McRae Shale (i.e. Mount McRae Shale sourced from below the oxidation zone). This approach provided two broad categories of classification namely pyritic waste and non-pyritic waste; the non-pyritic waste is assumed non-acid forming (NAF) whereas the pyritic waste is categorized as potentially acid forming (PAF) only if the sulfur content is above 0.2%. Material with sulfur content below the sulfur threshold was considered to represent a low risk of acid generation.

To develop an understanding of the waste distribution and material classification, a statistical analysis was carried out to establish the occurrence of sulfur within each lithological unit using all data within the mining void. To account for materials that would be removed from site (i.e. ore), data were differentiated as ore or waste. Figure 2 illustrates sulfur statistics for waste, with the pyritic waste classification shown separately. The figure shows that the median values of sulfur content for the waste classification were low and fell below the 0.2% sulfur cutoff. The corresponding range (as indicated by the whiskers) of the assays also fell below the cutoff for the majority of the lithological units. The range of assays for some of the lithologies however exceeded the sulfur cutoff. In the absence of significant NP this may indicate a risk of acid generation.

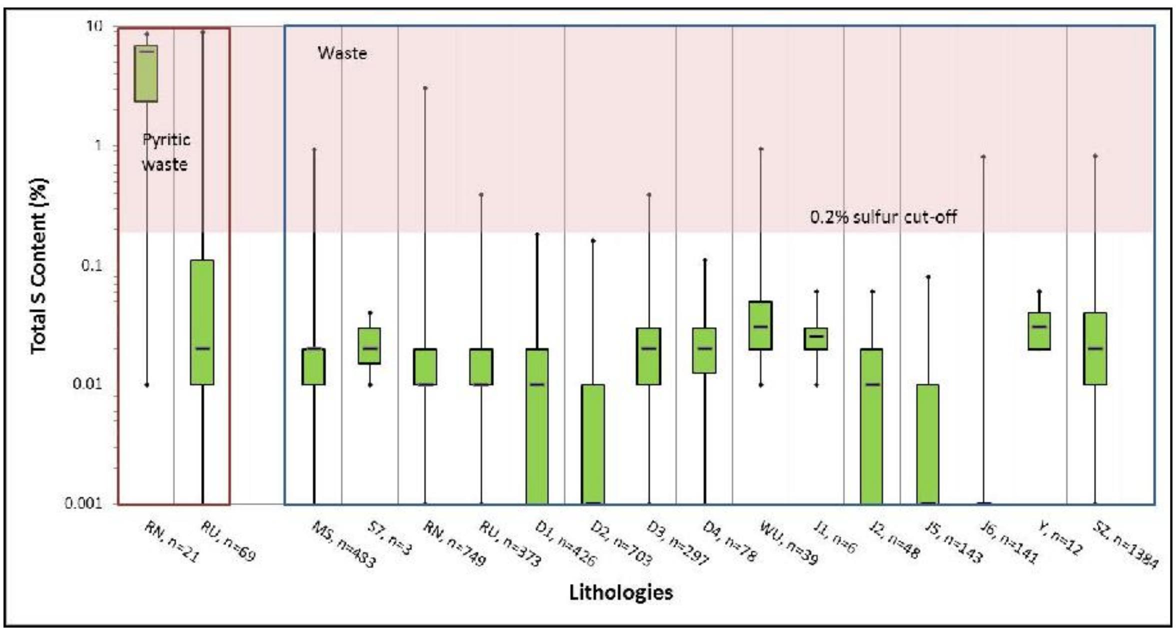

Figure 2 Box and whisker plots showing sulfur statistics in waste materials, by lithology

Note: The box and whisker plots show the minimum and maximum sulfur values (short horizontal dashes), median sulfur values (bold black dashes), and data falling within the 25th and 75th percentiles (green boxes). The number of samples, n, from each lithological unit is shown along the x-axis.

RU, RN – Mt McRae Shale (Upper and Nodular Zone, respectively); MS – Mt Sylvia, undifferentiated; S7 - Mt Sylvia (Bruno's Band); SZ – Surface Scree

Brockman Iron Formation: D1-4 – Units within the Dales Gorge Member; WU – Upper Whaleback Shale; J1-6 – Units within the Joffre Member; Y – Yandicoogina Shale.

Consistent with its classification, material categorized as pyritic waste contained a higher median sulfur grade, most notably for the Mount McRae Shale from within the Nodular Zone (RN); the majority of data for pyritic RN was above the 0.2% sulfur cut-off threshold. The Upper Zone of the Mount McRae Shale (RU) whilst classified as pyritic waste, showed a median sulfur content below the cutoff, but exhibited a large range in sulfur content.

On the assumption of a 0.2 % sulfur cutoff, the statistical analysis shows that the waste classification system would capture PAF materials within the pyritic waste category; however this is not necessarily the case for the waste category as illustrated by the range of assays exceeding the cutoff value for the remaining lithologies.

Therefore, the above analysis showed that to assess the overall potential risks of AMD, the range of sulfur values contained within each lithology is likely to influence the outcomes. Furthermore in the absence of NP data, a further level of conservatism in the form of a lower sulfur cut-off of 0.1 % was included in the subsequent evaluation.

Leapfrog® 3D modelling software[1] was used to process the drill-hole database to visualize the occurrence of the high sulfur zones within the mining void and that exposed on the final pit shell areas of reactive zones. To enable this, in addition to sulfur, the information imported into Leapfrog for 3D modelling purposes included:

- Geological wireframes;
- Pre-mining and proposed final (as mined pit shells) topographies; and,
- Pre-mining water table contours.

The resulting models were used to generate estimates of:

- Volumes of sulfur-bearing material that would report to waste rock dumps and ore stockpiles; and,
- Estimates of the pit wall exposure as a function of lithology and sulfur content.

Using these outcomes it was possible to build an understanding of the spatial distribution of sulfur-bearing materials.

The drill-hole assay data coordinates were then aligned with the block "mid-points" of the current mining models using Vulcan™ (3D modelling and mine planning) software[2], and blocks were classified according to the client's waste classification definitions, including a PAF waste category if > 0.2 % sulfur, to inform future mine planning and closure options at the site.

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[1] Leapfrog® Mining 3D modelling software was used for this study, which utilises a "toolbox" approach to 3D geological modelling, allowing processing, viewing and interpretation of drill-hole data. Leapfrog® is 3D geological modelling software which is designed to be used in the mining, exploration, environmental and geothermal energy industries. Leapfrog® is the registered trademark of ARANZ Geo Limited.

[2] Vulcan™ is 3D modelling and mine planning software, allowing users to validate and transform raw mining data into dynamic 3D models, mine designs and operating plans. Vulcan™ is trademark registered to Maptek™.

RESULTS

Geochemical Characteristics of Mined Lithologies

Based on the sulfur statistics (see Figure 2), the majority of the lithologies to be mined would be considered to pose a low risk of acid generation. However, the sulfur ranges for many lithologies extend to maxima that lie above the sulfur cut-off thresholds, indicating that there may be quantities of material from several of the lithological units that could pose a risk of AMD.

Potential for Acid and Metalliferous Drainage - Pit Walls

Figure 3 is a Leapfrog image of the final pit shell showing the lithological composition of the exposed pit walls. One approach to assess the potential for AMD from the pit walls is to examine the sulfur statistics for the lithologies in question. Based on the statistical evaluation, the proportion of data with sulfur values above the cut-off threshold can be quantified and used a guide to the proportion of PAF material present. However, this approach takes no account of potential spatial variability in the distribution of sulfur within the lithological units.

Figure 4 shows another Leapfrog image of the final pit shell, this time showing the distribution of sulfur on the pit wall based on the sulfur model developed from the available drill-hole data.

The degree of correlation between lithological exposure and sulfur content is not entirely clear cut, which may reflect the fact that the density of data available to support the geological model is greater than that available to support the sulfur model. However, comparison of Figures 3 and 4 shows that higher sulfur values are often coincident with exposure of the Mount McRae Shale and the immediately overlying Colonial Chert Unit (D1). Most of these exposures are located at or near the base of the pit. Sulfur 'hot-spots' are shown to also extend up to the pit crest, many of which are coincident with exposure of surface scree.

Using the Leapfrog model, it was possible to quantify the composition of the exposed pit wall according to sulfur content, by elevation (Table 1). Note that having taken account of spatial variability the total percentage of PAF exposed on the pit wall is greater than was estimated on the basis of bulk sulfur statistics. Pit wall rock with total sulfur content greater than 0.1% is now 6%, rather than 3%, and wall rock with sulfur content greater than 0.2% is 5% rather than 0.3%.

Having developed a model of the spatial distribution of sulfur on the pit wall, a more robust risk assessment for the potential for AMD can be achieved. For example, the location of higher sulfur materials relative to post-closure water levels can be accounted for in the long term risk assessment; only materials remaining above the long term water table would be expected to continue to represent a potential source of AMD post-closure.

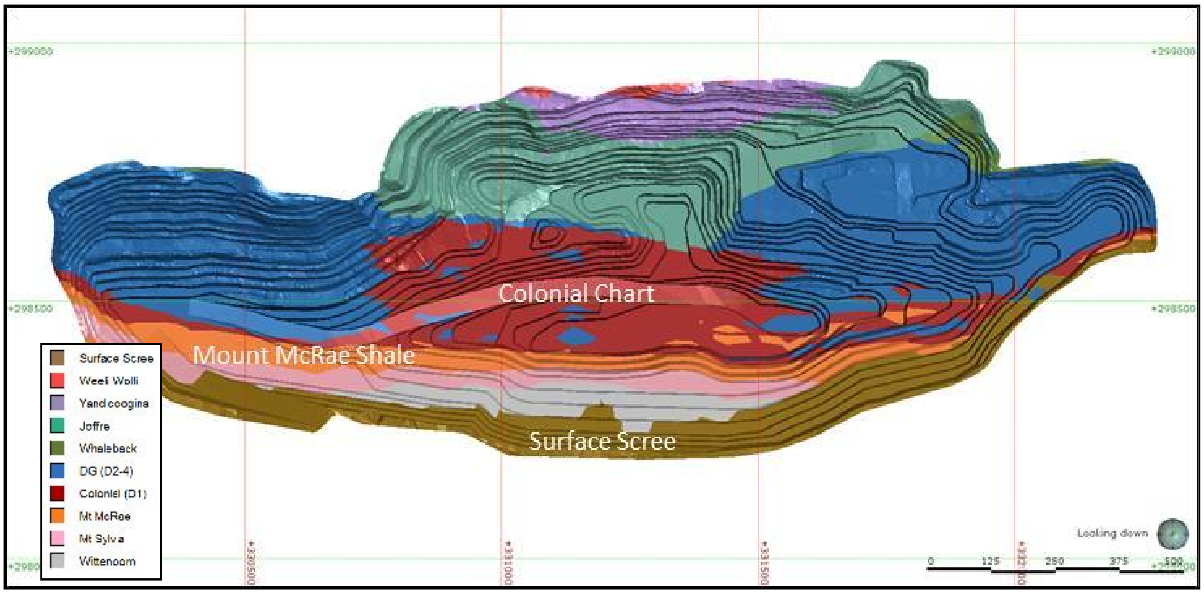

Figure 3 Leapfrog image of the pit shell, and showing lithological composition of the pit walls

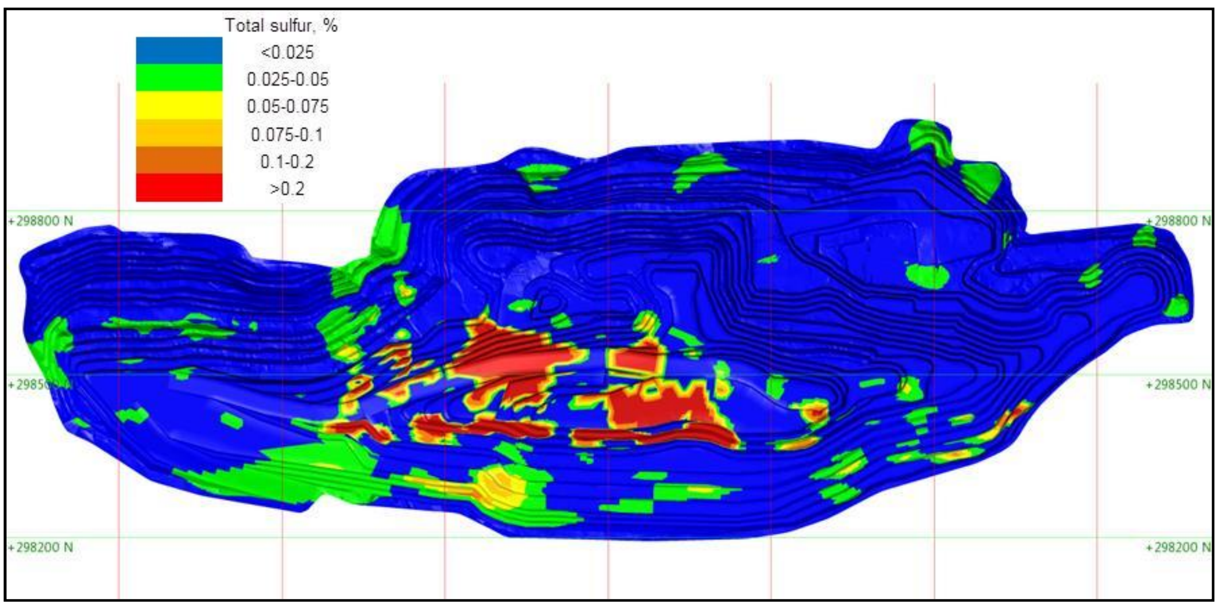

Figure 4 Leapfrog image of the pit shell showing the distribution of sulfur on the pit walls

Table 1 Estimate of the Areas of Exposed Sulfur-Bearing Rock, By Sulfur Category

Elevation Range (m)	Total Surface Area (m²)	Surface Area (m²), by Sulfur Category			
		<0.1%	0.1-0.2%	0.2-1%	>1%
382-390	13,000	13,000	-	-	-
390-400	54,000	35,000	5,000	13,000	1,000
400-410	52,000	35,000	3,000	7,000	6,000
410-420	43,000	34,000	2,000	2,000	5,000
420-430	53,000	40,000	2,000	4,000	8,000
430-440	48,000	40,000	1,000	2,000	5,000
440-450	60,000	52,000	2,000	3,000	3,000
450-460	83,000	77,000	2,000	2,000	1,000
460-470	86,000	82,000	1,000	4,000	-
470-480	88,000	85,000	1,000	2,000	-
480-490	146,000	145,000	1,000	-	-
490-500	144,000	143,000	1,000	-	-
500-505	34,000	34,000	-	-	-
505-510	76,000	76,000	-	-	-
510-515	49,000	49,000	-	-	-
515-520	81,000	81,000	-	-	-
520-530	73,000	73,000	-	-	-
530-540	80,000	80,000	-	-	-
540-550	55,000	55,000	-	-	-
550-560	46,000	46,000	-	-	-
560-570	31,000	31,000	-	-	-
570-580	14,000	14,000	-	-	-
580-590	13,000	13,000	-	-	-
590-600	12,000	12,000	-	-	-
600-610	11,000	11,000	-	-	-
610-620	6,000	6,000	-	-	-
620-630	4,000	4,000	-	-	-
630-640	-	-	-	-	-
Totals	1,458,000	1,368,000	21,000	39,000	30,000
Percentage of Total Surface Area		**94%**	**1%**	**3%**	**2%**
Estimates based on evaluation of bulk sulfur statistics		**97%**	**3%**		
		99.7%		**0.3%**	

Note: Highlighting has been used to indicate material with total sulfur content above sulfur cut-off thresholds (i.e. PAF). Note that an elevation range from 382 (pit base) to 640 mRL has been considered in the analysis. The images presented in Figure 3 and 4 have been clipped at approximately 505 mRL (the level of the lowest point along the pit crest)

In the current assessment, the potential for AMD in pit wall runoff is considered low due to the relatively low proportion of higher sulfur material exposed. With respect to the small proportion of higher sulfur material identified:

- Material located on or near the pit floor is hosted by Mount McRae Shale and Colonial Chert. These lithologies are known to host sulfide mineralization, and could represent sources of AMD. Because these materials would be expected to be submerged following water table rebound, they would not represent long-term sources of AMD, post-closure. Short-term leaching of pre-existing soluble oxidation products is possible.

- Material located near the pit crest is hosted by surface scree. Though some sulfur in this lithology is expected to be non-sulfidic (e.g. gypsum), geochemical characterization studies have confirmed the presence of sulfidic sulfur in a small subset of samples. Data from ongoing detailed geochemical characterization activities suggest that sufficient neutralization potential is present to classify the materials generally as NAF. These materials may however represent a potential source of neutral mine drainage (NMD).

Potential for AMD - Waste Storage Areas

The lithological composition of waste to be mined is shown in Figure 5, based on Leapfrog modelling of the lithological volumes within the pit shell. Estimates of the overall proportion of PAF material present in the waste is shown in Table 2. The estimates combine the volume of each lithology with the bulk sulfur characteristics of the materials.

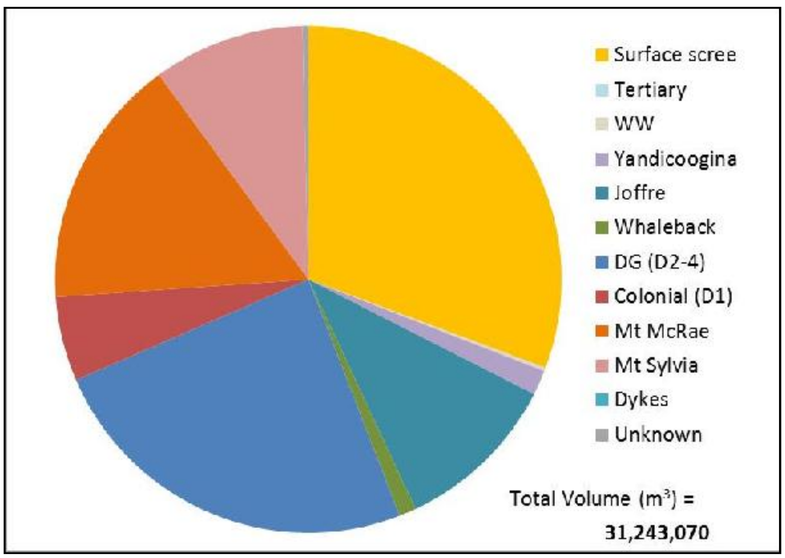

Figure 5 Pie-chart showing the lithological composition of waste to be mined from the pit

Table 2 Estimated proportions of PAF material in waste

Lithological Unit	% of waste volume	0.1% sulfur cut-off		0.2% sulfur cut-off	
		Proportion of PAF material in unit[1]	% of PAF material	Proportion of PAF material in unit[1]	% of PAF material
SZ	31%	10%	3%	5%	1.5%
WW	0.2%	[2]			
HJ	0.002%	[2]			
HE	0.05%	[2]			
Y	2%	0%	-	0%	-
J6	5%	1%	0.05%	1%	0.05%
J5	3%	1%	0.03%	0%	0%
J2	2%	1%	0.02%	0%	0%
J1	0.2%	5%	0.01%	0%	0%
WU	1%	10%	0.1%	5%	0.05%
D4	5%	5%	0.3%	0%	0%
D3	7%	5%	0.4%	1%	0.07%
D2	12%	1%	0.1%	1%	0.1%
D1	5%	3%	0.2%	1%	0.05%
RU	6%	5%/25%[3]	0.4%[4]	1%/5%[3]	0.1%[4]
RN	10%	5%/98%[3]	0.8%[4]	1%/95%[3]	0.4%[4]
S7	0.03%	0%	-	0%	-
S	10%	5%	0.5%	1%	0.1%
UN	0.4%	[2]			
Totals	**100%**		**5.9%**		**2.5%**

Notes:

[1] Proportion of PAF-classed material estimated on the basis of the percentile of the dataset that lies above the sulfur cut-off (0.1% or 0.2%).

[2] No data available for this volumetrically insignificant unit.

[3] General/un-oxidised 'pyritic' waste categories – as recorded in drill-hole logs

[4] Accounting for contributions from both general and pyritic waste categories

SZ – Surface Scree; Z – Tertiary Detritals; HJ – Weeli Wolli Iron Formation; HE – Weeli Wolli Dolerite; K – Dykes/Sills Brockman Iron Formation: D1-4 – Units within the Dales Gorge Member; WU – Upper Whaleback Shale; J1-6 – Units within the Joffre Member; Y – Yandicoogina Shale

RU, RN – Mt McRae Shale (Upper and Nodular Zone, respectively); S – Mt Sylvia, undifferentiated; S7 - Mt Sylvia (Bruno's Band);

Potential for AMD – Stockpiled Ore

As was the case with waste, the volumetric proportion of PAF material in ore grade materials was estimated to be low. Combined with short residence times within stockpiles, the ore materials were considered to represent a low to negligible risk of AMD.

AMD RISK AND WATER QUALITY

As described in the previous section, the approach developed allowed the identification and quantification of potential AMD sources for waste storage areas, ore stockpiles, and exposed pit walls. Based a semi-qualitative assessment the AMD risks associated with the potential sources were considered low. However, a more robust assessment would include the estimation of water quality and solute loadings that would result from each of these sources, and then determining the potential impacts on the downstream environmental receptors. The approach presented herein provides fundamental inputs that are required to complete such an assessment, comprising properties, quantities and exposures for materials that have a potential to generate AMD. The assessment would however also require kinetic test data (to provide reaction rates and solute release rates) water flow rates (i.e. infiltration, runoff) and flowpath analysis to understand impacts on the receptors.

The outcomes risk assessment can also be used to infer possible closure management strategies at the site which may include backfilling of the pit void. If the pits were backfilled to above the long-term regional groundwater table, groundwater flow would be re-established and flow would likely pass through the backfill. Upon inundation, oxygen would be excluded from the backfill to very low levels and oxidation of any residual sulfides present would essentially cease. Readily soluble solutes contained in the backfill placed below the final water table (i.e. generated prior to inundation) would be released to the groundwater following inundation. The total potential for solute release would depend on the degree of oxidation (i.e. the duration of exposure) of sulfide minerals prior to inundation. Solute generation would be expected to continue in reactive materials (backfill and wall rocks) that remain above the water table.

Should the pits remain as open voids post closure (or be backfilled to below the long-term groundwater elevation), they could act as indefinite sinks for groundwater and would capture some seepage and runoff from waste storage areas that fall within the draw-downs that would occur around the voids. Under this scenario, although the pit lakes would be anticipated to salinize over time due to evapo-concentration, impacts on the key environmental receptors would be unlikely.

CONCLUSIONS

Sulfur has been used as an indicator of the potential for AP, and therefore AMD risk (a conservative approach since surrogates for NP in the geological database were found to be unreliable). Using geological modelling tools, drill-hole data were utilized to develop models of sulfur distribution within the mine volumes to provide estimates of quantities of materials, and wall rock exposure on the final void, that may pose a risk of AMD. This information is required to semi-quantitatively infer the potential risk of AMD. Taking into account spatial variability in the distribution was found to be an important foundation for the assessment of AMD risk. With respect to the pit walls, if spatial variability was not accounted for, the potential for AMD could be under-estimated.

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