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Geochemical Risk Assessment Process for Rio Tinto's Pilbara Iron Ore Mines

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1. Introduction

Acid and Metalliferous Drainage (AMD) is a major environmental risk that should be regularly assessed at all new and existing iron ore mine sites. AMD can often be reduced or prevented by appropriate mine plans but where not managed properly, can lead to costly collection and treatment programs that must function for many decades. This is particularly evident at many historical and abandoned mine sites where the AMD was not identified prior to mining.

Whilst the release of acidity alone can have major impacts, the dissolution of metals (such as iron, aluminium, manganese, cadmium, copper, lead, zinc, arsenic and mercury) from surrounding country rock can also have significant downstream impacts on the environment. The water quality may impact on human health and thus increase public and regulatory focus and concern. Ultimately the 'social licence to operate' may be at risk.

Metalliferous drainage typically requires, at a minimum, low-pH conditions on a microscopic scale as a mechanism to initially solubilise contaminants. If the sulfide-bearing rock also has sufficient neutralising capacity, the acid generated is subsequently neutralised. However despite neutralisation, concentrations of some contaminants do not precipitate at near-neutral pH (ie. zinc, arsenic, nickel, and cadmium). Instead these contaminants remain in solution resulting in low-quality drainage. In cases where there has been sufficient neutralisation to remove all metals the water can still have elevated concentrations of sulfate resulting in elevated salinity. It is therefore important to adequately geochemically assess all material at a mine site to ensure that all aspects of AMD risk are considered.

A crucial step in leading practice management of AMD is to assess the environmental, human health, commercial and reputation risks as early as possible (CoA 2007). Reactive mineral waste can cause harm by: degrading water quality causing human health or ecological impacts; inhibiting vegetation establishment, posing a direct exposure risk to animals and humans; and degrading air quality through dust or gas emissions.

Rio Tinto and its subsidiary Rio Tinto Iron Ore (RTIO) have developed standards, strategies, procedures, management plans and guidance notes that can be used to assess AMD risk for mine sites. This paper summarises how these documents have been integrated and how site specific information is assessed for AMD risk at Rio Tinto's Iron Ore (RTIO) mines in the Pilbara region of Western Australia. Guidance for conducting ecological risk assessments

(Linkov et. al. 2002) or water quality risk assessments (ANZECC 2000) are more prevalent than that for AMD and geochemical risk assessments. RTIO's four stage process to evaluate the AMD and geochemical risks for a mine site are unique and comprehensive. This process could be used as a guide to conduct AMD and geochemical risk assessments at other mining operations.

2. RTIOs mining operations in the pilbara region

2.1 Location

Within the Pilbara of Western Australia, RTIO manages mines, ports and rail infrastructure for Hamersley Iron Pty Ltd (Greater Tom Price, Greater Paraburdoo, Marandoo, Greater Brockman and Yandicoogina (Yandi)), Robe River Iron associates (West Angelas and Mesa J (Pannawonica) and Hamersley HMS Pty Ltd (Hope Downs 1). Hereafter RTIO refers to all these groups.

Iron ore is mined in open cut truck and shovel operations using drilling and blasting. Blast holes are drilled by rotary and hammer drill rigs on 10 or 15 m benches designed to suit the geology or equipment of the individual mine. Iron ore from inland mine sites is transported via the 1,481 km railway network to port facilities located at Dampier and Cape Lambert (Fig. 1).

2.2 Mineral waste risks

Mineral waste is composed of bedrock or unconsolidated sediments that are disturbed or exposed by mining. Mineral waste can also be composed of mineral residue generated by the processing of ore. The environmental exposure hazards of reactive mineral waste whose innate physical, chemical or biological properties could now or in the future pose harm, are a risk that RTIO endeavour to manage, using best practice management techniques. RTIO also invests significantly in research and development in this area. During the 2009 financial year RTIO directly invested $1.2 million (Aus) into mineral waste research for the Pilbara. This research has included modelling of final pit void water quality, bioremediation, cover research, waste dump designs and geochemical characterisation (Green 2009).

Whilst not a risk at every mine site in the Pilbara, it is particularly important to evaluate the risk for Acid Rock Drainage (ARD), contaminants soluble at neutral pH, salinity and organic compounds (including spontaneous combustion hazards). Although not necessary a geochemical risk, fibrous minerals are also an important consideration for mining operations in the Pilbara.

2.3 Geological setting

Banded Iron Formation (BIF) derived iron deposits occur where BIF has been locally enriched in situ. BIF-derived iron deposits may be hosted in the Marra Mamba Iron Formation, or in the Joffre and Dales Gorge members of the Brockman Iron Formation (Fig. 2). Of the BIF-derived iron deposits, only those associated with the Dales Gorge member of the Brockman Iron Formation are likely to occur in close proximity to the potentially carbonaceous and sulfide-bearing Mount McRae Shale (MCS). Less reactive black shale can also be found in thinner bands than the MCS in the Footwall zone, Dales Gorge, Jeerinah Formation, Wittenoom Formation, Nanutarra Formation, Ashburton Formation and Whaleback Shale members.

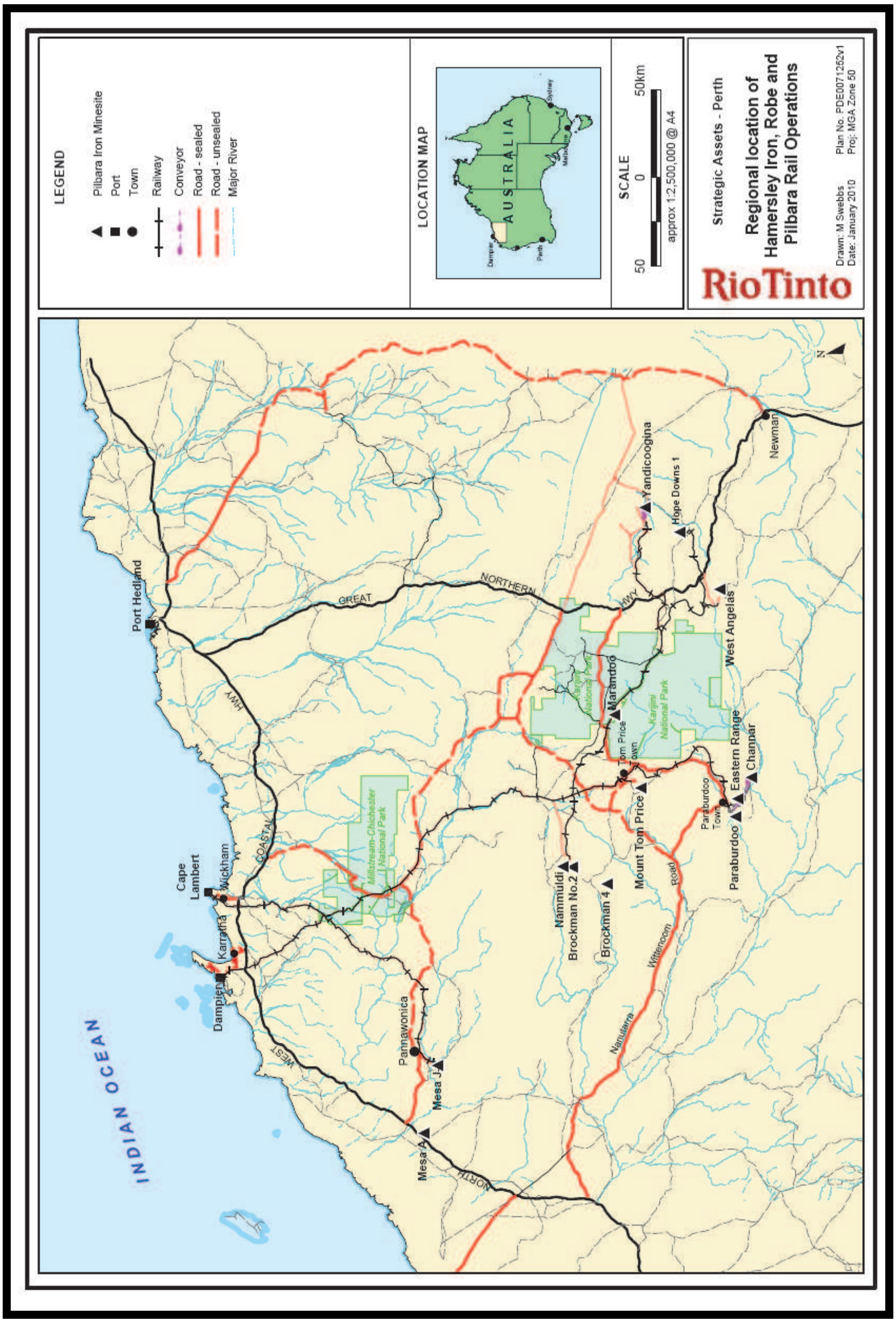

Fig. 1. The location of RTIO's Pilbara operations.

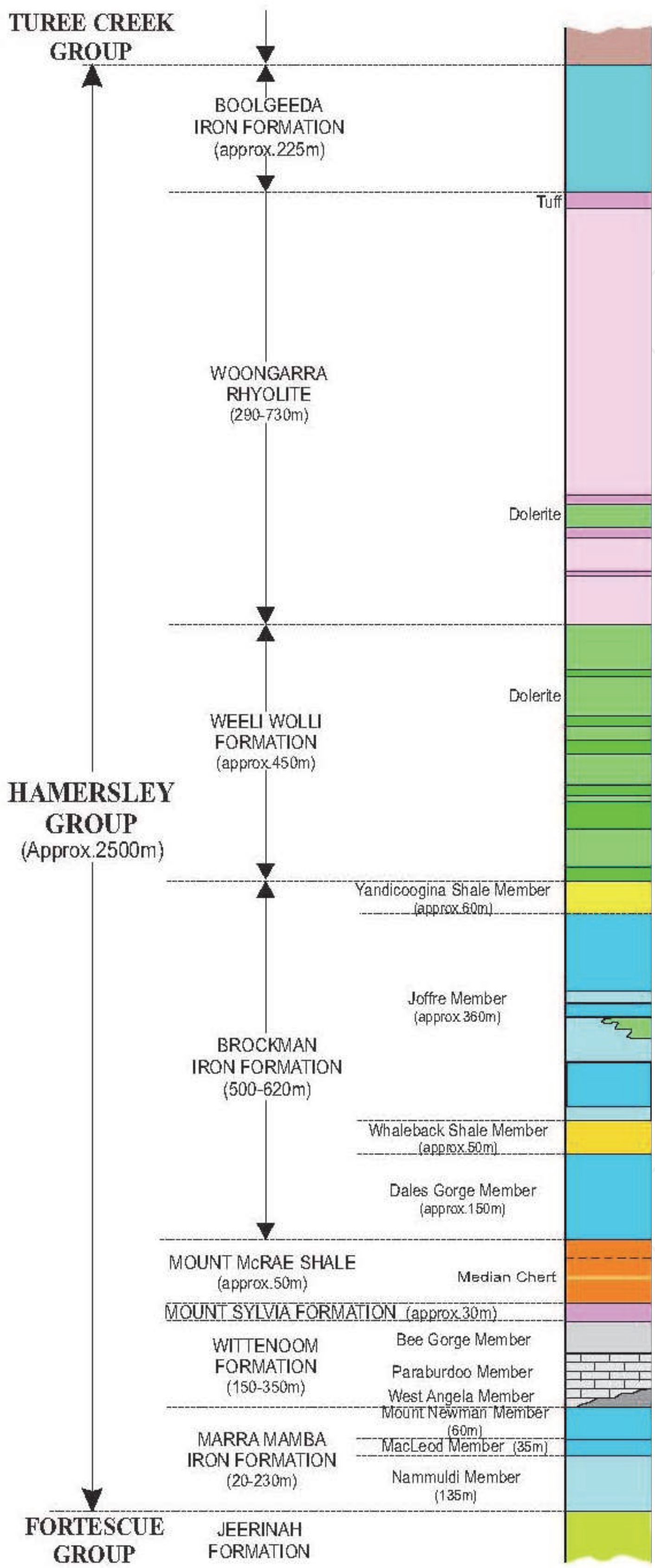

Fig. 2. Stratigraphic column of the Hamersley Group.

Enriched Marra Mamba Formation ore is most commonly found in the Newman member and whilst carbonaceous black shale is not typically associated with these units, pyrite can be found in all three members of the Marra Mamba Formation.

Detrital Iron Deposits (DIDs) and Channel Iron Deposits (CIDs) occur where enriched BIF has been exposed at the ground surface and material has been eroded and/or transported and redeposited. Detrital iron ore units, including unconsolidated scree, hematite conglomerate and CIDs of pisolite also occur in alluvial valleys. Sulfidic material can be associated with carbonaceous lignites and siderite interbedded with the iron ore deposits.

3. Corporate guidance

A number of Rio Tinto and RTIO documents are relevant for the management of AMD at mine sites (Fig. 3). There are 10 Environmental standards that are regularly audited against for compliance. Non compliance is tracked as audit actions within Rio Tinto. The ARD Standard applies to the full mine life cycle from exploration through to post-closure. It covers planning, implementation and operation, and performance monitoring. Rio Tinto have also embarked on an extensive risk review process that involved internal and external geochemical and hydrogeological experts visiting every Rio Tinto mine and project site with a significant potential AMD risk. Sites are initially screened using the Rio Tinto Hazard Screening Protocol to identify those mine sites with a significant potential AMD risk (Richards *et. al.* 2006). The risk reviews provide commentary on how each site is managing the hazard, identifies areas that need further investigation, and identifies management improvements needed to reduce the overall risk. Action plans are developed and tracked within Rio Tinto based on the findings from the risk reviews (An AMD risk review was completed in 2005 at the Pilbara operations).

In response to the Rio Tinto Standards, RTIO developed a mineral waste strategy and subsequently developed the Mineral Waste Management Plan (MWMP) that is applicable for every Pilbara mine site. This plan has two major sections. The first section describes the actions to be taken before mining commences at resource drilling, order of magnitude studies, pre-feasibility studies, feasibility studies to mine development. The second section of the plan describes the actions to be taken during mine operations and includes planning, operational and monitoring considerations. Extensive guidance is provided within the appendix of the plan including:

- Hyperlinks to all previous mineral waste related reports;
- Detailed description of known geological risk;
- Instructions for the inclusion of mineral waste information in the Resource block models;
- Analysis of mineral waste geochemical risk;
- Analysis of unconsolidated sediment geochemical risk; and
- Site water quality compliance criteria.

This plan is relevant for all RTIO mines in the Pilbara and is used to regularly monitor and assess AMD risk. The requirement for a risk assessment is an action within the plan.

If the risk assessment and work undertaken to comply with the MWMP identifies a significant AMD risk then the Spontaneous Combustion and ARD (SCARD) management plan needs to be implemented at the mine site. This plan describes the actions that need to be taken by long term planning, site planning, geology, survey, operational planning, blasting, hauling, hydrogeology, environment, health and safety and the mineral waste management team to reduce AMD risk at the mine site. Regular meetings are held at the mine with a representative from each group to discuss compliance with the plan and AMD risk. Extensive guidance is provided within the appendix of this document and includes:

- Hyperlinks to all previous mineral waste related reports;
- Detailed description of known geological risk;
- Dump designs;
- Rehabilitation and closure; and
- Contingency planning

Links are made in the SCARD management plan to the site specific documents for each mine site. These documents are mostly safe work procedures and health guidance notes that are specific to individual operations.

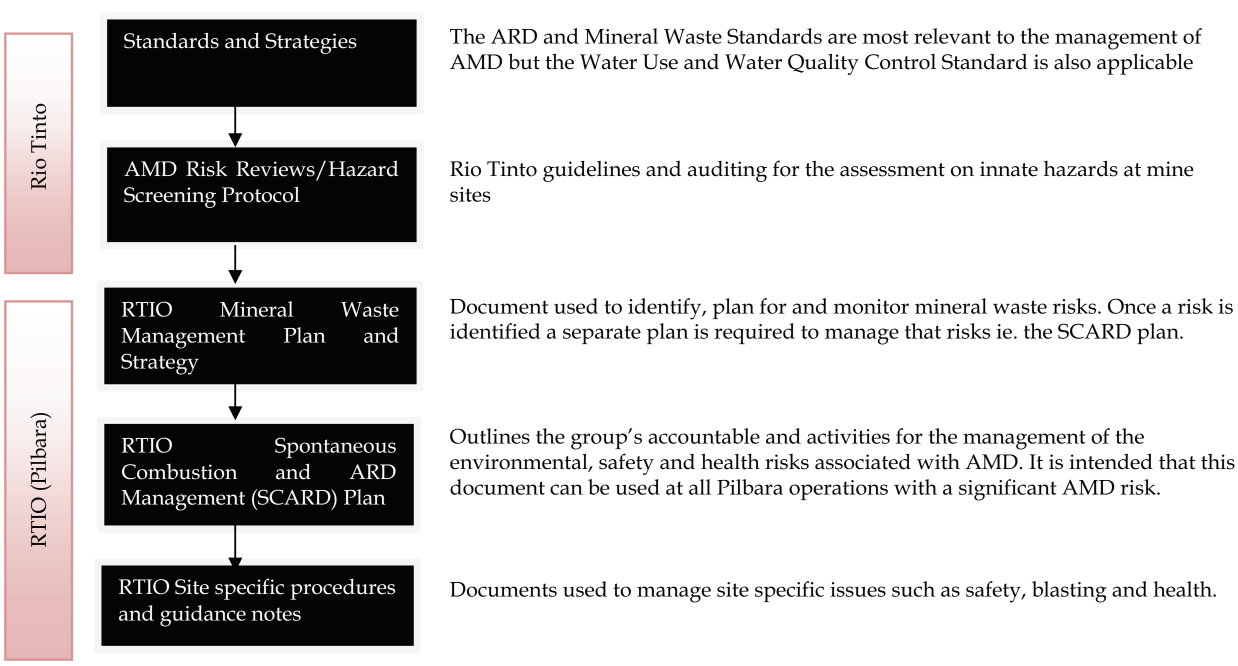

Fig. 3. Significant corporate guidance documents from Rio Tinto and RTIO for the management of AMD.

4. Risk assessment process

A thorough AMD and geochemical risk assessment enables the study team to analyse the issues, prioritise and make informed decisions. Continual awareness of risk management enhances and encourages the identification of greater opportunities for continuous improvement through innovation (AS/NZS ISO 31000:2009). Risk assessment also assists decision-makers to deal with uncertainty. The risk assessment process is designed to minimise uncertainty associated with potential and actual risks and hazards.

The objectives of the RTIO AMD and geochemical risk assessment process are specifically:

- To identify the hazards and resultant risks to the environment from the project as a whole;
- To identify opportunities to manage or avoid AMD upfront;

- To provide a rigorous basis for decision making and planning;
- To evaluate and prioritise the risks and identify management measures to mitigate the risks;
- To reduce unexpected occurrences;
- To reduce business risk and operational expense;
- To enhance due diligence studies, governance, stakeholder relationships and business reputation;
- To improve the health and safety of employees and the public;
- To identify research and development opportunities; and
- To minimise long term post closure risks, liabilities and environmental impacts.

There are four stages to the RTIO AMD and geochemical risk assessment for a deposit. The first stage can be completed by anyone within the business possessing good knowledge of the deposit. However the next three stages of the risk assessment require specialist AMD expertise. Progressively more knowledge is required through each of the stages to analyse the risk. Rio Tinto and RTIO retain much of this expertise internally.

4.1 Stage 1: preliminary AMD hazard score

During the order of magnitude or exploration phase of a mining project a preliminary assessment of AMD risk can be made based on the guidelines provided by Rio Tinto. This Hazard Screening Protocol ranks the hazard at a site based on the innate physical and chemical setting and no commentary is provided on the sites management measures. Readily available data is used to assess the likelihood for a significant AMD source at a site, as well as determining if there are dispersal pathways that could create significant down gradient environmental impacts. Numerical values are assigned for each of the following categories encountered at each site, according to a rating of relative influence:

- Geology (45%)
- Ore deposit type (30%)
  - Host and country rock neutralisation potential (10%)
  - Known ARD issues on site (5%)
- Incipient ARD Risk (5%)
  - Operational age (5%)
- Scale of Disturbance (25%)
  - Total waste stored on site (15%)
  - Footprint of disturbed area (10%)
- Transportation pathways (10%)
  - Water availability (7%)
  - Metal release to the environment (3%)
- Sensitivity of the receiving environment (15%)
  - Proximity to perennial/ephemeral water bodies (5%)
  - Alkalinity of water body or groundwater (5%)
  - Distance to closest protected/permanently inhabited area (5%)

A group of 10 experts were involved with the development of these factors and their weightings. The weighting factors were further refined by ranking a series of well known mines and ensuring it corresponded with the professional judgment of those experts involved.

Some modifications have been made to the broad Rio Tinto Hazard Score to make it more applicable for the Pilbara. These changes and a general description of the major factors are in the following sections. An example of a preliminary AMD hazard score assessment for a site is demonstrated in Fig. 4.

Project Name	Example site
Assessment Date	12/11/2010
Compiled by	Ros Green
Final ARD Hazard Assessment	MODERATE

Version Date: 5/03/10
Version Number: 2

RTIO AMD Hazard Score

1. Preliminary Assessment (Order of Magnitude/Exploration)

A. Preliminary Geology Hazard

	Select Relevant Option Below	Score	Option Details
Ore Deposit Type	C) Enriched Marra Mamba Formation and Joffre Member, and/or channel and detrital ore bodies mined below the water table (un-oxidised lignite and black shales other than Mt McRae may be present). Enriched Dales Gorge Member mined above the water table only	14	No PAF material expected
Host & Country Rock Neutralising Potential	None (<5%)	10	Minor calcrete in project area
Brownfield's / Greenfields	Brownfield		
Known AMD Issues on Site	No	0	
		Geology Hazard Score	24

Complete following sections

B. Incipient AMD Risk

	Select Relevant Option Below	Score
Operation Age	< 5 years	5

*By default, all new projects should receive a <5 years value

C. Scale of Disturbance

	Select Relevant Option Below	Score
Total Waste Stored	50 - 250 million tonnes	5
Footprint	250 - 1000 hectares	6

D. Transport Pathways

	Select Relevant Option Below	Score
Project / Exploration?	No	
Precipitation / Areal Potential Evapo-transpiration Ratio	1/10 to 1/3 ratio_mining below the water table in a rock mass that is connected to a regionally significant aquifer	3

*All new projects should respond Yes to Project / Exploration

E. Sensitivity of Receiving Environment

	Select Relevant Option Below	Score
Distance to Perennial Water Bodies	>2000 metres	0
Distance to Ephemeral Water Bodies	>2000 metres	0
Alkalinity	>35 mg/L	1
Distance to closest protected / permanently inhabited area	<500 metres	5

Preliminary Hazard Assessment

Preliminary Hazard Score	49
Preliminary Risk Assessment	MODERATE

Fig. 4. Example of the use of preliminary AMD Hazard score to assess a site.

4.1.1 Geology

Most RTIO deposits in the Pilbara are ore bodies that exist under reducing conditions but whose genesis is not directly related to sulfide mineralisation. Supergene enriched BIF or

Detritals that are above the water table and have been exposed to long term weathering are unlikely to contain sulfides within the ore however sulfide bearing shale or lignite may be inter-bedded with or lie stratigraphically below the ore body. The risk ranking score for the RTIO deposits in the Pilbara assigns a higher risk to below water table mining (Table 1). Mining of ore within the Dales Gorge Formation is assigned a higher score than other ore body stratigraphies due to the underlying and typically reactive black MCS.

Ore Deposit Type	Score
A) Formation by active surficial processes in equilibrium with the atmosphere.	0
B) Enriched Marra Mamba Formation or Joffre Member, and/or channel and detrital ore bodies mined above water table only (no Mt McRae Shale present and all rock types likely oxidised).	7
C) Enriched Marra Mamba Formation or Joffre Member, and/or channel and detrital ore bodies mined below the water table (un-oxidised lignite and black shales other than Mt McRae may be present). Enriched Dales Gorge Member mined above the water table only.	14
D) Enriched Dales Gorge Member mined below the water table (un-oxidised Mt McRae shale likely present)	19
E) Formation is directly associated with low-grade (< roughly 10 % total sulphur) acid generating sulphide mineralisation (not applicable to Pilbara Iron deposits).	23
F) Formation is directly related to high-grade (> roughly 10% total sulphur) or very reactive acid generating sulphide mineralisation (not applicable to Pilbara Iron deposits).	30

Table 1. Hazard scores based on the geology of the deposit.

Enriched and un-enriched BIF mined in the Pilbara typically has a low neutralising potential. Shales also typically have low neutralising potential. However calcretes mined in Detrital deposits can have readily available neutralising potential (Acid Neutralising Capacity or ANC of 265-660 kg H_2SO_4/t). In addition dolomite within the Wittenoom Formation (ANC of 301-885 kg H_2SO_4/t), carbonaceous BIF (ANC of 134-333 kg H_2SO_4/t) and Dolerites (ANC of 63-92 kg H_2SO_4/t) can offer some readily available neutralising potential. In most cases the risk assessment score for neutralising potential for Pilbara deposits is low.

4.1.2 Incipient AMD risk

Since AMD may take many years to manifest depending on the aridity of the climate and the host rock neutralising potential the age of the operation provides important information on the likelihood of AMD. New operations or a significant change to an existing operation (such as the recent initiation of mining below the water table) will be assigned the highest score.

4.1.3 Scale of disturbance

There is a greater potential for a large contaminant flux into the environment for larger masses of material exposed and therefore a higher score is given to mine sites with a large mass of mineral waste or a large disturbed footprints associated with waste disposal or open pits.

4.1.4 Transportation pathways

The ratio of precipitation to evapotranspiration is used as a proxy for the amount of water that is available to transport sulfide oxidation products from their point of production to the down gradient receiving environment. Within the Pilbara region the mean annual rainfall is typically 375 mm and annual evaporation varies from 3,000 to 3,600 mm. In arid climates such as the Pilbara the annual precipitation is much lower than the potential evapotranspiration rates. Most mines in the Pilbara have a precipitation to evaporation ratio of 1/10 to 1/3. To account for greater water availability and potential for contamination migration, ore bodies located below the water table are assigned a higher score than ore bodies located above the water table (Table 2).

Average local precipitation divided by areal potential evapotranspiration	**Existing operations**	**Exploration / Development**
< 1/10 ratio: mining above the water table exclusively	0	0
< 1/10 ratio: mining below the water table in an aquitard or an isolated aquifer	1	2
< 1/10 ratio: mining below the water table in a rock mass that is connected to a regionally significant aquifer	2	3
1/10 to 1/3 ratio: mining above the water table exclusively	1	2
1/10 to 1/3 ratio: mining below the water table in an aquitard or an isolated local aquifer	2	3
1/10 to 1/3 ratio: mining below the water table in a rock mass that is connected to a regionally significant aquifer	3	5
1/3 to 1/2 ratio	3	5
1/2 to 1.5/1 ratio	6	8
> 1.5/1 ratio	7	10

Table 2. Hazard scores based on the precipitation and potential evapotranspiration for the deposit.

4.1.5 Sensitivity of the receiving environment

The environmental sensitivity is assessed by assigning a score for the proximity to perennial and ephemeral water bodies, the buffering capacity of the receiving water and the proximity to protected or permanently inhabited areas.

4.2 Stage 2: technical AMD and geochemical risk assessment report

The identification of potential AMD issues at the exploration and feasibility phases is critical, as these mine planning phases are often linked with community consultation, environmental impact assessment and regulatory approvals. During feasibility studies for new mine sites there is a requirement in the Mineral Waste Management Plan for a detailed AMD and geochemical risk assessment report to be completed for those sites that scored moderate or high in the preliminary AMD Hazard Score. This report assesses the following information:

4.2.1 Background information

Background information on the sites geology, climate, hydrogeology, surface water and surrounding environment are necessary to understand the risk and potential impacts.

4.2.2 Sulfur distribution (drill hole data interrogation)

The total sulfur concentration is measured in most drill hole assays for a deposit and this data can be interrogated to assess the AMD risk.

4.2.2.1 Observed pyrite

The number of pyrite observations in each stratigraphic unit can be useful for assessment of risk, however this assessment can not be used alone due to the difficulty in observing pyrite in some samples depending on drilling method or the nature of the material.

4.2.2.2 Total sulfur analysis

Extensive geochemical, Acid Base Accounting (ABA) and Net Acid Generation (NAG) test characterisation work has found that a total sulfur concentration of 0.1% is the most appropriate boundary between non acid forming and potentially acid forming black shale. For other lithologies such as BIF and Detritals a 0.3% total sulfur concentration is the most appropriate boundary. However, these boundaries need to be re-confirmed for each new deposit to ensure they are appropriate.

The number of samples in each lithology with total sulfur concentrations exceeding 0.1% or 0.3% is evaluated to identify high risk lithologies. Selective management of some higher sulfur rock masses may not be needed in some circumstances depending on the geology and overall percentage of sulfur in the material to be disturbed by mining. It may also be difficult to define mineable units of some lithologies with low elevated sulfur percentages that are scattered within the lithology.

It is useful to look at the spatial distribution of elevated sulfur material within the pit shell using three dimensional software (Fig. 5). Occasionally elevated total sulfur concentration can be found within metres of the surface and in these cases it is likely that the sulfur represents sulfates rather than sulfides. At some mine sites (not known at RTIO Pilbara mine sites) this could also be due to acid sulfate soils.

4.2.2.3 Drillhole sulfur analysis considering proposed pit shell

The previous analysis used all drill hole data for the deposit and does not account for those materials that ultimately fall within the pit shell. Therefore an analysis of sulfur values within the pit shell is also undertaken (Table 4). Occasionally high sulfur values are found near the deposit but this material will ultimately not be mined. The previous analysis can be used to identify this material and it is important to consider this for any pit shell changes or

Strand-tag group	**Total samples assayed for S**	**Number of samples with S>0.1%**	**Number of samples with S>0.3%**	**Percentage of total samples with S>0.1%**	**Percentage of total samples with S>0.3%**
CLA	568	2	0	0.35	0.00
CAL	704	3	2	0.43	0.28
DET waste	1,170	27	6	2.31	0.51
DET mineralised	526	2	0	0.38	0.00
DOR	53	2	0	3.77	0.00
WD waste	280	0	0	0.00	0.00
ANG waste	879	6	6	0.68	0.68
ANG mineralised	154	0	0	0.00	0.00
N2U BIF	78	1	1	1.28	1.28
N2L BIF	106	0	0	0.00	0.00
NE1 BIF	264	0	0	0.00	0.00
NEW mineralised	895	1	1	0.11	0.11
NEW HYD	200	0	0	0.00	0.00
MAC BIF	192	12	8	6.25	4.17
MAC mineralised	68	1	0	1.47	0.00
MAC HYD	77	5	0	6.49	0.00
NAM BIF	59	8	1	13.56	1.69
UNKNOWN	1	0	0	0.00	0.00
Total number of samples assayed		6,274	6,274		
Total number of samples with S>0.1%/0.3%		70	25		
Percentage of total with S>0.1%/0.3%		1.12	0.4		
Total number of waste samples		4,353	4,353		
Total number of waste samples with S>0.1%/0.3%		61	24		
Percentage of total waste samples with S>0.1%/0.3%		1.40	0.55		

Table 3. An example of total sulfur analysis for a deposit.

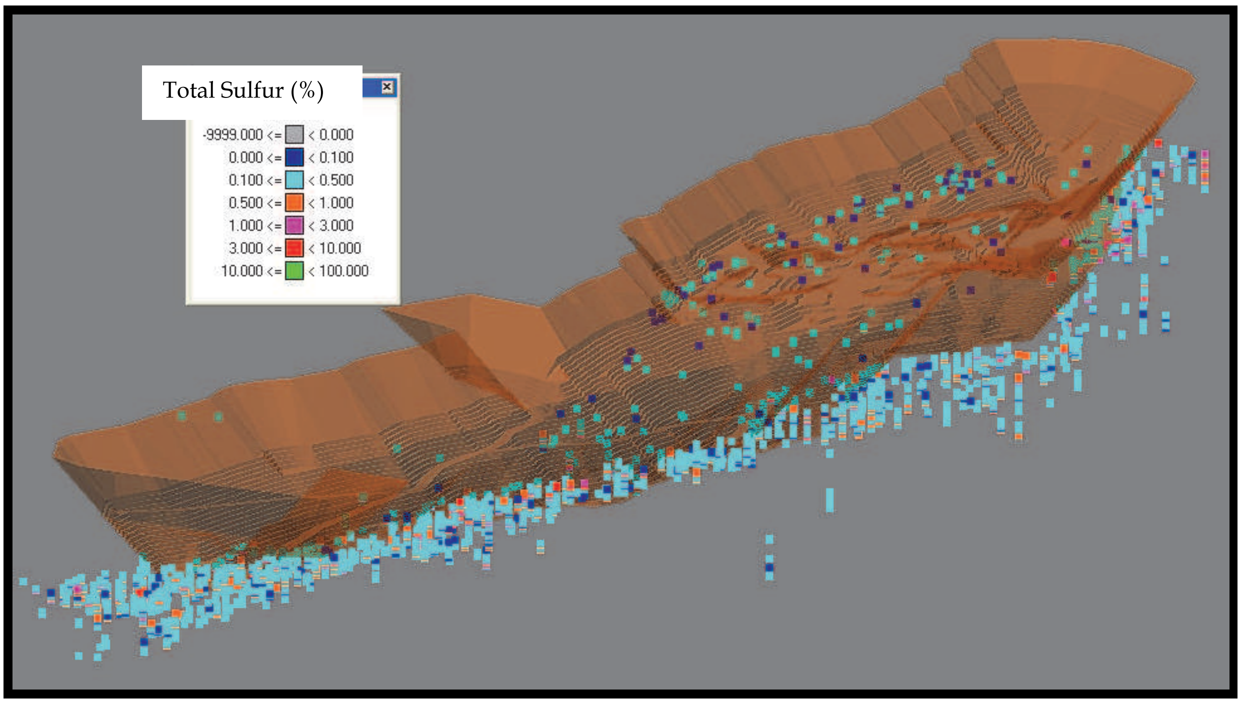

Fig. 5. An example of the spatial distribution of total sulfur (≥ 0.1%) in drill hole composites and the pit shell.

if there is any dewatering activity. During dewatering sulfides in the pit wall may become unsaturated and then once mining has finished and the water table recovers contaminants could be mobilised.

Total number of samples assayed for S within pit shell:	34,478
Number of samples with S>0.3% within pit shell:	97
Percentage of total with S>0.3% within pit shell:	0.28%
Total number of samples assayed for S within pit shell and BWT (580 mRL):	22,531
Number of samples with S>0.3% within pit shell and BWT:	92
Percentage of total with S>0.3% within pit shell and BWT:	0.41%

BWT= Below Water Table

Table 4. An example of the total sulfur value greater than 0.3%, within a deposit filtered using the proposed final pit design

4.2.3 Total sulfur analysis within the mining model

Sulfide risk categories have been created in the mining model so the tonnes of sulfidic material can be predicted. The total sulfur concentration also exists within the mining model and can be interrogated for sulfur risk by lithology and as a function of waste rock production over time (Table 5). Determining the tonnes of sulfidic material is important for assessing which lithologies present the greatest risk for AMD and for determining if there is adequate inert or neutralising material available for the proposed dump, co-disposal, encapsulation or cover designs.

	Sulfur bin (%)	ALLUVIALS	DETRITALS	ANG	N2U	N2L	N2U	NE1	NE1C	MAC	UNKNOWN	Grand Total
High Grade	0.05	367,915		12,515,739	134,136,666	106,449,580	134,136,666	63,297,998	18,395,043	512,184	19,615	335,694,741
	0.1	10,438		434,940	3,527,892	5,895,381	3,527,892	5,883,028	1,869,099	76,669		17,697,448
	0.15			89,007	125,894	329,666	125,894	380,026	187,424	6,851		1,118,868
	0.2				25,129	14,067	25,129	21,724	13,664			74,584
	0.25					7,777			7,798			15,575
	0.3					6,868			7,636			14,504
High Grade Total:		**378,354**		**13,039,686**	**137,815,581**	**112,703,339**	**137,815,581**	**69,582,776**	**20,480,663**	**595,705**	**19,615**	**354,615,718**
Low Grade	0.05	525,632	243,426	13,697,983	24,998,317	26,039,298	24,998,317	25,852,967	12,013,460	1,965,534	167,826	105,504,441
	0.1	20,748	51,109	1,225,327	2,406,989	3,011,675	2,406,989	4,946,674	1,539,043	675,792	17,173	13,894,531
	0.15		8,540	168,303	320,199	468,331	320,199	617,400	231,352	318,761		2,132,888
	0.2		8,456		17,709	63,159	17,709	112,211	73,648	6,408		281,592
	0.25					12,988		31,109	6,855			50,952
	0.3					13,195		19,355	6,541			39,090
	0.35							6,583	6,903			13,486
	0.4							7,151				7,151
Low Grade Total:		**546,380**	**311,532**	**15,091,613**	**27,743,214**	**29,608,646**	**27,743,214**	**31,593,450**	**13,877,802**	**2,966,495**	**184,999**	**121,924,130**
Waste	0.05	317,191,667	8,164,714	355,124,059	110,429,507	120,723,550	110,429,507	573,271,969	54,776,561	8,126,994,393	98,240,911	9,764,917,331
	0.1	4,191,456	4,256,425	25,456,407	1,364,124	1,475,777	1,364,124	9,860,334	953,480	73,114,232	900,518	121,572,753
	0.15	321,359	572,522	5,706,208	278,130	307,462	278,130	646,876	385,653	12,420,470	29,675	20,668,355
	0.2	15,280	48,335	1,868,722	38,511	130,478	38,511	85,301	50,055	6,950,247		9,186,929
	0.25			496,207	6,414	35,441	6,414	23,945	37,976	1,918,752		2,518,735
	0.3			265,838				13,098	6,425	746,054		1,031,415
	0.35			168,353		6,245		13,020	6,627			194,246
	0.4			50,948		6,159		6,259				63,366
	0.45			53,027								53,027
	0.5			19,681								19,681
	100								12,649			12,649
Total Waste:		**321,719,762**	**13,041,996**	**389,209,451**	**112,116,686**	**122,685,114**	**112,116,686**	**583,920,800**	**56,229,426**	**8,222,144,148**	**99,171,104**	**9,920,238,487**
Grand Total:		**322,644,495**	**13,353,527**	**417,340,750**	**277,675,481**	**264,997,099**	**277,675,481**	**685,097,026**	**90,587,892**	**8,225,706,347**	**99,375,718**	**10,396,778,335**

Table 5. An example of estimated volumes of material predicted to be mined at a deposit (for all wet and dry material, in tonnes)

4.2.4 Potential sulfide exposures on the final pit walls

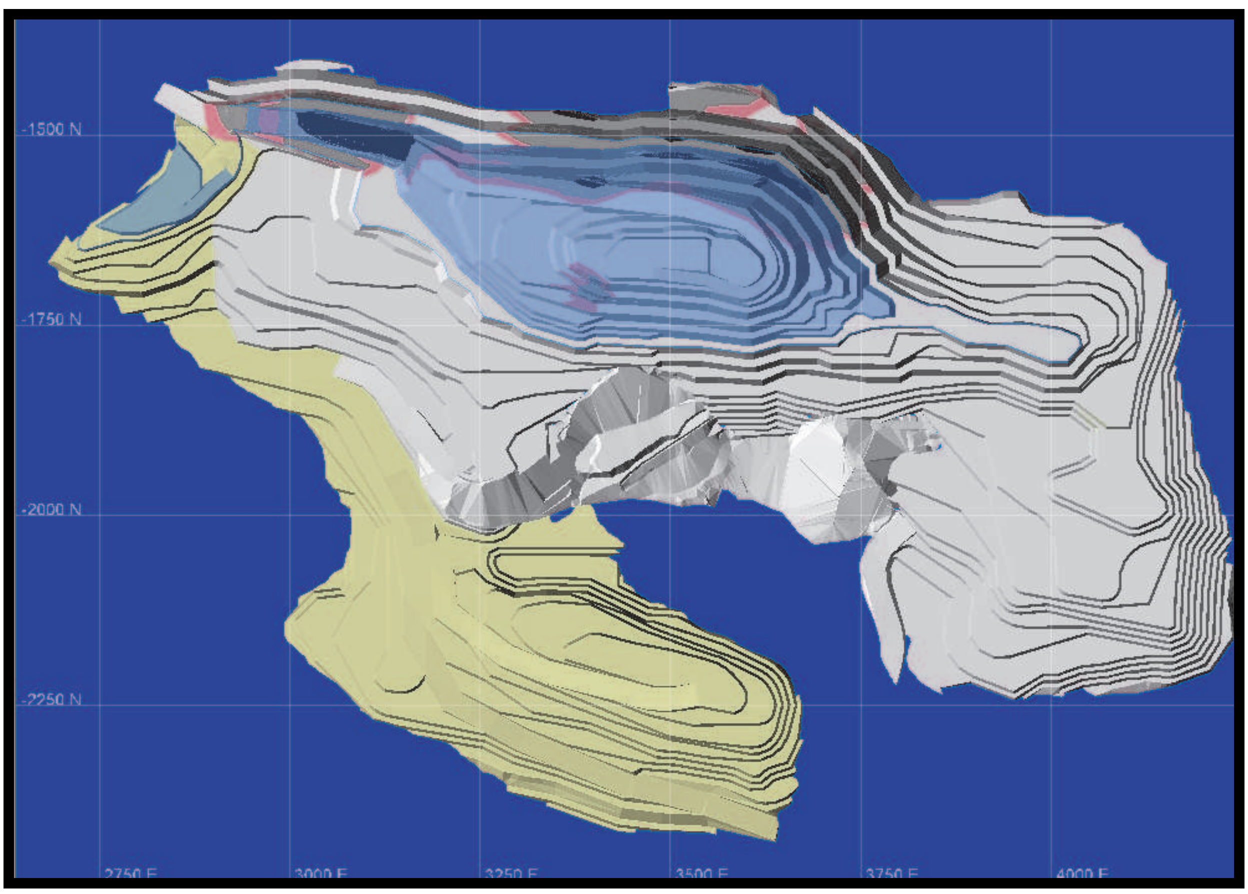

Fig. 6. An example of surface exposures of PAF material relative to the pit void catchment (light grey, where yellow represents the area which is unlikely to contribute to surface water runoff). Oxidised material = pink, low risk = dark grey, high risk = black and blue represents the pre-mining water table.

Predicting the surface area and location of Potentially Acid Forming (PAF) material at mine closure provides information on the risk of an acidic pit lake developing at mine closure (Fig. 6). This information can be used to dictate necessary backfill levels, surface water diversions or be used in final void water quality modelling studies to predict the evolving water quality of the pit lake. Predicting the surface area and location of PAF material year by year can also be useful in regard to predicting the quality of the surface water runoff generated during mining. This information could be used to limit PAF exposures during typically high rainfall periods and thereby reduce the amount of potentially contaminated water requiring treatment.

4.2.5 Acid base accounting test work results

Recognised ABA and NAG analytical techniques provide confirmatory information on typical Non Acid Forming (NAF)/PAF cutoffs based on total sulfur (AMIRA 2002; DoITR 2007; Gard Guide 2009; Price 2009). The low capacity to generate acidity can also be identified. Sometimes it can be difficult to determine if a sample is NAF or PAF and an uncertain classification can be assigned. These tests can also provide useful information on the neutralising capacity of a sample, the amount of potential acidity and its rate of release, other contaminants that are enriched and could mobilise into water and intrinsic oxidation rates. RTIO also undertake additional tests to determine the reactivity of the material with nitrogen based explsoives. The premature detonation of explosives with nitrogen based explosives is a safety risk for some materials and inhibited explosives are used when necessary to reduce this risk.

4.2.6 Chemical enrichment

4.2.6.1 Solid enrichment

Trace element data (Al, As, Ca, Cl, Co, Cr, Cu, Fe, Pb, Mg, Mn, Ni, P, K, S, Si, Na, Sr, Ti, V, Zn and Zr) is routinely collected from drill hole samples and is analysed as part of the AMD and geochemical risk assessment report to determine chemical enrichment. The extent of enrichment is reported as the Geochemical Abundance Index (GAI), which relates the actual concentration with median crustal abundance (Bowen 1979) on a log 2 scale. The GAI is expressed in integer increments where a GAI of 0 indicates the element is present at a concentration similar to, or less than, median crustal abundance and a GAI of 6 indicates approximately a 100 fold enrichment above median crustal abundance. As a general rule, a GAI of 3 (about a ten fold enrichment) or greater signifies enrichment that warrants further examination.

In addition, to this detailed look at assay information in the drill hole database, chemical enrichment is determined for each major lithology type during major drilling campaigns. The GAI is calculated for each lithology and additional less commonly enriched elements are also periodically analysed (ie. Ag, B, Be, Cd, F, Hg, Mo, Sb, Se, Th and U). A table of trigger values has been generated within the Mineral Waste Management Plan and this table can be used for quick comparison of concentrations (rather than calculating the GAI each time).

4.2.6.2 Liquid extracts

Solid enrichment of an element does not necessarily pose environmental risks unless the element is also bio-available and/or can be mobilised into surface and groundwater. A

Analyte	mg/kg or ppm	%
Ag	0.59	
As	13	
B	85	
Ba	4,243	0.4
Be	22.06	
C	20,000	2
Cd	0.93	
Cl	1,103	
Co	170	
Cr	849	
Cu	424	
F	8,061	0.8
Hg	0.42	
Mn	8,061	0.8
Mo	10.2	
Ni	679	
P	8,485	
Pb	119	
S	1,000	0.1
Sb	1.70	
Se	0.42	
Sn	19	
Sr	3,140	0.3
Th	102	
U	20	
V	1,358	
Zn	636	

Table 6. Trigger values based on the median crustal abundance. [1]

liquid extract test is undertaken to provide a quick indication of contaminant mobility. A solid and liquid water extract (1:2 ratio respectively) is thoroughly mixed and left overnight before the liquor is siphoned off and then the pH and Electrical Conductivity (EC) is measured. The liquor is then filtered (through a 45 µm filter), acidified and analysed. The average concentration for each element from each lithology is then compared against background concentrations, ANZECC and ARMCANZ (2000) stock water guidelines or NHMRC (2004) Australian drinking water guidelines depending on the likely end water use. The liquid extracts are a quick indication of the:

- Leachability of metals under the prescribed laboratory conditions (crushed samples, pure water as a leachant and a known water-to-rock ratio); and
- The condition of the sample with respect to weathering (ie if the sample is 'fresh', or if it is PAF but has not yet acidified, the test may not necessarily identify all the metals of concern in the longer term). However, while these laboratory tests may be used to infer which contaminants might be released from the materials under laboratory conditions, they do not necessarily reflect the metal concentrations that may occur in leachates generated in the field.

The overall objective of the geochemical analysis is to provide a quick first pass test to determine whether the waste material to be mined is inert. If geochemical test work indicates that the waste lithology may not be inert then further analysis such as column leach or humidity cell experiments are undertaken. These kinetic tests are run over many months or years.

[1] Triggers were derived from the median crustal abundance (Bowen 1979). The values are equivalent to a GAI of 2.5 and when rounded up 3 (i.e. $10^{(3x\log(2))x1.5x(\text{crustal abundance})}$). This is equivalent to an 8.5 times increase above the median crustal abundance.

4.3 Stage 3: detailed AMD hazard score

The technical AMD and geochemical risk assessment report provides sufficient information to complete the detailed AMD Hazard Score Assessment. The RTIO AMD Hazard Score was developed to ensure a consistent assignment of risk for each deposit and operation at RTIO's Pilbara operations.

2. Detailed Assessment (Pre Feasibility/ Feasibility/Mining)

This assessment should be completed by an AMD expert

Pit	**Example site - BWT**		
F. Geochemical Hazard (Interrogate the drill hole database)			
Geochemical Summary			
Number of total sulfur concentrations collected	87,341		
Lithologies assayed	All major material types within the pit shell		
Likely PAF materials in bulk	**Nil**	If relevant, list lithologies	
	Comments	**Example site - BWT**	**Other RTIO mine sites within similar lithology**
Number of acid base accounting (ABA) samples	Due to lack of sulfides found no ABA could be undertaken	0	38
Number of column leach experiments	Due to lack of sulfides found no ABA could be undertaken	0	3
Score			
	Select Relevant Option Below	**Score**	**Option Details**
Waste sulfur risk	Total number of waste samples with S>0.1% is less than 3%	0	For total drillhole samples, 0.78%; for waste drillhole samples, 0.71%
Ore grade sulfur risk	Total number of ore grade samples with S>0.1% is less than 3%	0	
Spatial distribution of sulfur	Sulfur scattered throughout the pit and through numerous lithologies	3	Unlikely that sulfur represents sulfides
Chemical enrichment	Enrichments of contaminants that are unlikely to mobilise into groundwater	1	As, Fe, Sn enriched but unlikely to be mobile
G. Mine Planning Hazard			
	Select Relevant Option Below	**Score**	**Option Details**
PAF material management	No special waste management needed	0	
Bulk NPR (Mass of neutralising material x mean ANC) / (Percent of lithology greater than 0.1% x tonnes of lithology x mean sulfur concentration for all data greater than 0.1 x 30.6 + repeat for each PAF lithologies)	>3	0	estimated
PAF rock mass disturbed or exposed (waste tonnes with S>0.1%)/(total tonnes of waste)*100	< 3% of the total disturbed mass	0	No PAF material expected
Pit backfilling	Pit will be backfilled to above the post mining water table but below ground surface	2	Proposed
H. Water Management Hazard			
	Select Relevant Option Below	**Score**	**Option Details**
Dewatering volume	80-160 ML/day	2	Peak max. 100 ML/day
Surface water	Creek flow	7	
Water treatment during Operation	No water treatment or special management for AMD needed	0	
Final void management	No PAF rock exposures likely on final pit shell	0	
Combined Hazard Assessment			
Preliminary Assessment Score	49		
Detailed Assessment Score	15		
Combined Hazard Score	27		
Risk Ranking	**LOW**		

Fig. 7. Example of the use of the detailed AMD Hazard score to assess a site.

The preliminary AMD Hazard Score is relevant during order of magnitude or exploration studies where information is lacking however during pre-feasibility, feasibility, development or mining of a deposit a more refined, defensible and repeatable hazard assessment is required. The hazard assessment should lead to a consistent assignment of risk so that all personnel involved in project development understand the implications of each risk rating.

The ranking system outlined in the following section is designed to identify those orebodies, open pits and waste rock dumps which, though they may contain small amounts of PAF material, are unlikely to pose a risk to water quality or revegetation programs. No special waste or water management above that already required for inert materials would be required for these low risk sites. Conversely a high risk site could generate widespread AMD and environmental impacts without special management of waste rock and water during operation. Acidic pit lake formation would be near certain without extensive backfilling at closure. To control the potential AMD impacts from a high risk site, strategic changes to the life of mine plan would likely be justified. PAF materials would also probably require special management at moderate risk sites, but given sulfur contents and material balances, the management could be easily addressed at an operational/tactical rather than a strategic level.

The RTIO detailed AMD Hazard Score is specific for the Pilbara operations and can be used to compare the AMD risk of different operations against each other (Fig. 7). However, because it is specific to iron ore deposits in the Pilbara region, the hazard score is conservative and is likely to over-estimate the risk when compared against porphyry copper or some coal deposits. A summary of the different categories within the detailed AMD Hazard Score are discussed in the following sections:

4.3.1 Geochemical hazard

An assessment of the total sulfur content in waste and ore and the overall spatial distribution of sulfur in the deposit are used to provide a detailed geochemical hazard score. All data for this analysis should be derived from the drill hole database.

4.3.1.1 Waste sulfur risk

Waste sulfur risk	Score
Total number of waste samples with S>0.1% is less than 3%	0
Total number of waste samples with S>0.1% is between 3% and 10%, less than 0.5% of samples have S>0.3%	2
Total number of waste samples with S>0.1% is between 3% and 10%	7
Total number of waste samples with S>0.1% is greater than 10%	10

Table 7. Scores assigned to waste sulfur risk.

All total sulfur measurements for waste rock within the deposit or pit should be used to determine the waste sulfur risk. It is conservatively assumed that all total sulfur measurements represent sulfide minerals (i.e. pyrite) however it is likely in some deposits that sulfur near the surface is actually in the form of sulfate minerals (i.e. gypsum, alunite, schwertmannite, jarosite).

The number of samples per waste lithology with a total sulfur concentration greater than 0.1% can be calculated using strand/tag or geozone information however if this data has not been populated then stratigraphy logging can also be used. This value should be compared against the total number of waste samples assayed to determine the relative risk (Table 7).

4.3.1.2 Ore grade sulfur risk

Using a similar methodology to Section 4.3.1.1 the number of ore grade samples with total sulfur measurements greater than 0.1% should be compared against the total number of ore-grade samples to determine the relative risk (Table 8). Scores are lower for the sulfur characterisation of ore compared to waste due to most ore being transported away from the mine site.

Ore grade sulfur risk	**Score**
Ore grade material will not be stockpiled	0
Total number of ore grade samples with S>0.1% is less than 3%	0
Total number of ore grade samples with S>0.1% is between 3% and 10% but less than 0.5% of the samples have S>0.3%	2
Total number of ore grade samples with S>0.1% is between 3% and 10%	4
Total number of ore grade samples with S>0.1% is greater than 10%	5

Table 8. Scores assigned to ore grade sulfur risk.

4.3.1.3 Spatial distribution of sulphur

Spatial distribution of sulfur	**Score**
Sulfur scattered throughout the pit and through numerous lithologies	3
Sulfur concentrated within one or two lithologies (i.e. MCS and FWZ)	5

Table 9. Scores assigned to spatial distribution of sulfur.

High sulfide sulfur zones that are scattered throughout the deposit will be difficult to selectively manage compared to high sulfur zones confined to one or two lithologies. Overall sulfide oxidation within waste dumps that group all high sulfur material together will generally be lower than if high sulfur material is broadly intermixed with inert material. This is particularly true if the high sulfur material is encapsulated or covered with inert material. However, high sulfur material scattered throughout the deposit is also likely to be diluted as it is mined and it is possible that any neutralisation potential in the country rock or groundwater may have capacity to buffer the acidity released compared to the acidity released from a single large mass of high sulfur rock concentrated in one location. Typically within RTIO Pilbara operations the sulfur scattered throughout the deposit has low total sulfur concentrations (i.e. < 0.3%) and therefore this risk is deemed lower than that of sulfur concentrated within one or two lithologies (Table 9).

4.3.1.4 Chemical enrichment

The mean concentration for each element measured in the lithology should be compared to the average crustal abundance to determine if there is significant enrichment (Section 4.2.6). In some cases further test work (i.e. liquid extracts or kinetic leach experiments) may be necessary to assess the overall risk of an enriched element becoming mobile within surface water or groundwater aquifers (Table 10).

Chemical enrichment	**Score**
No enrichment of contaminants	0
Enrichments of contaminants that are unlikely to mobilise into groundwater	1
Enrichments of contaminants that are likely to mobile into groundwater	5

Table 10. Scores assigned to chemical enrichment risk.

4.3.2 Mine planning hazard

The mine planning hazard score is determined by analysing the mining model for the quantity of PAF material as delineated by a sulfide risk variable, the relative tonnes of neutralising material, and also considers the tonnes of material with elevated sulfur grades. Waste dump plans should also be assessed for risk to the receiving environment.

PAF material management

PAF waste dumps located in pit are more secure than disposal in above ground rock dumps (Table 11). In pit disposal is the preferred disposal location due to:

- Reduced risk of erosion exposing sulfides in the long term;
- Inhibiting convective oxygen transport because the waste is surrounded by relatively impermeable rock walls;
- Reduced footprint of the waste disposal facilities;
- Reduced volume of inert or net neutralising waste needed to encapsulate the sulfides; and
- The formation of acidic or hyper-saline pit lakes may be prevented if the pit can be filled to above the post-mining water table.

PAF material management	**Score**
No special waste management needed	0
PAF waste dumps will be in-pit	2
PAF waste dumps will be in pit and out of pit	4
PAF waste dumps will be out of pit	5

Table 11. Scores assigned to PAF material management.

4.3.2.2 Bulk neutralisation potential ratio

The Neutralisation Potential Ratio (NPR) can be used to provide a quick bulk assessment of the likelihood of alkalinity within other lithologies buffering any acidity produced (Table

12). It is unlikely that neutralisation will be 100% effective and geochemical characterisation may be necessary to confirm the characteristics of material at the site. The bulk NPR can be calculated by:
[mass of neutralising material x mean ANC]
[mass of acid producing material x mean potential acidity]
The bottom line of the equation is calculated by the sum of all acid producing lithologies:
[Lithology 1: percent of lithology with S greater than 0.1% x total tonnes of lithology x mean sulfur concentration of lithology for all samples with sulfur assay values greater than 0.1 x 30.6]
+
[Lithology 2: percent of lithology with S greater than 0.1% x total tonnes of lithology x mean sulfur concentration of lithology for all samples with sulfur assay values greater than 0.1 x 30.6]
+
[Lithology 3 etc]

Bulk NPR of entire rock mass to be disturbed or exposed	Score
<1	5
1 to 3	3
>3	0

Table 12. Scores assigned to NPR.

4.3.2.3 PAF rock mass disturbed or exposed

The tonnes of PAF rock mass disturbed can be calculated by extracting the tonnes of material with S>0.1% in the mining model or from sulfide risk variables that have been added to the mining model. If the sulfide risk variable is available then this should be used in preference to evaluate the total tonnes of material with S>0.1%. This analysis provides a more detailed assessment for the scale of disturbance which was addressed in the preliminary assessment (Table 13).

PAF rock mass disturbed or exposed	Score
< 3% of the total disturbed mass	0
3 to 10% of the total disturbed mass	5
> 10% of the total disturbed mass	10

Table 13. Scores assigned to PAF rock mass disturbed or exposed.

4.3.2.4 Pit backfilling

A pit that is backfilled when the mine is closed is likely to have a lower risk of AMD generation compared to an open pit (Table 14). Covering sulfide exposures will also reduce the risk of AMD.

4.3.3 Water management hazard

The water management hazard score is derived from an assessment of likely water discharge volumes and quality. The final void water quality is also considered as this can contribute significantly to the mine closure cost.

Pit backfilling	Score
Pit will not be backfilled	5
Pit will be backfilled below the post mining water table	4
Pit will be backfilled to above the post mining water table but below ground surface	2
Waste will be tipped over black shale exposures	2
Pit will be backfilled to ground level	0

Table 14. Scores assigned to pit backfilling scenarios.

4.3.3.1 Dewatering volume

Dewatering of mine voids is required to provide access to below watertable ore and to reduce geotechnical risk of slope failures. On mine closure there is potential for AMD generation as sulfides are rewetted by the recovering water table. A more detailed investigation would be required to quantify this risk (for example investigating the distribution of sulfur in the pit wall). A large dewatering campaign could also be more of a problem if the groundwater became acidic in the future owing to leaching of acidic material from pit walls (Table 15).

Water discharge	Score
No releases of water	0
0 to 80 ML/day	1
80-160 ML/day	2
> 160 ML/day	3

Table 15. Scores assigned to water discharge.

4.3.3.2 Surface water management

Surface water is likely to more significantly contribute to AMD generation than groundwater within the Pilbara. Therefore, the combined scores of an assessment of the pit surface area and the surface water catchment are greater than the score for dewatering discharge in Table 15 (Table 16). Surface water management plans and/or consultation with site personnel or RTIO hydrologists will be necessary to determine the risk of increased surface water runoff from the catchment above a pit or from a creek that has not been diverted around a pit.

Surface water	Score
Isolated pit	0
Catchment area above the pit	5
Creek flow	7

Table 16. Surface water assessment of the pit.

4.3.3.3 Water treatment during operation

Water requiring treatment during operation may also require treatment on mine closure. The cost during operation and mine closure may be significant (Table 17).

Water treatment during operation	Score
No water treatment or special management for AMD needed	0
Water treatment or special water management may be needed during operation	3
Water treatment or special management will be needed during operation	5

Table 17. Scores assigned to water treatment during operations.

4.3.3.4 Final void management

Large exposures of elevated sulfur material on the pit wall are more likely to generate an acidic pit lake on mine closure. Acidic voids are unlikely to be acceptable to the regulators on mine closure and therefore ongoing treatment or backfilling could be required (Table 18). Final exposures on the ultimate pit wall can be calculated using the final pit shell and sulfide risk variables or geology strands. The detailed AMD and geochemical risk assessment report should also investigate the position of this material relative to the post-mining water table (if available) (Fig. 6).

Final void management	Score
No PAF rock exposures likely on final pit shell	0
Less than 3% PAF exposed	2
3% to 10% PAF exposed	7
Greater than 10% PAF exposed	10

Table 18. Scores assigned to final void management.

4.3.4 Combined hazard assessment

The RTIO detailed AMD Hazard Score has been calibrated with data from the existing AMD and geochemical risk assessment reports, known risks at several mine sites and judgement of AMD experts.

The combined AMD hazard score is derived by adding the individual scores relating to the preliminary assessment, detailed geochemistry, mine planning and water management. A score of 30 or less receives a low AMD hazard ranking. These sites are the least likely to generate significant AMD or cause significant metals loading into the environment. A score between 30 and 50 receives a moderate hazard ranking. These sites are more likely to generate either significant AMD or circum-neutral pH contact waters with elevated salinity and/or metals content. A score of 51 to 65 receives a high AMD hazard ranking, and a score of 66 or higher receives a very high ranking. These sites pose a significant environmental, financial and/or reputational risk because of their potential to generate large AMD fluxes.

4.4 Stage 4: AMD risk assessment of management strategies

The final stage in the risk assessment process involves analysis of all possible scenarios, causes and potential impacts. An inherent risk is assigned based on consequence and likelihood. Inherent risk provides an indication of the "true" risk of the impact occurring when there are no controls in place to mitigate the risk. To score inherent risk it is assumed that the impact will occur and therefore the probability descriptors of almost certain, likely or possible should be used and unlikely or rare can not be used.

Some examples of inherent risks from AMD include:

- Sulfidic material within waste dumps generates AMD in surface and groundwater;
- Spontaneous combustion or convective gas transport within the dump causes dump instability;
- The final pit lake that develops once mining ceases is polluting, impacting local groundwater and fauna;
- Dewatered water develops into AMD and impacts on flora and fauna if it is disposed of within a creek;
- Sulfidic exposures on the pit wall react with rainwater to generate AMD within the pit causing health and environmental impacts; and
- Re-establishment of water table post mining causes dissolution of efflorescent salts resulting in increasing contaminant concentrations in groundwater.

A current risk is then assigned based on the implementation of controls and management measures. If necessary the residual risk is also addressed. Controls can be physical, procedural and behavioural. Some examples of controls that could be implemented to reduce risk include:

- Encapsulation of sulfidic material within inert material;
- Placement of covers over sulfidic material ie. store and release, shedding, alkalinity;
- Appropriate co-disposal of material with neutralisation potential;
- Acid water treatment or containment systems;
- Bunding to separate inert water from AMD;
- Training;
- Management plans and auditing for compliance against the plans; and
- Pit backfilling to above the post-mining water table or to cover PAF material exposed on the pit wall.

5. Conclusions

One of the key challenges facing the mining industry is the management of AMD, to minimise risks to human health and the environment. A crucial step in leading practice management of AMD is to assess the risk as early as possible, so that appropriate pro-active management strategies can be selected and implemented. This includes assessment of environmental, human health, commercial and reputation risks. RTIO have developed a four stage risk assessment process to thoroughly assess the risk of AMD:

1. Preliminary AMD Hazard Score
2. Technical AMD and geochemical risk assessment report
3. Detailed AMD Hazard Score
4. AMD risk assessment of management strategies

Progressively more knowledge is required through each of the stages to analyse the risk. All stages can be completed prior to mining and this allows the AMD risk to be fully evaluated before considerable investment or works have occurred. The upfront identification of risk means that options such as avoidance and appropriate management strategies can be appropriately explored. Effort is focused on pro-active prevention or minimisation rather than control or treatment whenever possible.

The quantitative AMD Hazard score means that a consistent assignment of risk is assigned to each deposit and operation. It is accompanied by a technical risk assessment completed by an AMD expert to ensure the quantitative score is reasonable. Finally the risk to human health and environment is assessed individually and then reassessed after appropriate management strategies have been implemented.

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