McArthur River Mine

Overburden Management Project

6

Materials Characterisation

Draft Environmental Impact Statement

6 Materials Characterisation

6.1 Introduction

During the mining process at McArthur River Mine (MRM), large quantities of overburden require removal to provide access to the orebody that is located deeper beneath the surface. Depending on the stage of mining, different overburden types with differing characteristics are mined and brought to the surface. Overburden is required to be managed depending on its characteristics. Some types may have potential impacts on the environment, whereas others provide useful resources for construction and rehabilitation. This chapter discusses the different material types mined at MRM and explains their properties and management requirements.

The chemical characteristics of overburden are the key focus of overburden management at MRM. Understanding these is important for the protection of environmental values downstream of the project area. The objective of overburden characterisation and classification is to establish geochemical criteria for the effective segregation of the various material types so that they can be managed appropriately. As a result, changes in overburden classification have a direct effect on the placement of overburden on-site. The geochemical understanding, prediction and identification of overburden at MRM has evolved significantly over the last decade, driven by advances in geochemical sampling and testing, evolving industry practice, stakeholder expectations and changing regulatory frameworks. This evolution in understanding and management is presented throughout this chapter. It presents the improvement of the overburden classification system over time, particularly since the Phase 3 Development Project Environmental Impact Statement (Phase 3 EIS), provides a description of the additional sampling and data that has informed this and discusses some of the key management opportunities that have been identified.

The technical reports that support this chapter have been included as **Appendix L – Kinetic Geochemistry Report** and **Appendix M – Static Geochemistry Report**.

6.1.1 Overburden Characterisation at MRM

The identification and appropriate management of different overburden types is an important part of mining operations at MRM. It relies on the accurate geochemical characterisation of overburden in order to correctly estimate the potential environmental risk associated with each type.

At MRM, the evolution of geochemical understanding over recent years has resulted in a fundamental revision and update of overburden classification criteria since the original criteria were established in 2005 by URS. McArthur River Mining Pty. Ltd. (McArthur River Mining) have allocated significant resources to geochemical studies and overburden characterisation since 2011, in line with Phase 3 EIS commitments. These include:

- four exploration drilling campaigns focussing on overburden characterisation (2011, 2012, 2014 and 2015);
- numerous investigations by external consultancy firms between 2012 and 2016 into overburden geochemistry; and
- two drilling campaigns on the North Overburden Emplacement Facility (NOEF) with installation of monitoring wells for water, and other instrumentation to measure temperature and sample gases in the pile (2014 and 2015).

The MRM geochemical studies and procedures are leading industry practice in many aspects. These are discussed below.

6.1.1.1 Overburden Characterisation Drilling

The MRM drill core assay dataset is comprehensive, consisting of over 10,000 assays from over 300 drill holes for overburden lithologies alone. Of those, approximately 4,000 samples have the full acid base accounting (ABA) analysis suite and elemental concentrations enabling classification for the potential for acid drainage (AD), saline drainage (SD) and neutral metalliferous drainage (NMD) (refer to **Section 6.1.2**).

6.1.1.2 Kinetic Geochemical Testing

The MRM kinetic geochemical testing program is robust and is based on multiple concurrently running internationally recognised testing methods including conventional column leach tests, humidity cell tests and oxygen consumption tests. The kinetic tests have been continuing since 2015.

In addition to laboratory testing, a large scale leaching experiment under field conditions has been undertaken since 2014 to assess the leaching potential of mined overburden material under site climatic conditions and will continue in order to support ongoing environmental management and review.

6.1.1.3 Overburden Classification

The MRM overburden classification criteria have evolved over time, since the original scheme in 2005, as a result of increasing knowledge and understanding of the materials. The current criteria are based on site specific values and take into consideration the specific geochemistry of the MRM overburden, an approach considered best practice by international guidelines.

The classification criteria take into consideration all aspects of acid and metalliferous drainage (AMD) including AD, SD and NMD. In addition, the classification criteria chosen are deliberately conservative when compared to other accepted classification methods. This may result in an overestimation of the quantity of PAF material, but is considered to be more robust and safer in terms of long-term risk management.

6.1.1.4 Grade Control of Overburden

McArthur River Mining has introduced in-pit grade control of all overburden at the blast block level to validate classification prior to load and haul operations. This level of control over overburden identification and movement is representative of best industry practice.

6.1.1.5 Resource Block Model Estimations

The quantities and grades of a geological resource are determined using a geological block model. A block model is essentially a 3D computer model of the subsurface geology created using the geological data gathered through drilling the prospective zone. It is composed of specifically sized "blocks", each block being characterized by a set of parameters such as grade, density, and rock type, determined by statistical methods. Once a block model has been constructed, it is used to determine the ore resources and reserves as well as the nature and quantities of overburden materials.

Classification in the resource block model is based on the direct estimation of ABA parameters including maximum potential acidity (MPA) and acid neutralising capacity (ANC). Thus, classification does not rely on the interpretation of proxy indicators for material geochemical properties, a common practice in the industry.

Overburden classification and management practices at MRM today represent industry best practice and are at the forefront of research and development in the field.

6.1.2 Definition of Acid Mine Drainage

The potential geochemical effects on surface and groundwater quality resulting from mining activities have been labelled as acid rock drainage (ARD), acid mine drainage, and acid and metalliferous drainage. Although meant to describe the same processes, the terms encompass a wide range of possible impacts from increased salinity, neutral pH and low dissolved metals to very acidic pH, high metal concentrations and depleted oxygen conditions. The slightly different meanings between the two terms both with the acronym AMD, in particular, can lead to misunderstandings unless the terms are clearly defined.

In order to avoid potential misinterpretations in this EIS, AMD refers to acid and metalliferous drainage, i.e. possible impacts including saline drainage, neutral metalliferous drainage and acid drainage. This definition is identical to the industry standard definition used in Australia, published in 2007 by the Department of Industry, Tourism and Resources in the guidelines on Acid and Metalliferous Drainage (DITR, 2007).

At MRM, AMD is further subdivided into three broad sub-categories reflecting differing behaviours, differing potential environmental impacts, and differing potential environmental remediation strategies:

- acid drainage (AD): specifically refers to drainage characterised by low pH, and potentially elevated salinity and elevated metal concentrations;
- neutral metalliferous drainage (NMD): refers to drainage characterised by circumneutral pH waters with elevated metal concentrations and potentially elevated salinity; and
- saline drainage (SD): refers to drainage characterised by elevated salinity, with circumneutral pH and metal concentrations similar to background levels.

6.1.3 Current Material Types

6.1.3.1 Geochemical Properties

Overburden material is currently separated into five distinct categories based on geochemical compositions. The classes reflect the respective AMD generation effects and each class is managed differently to minimise undesirable effects. A single lithostratigraphic unit may contain several rock classes, and the classes do not correspond to particular rock types. Therefore, the classes are purely geochemically based and are completely independent of lithology or lithostratigraphic origin. The MRM classification scheme and criteria are discussed in **Sections 6.4 and 6.5**.

The five classes of overburden material, in order of increasing potential for environmental impact, are:

- low salinity non-acid forming (high capacity) (LS-NAF(HC));
- metalliferous saline non-acid forming (high capacity) (MS-NAF(HC));
- metalliferous saline non-acid forming (low capacity) (MS-NAF(LC));
- potentially acid forming (high capacity) (PAF(HC)); and
- potentially acid forming (reactive) (PAF(RE)).

The overburden classes take into consideration the effects of AD, NMD and SD, as well as the potential for spontaneous combustion. The "capacity" of LS-NAF(HC), MS-NAF(HC), and MS-NAF(LC) refers to acid consumption capacity, while for PAF(HC) it refers to acid production capacity. Spontaneous combustion is the propensity of some sulphide and carbon rich rocks to self-heat due to rapid oxidation. It is characterised by high temperatures and the emission of gases, in particular, sulphur dioxide.

The geochemical characteristics of each class are presented in **Section 6.6**.

6.1.3.2 Physical Properties

To assist with material management, overburden is grouped into four principal categories based on its lithological and geotechnical properties. It is important to note that the physical categories do not necessarily correlate to their geochemical classification.

6.1.3.2.1 Clays

Clays are fine grained unconsolidated sediments dominated by clay and silt size particles whose geotechnical properties make them suitable for the construction of low permeability barriers such as a compacted clay liners (CCL) in dams and compacted clay layers on the NOEF (both referred to as CCLs). The clays are a particularly important resource at MRM.

6.1.3.2.2 Alluvium

Alluvium refers to unconsolidated sediments in the overburden dominated by silts, sands and gravels with various amounts of clays. Geotechnically, the material is considered unsuitable for the construction of low permeability barriers such as CCLs. The term includes residual soils and colluvial deposits as well as true alluvial sediments. Alluvial material is also an important resource for construction at MRM.

6.1.3.2.3 Shales

Shales are fine grained, well bedded, jointed and fissile sedimentary rock. At MRM, the shales are dolomitic (contain carbonate) with variable amount of micro-crystalline pyrite laminae. The term 'shale' has been traditionally used loosely at MRM and includes well-bedded siltstones as well as mudstones. Shales preferentially fracture along bedding and jointing planes.

6.1.3.2.4 Breccias

Breccias are clastic sedimentary rocks composed of angular to sub-angular, randomly oriented clasts of predominantly dolomite and shale cemented in a carbonate matrix. The breccias constitute the hardest and most competent rocks in the MRM sequence.

6.2 Geology

6.2.1 Regional Geology

The Project area is located in the McArthur River alluvium and fractured rocks of the Proterozoic McArthur Group, which, along with Roper, Nathan and Tawallah groups form the McArthur Basin. The regional geology is presented in **Figure 6-1**.

The McArthur Group is an interbedded sequence of dolostones, sandstones, shales and siltstones comprising two sub-groups; the Batten sub-group and the underlying Umbolooga sub-group. It is up to 4,000 m thick in the McArthur River district where it is best exposed. The Middle Proterozoic McArthur River Group contains the oldest rocks in the McArthur Basin.

The Umbolooga subgroup of the McArthur River Group is comprised of interbedded cycle dolostones, dolomitic siltstone, sandstone and shale. The Batten subgroup overlies the Umbolooga and is comprised of a succession of shallow marine deposits, chiefly dolomitic siltstone, cherty dolostone, pyritic shale, quartz sandstone and evaporites.

The Bukalara Plateau, the main local geographic feature is composed of the Early Cambrian Bukalara Sandstone overlying folded Proterozoic material. The Plateau lays unconformably over dolomitic sediments in the McArthur Group. Bukalara Sandstone is jointed, slightly feldspathic and has distinctive cross-bedding.

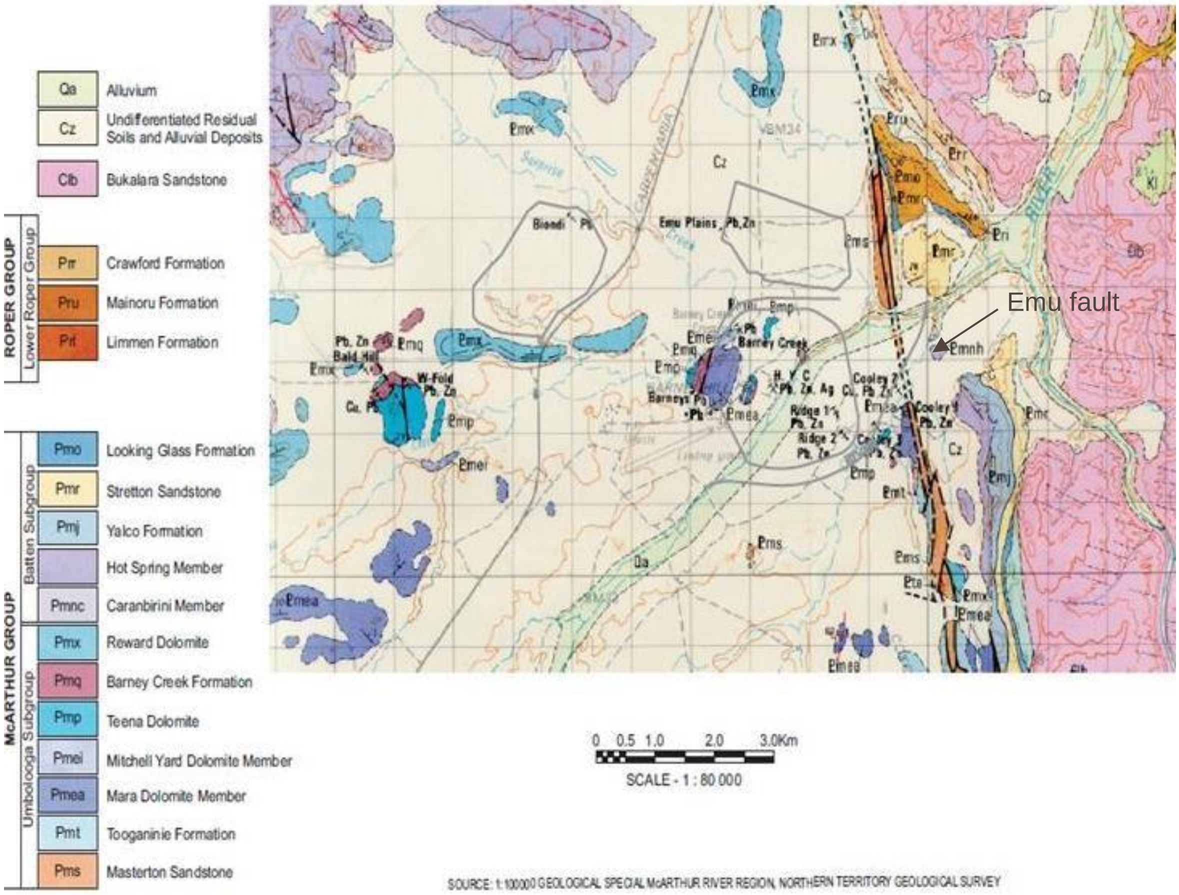


Figure 6-1 Regional Geological Setting

The McArthur River Basin contains faulting, gentle folding and is non-metamorphic. The Batten Fault Zone (Batten Trough) occurs in the south of the basin and trends north. It is an extensively faulted zone approximately 70 km wide. The Emu Fault Zone to the east of the Batten Fault Zone is a major structural lineament in the Project area (refer to **Figure 6-1**).

6.2.2 Mine Site Geology

6.2.2.1 Mine Stratigraphy

The *Here's Your Chance* (HYC) mineralisation contains the target orebody at MRM and occurs within the sediments of the Barney Creek Formation, which is a member of the Umbolooga sub-group. The Barney Creek Formation overlies the Teena Dolomite and predominantly comprises three interbedded rock types:

- Finely laminated pyritic bituminous dolomitic shale, consisting of quartz, potassium feldspar, albite, ankerite, calcite, chlorite, illite and kaolinite with an average grain size of less than 20 microns. Pyrite varies from trace amounts to almost massive pyrite. Dolomite occurs as detrital grains and as nodular dolomite that appears to have grown diagenetically at the expense of sulphides. Nodular dolomite increases towards the outer limits of the deposit.
- Sedimentary turbidite breccia which ranges from chaotic slump breccia in the north of the deposit, to well graded silt beds in the south of the deposit.
- Minor tuff bands composed of interbedded hard quartz-feldspar-dolomite and soft, friable illite quartz-feldspar.

The mine sequence is separated into 10 distinct lithostratigraphic units. The general stratigraphy in the open cut area is presented in **Figure 6-2**. The Upper Breccia unit is absent as it is only present at the southern margin of the open cut.

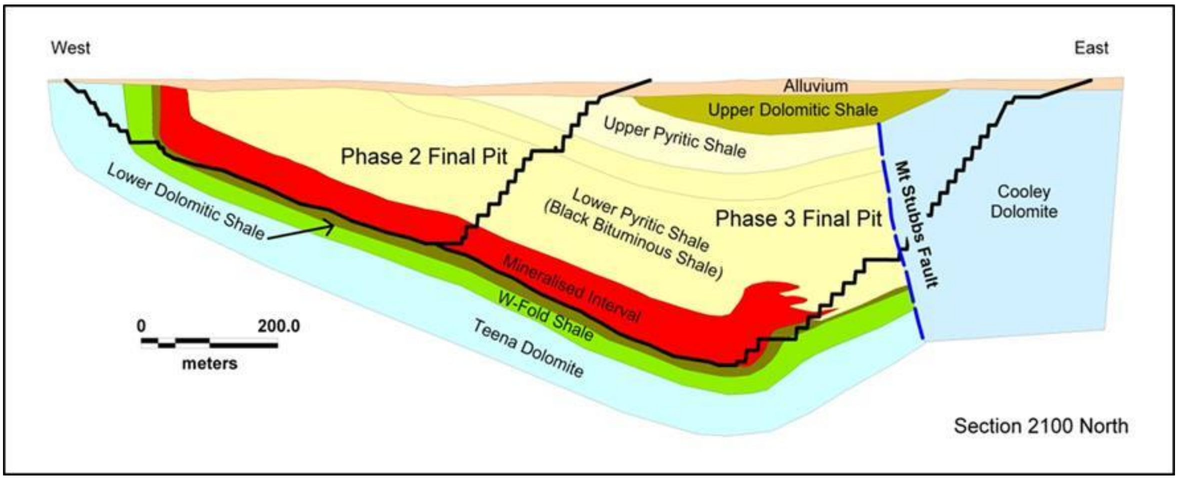


Figure 6-2 General Stratigraphy and Schematic Final Open Cut Extents

Since 2012, intensive geochemical testing and revision of the overburden classification criteria has led to a refinement of the mine stratigraphy by site geologists. The revision has focused on the very heterogeneous Lower Pyritic Shale (LpH), where seven distinct stratigraphic sub-units are now identified. The sub-units correspond to successive pyritic shale and sedimentary breccia intervals, and enable a much more precise characterisation of the Lower Pyritic Shale. The detailed mine stratigraphy is presented in **Table 6-1**.

Table 6-1 Mine Stratigraphy

Unit	Code	Name	MRM sub-units		Main Lithology
Hanging Wall Sequence	Qa	Quaternary Alluvium			Clays, silt, sand, gravel
	Cd	Cooley Dolomite			Dolomitic Breccias
	UpX	Upper Breccia			Dolomitic Breccias
	UdH	Upper Dolomitic Shale			Dolomitic Shales
	UpH	Upper Pyritic Shale			Pyritic Shales
	BbH	Black Bituminous Shale			Pyritic Shales
	LpH	Lower Pyritic Shale	LpH a	LpH 7	Pyritic Shales
			LpH b	USM	Tuff
				LpH 6	Pyritic Shales
				LSM	Tuff
				LpH 5	Pyritic Shales
			LpH c	LpHBX 4	Dolomitic Breccias
				LpH 4	Pyritic Shales
				LpHBX 3	Dolomitic Breccias
				LpH 3	Pyritic Shales
				LpHBX 2	Dolomitic Breccias
				LpH 2	Pyritic Shales
				LpHBX 1	Dolomitic Breccias
			LpH d	LpH 1	Pyritic Shales
Orebody	OB #2 to #8	*Here's Your Chance*			Mineralised Shales
Footwall Sequence	LdH	Lower Dolomitic Shale	LdH Upper		Pyritic Shales
			LdH Lower		Dolomitic Shales
	WFS	W-Fold Shale			Dolomitic Shales
	Pmp	Teena Dolomite			Dolomitic Shales

6.2.2.2 Orebody

The ore zone is stratiform and hosted in mineralised pyritic dolomitic shales. The orebody comprises seven distinct mineralised horizons, or seams, separated by dolomitic siltstones and sedimentary breccias. The orebody horizons, numbered from 2 through to 8, have varying grades and thicknesses, with barren or weakly mineralised interbeds between them. The total thickness of the mineralised package is around 55 metres (m) and varies in depth from 0 to 400 m below the surface.

The bedding strike is approximately north to south with steeply dipping (70° to vertical) beds in the shallow Western Hinge Zone, flattening to a dip of approximately 17° to 25° in a central zone, with folding of beds occurring in the deeper eastern Lower Fold Zone.

The mineralised beds thin towards the north as the inter-beds thicken. In addition to a number of minor faults (< 5 m throw), the Woyzbun Fault in the southwest separates a southern block which has been down-thrown by 100 m to 120 m.

6.2.2.3 Footwall Lithologies

The footwall lithologies consist of the Lower Dolomitic Shale, W-fold Shale, and Teena Dolomite. A description of these is provided below:

6.2.2.3.1 Lower Dolomitic Shale

The Lower Dolomitic Shale is the immediate footwall interval. It consists of interbedded weakly pyritic shale, sedimentary turbidite breccia and frequent tuff beds. The shale is often nodular and contains large dolomitic concretions. The interval hosts sub-economic low level mineralisation including the low grade nodular 1 orebody.

6.2.2.3.2 W-fold Shale

The W-fold Shale (WFS) underlies the Lower Dolomitic Shale. The interval consists of green and red shales, with frequent clay tuff beds. It generally contains no sulphide minerals.

6.2.2.3.3 Teena Dolomite

The Teena Dolomite (Pmp) underlies the W-fold Shale, the contact with which is gradational. The unit is a light grey dolomite with occasional clay tuff beds. It generally contains no sulphide minerals.

6.2.2.4 Hanging Wall Lithologies

The hanging wall sequence is comprised of six separate units. A description of these is provided below:

6.2.2.4.1 Upper Breccia

The Upper Breccia (UpX) occurs at the top of the sequence and consists of poorly sorted sedimentary breccia with occasional volcanic and sandstone clasts. It is essentially un-mineralised and contains no to very little sulphides. It only occurs south of the Woyzbun Fault, so is restricted to the southeast of the open cut.

6.2.2.4.2 Upper Dolomitic Shale

The Upper Dolomitic Shale (UdH) interval occurs beneath the Upper Breccia in the southeast corner of the deposit, and is the uppermost lithology in the remainder of the open cut area. It is characterised by generally very weakly pyritic dolomitic shale with minor tuff and graded turbidites.

6.2.2.4.3 Upper Pyritic Shale

The Upper Pyritic Shale (UpH) comprises pyritic shale with numerous thin graded beds and occasional tuff bands.

6.2.2.4.4 Black Bituminous Shale

The Black Bituminous Shale (BbH) is characterised by black pyritic shales containing elevated levels of organic carbon. It contains a few thick bedded graded arenites and thin (clay) tuff beds.

6.2.2.4.5 Lower Pyritic Shale

The Lower Pyritic Shale extends from the base of the Black Bituminous Shales to the top of number 8 orebody. It is highly heterogeneous comprising a succession of pyritic shales interbedded with coarse graded breccia and minor tuff bands. The upper part of the sequence is dominated by shales, while breccia dominates the lower part of the sequence, thickening towards the north.

6.2.2.4.6 Cooley Dolomite

The Cooley Dolomite (Cd) occurs along the eastern margin of the deposit. It is generally considered to be a fault bounded block of Teena and Mara dolomite members which underwent several episodes of brecciation. The Cooley Dolomite commonly hosts coarse grained sphalerite and galena as veins, disseminations and breccia matrix.

A zone of complete oxidation exists at the alluvium / rock contact and has a maximum depth of about 20 m in the western area of the site.

6.2.2.5 Regolith

Within the mineral leases, Quaternary sediments overlie the rocks of the Barney Creek Formation and consist of colluvial, alluvial, lacustrine sediments and residual soils. The sediments are dominated by unconsolidated clays, sands, silts, and gravels. These Quaternary strata are overlain by more recent alluvial material, sand and clay deposited on the floodplains, flood terraces, levees and channel floors of the McArthur River and the Glyde River. The cover sequence is highly variable with a thickness varying between 1 m and 25 m.

6.3 Geochemistry

6.3.1 Previous Geochemical Investigations

Several geochemical investigations have been conducted on the overburden materials as part of the MRM open cut and Phase 3 EIS. The historical data largely focusses on static geochemical test results, with limited kinetic leach testing. Past geochemical investigations include:

- Kinetic leach column project: Stage 2 project review. URS, 2004;
- Geochemical Assessment of Overburden and Tailings Materials Including Conceptual Design of Overburden Emplacement Area. URS Report, 2005;
- Kinetic leach column project: MRM Overburden Stage 3 Project Review. URS, 2005;
- Kinetic leach column project: MRM Overburden Stage 4 Project Review. URS, 2006;
- Kinetic leach column project: MRM Overburden Stage 5 Project Review. URS, 2007;
- Stage 7 Kinetic leach column program update. URS, 2011;
- MRM Initial Static Testing Results: Northern Overburden Emplacement Facility. KCB, 2012;
- MRM Desktop geochemical Review. KCB, 2014;
- MRM Waste Classification Guide. KCB, 2014;

- MRM Low grade ore stockpile characterisation. KCB, 2014; and
- MRM Geochemistry: Additional NOEF testing results. KCB, 2014.

6.3.2 Geochemical Testing Methodologies

This section provides an explanation of the geochemical testing methodologies utilised to characterise MRM overburden.

6.3.2.1 Acid-Base Accounting

Acid-base accounting uses static geochemical analyses to determine the acid-base balance and metal content of the overburden material. The analyses and test work conducted for all samples is detailed below.

6.3.2.2 Total Sulphur

The total sulphur (S) content is required to calculate the maximum amount of acid that can potentially be generated by a sample when exposed to oxidising conditions (exposed to oxygen). It is expressed in percentage weight. When sulphur is in the form of sulphide, commonly as metal sulphides such as pyrite, which has the chemical formula FeS_2, it can oxidise in the presence of oxygen and water to form sulphuric acid (H_2SO_4). The maximum amount of acid that can potentially form if all sulphide sulphur is oxidised can be calculated from the sulphur content.

6.3.2.3 Maximum Potential Acidity

Total sulphur content is used to calculate the maximum potential acidity (MPA) of acid that can be generated by the sample:

$$MPA\ (kgH_2SO_4/t) = S\% \times 30.6$$

The MPA value assumes that pyrite is the primary source of sulphur and that all the sulphur will oxidise; this is a conservative assumption. The 30.6 value is calculated from the stoichiometry of the following equation:

$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightarrow Fe(OH)_3 + 2H_2SO_4$$

According to the first equation, a sample containing 1% sulphur has the potential to generate a maximum of 30.6 kilograms of sulphuric acid per ton (kg H_2SO_4/t) if all of the sulphur is oxidised.

6.3.2.4 Acid Neutralising Capacity

The acid neutralising capacity (ANC) measures the amount of acid that can be neutralised by acid consuming minerals present in the sample, predominantly carbonates such as calcite and dolomite. A common procedure to estimate the ANC is the modified Sobek Method, where a known amount of hydrochloric acid is added to a known mass of sample. Once the reaction is complete, the solution is back titrated with sodium hydroxide to measure the quantity of acid that was consumed. The ANC is expressed in kg H_2SO_4/t.

6.3.2.5 Net Acid Producing Potential

Net acid producing potential (NAPP) is the difference between the MPA and the ANC of the sample and is expressed in kg H_2SO_4/t.

$$NAPP = MPA - ANC$$

In theory, if the MPA is greater than the ANC then the sample can potentially produce acid after all of the ANC is consumed. If the ANC is greater than the MPA, then the material can potentially remain neutral because there will be excess ANC after all of the sulphur is consumed. The acid produced by sulphide oxidation would have been neutralized by the ANC. A negative NAPP indicates that the sample generates less acid than it is capable of neutralising, and is therefore unlikely to generate acidity. A positive value indicates that the sample produces more acid than it is capable of neutralising, and is therefore likely to generate acidity.

6.3.2.6 Neutralisation Potential Ratio

The neutralisation potential ratio (NPR) is the ratio of ANC over MPA.

$$NPR = \frac{ANC}{MPA}$$

The NPR is generally used to indicate the probability that a sample may produce acidity. Samples with NPR values less than 1 are considered likely to generate acidity, while samples with NPR values greater than 2 are considered as likely to be acid consuming. Material with NPR values between 1 and 2 are considered uncertain and need to be compared to other ABA criteria before final classification. The uncertain status is the result of 2 possible chemical reactions that can occur during neutralization. One reaction needs only 1 ANC unit to neutralize 1 MPA unit and if this were the only possible reaction, then an NPR value greater than 1 would be acid consuming. However, another possible chemical reaction requires 2 units of ANC to neutralize 1 unit of MPA. Which neutralization reaction will occur depends on physio-chemical conditions in the environment and is not readily predictable. Therefore, an NPR value of 2 or greater is used as a conservative criterion to classify the material as NAF.

6.3.2.7 Net Acid Generation

Net Acid Generation (NAG) is a test in which hydrogen peroxide is used to oxidise the sulphur in a sample (in the form of pyrite) and produce sulphuric acid. The acid generated reacts with the acid consuming minerals present in the sample (e.g. calcite and dolomite). The net resultant acidity is measured and expressed as a pH value (NAG pH). A NAG pH of less than 4.5 is considered acidic and indicates that the material is likely to be net acid forming (NAF).

6.3.2.7.1 Sequential NAG

The sequential NAG is a multi-stage procedure involving a series of single addition NAG tests on the one sample. This test is recommended when testing samples with high sulphide content (such as MRM samples) because of the possible catalytic breakdown of the hydrogen peroxide before it has had a chance to oxidise all of the sulphides present in the sample.

6.3.2.7.2 Kinetic NAG

A kinetic NAG test is essentially the same as a single addition NAG test, except that the temperature, pH, and sometimes electrical conductivity, of the liquor are recorded as the test proceeds. Variations in these parameters during the test provide an indication of the kinetics of sulphide oxidation and acid generation during the test. These in turn can provide an insight into the behaviour of the material under field conditions, for example the lag time before acid conditions develop.

6.3.2.8 Chromium Reducible Sulphur

Chromium Reducible Sulphur (CRS) is test specifically measures the reduced (sulphide) forms of sulphur. It can give a more accurate measure of the acidity generation potential of a sample by excluding non-acid generating forms of sulphur such as native sulphur or sulphate minerals from the results.

6.3.2.9 Soluble Sulphate

Soluble sulphate does not contribute acidity, however will contribute to increases in the salinity of leached waters.

6.3.2.10 Acid Buffering Characteristic Curves

Acid buffering characteristics curves ABCC test involves slow titration of a sample with acid while continuously monitoring pH. The test provides an indication of what portion of the ANC measured in a sample is actually available for acid neutralisation.

6.3.2.11 Mineralogy

6.3.2.11.1 X-Ray Diffraction (XRD):

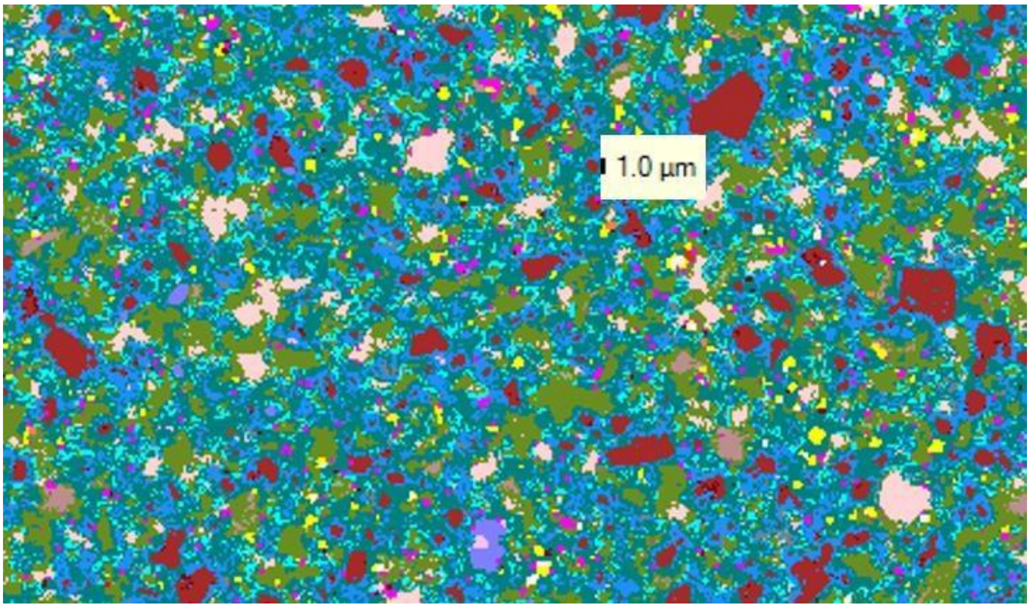
X-ray powder diffraction analysis was used for the identification of mineral phases present in all the overburden lithologies present at MRM. For overburden characterisation purposes, it is particularly important for the identification and quantification of the carbonates present (calcite, dolomite, ankerite, and siderite) and the iron sulphides (pyrite, pyrrhotite, marcasite, etc.).

6.3.2.11.2 Quantitative Evaluation of Minerals by Scanning Electron Microscopy

Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) is a method developed by the CSIRO that provides an integrated and automated quantitative analysis of rocks and minerals. The system comprises a scanning electron microscope with a large specimen chamber and four light-element, energy-dispersive X-ray spectroscopy detectors. QEMSCAN data includes bulk mineralogy and calculated chemical assays.

QEMSCAN was used to gain high resolution information as to mineral grain sizes and shapes as well as mineral associations present in the overburden. This provides valuable information regarding key processes such as the likely reactivity of the material and availability of neutralising minerals.

Figure 6-3 to **Figure 6-6** present some of the very high resolution mineral maps obtained for MRM material.



Mineral Name	%
Mica	39.24
Feldspars	20.68
Ankerite	12.11
Amphibole	8.12
Dolomite	5.75
Quartz	4.59
Mica Pyrite Intergrowth	2.06
Pyroxene (Diopside)	1.43
PyriteSilicate Intergrowth	1.11
Others	1.00
Other Silicates	0.92
Pyrite	0.90

Figure 6-3 Hanging Wall Siltstone Mineral Map.

In **Figure 6-3** the 1 micrometre (µm) scale presents the resolution that can be achieved with this method. Understanding the micro-crystalline structure of overburden rocks is essential in correctly interpreting bulk geochemical results. **Figure 6-4** shows the very high dolomite content and localised presence of ankerite associated with pyrite.

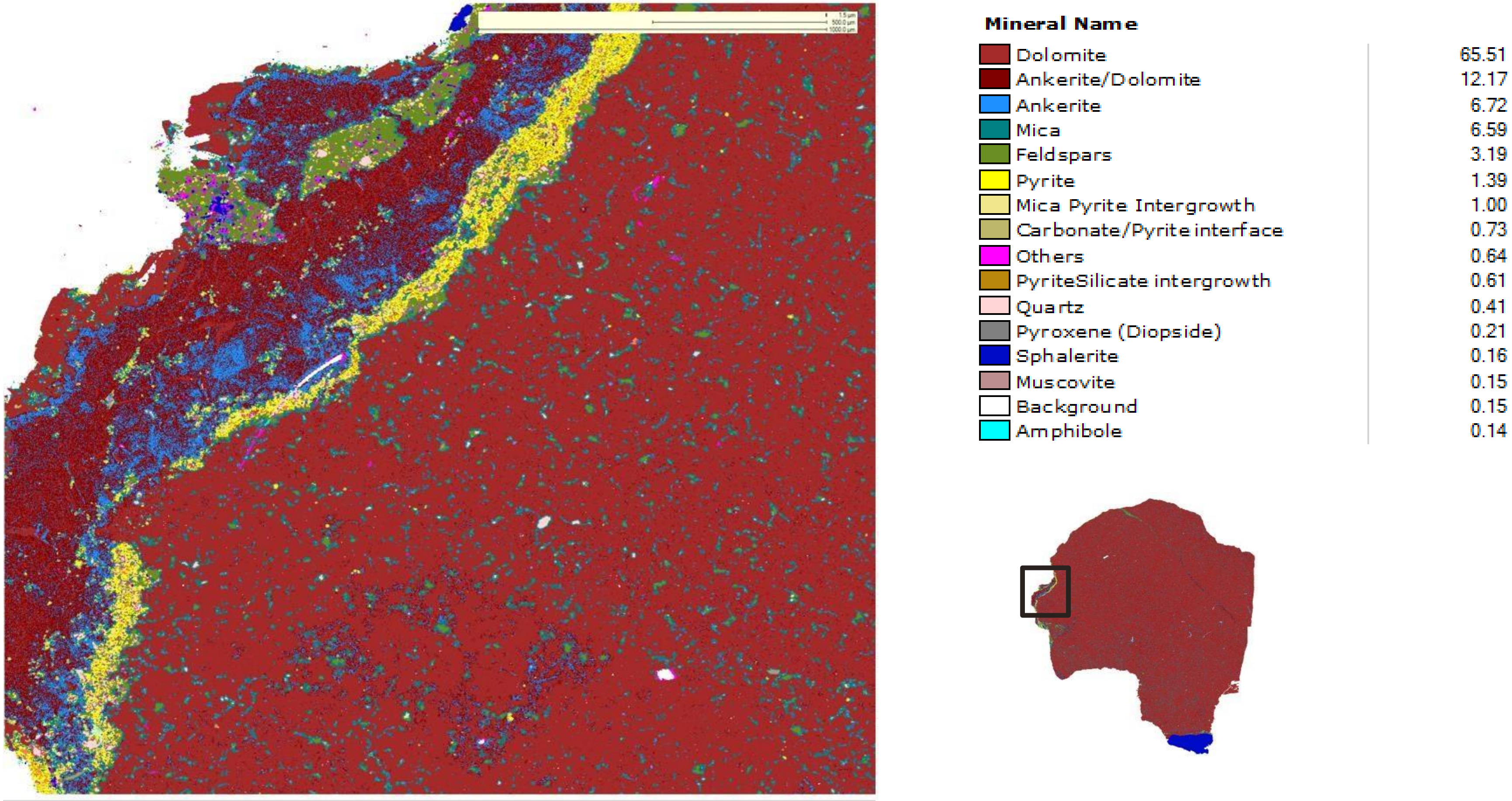


Figure 6-4 Dolomite Mineral Map with Pyrite Vein.

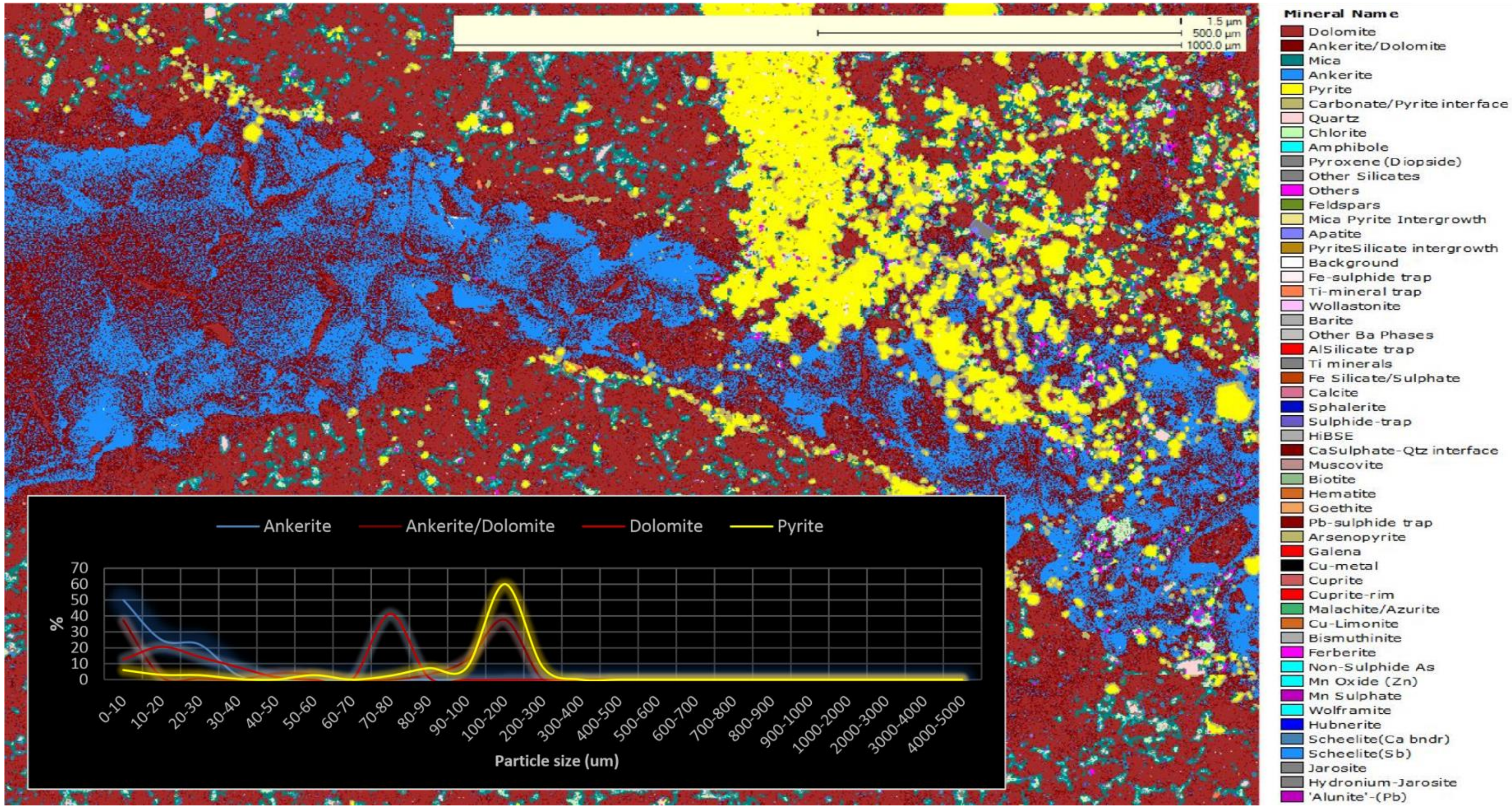


Figure 6-5 Dolomite Mineral Map with Pyrite and Ankerite Veins

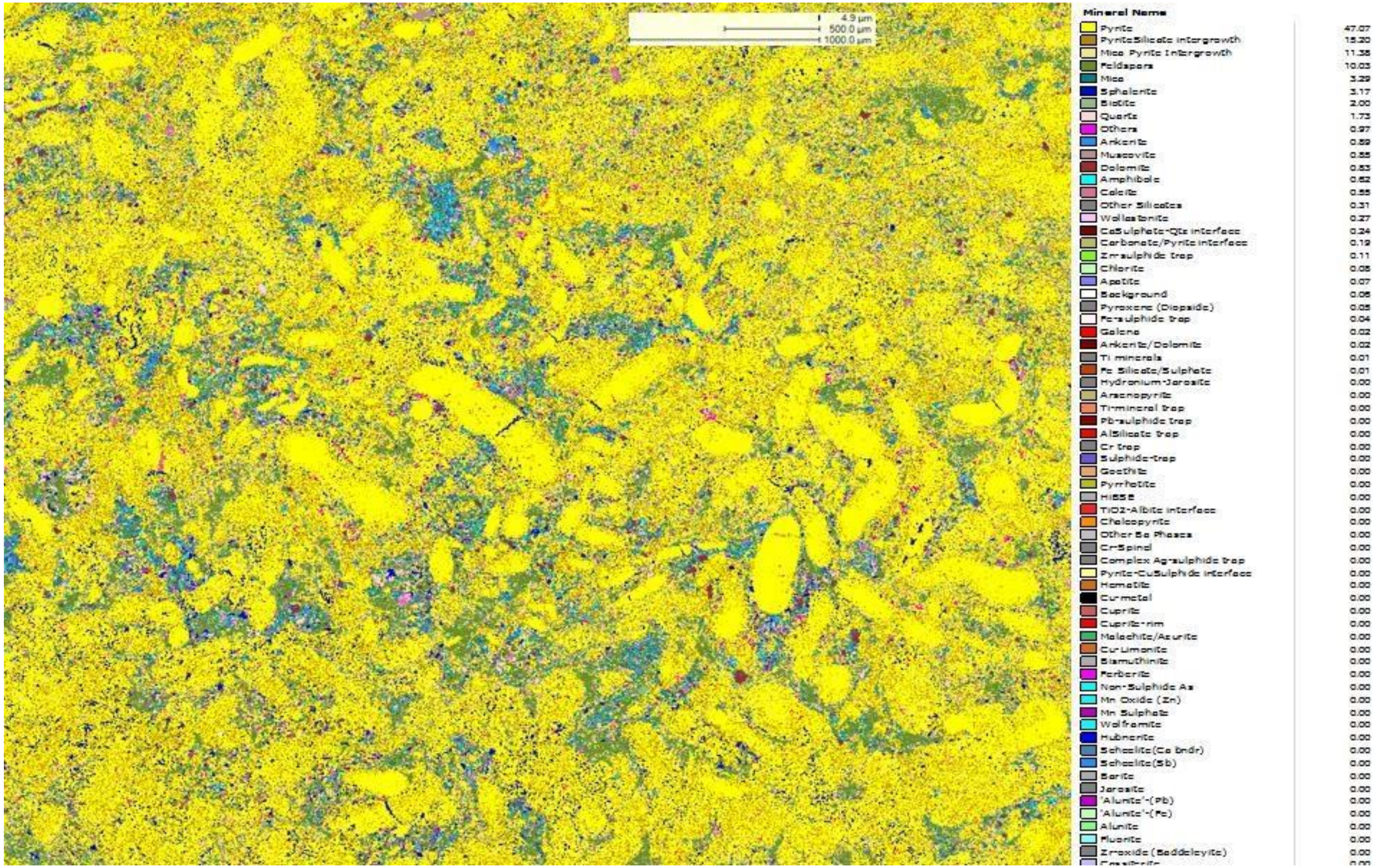


Figure 6-6 High Pyrite Content Sample Exhibiting Micro-Crystalline Structures

6.3.2.12 Elemental Abundances

Elemental abundance measurements in overburden in the laboratory are made using both Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Elemental abundance measurements for overburden grade control purposes in the field are made using a portable X-ray Fluorescence (pXRF) analyser.

The full analysis suite includes the following elements: zinc, lead, copper, magnesium, aluminium, silicon, phosphorous, chlorine, potassium, calcium, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, arsenic, selenium, rubidium, strontium, zirconium, niobium, molybdenum, palladium, silver, cadmium, tin, antimony, tellurium, caesium, barium, hafnium, tantalum, tungsten, rhenium, gold, mercury, bismuth, thorium and uranium.

Relative enrichment in an element is conventionally determined using the Geochemical Abundance Index (GAI):

$$GAI = log_2 \frac{C}{1.5 \times S}$$

Where C is the measured concentration in the sample, and S is the median crustal abundance of the element. The GAI is a binary logarithm expressed as an integer, and a GAI index of 3 and above is generally considered as enriched relative to the earth's crust and therefore should be considered in further geochemical assessments.

6.3.2.13 Leachate Extractions

Leachate extraction tests on MRM overburden materials consisted of Shake Flask Extractions (SFE) and NAG liquor analyses.

6.3.2.13.1 Shake Flask Extractions

The sample is shaken in contact with deionised water for 24 hours, and the resultant water is analysed for elemental abundances. While indicative of the readily leachable fraction by water, the resultant concentrations are influenced by contact time, particle size and liquid to solid ratios. As such, using SFE results on fresh un-oxidised samples provide an indicator of potentially soluble constituents and are not reliable for estimating field leachate water quality.

6.3.2.13.2 NAG Liquor Analyses

Liquid is analysed following completion of a NAG test after all the sulphides have oxidised and reacted with the available buffering minerals. The resulting concentrations in the leachate can provide an indication of constituents that have the potential to leach during sulphide oxidation and that should be assessed in further detail by other kinetic methods.

6.3.2.14 Kinetic Testing

Prior to the studies conducted for this EIS, the only kinetic testing data available was the column leaching experiments initiated by URS in 2004. Multiple kinetic tests were later implemented to develop a robust evaluation of geochemical reactivity and water quality. Laboratory and field kinetic testing programs have been established and produced more refined and definitive information and will be ongoing to support continuing environmental management and review. The testing methods are described in the following sections.

6.3.2.14.1 Standard Humidity Cells

A standard humidity cell test is conducted at the bench scale and follows the Mine Environment Neutral Drainage (MEND) methodology (MEND 2009). Humidity cell tests are designed to mimic weathering at the laboratory scale in a controlled fashion. The sample is subjected to alternating cycles of dry and moist air to simulate precipitation cycles. The sample, typically consisting of 1 kilogram (kg) of crushed material, is then soaked for a specific length of time with deionized water, and the water is then collected and analysed for a number of parameters including pH, sulphate, acidity, alkalinity, conductivity and metals. The test determines the rate of sulphide oxidation, acid generation, and the variation over time in leachate water quality.

6.3.2.14.2 Leach Column Testing

The leach column testing was conducted using the Australian standard AMIRA methodology. The leach column tests are similar to the HC tests: free draining columns are normally loaded with 2-3 kg of crushed overburden and subjected to wetting and drying cycles to encourage oxidation and flushing of oxidation products. Water flushed through the column sample is collected and analysed for a variety of parameters to provide information on sulphide reactivity, oxidation kinetics, metal solubility and the leaching behaviour of the test materials.

6.3.2.14.3 Oxygen Consumption Rate

The oxygen consumption rate (OCR) testing was undertaken using both small oxygen consumption cells and large oxygen consumption cells. OCR testing differs from humidity cell and leach column testing in that the oxidation rate is determined by directly measuring the oxygen that is consumed in the experimental apparatus following exposure of the sample to a wetting and drying cycle. The tests were undertaken at a range of moisture contents to assess sulphide reactivity as a function of liquid to solid ratios.

6.3.2.14.4 Large-scale Field Barrel Leaching

The large-scale field barrel leach program is designed to complement the laboratory experiments by "upscaling" the leach columns using actual mined overburden fragments (rather than the much smaller particles typically present in the crushed samples used in column or humidity cell tests) leached under actual climatic conditions. The experiment uses 200 litre barrels loaded with overburden that are left exposed to the atmosphere. The first flushes at the start of the wet season are sampled, followed by monthly sampling for the remainder of the wet season. The program is currently in its third year of operation.

6.3.3 Geochemical Data Sets

6.3.3.1 Drill Core Database

The total MRM assay data set consists of over 10,000 samples of overburden alone, obtained from 360 holes drilled between 1961 and 2015 over the life of mine (LOM) open cut area. Of these, 4,109 samples include the full ABA analyses suite used to inform classification.

A systematic review of the dataset conducted in 2014 identified inconsistencies within the 1961-2000 overburden ABA data (660 samples including 133 ABA analyses). In particular, the ANC determinations and total sulphur assays for the data prior to 2000 are not considered reliable, and both parameters are critical to the correct classification of overburden. The values in the older records are abnormally low and not consistent with all subsequent drill programs which have higher standards of quality control. As a precaution, the 1961 to 2000 dataset has been excluded from both the geochemical analysis and block model estimations. Geochemical analysis and interpretation is based on the 3,976 samples from 98 drill holes from the 2002-2015 dataset.

6.3.3.2 Geological Block Model Estimations

Estimations of material quantities and of the spatial distribution of the five overburden classes rely on geological block model estimations. Significant improvements to the block model have been made through 2014-2016 in both lithostratigraphic resolution and estimation parameters. In particular, the direct estimation of ABA parameters for the hanging wall sequence of the orebody has removed the need to rely on proxy indicators for NAF and PAF identification. This makes the block model classification criteria identical to the geochemical criteria, significantly improving the reliability of the block model estimations.

The block model classification criteria are discussed in more detail in **Section 6.5**.

6.3.3.3 In-Pit Grade Control

The block model classification of each individual overburden blast is checked by in-pit grade control, which determines final classification. In-pit grade control of overburden lithologies uses portable X-Ray Fluorescence (pXRF) analyses of blast hole samples. Field pXRF analyses are used for confirming both NAF/PAF classification and for the identification of potentially metalliferous/saline NAF by screening for critical elemental abundances such as antimony, arsenic, bismuth, cadmium, chromium, copper, iron, lead, manganese, molybdenum, selenium, sulphur and zinc.

The XRF results are verified in the laboratory and calibrated using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) analyses.

The in-pit grade control of overburden criteria and methodology are discussed in more detail in **Section 6.7.**

6.3.3.4 OEF Monitoring Samples

A monthly Overburden Emplacement Facility (OEF) monitoring program has been conducted by McArthur River Mining since 2009. Originally concentrated on the NAF cells of the NOEF with the aim of monitoring possible PAF contamination, the program was expanded in 2014 to include all OEFs and the PAF cells.

On average, 250 samples are collected for ABA and elemental analyses each year to monitor correct overburden placement. The OEF monitoring program is discussed in more detail in **Section 6.8**.

6.3.3.5 Kinetic Testing

Laboratory OCR determination, humidity cell testing, and leach column tests were commenced in 2015 as part of this EIS process. Relevant kinetic tests continue to be monitored. Based on the results of the static geochemistry testing, 18 samples were selected for more detailed kinetic testing. Sample information is presented in **Table 6-2.**

McArthur River Mining is continuing its large scale field barrel leaching experiment for overburden material. The first results were obtained in December 2014, and the experiment will be continued for at least five years to assist with ongoing environmental management and review.

Table 6-2 Kinetic Testing Samples

Sample ID	Lithology	Overburden class	Humidity cell duration (weeks)	Column leach duration (weeks)
44284	Cooley Dolomite	MS-NAF(HC)	> 100	> 95
44288	Cooley Dolomite	MS-NAF(HC)	> 100	
44072	Upper Pyritic Shale	PAF(RE)	> 100	> 95
44079	Black Bituminous Shale	PAF(RE)	> 100	> 95
44084	Black Bituminous Shale	MS-NAF(LC)	> 100	
44106	Upper Pyritic Shale	MS-NAF(LC)	> 100	
44007	Upper Breccia	LS-NAF(LC)	61 (terminated)	53 (terminated)
44016	Upper Breccia	LS-NAF(LC)	> 100	
44093	Lower Pyritic Shale	PAF(HC)	> 100	> 89
44127	Lower Pyritic Shale	MS-NAF(LC)	> 92	
44057	Upper Dolomitic Shale	MS-NAF(LC)	> 92	> 89
44060	Upper Dolomitic Shale	LS-NAF(LC)	> 100	
KWFS-03	W Fold Shale	MS-NAF(HC)	> 92	
KWFS-06	W Fold Shale	LS-NAF(HC)	> 92	> 89
KLDH-04	Lower Dolomitic Shale	MS-NAF(HC)	> 92	
KLDH-11	Lower Dolomitic Shale	PAF(HC)	> 92	> 89
44004	Siltstone	MS-NAF(HC)	> 92	
44065	Upper Pyritic Shale	PAF(RE)	> 92	

6.4 Overburden Classification

6.4.1 Historical Classification at MRM

This section provides a summary of the evolution of the overburden classification system at MRM. Prior to 2005, MRM operated as an underground mine and limited overburden was mined. The overburden that was mined was stored underground.

6.4.1.1 2005 Classification System

From 2005 until 2013, overburden classification criteria at MRM were based on the 2005 URS report on the geochemical assessment of overburden and tailings material (refer **Table 6-3**). The classification used NAPP and NAG pH to classify overburden material as either non-acid forming (NAF) or potentially acid forming (PAF). Samples showing a discrepancy between the two tests were regarded as unclassified (UC) and required further testing prior to final classification as either NAF or PAF.

Table 6-3 2005 MRM Overburden Classification Criteria

NAPP	NAG pH	Class	Description
NAPP < 0	pH > 4.0	NAF	NAF material is unlikely to generate acidity but may generate neutral mine drainage
NAPP > 0	pH < 4.0	PAF	PAF material has the capacity to generate significant acidity and may lead to acid mine drainage if not managed properly
NAPP > 0 NAPP < 0	pH > 4.0 pH < 4.0	UC	Materials showing a discrepancy between the NAPP and NAG pH values are unclassified. Further testing is required prior to classification

Following the more recent geochemical analysis of MRM overburden, and improved understanding of its properties, a number of limitations with the 2005 criteria were identified. While conforming to international guidelines such as AMIRA (2002), the classification considered the acid generation risk only. All NAF was considered to be environmentally benign. The NAG pH value of 4 is slightly lower than the recommended value of 4.5 used in other equivalent classifications (DITR, 2007). Uncertain samples were defaulted to NAF based on their NAG pH value, considered more reliable than the NAPP. This potentially could lead to an underestimation of PAF material.

6.4.1.2 2012 Investigations

Following an overburden characterisation drilling campaign undertaken in 2012 as part of the Phase 3 EIS, a comprehensive geochemical investigation program was initiated. The program covered all aspects of overburden characterisation and classification at MRM. This included analysis and interpretation of the 2011 drill program results by Klohn Crippen Berger Ltd. In 2013, a review of all overburden characterisation data available in the drill core database, a review of overburden classification procedures and in-pit identification and geological mark-up.

The geochemical segregation of NAF and PAF materials at MRM was found to conform to international practice, and the proportion of NAF and PAF in drill core samples was found to be relatively consistent between successive drill campaigns with approximately 30% PAF present in the sample population. The proportion of PAF in drill core samples was significantly higher than predicted by the geological resource model (approximately 15%), suggesting a potential underestimation of the estimated PAF volumes by the block model.

A significant fraction of the hanging wall overburden material was recognised as being enriched in elements of potential environmental concern including sulphur, zinc, lead, arsenic, cadmium, antimony, bismuth and molybdenum. A fraction of the NAF material previously considered environmentally benign was found to pose a potential risk of SD and NMD.

This led to the development of new classification criteria for the segregation of NAF into low-salinity NAF (environmentally benign), and saline and metalliferous NAF. The new classification was based on five classes of material instead of the existing two.

Field identification methods were also developed based on portable XRF for in-pit mark-up of overburden classes by site geologists. The application of grade control procedures for overburden mining was investigated as a replacement for the visual lithostratigraphic mark-up previously used.

This review also led to the establishment of a long term, large scale field barrel leaching experiment to inform prediction of leachate water qualities. The revised classification and management plan was implemented in January 2014 and remains the current classification (refer **Section 6.4.2**).

6.4.2 MRM/KCB 2014 Classification

6.4.2.1 MRM/KCB 2014 Classification System

The MRM/KCB 2014 overburden classification system is based on the recommendations of the 2013 McArthur River Mine Waste Classification Guide by KCB, (KCB, 2013). It followed a comprehensive review of all available geochemical data as well as a large amount of new geochemical work undertaken by McArthur River Mining and KCB through 2012 and 2013 (refer to **Section 6.4.2.1**). The current classification was initially implemented in January 2014 and replaced the original 2005 classification (URS, 2005) which had been used by McArthur River Mining from 2005 to 2013 inclusive.

The objective of the new classification was to establish geochemical criteria for the effective segregation of the various overburden classes by taking into consideration all forms of AMD, in line with industry leading practice as outlined by both Australian and international guidelines (AMIRA, 2002; DITR, 2007; GUARD, 2009). The site specific potential for spontaneous combustion was also considered.

The classification criteria and corresponding classes are presented in **Table 6-4.**

Table 6-4 2014 MRM Overburden Classification Criteria

Classification	Characteristics	Description and Handling
LS-NAF(HC)	NPR ≥ 2, sulphur < 1%, zinc < 0.4 %, lead < 0.04%, and copper < 700 parts per million (ppm)	Material considered at low risk of generating Acid Mine Drainage and Saline Metalliferous drainage. Generally characterised by a high acid consumption capacity. This material is considered environmentally acceptable and suitable for placement in environmentally sensitive areas such as the OEF outer cover
MS-NAF(HC)	NPR ≥ 2, sulphur ≥ 1%, zinc ≥ 0.4 %, lead ≥ 0.04%, and copper ≥ 700 ppm	Material considered at low risk of generating Acid Mine Drainage but higher risk of generating Saline Metalliferous drainage. Generally characterised by a high acid consumption capacity This material is not considered environmentally benign and requires some form of mitigation and water management strategy.
MS-NAF(LC)	1 ≤ NPR < 2	Material considered at low risk of generating Acid Mine Drainage but higher risk of generating Saline Metalliferous drainage. While non-acid forming, this material is likely to provide limited acid consumption capacity. This material is not considered environmentally benign and requires some form of mitigation and water management strategy.
PAF(HC)	NPR < 1, and sulphur < 10%	Material considered at risk of generating Acid Mine Drainage, and is likely to have a significant capacity to do so. Samples classed as undefined according to the DITR 2007 classification are included in the PAF(HC) category at MRM. This material is not considered environmentally benign and requires some form of encapsulation and water management strategy.
PAF(RE)	NPR < 1,and sulphur ≥ 10%	Reactive PAF Material considered at high risk of generating Acid Mine Drainage, and has the highest capacity to do so. This material is also at high risk of self-heating which may progress into spontaneous combustion. This material is not considered environmentally benign. It requires encapsulation and is likely to require specific additional handling strategies to prevent the onset of spontaneous combustion.

Only one class (LS-NAF(HC)) is considered environmentally benign. All other classes are considered to require some form of encapsulation to limit oxidation and some form of water management strategy.

There is no segregation between SD risk and NMD risk. Rocks classed as one are automatically assumed to be at risk of the other (hence the MS prefix). This is both a conservative and a practical consideration, as differentiated classes of NAF between saline and/or metalliferous drainage risks would be impractical to mine selectively and manage separately.

Occasional reference is made to PAF(HW). This is a subset of PAF(HC) located in the open cut hanging wall. It has been classified differently for operational purposes rather than significant geochemical differences.

6.4.2.2 MRM/KCB 2014 Classification Criteria

6.4.2.2.1 Neutralising Potential Ratio

Evaluation of the potential acid drainage risk uses the Neutralisation Potential Ratio (NPR) in place of the NAPP/NAG pH values. This is a safer and more conservative approach given the specific geochemistry of MRM materials.

MRM overburden has a combination of high sulphide content and high acid buffering capacity which means that the NAG pH may not be a reliable indicator of acidity owing to limitations of the procedure (incomplete oxidation of sulphides, large buffering capacity present) (refer to **Section 6.3.2.1**). This can lead to an underestimation of the acid generation risk of the material, and can be responsible for a large proportion of "uncertain" samples in a NAPP/NAG pH diagram. This does not imply that NAG pH tests have no value for MRM overburden assessment. NAG pH tests continue to be conducted as part of the standard ABA geochemical testing of overburden material and used in the evaluation, but classification relies on the more conservative NPR value.

The NPR is calculated using the Maximum Potential Acidity (MPA) (refer to **Section 6.3.2.1**). The MPA is in turn calculated using total sulphur and relies on the conservative assumption that all of the sulphur in the overburden lithologies is present in pyrite. While this assumption is well supported by the geochemical data (refer to **Figure 6-7**), Chromium Reducible Sulphur results from overburden indicate that approximately 20% of the total sulphur may not be present as oxidisable sulphide sulphur (**Figure 6-7**) and therefore may not directly generate acidity. This is likely to result in an overestimation of the acid generation potential used in the NPR calculation, and hence provides a more conservative classification.

Adoption of the NPR in the classification system eliminates the generation of 'uncertain' sample classifications, as is the case with a NAPP/NAG pH classification scheme. Uncertain samples are automatically defaulted to PAF in the current MRM classification. This is a deliberate and conservative approach which is likely to result in an overestimation of PAF quantities during mining.

Because NPR is based on the ratio of ANC to MPA (NPR = ANC/MPA) rather than the difference between the two as in the NAPP (NAPP = MPA – ANC), the NPR is intrinsically more accurate at estimating the long-term risk of acid drainage generation. This can be demonstrated by comparing two different sample examples:

- One sample has an ANC of 400 kg H_2SO_4/t and an MPA of 390 kg H_2SO_4/t. This results in a NAPP value of -10 kg H_2SO_4/t and an NPR of 1.03.
- Another sample has an ANC of 15 kg H_2SO_4/t and an MPA of 5 kg H_2SO_4/t. This also results in a NAPP value of -10 kg H_2SO_4/t but an NPR of 3.

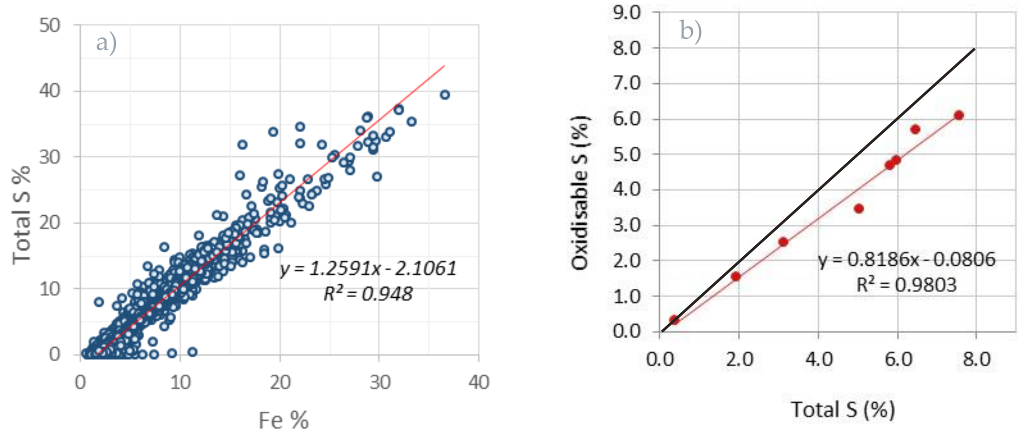


Figure 6-7 a) Sulphur (S) vs. Iron (Fe), and b) Sulphur vs. CRS in Overburden

In both cases, the samples are classed as NAF with a net acid consumption capacity of 10 kg H_2SO_4/t. But while they both have identical NAPP values, their acid generation risk profiles are very different. The first sample has an NPR of 1.03, indicating that its acid generation capacity is almost equal to its acid neutralising capacity, while the second sample with an NPR of 3 has three times more acid neutralising capacity than acid generation capacity. As discussed above, some neutralization reactions can require 2 units of ANC for 1 unit of MPA and therefore the NPR of 2 incorporates this while the NAPP does not. It is clear that while both have identical NAPP values; the probability of the first sample generating acid is significantly higher than for the second one. This can only be captured by the NPR, hence why it is preferred at MRM.

6.4.2.2.2 Sulphur

The primary source driving risk of saline drainage generation from MRM overburden is associated with the release of soluble sulphate. These result from the oxidation of sulphide minerals and subsequent neutralisation by carbonates rather than sodium chloride or any other salt present in overburden.

The potential risk of saline drainage generation is estimated using total sulphur content of the rock. The total sulphur cut-off value used in the 2014 classification is 1% sulphur. It is only applied to separate LS-NAF from MS-NAF(HC). All other classes are considered to be potentially metalliferous saline. The 1% cut-off value is based on the following considerations.

While 1% sulphur is used as the cut-off value in the classification, in practice the vast majority of samples with less than 1% sulphur have a much lower sulphur content than that, with 76% of all samples having sulphur contents less than or equal to 0.5% sulphur. The median value is very low at 0.15% sulphur, and the mean value is 0.23% sulphur. The 1% value is very effective at isolating the very low sulphur fraction of the MRM overburden.

Comparatively few samples have sulphur values in the order of 1%, making it an effective cut-off as it does not artificially split a sample population. **Figure 6-8** presents the frequency distribution of samples with less than 2% sulphur in the MRM drill core data for all lithologies and all overburden classes, and shows the relatively low number of samples between 1% and 1.5% sulphur.

While a lower cut-off value could be defined on geochemical grounds alone without significantly affecting estimates of LS-NAF quantities, the 1% value avoids potentially unnecessary selective mining in lithostratigraphic units which are mined as LS-NAF. **Figure 6-9** presents the frequency distribution of sulphur in the W-Fold Shale, Teena Dolomite and Upper Breccia units together with the 1% cut-off value. Although 89% of these samples have sulphur content less than 0.5%, the 95th percentile is 1.08, very close to the 1% cut-off value. Therefore selective mining in these units would significantly increase operational complexity for negligible benefit.

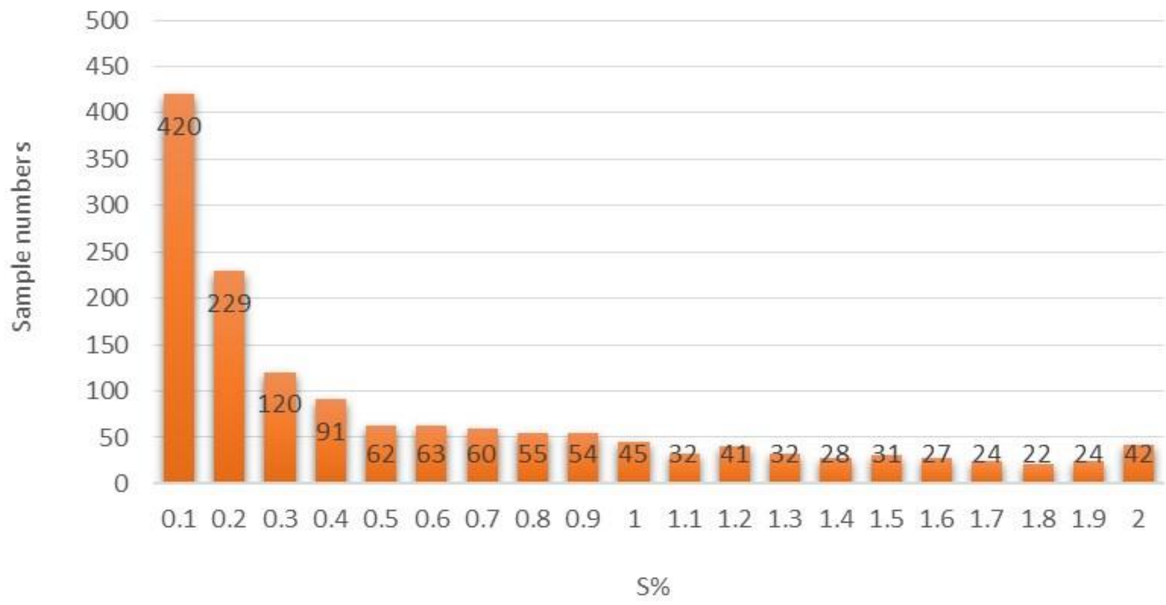


Figure 6-8 Frequency Distribution of < 2% Sulphur

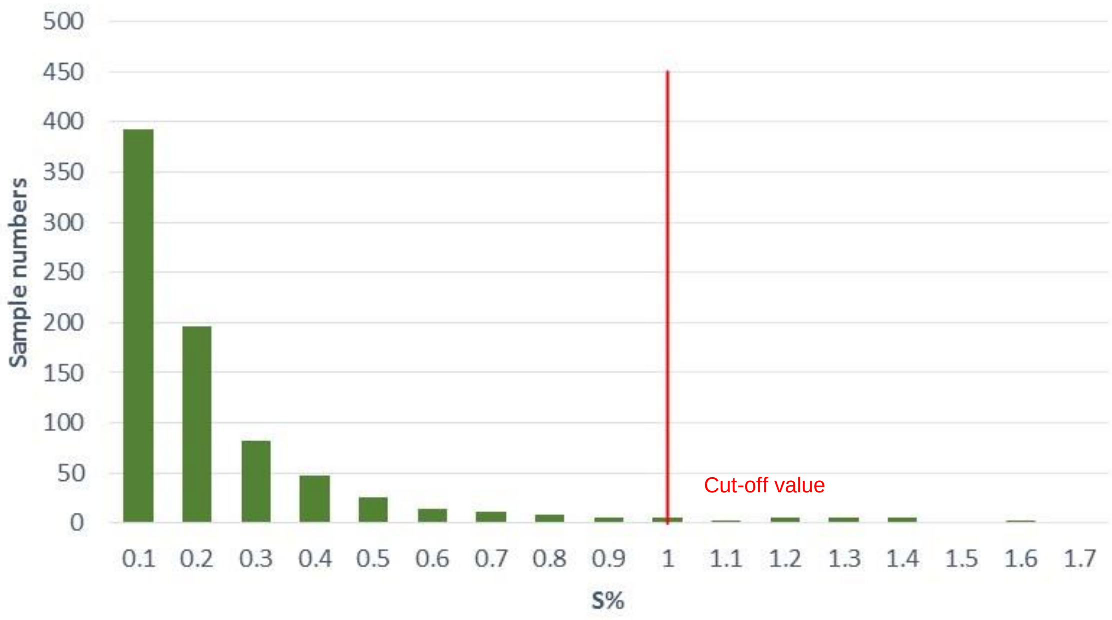


Figure 6-9 Frequency Distribution of Sulphur in WFS, Pmp and UpX Units

6.4.2.2.3 Metal concentrations

Evaluation of the potential NMD effects uses zinc, lead and copper elemental abundances in overburden material as key indicators of metalliferous enrichment. Zinc, lead and copper were selected for two reasons. They are by far the best populated metal values available in the overburden drill cores, and high sulphur, zinc, lead and copper values correlate well to enrichment in other elements including arsenic, antimony, cadmium and selenium.

In the absence of relevant kinetic leaching results, in 2014, the metal cut-off values were derived from shake flask extraction and NAG pH liquor analysis results conducted by KCB. While providing a good first pass estimate, it was recognised that validation of the cut-off values using kinetic geochemical testing results was required. This testing was undertaken in 2015 and 2016. Because of this limitation, conservative values were used as metal cut-off concentrations. The selected values were:

- zinc, 0.4%;
- lead, 0.04%; and
- copper, 700 ppm.

While the four elements (sulphur, zinc, lead and copper) are used as key indicators, 42 elements are routinely monitored for significant enrichment through in-pit grade control (see **Section 6.7**). These include elements which are known to be deleterious and are suspected to be enriched in certain lithological units of the deposit: zinc, lead, copper, aluminium, chromium, manganese, arsenic, molybdenum, silver, cadmium, antimony and bismuth.

6.4.3 MRM/KCB 2016 Classification

6.4.3.1 2016 Classification System

The MRM/KCB 2016 classification improves the 2014 classification with updated cut off values following kinetic geochemical testing undertaken though 2015 and 2016. The changes are relatively minor. The most significant change affects the identification of potentially reactive PAF(RE) material. The changes do not affect the number of material classes and/or their properties, but bring the cut-off values in line with the more recent geochemical testing.

The key changes include the following:

- update of the zinc cut-off value from 0.4% to 0.12%;
- removal of the copper criteria;
- addition of arsenic and cadmium cut-off values; and
- change of the PAF(RE) criteria based on geology.

Further discussion of these changes is provided in **Section 6.4.3.2** below.

The proposed updated classification criteria and corresponding classes are presented in **Table 6-5.**

Table 6-5 MRM/KCB 2016 Overburden Classification Criteria

Classification	Characteristics	Description and Handling
LS-NAF(HC)	NPR ≥ 2 sulphur < 1%, zinc < 0.12, lead < 0.04%, arsenic < 40 ppm, cadmium < 10 ppm	Considered at low risk of generating AMD. Generally characterised by a high acid consumption capacity. Suitable for placement in environmentally sensitive areas such as the OEF outer cover.
MS-NAF(HC)	NPR ≥ 2, sulphur ≥ 1%, with either zinc ≥ 0.12 %, lead ≥ 0.04%, arsenic ≥ 40 ppm, or cadmium ≥ 10 ppm	Considered at low risk of generating AD but higher risk of generating SD and NMD. Generally characterised by a high acid consumption capacity. This material is not considered environmentally benign and requires some form of encapsulation and water management strategy.
MS-NAF(LC)	1 ≤ NPR < 2	Considered at low risk of generating AD but higher risk of generating SD or NMD. While non-acid forming, this material is likely to provide limited acid consumption capacity. This material is not considered environmentally benign and requires some form of encapsulation and water management strategy.
PAF(HC)	NPR < 1	Considered at risk of generating AD, and is likely to have a significant capacity to do so. Samples classed as undefined according to the DITR 2007 classification are included in the PAF(HC) category. This material is not considered environmentally benign and requires some form of encapsulation and water management strategy.
PAF(RE)	NPR < 1, sulphur ≥ 10%, and BbH	Reactive PAF Material considered at high risk of generating AD, and at high risk of self-heating which may progress into spontaneous combustion. This material is not considered environmentally benign. It requires encapsulation and is likely to require specific additional handling strategies to prevent the onset of spontaneous combustion.

6.4.3.2 2016 Classification Criteria

6.4.3.2.1 Sulphur

The 1% total sulphur cut-off value for LS-NAF/MS-NAF remains unchanged in the proposed classification. Humidity cells and column leach testing results indicate that the value is appropriate (KCB, 2016). Field barrel leachate data indicates that samples with less than 1% sulphur leach sulphate concentrations below the site trigger value, with a cumulative loading rate of less than 10 mg/kg (**Figure 6-10**). All samples exceeding the trigger values are successfully classified as MS-NAF or PAF overburden types (**Figure 6-11**).

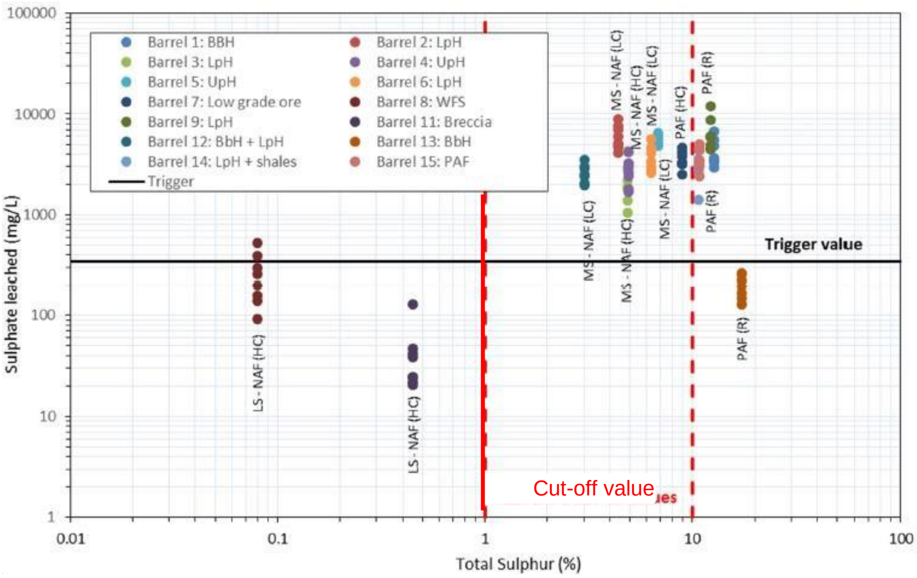


Figure 6-10 Total Sulphur vs. Sulphate in Field Barrel Leach Tests

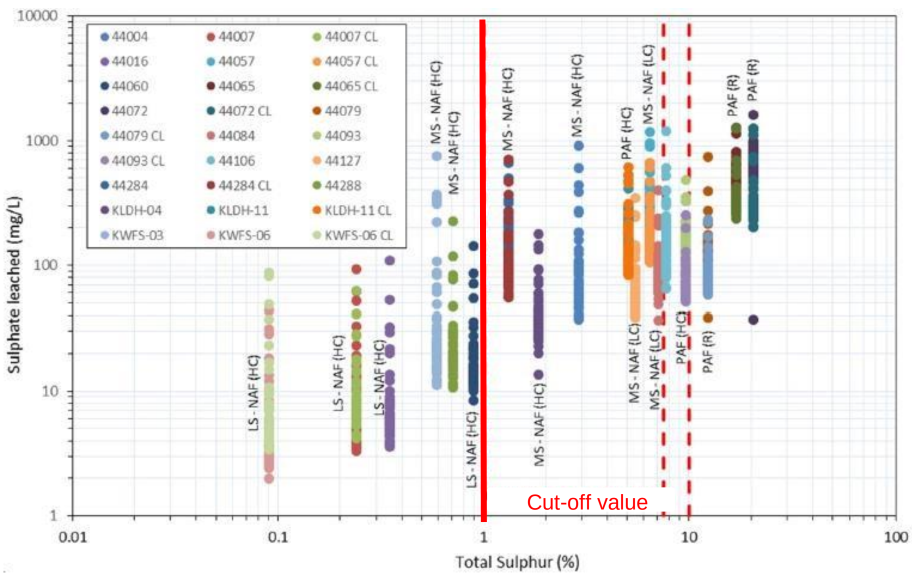


Figure 6-11 Total Sulphur vs. Sulphate in Humidity Cells and Column Leach Tests.

6.4.3.2.2 Zinc

The humidity cells and column leach testing results indicate that the 0.4% zinc cut-off value may not be conservative: several samples leached elevated zinc while having whole rock zinc concentrations less than 0.4% (**Figure 6-12**). However, these samples were already classified as MS-NAF or PAF according to other parameters so it would have no effect on their classification or management. Nevertheless, if a zinc cut-off is to be effective, it must be consistent with the available data. Based on the data set, a more conservative zinc value of 0.12% has been deemed appropriate and robust and will bring the zinc value in line with kinetic leaching results.

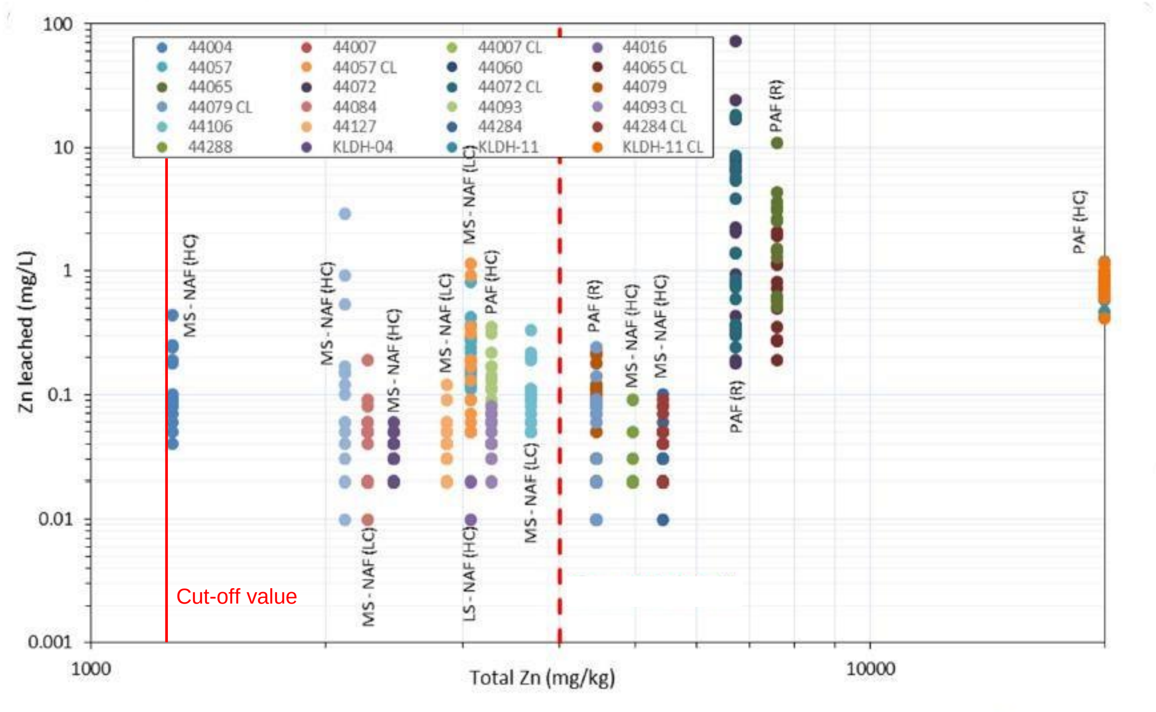


Figure 6-12 Whole Rock Leached Zinc (Zn) vs. Total Zinc.

The revised zinc value has no effect on the current LS-NAF resources or past stockpiles because of the very low zinc content of lithologies mined as LS-NAF. **Figure 6-13** presents the zinc cumulative percentage for the Quaternary Alluvium, W-Fold Shale, Teena Dolomite, and Upper Breccia lithostratigraphic units which constitute the potential LS-NAF reserves on site. The change from 0.4% (dashed line) to 0.12% (solid line) moves the value of the cut-off from the 99th percentile to the 98th percentile, a change which is inconsequential.

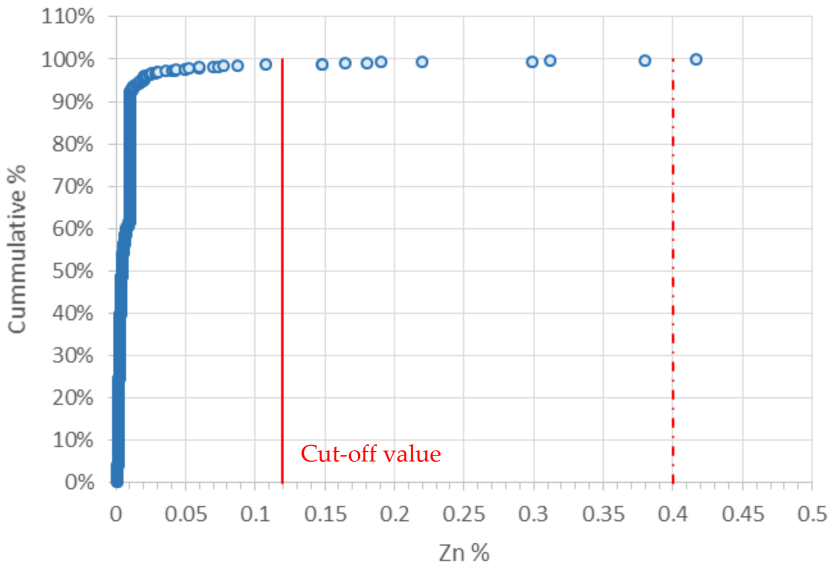


Figure 6-13 Cumulative Zinc (Zn) (Qa, WFS, Pmp and UpX)

6.4.3.2.3 Lead

The lead cut-off value of 0.04% remains unchanged. Humidity cells and column leaching results indicate that it is effective and sufficiently conservative (refer **Figure 6-14**).

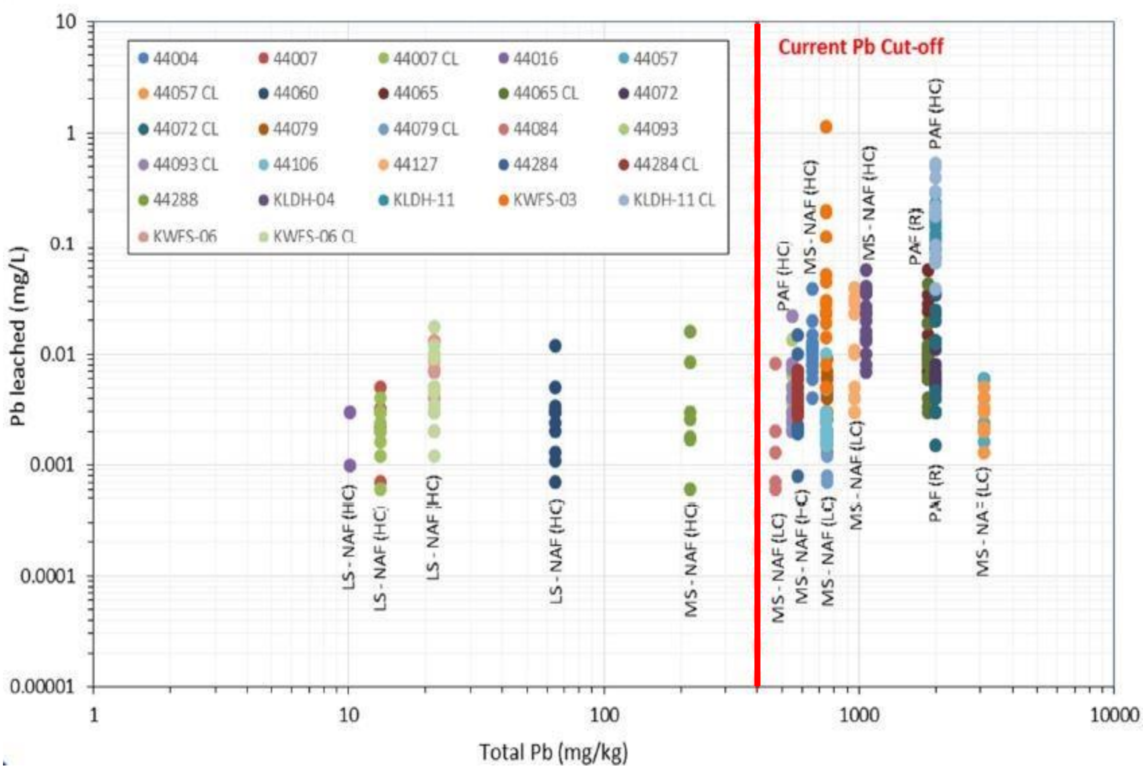


Figure 6-14 Whole Rock Lead (mg/kg) vs. Leached Lead (mg/L)

6.4.3.2.4 Copper

The leached copper concentrations from the laboratory kinetic testing were mostly below instrumental detection limits or very low for all overburden classes. With the exception of some first-flush values, the field barrel leach results indicate that no samples leach copper above the site trigger value. The whole rock copper concentrations of two of the field barrels are among the highest copper containing samples encountered in the overburden, and the field barrels indicate that limited copper is leached under field conditions.

The copper cut-off has been removed from the proposed classification as it is considered to be redundant.

6.4.3.2.5 Arsenic

Arsenic can leach at elevated concentrations under neutral conditions and is a contaminant of concern (COC). Arsenic has been added to the Overburden classification criteria as a precaution. Based on the kinetic data, a conservative cut-off values of 40 mg/kg is suggested (refer to **Figure 6-15**).

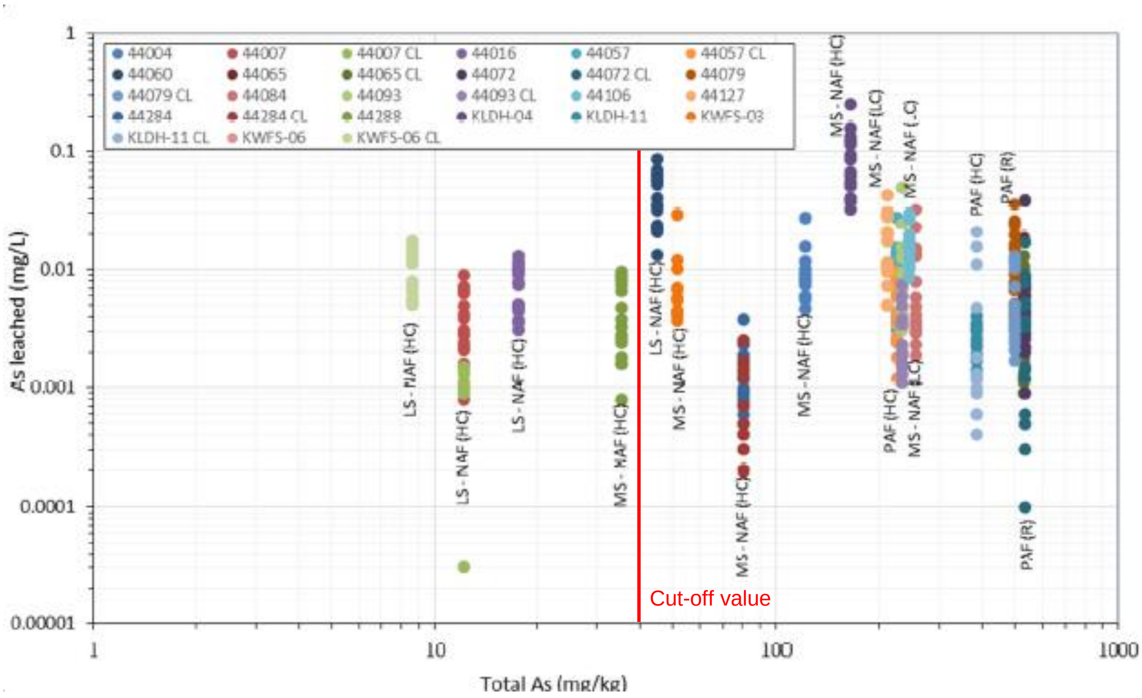


Figure 6-15 Whole Rock Arsenic vs Leached Arsenic

6.4.3.2.6 Cadmium

Cadmium was also identified as a COC. It is known to leach under neutral pH conditions. The leachate concentrations observed in the laboratory kinetic tests and the field barrel tests (KCB, 2016) indicate that some of the samples are leaching cadmium concentrations above the site trigger value (**Figure 6-16**). Consequently, all of the samples have been classified as MS-NAF and a cadmium criterion has been added to the proposed overburden classification. Based on humidity cell and column leach data, a cut-off value of 10 ppm has been adopted.

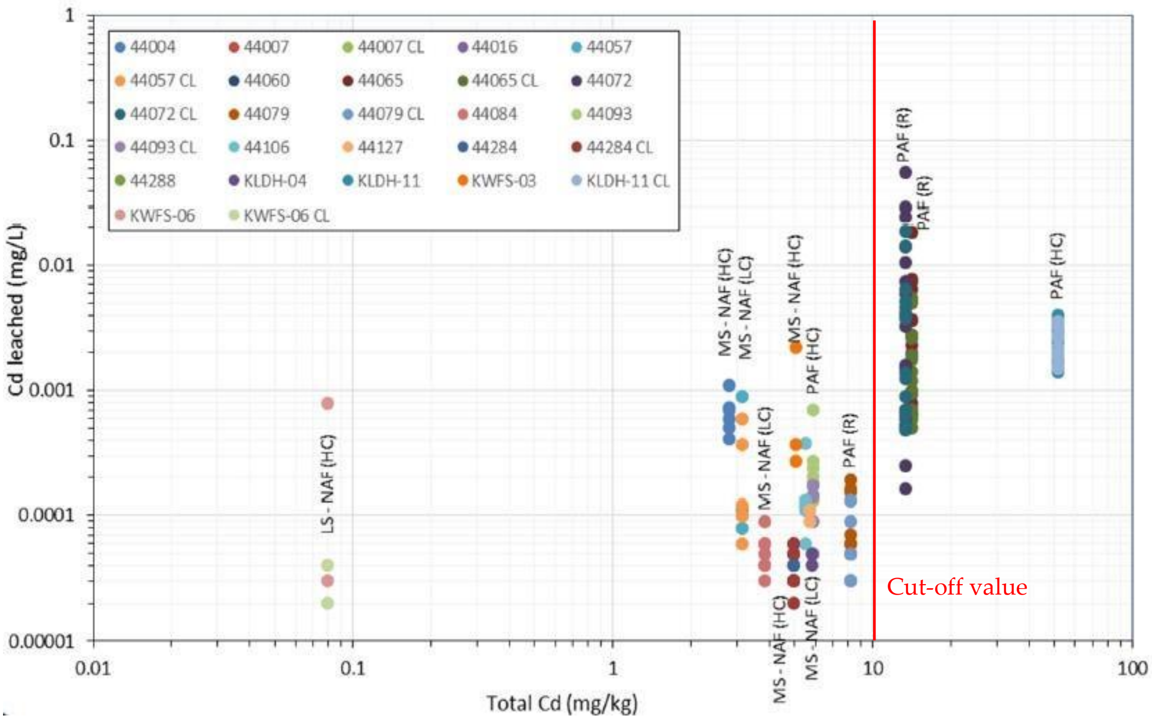


Figure 6-16 Whole Rock Cadmium vs. Leached Cadmium

6.4.3.2.7 PAF(RE)

PAF(RE) overburden can affect the quality of drainage and contact waters if not mitigated, and, therefore must be managed appropriately. The correct identification and quantification of PAF(RE) in advance of mining activities is needed for the effective management of the material within the NOEF.

Several factors may lead to the onset of self-heating and the development of spontaneous combustion in pyritic overburden. They can be grouped in two broad categories: extrinsic factors – those which result from the environment in which the pyritic rocks are placed, such as dumping strategy, OEF architecture and geometry and availability of oxygen and water; and intrinsic factors which result from the composition of the rocks themselves, such as presence of organic carbon, fine grained pyrite and in situ moisture contents.

All PAF material has the potential to self-heat and develop spontaneous combustion over time if not mitigated. The aim of the PAF(RE) criteria is therefore to isolate the material which has the intrinsic ability to combust within a short period following exposure, as this material needs to be segregated and requires specific handling and encapsulation.

The new classification criteria (Black Bituminous Shale and sulphur > 10%) takes into account both the pyrite content and the total organic carbon (TOC) content of the rock. Both parameters have been shown to be important controls on the susceptibility of pyritic rocks to spontaneous combust.

As presented in **Figure 6-17**, the Black Bituminous Shale is chemically and visually distinct from all other lithostratigraphic units in having significantly higher organic carbon content. The TOC broadly ranges from 1 to 4% with no samples below 0.5%, while all other lithologies have 95% of samples with TOC values below 1%.

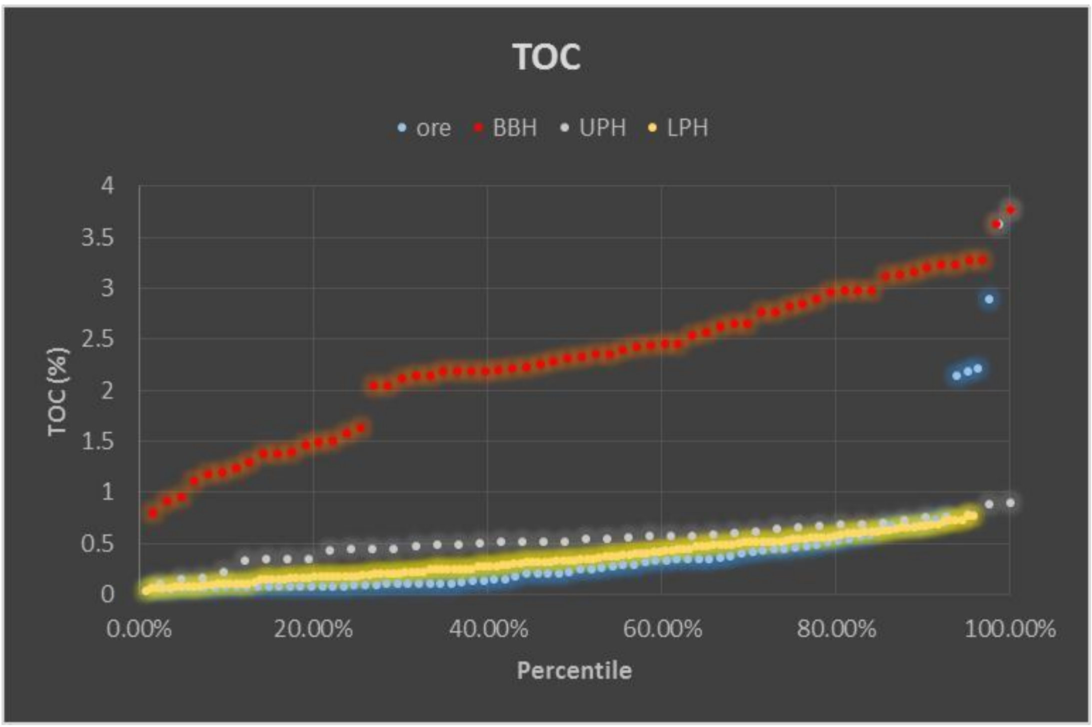


Figure 6-17 Total Organic Carbon (TOC) (Ore, BbH, UPH & LPH)

Figure 6-18 presents the distribution of PAF(RE) in the April 2016 open cut shell predicted by the geological block model based on the Black Bituminous Shale and S > 10% criteria. The spatial distribution matches very closely the spatial distribution of observed elevated temperatures and sulphur dioxide production in the open cut.

The geological block model results using the new criteria are much closer to historical records of spontaneous combustion than those resulting from a simple sulphur cut-off value. A simple sulphur cut-off value would class as PAF(RE) other lithologies where self-heating has not been observed, resulting in a less accurate classification.

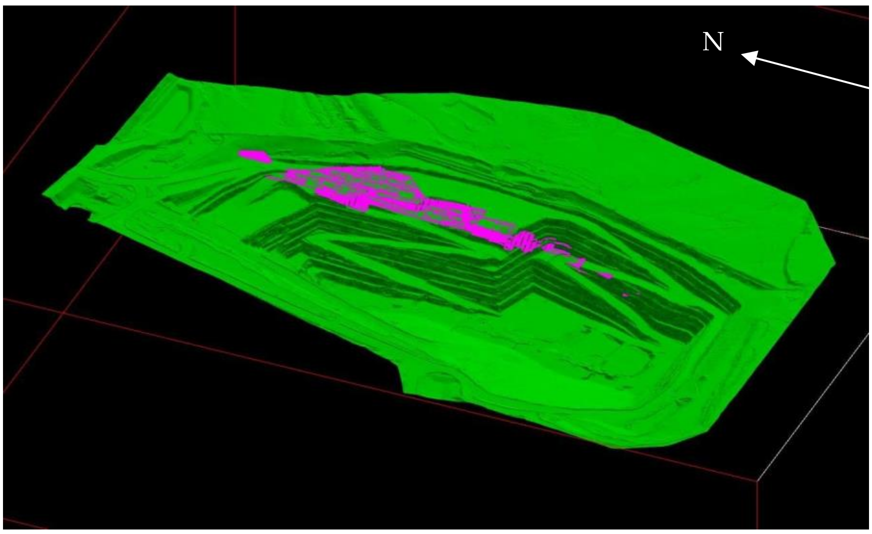


Figure 6-18 Block Model Estimates for PAF(RE) (purple) April 2016 Open Cut

6.4.4 Australian Guidelines

6.4.4.1 DITR 2007 classification

For comparative purposes, and to demonstrate that the MRM classification is conservative, the Australian Department of Industry Tourism and Resources (DITR, 2007) AMD classification guideline criteria are presented in **Table 6-6.**

Table 6-6 DITR (2007) Overburden Classification Criteria

NAPP (kgH_2SO4/t)	NAG pH	Class	Description
NAPP ≤ -100	pH ≥ 4.5	Non-acid forming, acid consuming (NAF-AC)	Material considered at low risk of generating acid mine drainage, and provides reasonable acid consuming capacity.
-100 < NAPP ≤ 0	pH ≥ 4.5	NAF	Material considered at low risk of generating acid mine drainage, however is likely to provide limited acid consuming capacity.
0 < NAPP ≤ 10	pH < 4.5	Potentially acid-forming, low capacity (PAF-LC)	Material considered at higher risk of generating acid mine drainage, however is likely to have a limited capacity to do so. Requires encapsulation.
NAPP > 10	pH < 4.5	PAF-HC	Material considered at higher risk of generating acid mine drainage, and is likely to have a significant capacity to do so. Requires encapsulation.
NAPP ≤ 0	pH < 4.5	Uncertain	The testing is inconclusive. Further testing required to adequately characterise the material.
NAPP > 0	pH ≥ 4.5	Uncertain	The testing is inconclusive. Further testing required to adequately characterise the material.

The classification is based on the AMIRA (2002) published guidelines for acid mine drainage. As such, it only covers the risk of acid drainage and does not consider the risk of saline and neutral metalliferous drainage. This is not necessarily a limitation, as the guidelines recognise that the risk of SD and NMD should be assessed on a site specific basis. As a result, generic criteria cannot be derived.

6.4.5 Overburden Classification Results

This section presents a comparison of the various overburden classification systems results when applied to the MRM geochemical dataset.

6.4.5.1 2017 Classification System

The classification results from 3976 drill core samples is presented in **Figure 6-19**. The NPR = 1 line corresponds to the NAF/PAF boundary, while the NPR = 2 line corresponds to the NAF-LC/NAF-HC boundary.

The same data is presented in **Figure 6-20** as a NAPP/NAG pH diagram for the readers more familiar with this format. The relative proportions of sample classifications are presented in **Table 6-7** together with a summary of average ABA values.

Table 6-7 KCB (2017) MRM Overburden Classification Results

	Classification	#	MPA (kg H_2SO4/t)	ANC (kg H_2SO4/t)	NAPP (kg H_2SO4/t)	NPR	NAG pH	Sulphur (%)
NAF (66.2%)	LS-NAF(HC)	247 (8.9%)	15	555	-540	38	9.2	0.5
	MS-NAF(HC)	850 (30.8%)	88	416	-329	4.7	8.4	2.9
	MS-NAF(LC)*	732 (26.5%)	184	253	-68	1.4	7.7	6.0
PAF (33.8%)	PAF(HC)	443 (16.0%)	258	206	52	0.8	4.4	8.4
	PAF(RE)	492 (17.8%)	453	191	262	0.4	2.7	14.8

*MS-NAF(LC) is classed as NAF but is managed as uncertain.

As presented in **Table 6-7**, 66.2% of samples are classified as NAF, with 39.7% having an NPR greater than 2 and strongly negative mean NAPP values of -540 and -329 kgH_2SO_4/t, characteristic of acid consuming materials.

26.5% of samples have an NPR value between 1 and 2 (average of 1.4) and are therefore classified as a MS-NAF(LC). Although it is not a definite PAF material, its potential to generate acid over the long term is somewhat uncertain and therefore will be managed conservatively.

As can be seen from **Table 6-5** the sulphur and metal cut-off values are only relevant in distinguishing the LS-NAF(HC) material from the MS-NAF(HC) material. All other classes are automatically considered to have the potential to generate metalliferous and/or saline drainage.

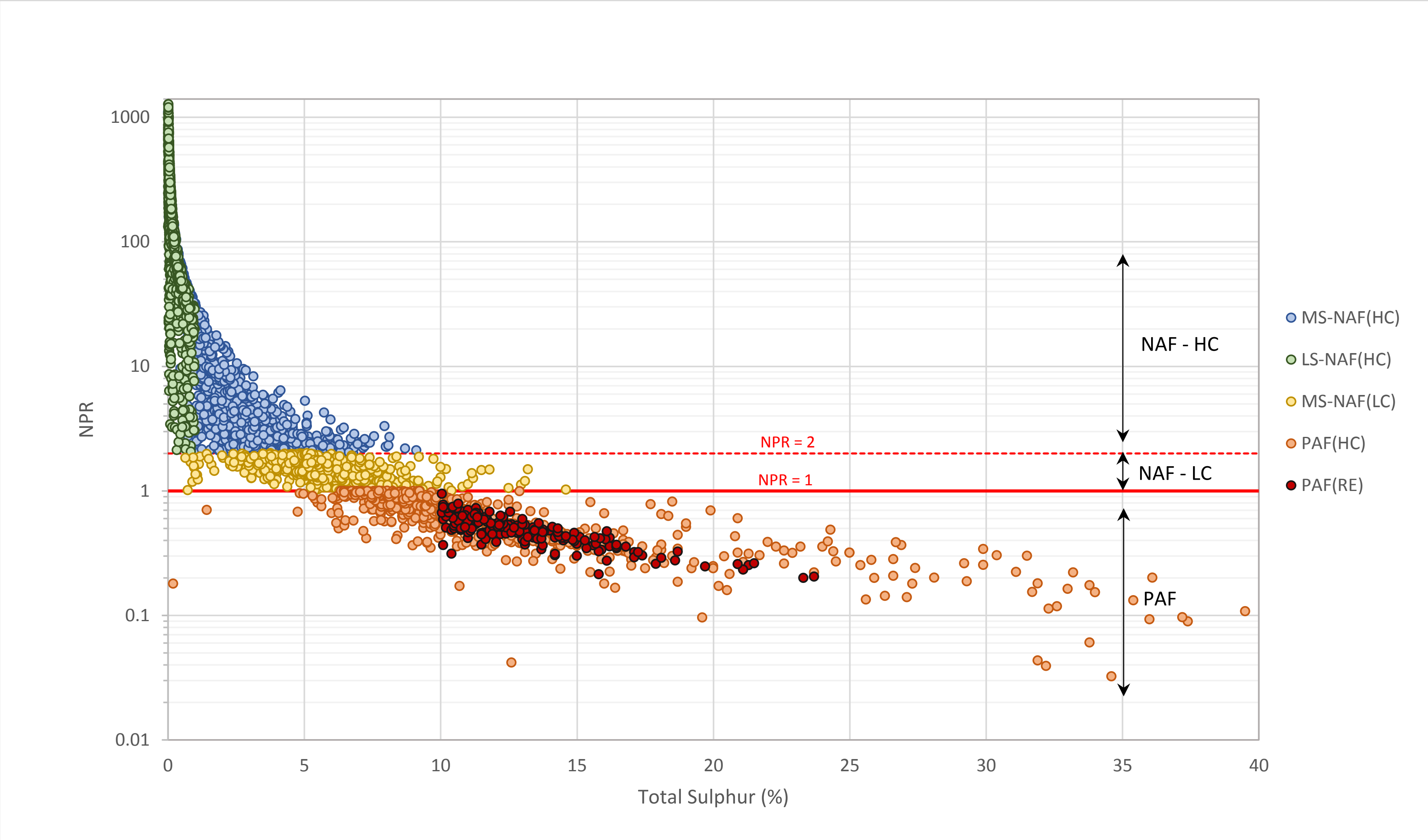


Figure 6-19 NPR vs. Total Sulphur (%) (MRM/KCB 2016 Classification)

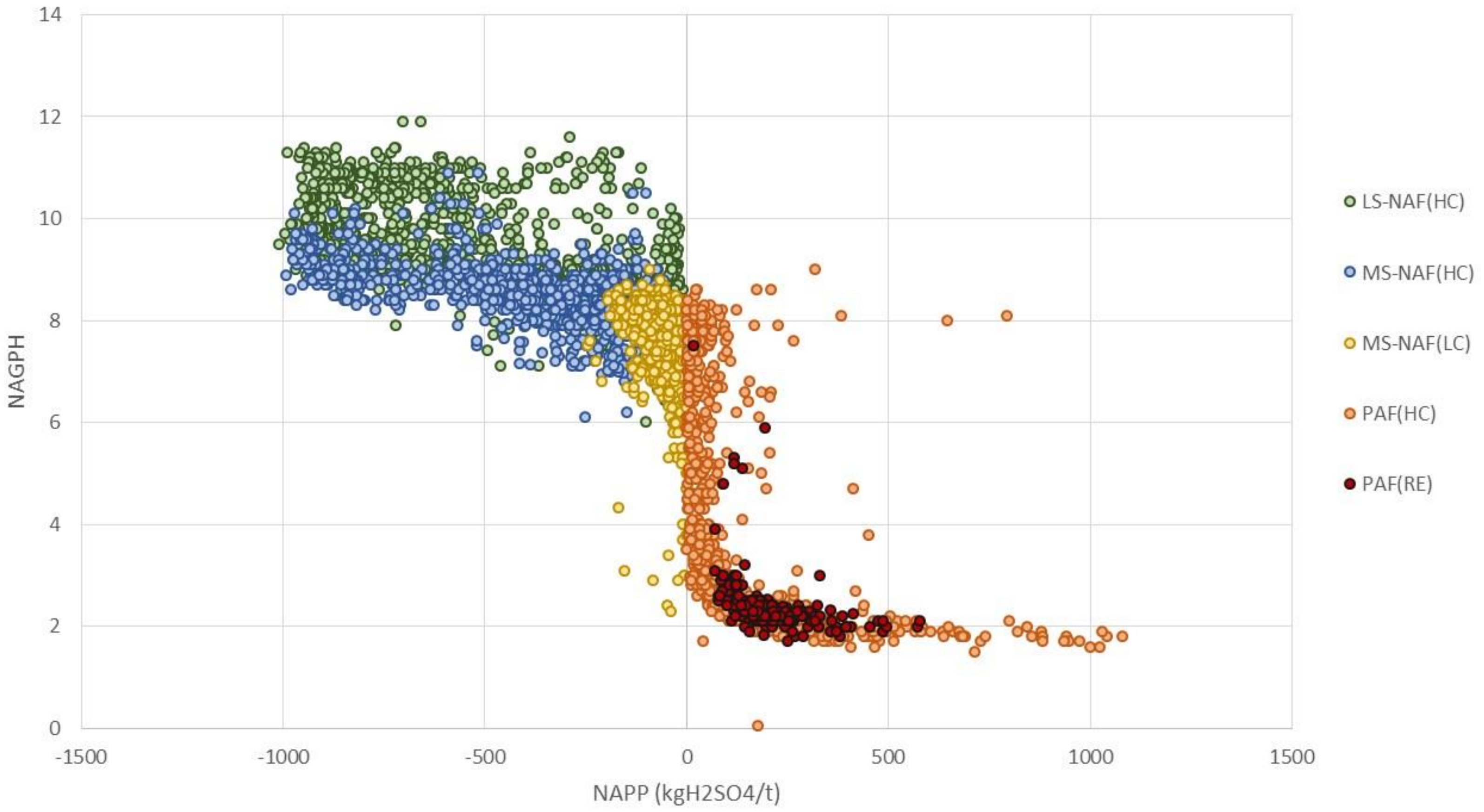


Figure 6-20 NAPP vs NAG pH by Overburden Classification

Approximately a quarter of all samples are LS-NAF(HC). For clarity, **Figure 6-21** presents the relative proportion of LS-NAF according to its origin: only 7% of samples represent the material mined as LS-NAF within the open cut shell. The open cut material corresponds to the footwall units W-Fold shales and Teena Dolomite. A further 6% occur within hanging wall units which cannot be segregated during mining, so will be mined as MS-NAF. The largest proportion (13%) represents the regolith (refer to **Section 6.2.2.5**) and the ex-pit quarries (refer to **Chapter 3 – Project Description and Justification**) identified as potential sources of LS-NAF(HC). A total of 33.8% of samples were classified as PAF.

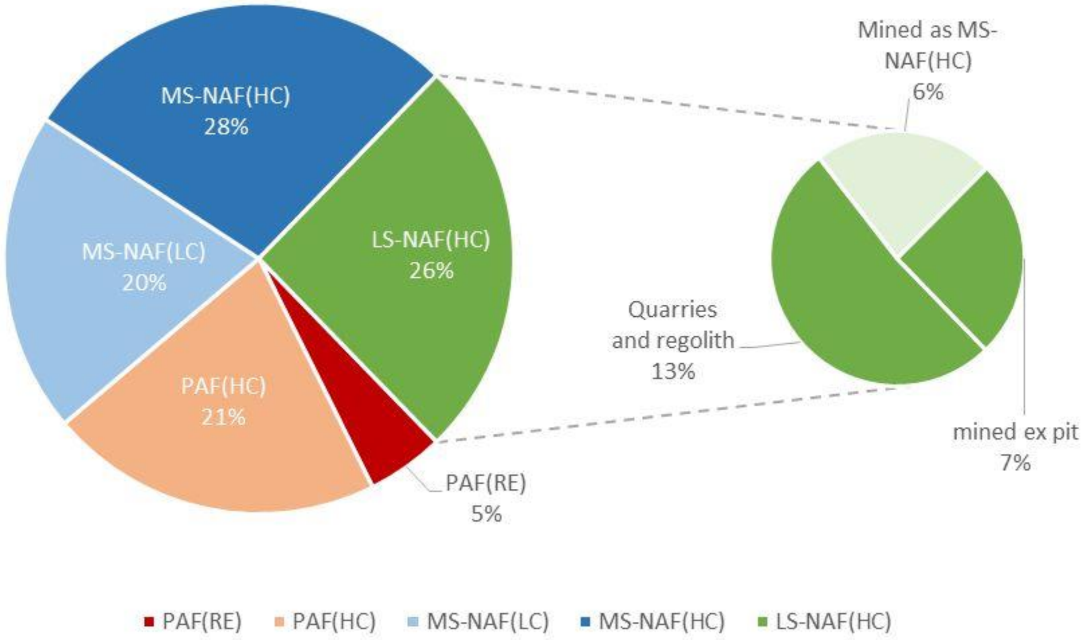


Figure 6-21 Proportional Overburden Classes with Quarries and Regolith

6.4.5.2 Comparative Classification Assessment

6.4.5.2.1 Proposed (2017) versus Current (2014) Classification Systems

Figure 6-22 presents the results from the revised 2017 classification based on the 2016 database compared to the results from the 2014 database (**Figure 6-23**). For a meaningful comparison, only run of mine overburden is considered, so the samples from the regolith and the ex-pit quarries collected in 2015 are omitted.

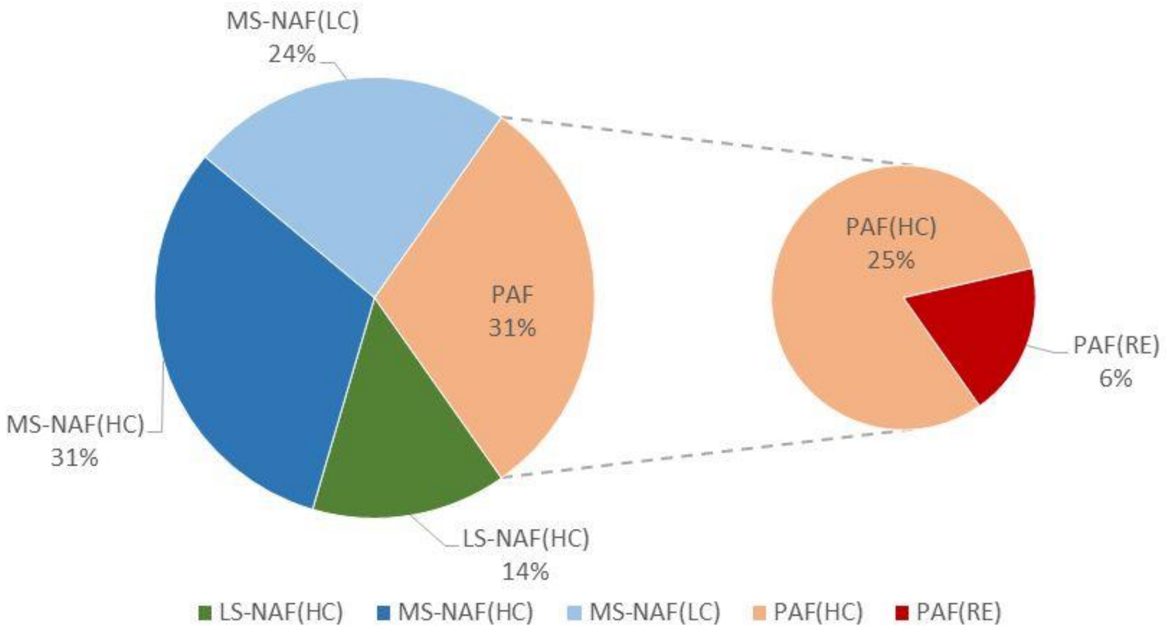


Figure 6-22 Proportional Overburden Classes per 2016 database

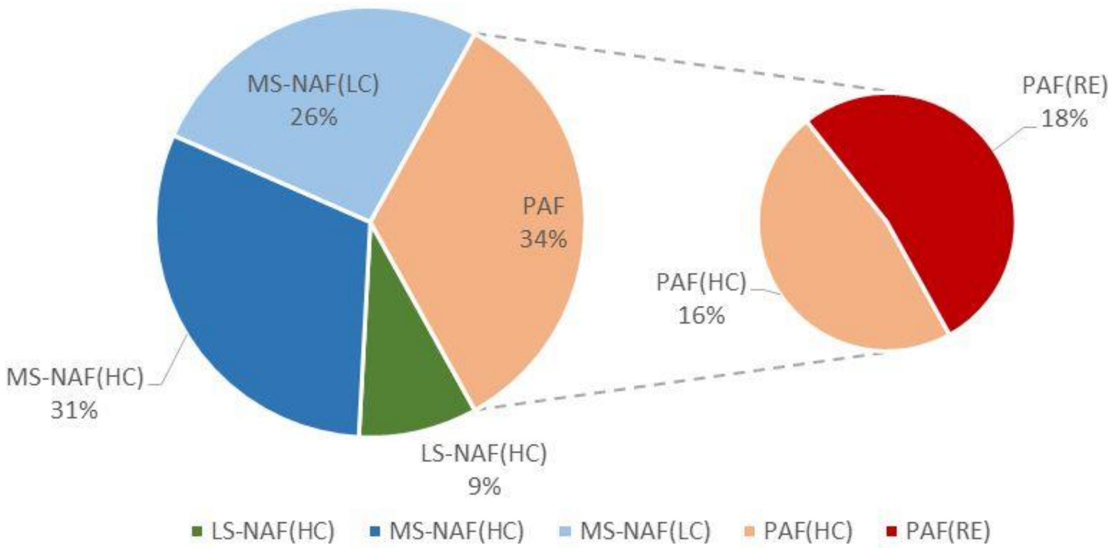


Figure 6-23 Proportional Overburden Classes per 2014 database

The relative proportions of the overburden classes are consistent between the two databases and two classification criteria. The 2016 results show a higher proportion of LS-NAF(HC) samples (14% compared to 9% in 2014) interpreted as representing differences the 2014 and 2015 drilling campaigns that were designed to better identify LS-NAF(HC) resources.

The relative proportions of PAF are very similar between the two datasets with 31% and 34%, respectively. An important difference between the relative proportions is the lower fraction of PAF(RE) of 6% in 2016 compared to 18% in 2014. The change in proportion directly reflects the change in criteria between the two classifications, with the 2016 reactive PAF being restricted to the Black Bituminous Shale.

6.4.5.2.2 Proposed MRM (2017) versus DITR (2007) Classification

For comparison, the MRM dataset was reclassified according to the DITR guidelines to determine the relative performance of the proposed MRM classification against an industry standard guideline. The results are presented in **Figure 6-24** and **Table 6-8.**

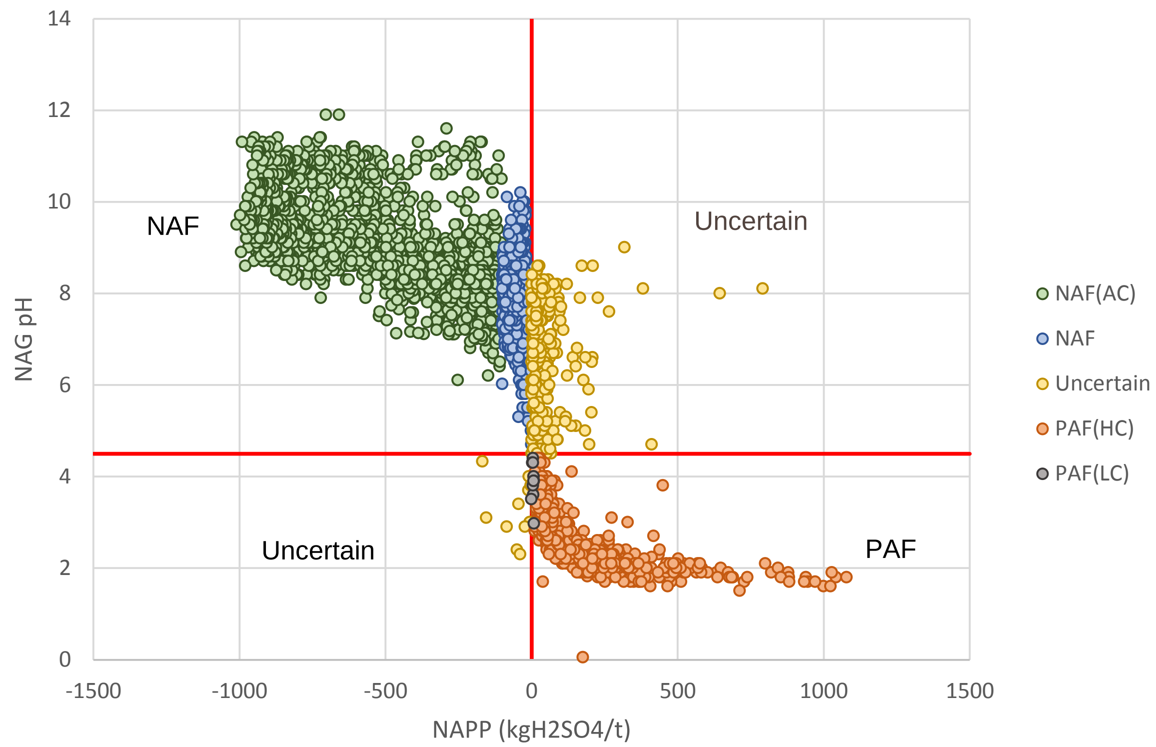


Figure 6-24 DITR 2007 Classification Results on 3976 Drill Core Samples

Table 6-8 DITR 2007 Overburden Classification Results with Average Values

	n	MPA	ANC	NAPP	NPR	NAG pH	S%	Percentage of samples		
NAF-AC	1222	88.09	442	-353	5	8.5	2.9	44.2%	65.7%	NAF
NAF	594	172.89	224	-51	1.3	7.7	5.6	21.5%		
Uncertain	243	272.98	223	50	0.8	6.5	8.9	8.8%	34.3%	PAF
PAF-LC	8	247.06	241	6	1.0	3.9	8.1	0.3%		
PAF-HC	697	390.33	190	200	0.5	2.5	12.8	25.2%		

Comparison between the MRM 2017 and DITR classifications shows that the proportions of NAF and PAF in both classifications are consistent (66.2% vs. 65.7% NAF and 33.8% vs. 34.3% PAF if uncertain samples are included in the PAF class), although only 25.2% of samples are considered “true” PAF in the DITR classification.

The proportion of high capacity/acid consuming NAF is similar in both classifications, the MRM classification being slightly more conservative again (39.7% vs. 44.2%). The DITR 2007 NAF class corresponds essentially to the MS-NAF(LC) class in the MRM/KCB 2016 which is again managed conservatively owing to its uncertain and metalliferous saline nature.

The primary difference is that the MRM/KCB 2016 classification considers the potential risk of Neutral Metalliferous Drainage and Saline Drainage by incorporating metal cut-offs. The MRM/KCB 2016 classification is therefore considered to be robust and conservative relative to industry standard classification systems

6.5 Geological Block Model

As outlined in **Section 6.1.1**, a geological block model is a 3D computer model of the subsurface geology created using the geological data gathered through drilling the prospective zone. It is composed of specifically sized "blocks", each block being characterized by a set of parameters such as grade, density, rock type, and other properties determined by statistical methods. Once a block model has been developed, it is used to determine the ore resources and reserves as well as the nature and quantities of overburden materials.

6.5.1 Block Model Boundary Criteria

Boundary criteria are the parameters used in the block model to define the various rock classes. They can be a set of numerical cut-off values or conditions (e.g. sulphur < 1%) or a defined lithostratigraphic interval (for example Lower Pyritic Shale). The boundary criteria are critical in the correct definition of the different material classes in overburden materials. The below sections describe the improvements to block model boundary criteria that have been made since the Phase 3 EIS.

6.5.1.1 2005 to 2013 Boundary Criteria

Overburden classification in the block model mirrored the URS classification criteria in that it was based on the interpolation of iron as a proxy for the NAPP, and NAG pH. The interpolation was completed for all blocks using ordinary kriging parameters (a form of statistical estimation process), and was then used to apply NAF/PAF criteria to all blocks. The cut-off parameters for NAF and PAF were:

- iron greater than 7.5% with pH less than 4 for PAF lithology; and
- iron less than or equal to 7.5% with pH greater than or equal to 4 for NAF lithology

In the block model, total iron content was used as a proxy indicator for sulphur and for the NAPP. It was based on the assumptions that:

- Most of the iron in the hanging wall and foot wall lithologies is present in pyrite and will directly correlate to sulphur content. This correlation was well supported by the geochemical data.

- Overburden material with less than 7.5% iron have a negative NAPP value, indicating that their ANC exceeds their acid production potential and are therefore classed as NAF. This was also reasonable according to the geochemical data.

The use of Iron as a proxy for the NAPP, while acceptable and statistically reasonable, is weak on geochemical grounds and could yield inaccurate estimations on a local scale.

The use of pH as a boundary criterion is not optimal. The estimation process is likely to result in incorrect estimated values, resulting in a bias towards NAF pH values and a broad underestimation of PAF.

6.5.1.2 Boundary Criteria (2014)

The development of new classification criteria required new block model boundary criteria. Three criteria/indicators were required for the resource model to match the 2014 MRM classification. These included the following:

- An indicator for material with the potential to produce saline drainage. Saline drainage in the MRM overburden is related to the release of sulphates. The key indicator for sulphate production was total sulphur, which was directly estimated through the block model.
- An indicator for material with the potential to generate acid drainage. The new classification uses the NPR ratio to assess acid potential. In the absence of direct estimation of ANC, a proxy indicator for the NPR was required. The resource model used the correlation between total sulphur content and NPR (refer to **Figure 6-25).**
- An indicator for material with the potential to generate NMD. The NMD potential was evaluated using zinc, lead and copper content as key indicators for metalliferous enrichment.

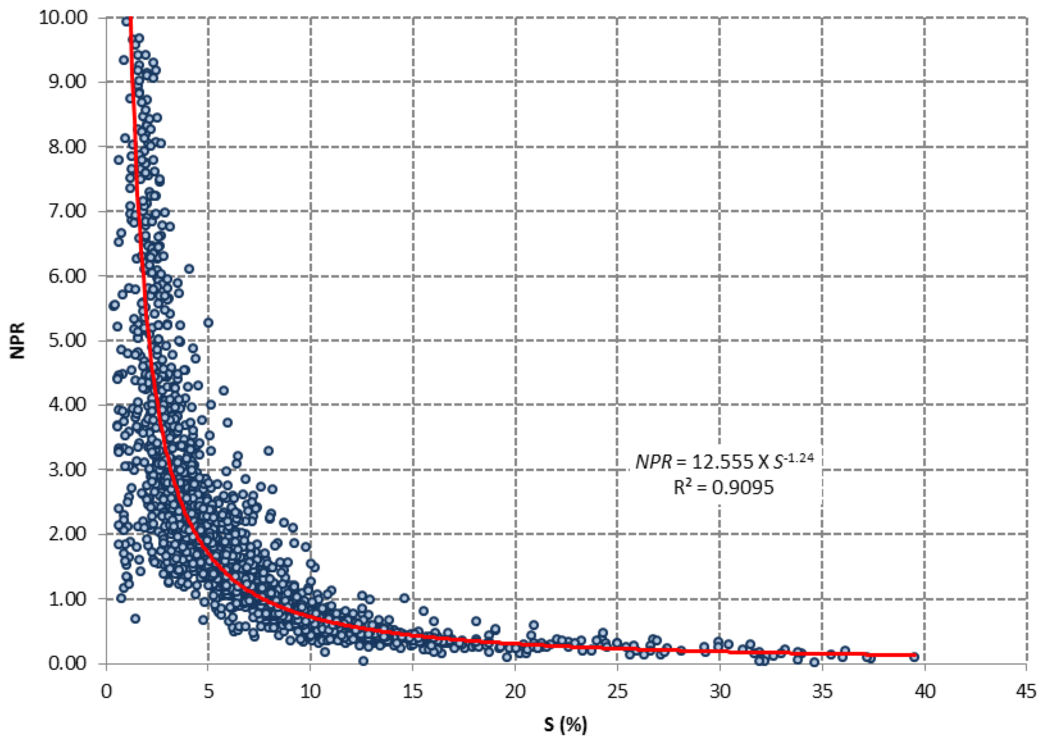


Figure 6-25 NPR vs Total Sulphur.

The relationships in **Table 6-9** were used to derive ABA cut-off values for the block model boundaries.

Table 6-9 ABA Cut-Off Values by Overburden Class

Overburden Class	Lower Sulphur Limit	Upper Sulphur Limit
LS-NAF(HC)	-	≤1 %
MS-NAF(HC)	> 1%	≤ 4%
MS-NAF(LC)	> 4%	≤ 7%
PAF(HC)	> 7%	≤ 10%
PAF(RE)	> 10%	-

Comparative results between the geochemical classification and the block model sulphur proxy showed good model-wide agreement between the two methods.

The use of pH as a criterion was abandoned, as it was shown to be largely responsible for the underestimation of PAF quantities in the resource model.

The use of the relationship between sulphur and NPR resulted in a significant improvement in estimations. However, it was still considered by McArthur River Mining that a more direct estimation of ANC and hence calculation of NPR for each block would represent a stronger basis for the block model boundaries.

6.5.1.3 Proposed Boundary Criteria (2016)

Historically, the resource model boundary criteria were reliant on proxy parameters in order to estimate overburden classes. Following extensive improvement to the resource model throughout 2014 and 2015, resource model boundary criteria are now identical to the geochemical overburden classification criteria, completely dispensing the need to rely on proxy indicators and thereby rendering the block model estimations more reliable. The criteria/indicators used are:

- total sulphur used both as an indicator for material with the potential for generating SD dominated by sulphate;
- the calculation of the NPR using the ANC and MPA; and
- zinc and lead content as the key indicators for the potential to generate NMD.

6.5.1.3.1 Total Sulphur

Total sulphur is a key criterion as it is used in both the evaluation of saline drainage potential and acid drainage potential. Sulphur sampling density is sufficient and is estimated through the model by interpolation using ordinary kriging parameters (refer to **Figure 6-26**). As is the case with the geochemical classification, the use of total sulphur relies on the principal assumptions that most of the sulphur in the hanging wall and foot wall lithologies is present in pyrite, an assumption well supported by the geochemical data (refer to **Figure 6-27**).

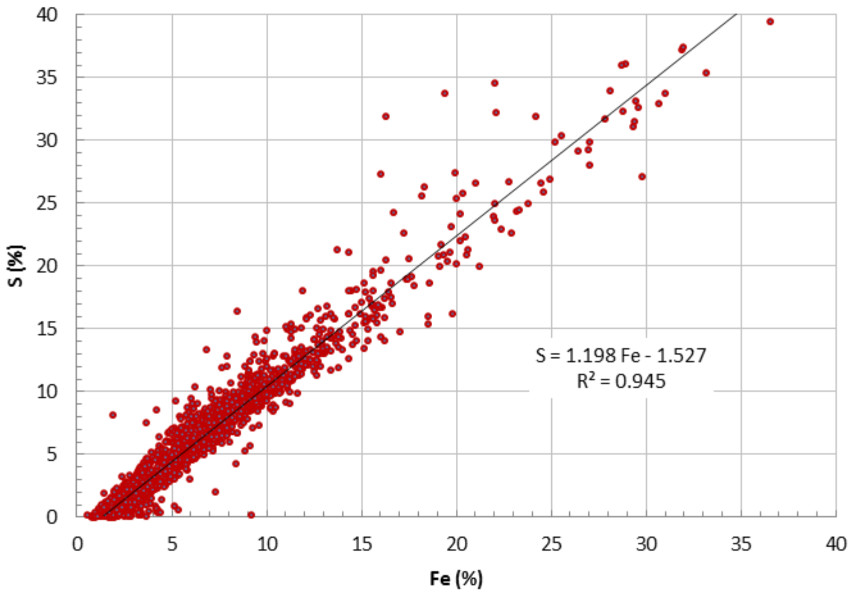


Figure 6-26 Iron and Sulphur in the Hanging Wall Lithological Units

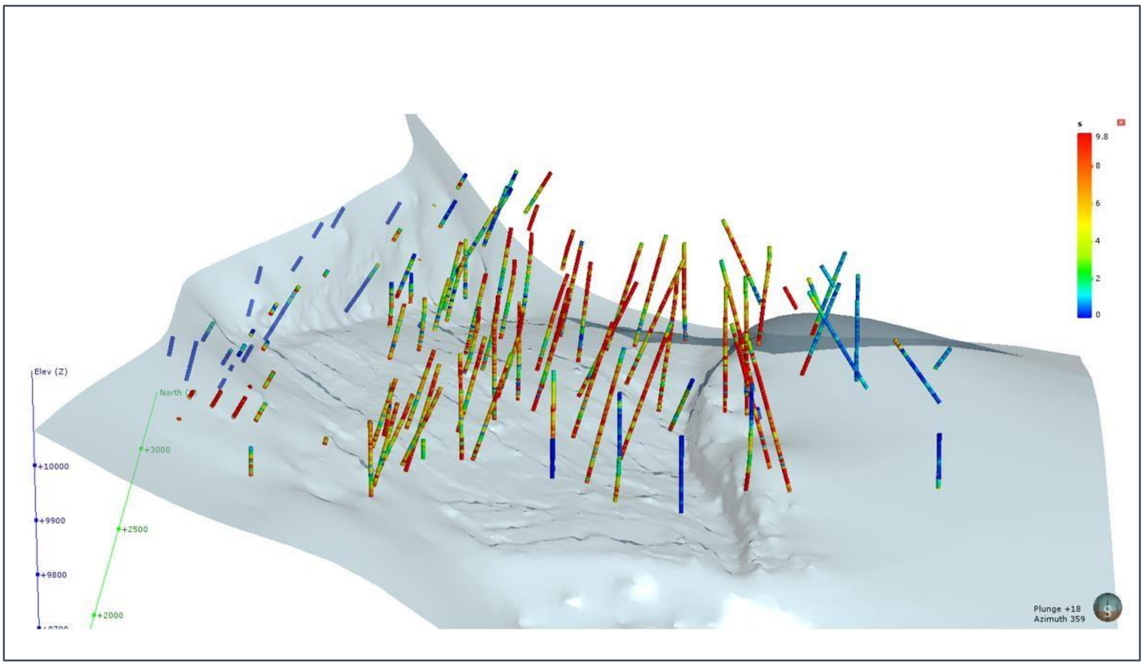


Figure 6-27 Hanging Wall Sulphur Distribution.

The surface presented in **Figure 6-27** is the modelled footwall of the ore body. The figure shows the distribution of the drill cores through the overburden, with the sulphur contents within each core graphically shown as a colour scale from blue (0%) to red (9% and above).

6.5.1.3.2 Neutralising Potential Ratio

The NPR is calculated for each block using the ANC and the MPA. At MRM, the ANC spatial density is sufficient for it to be meaningfully estimated through the model. **Figure 6-28** presents the distribution of ANC values through the hanging wall of the orebody with the surface of the modelled footwall of the orebody.

The MPA is calculated for each block from the estimated total sulphur, and the NPR is calculated for each block using the estimated ANC value.

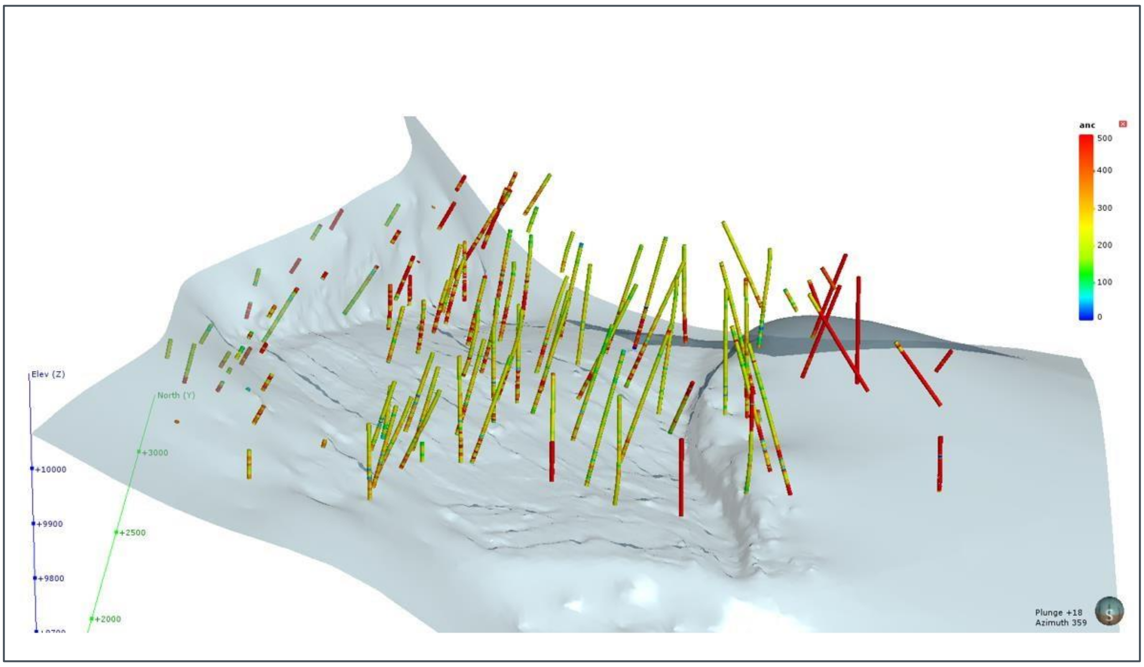


Figure 6-28 Hanging Wall ANC

6.5.1.3.3 Metal Contents

The resource model metal boundary criteria are identical to those in the geochemical classification. Zinc and lead were selected because they are the best populated metal values available in the overburden drill cores, and high zinc and lead values generally correlate to enrichment in other elements, including: arsenic, antimony, cadmium and selenium. **Figure 6-29** and **Figure 6-30** presents the distribution of zinc and lead values through the hanging wall of the orebody. The cut-off values for metalliferous rock are zinc > 0.12% or lead > 0.04%.

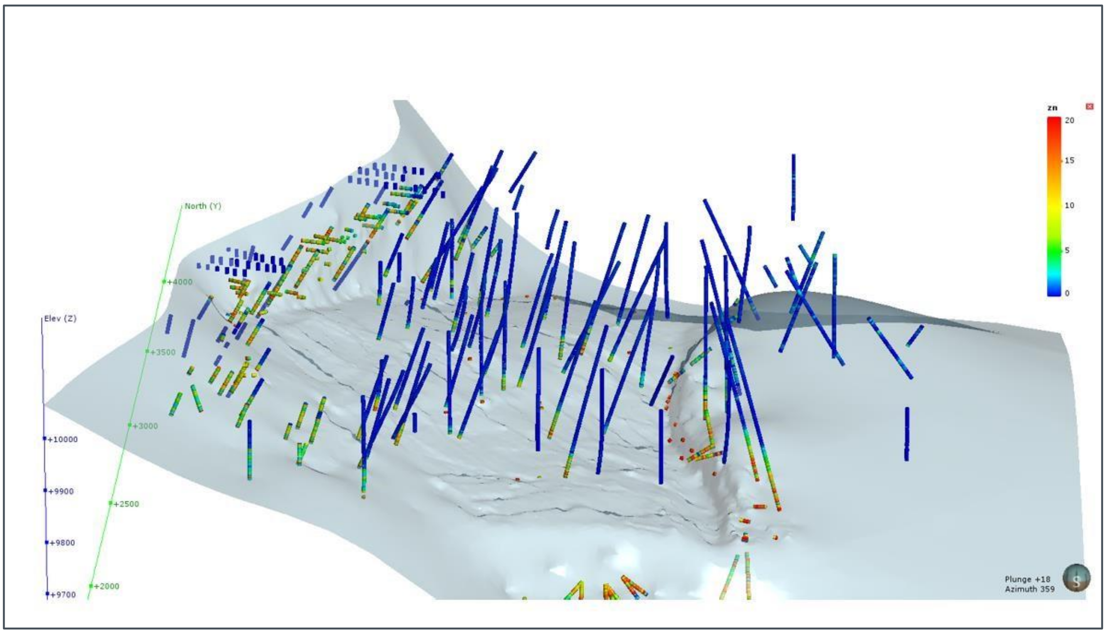


Figure 6-29 Hanging Wall Zinc

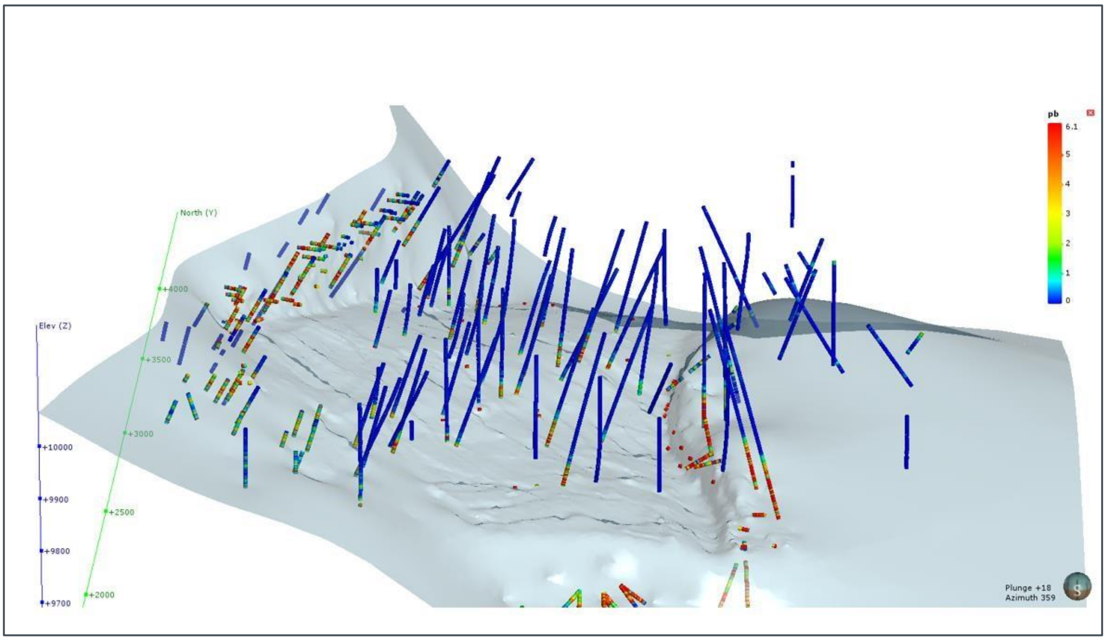


Figure 6-30 Hanging Wall Lead

6.5.2 Block Model Estimations

6.5.2.1 Spatial Distributions

The spatial distributions of material classes are presented in **Figure 6-31** to **Figure 6-38**. In the case of overburden materials, quantities of LS-NAF(HC) which are present but too small to be mined separately are counted as MS-NAF so only actual minable quantities are taken into consideration.

Figure 6-31 presents the distributions of the different overburden classes in the LOM open cut graphically. The distributions vary depending on location. A typical section from west to east through the centre of the open cut has been selected as an example figure. A discussion of the distribution of the various overburden classes follows.

LS-NAF(HC) reserves are presented in **Figure 6-32** together with the LOM open cut shell including the ex-pit quarries. As presented in the figure, the only areas mined as LS-NAF(HC) are in the footwall of the orebody and the Woyzbun Quarry. Any LS-NAF(HC) in the hanging wall is mined as MS-NAF and not accounted for in the LS-NAF(HC) reported quantities.

MS-NAF(HC) shown in **Figure 6-33** corresponds to the dolomitic breccias of the Lower Pyritic Shale, the Upper Dolomitic Shale and the Cooley Dolomite. The block model estimations present a very good match with the lithological data.

MS-NAF(LC) shown in **Figure 6-34** corresponds to the dolomitic and pyritic shales of the hanging wall units with the exception of the Cooley Dolomite. It is closely associated, spatially with PAF(HC).

The majority of PAF(HC) as shown in **Figure 6-35** corresponds to the Upper Pyritic Shale, Black Bituminous Shale and Lower Pyritic Shale. While most of the mined PAF(HC) will be placed in the NOEF, a small subset of this material has been segregated for in pit disposal after the cessation of mining operations. It represents the most pyritic material in the MRM overburden and is defined as having more than 20% sulphur. It is limited in extent, being spatially restricted to a distinct stratigraphic layer of the Lower Pyritic Shale. It presents a relatively small quantity of overburden.

The distribution of PAF(HW) is shown in **Figure 6-36** and its location relative to the Western Fault and Black Bituminous Shale is shown in **Figure 6-37**.

The location of the PAF(RE) in the LOM open cut is presented in **Figure 6-38**. It is exclusively restricted to the Black Bituminous Shale. It is distributed throughout the LOM open cut, with the largest volumes being located in the northern half of the open cut. This is in very good agreement with historical observations of in-pit reactive material.

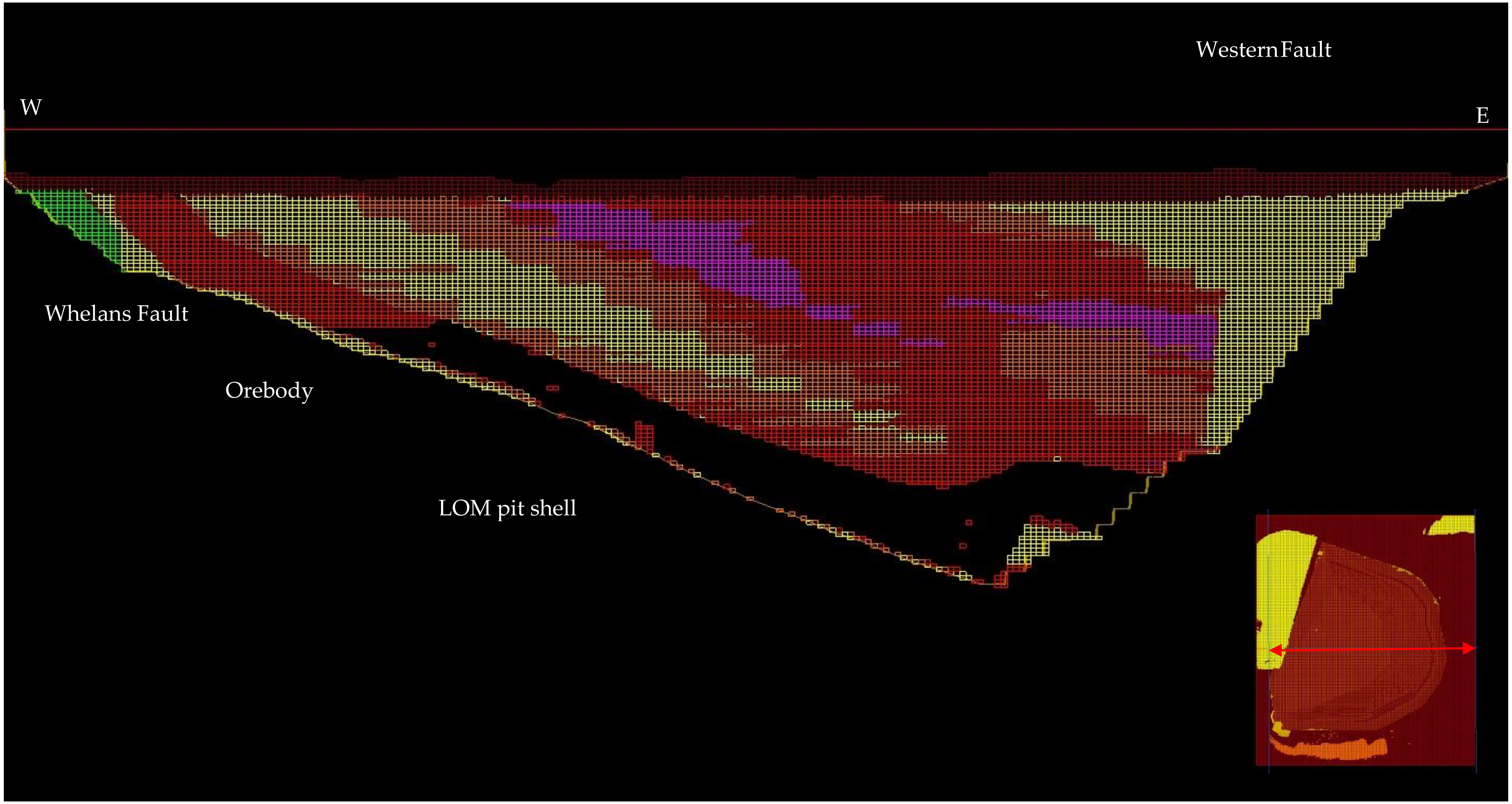


Figure 6-31 West-East Open Cut Cross-section Showing Overburden Class Distribution.

LS-NAF(HC): green; MS-NAF(HC): yellow; MS-NAF(LC): orange; PAF(HC): red; PAF(RE): pink; ore body: black/red.

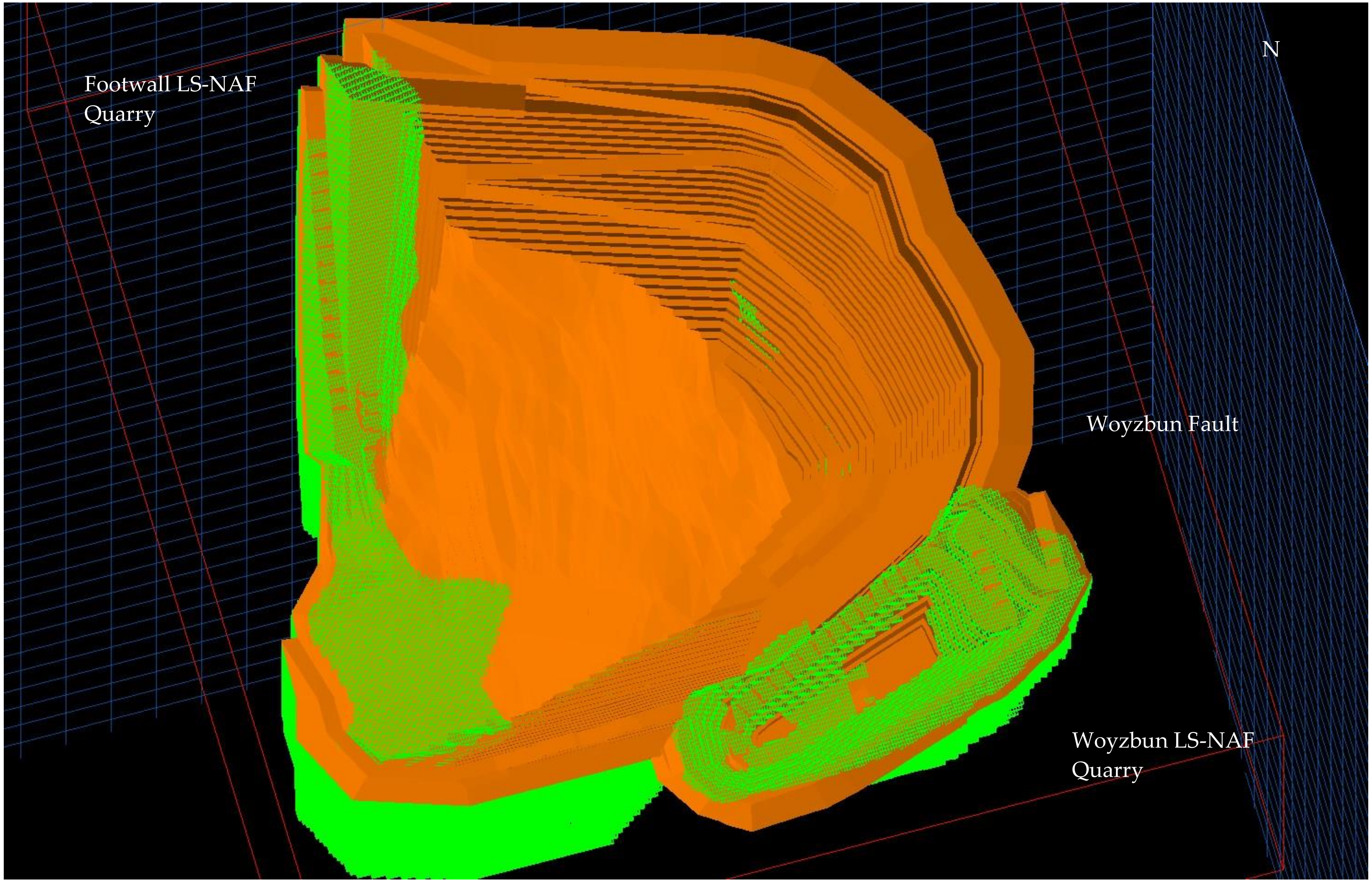


Figure 6-32 LS-NAF(HC) Distribution in the Open Cut and Quarries.

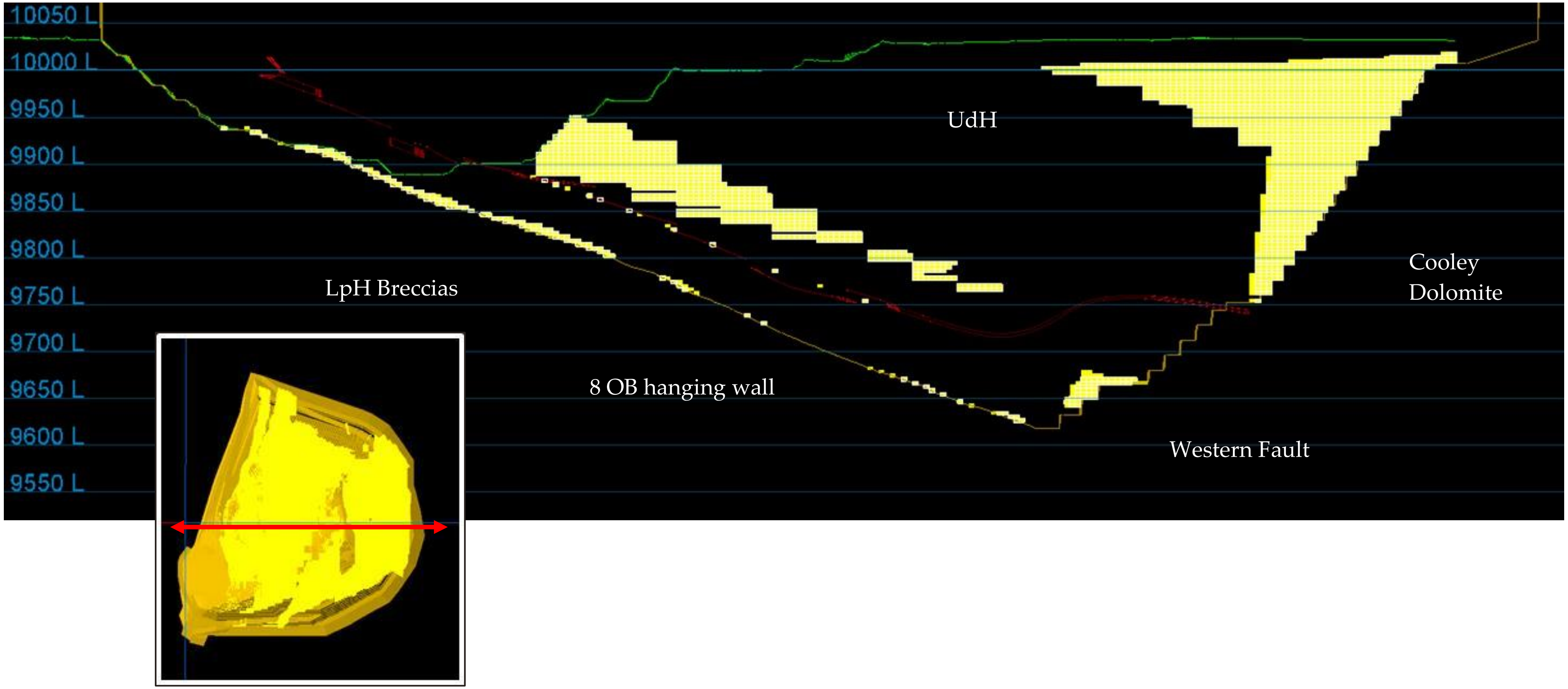


Figure 6-33 MS-NAF(HC) Distribution in the Open Cut

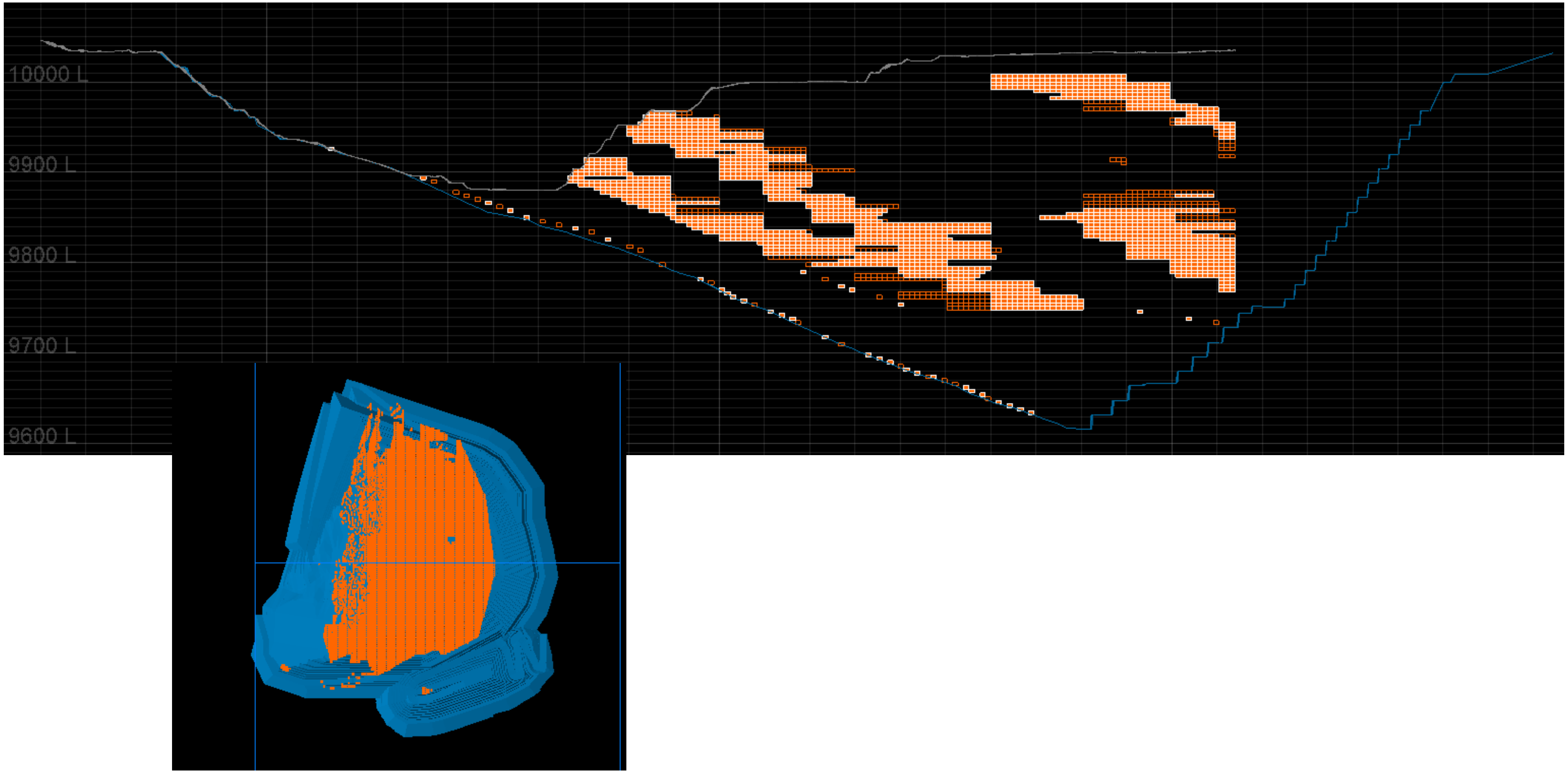


Figure 6-34 MS-NAF(LC) Distribution in the Open Cut

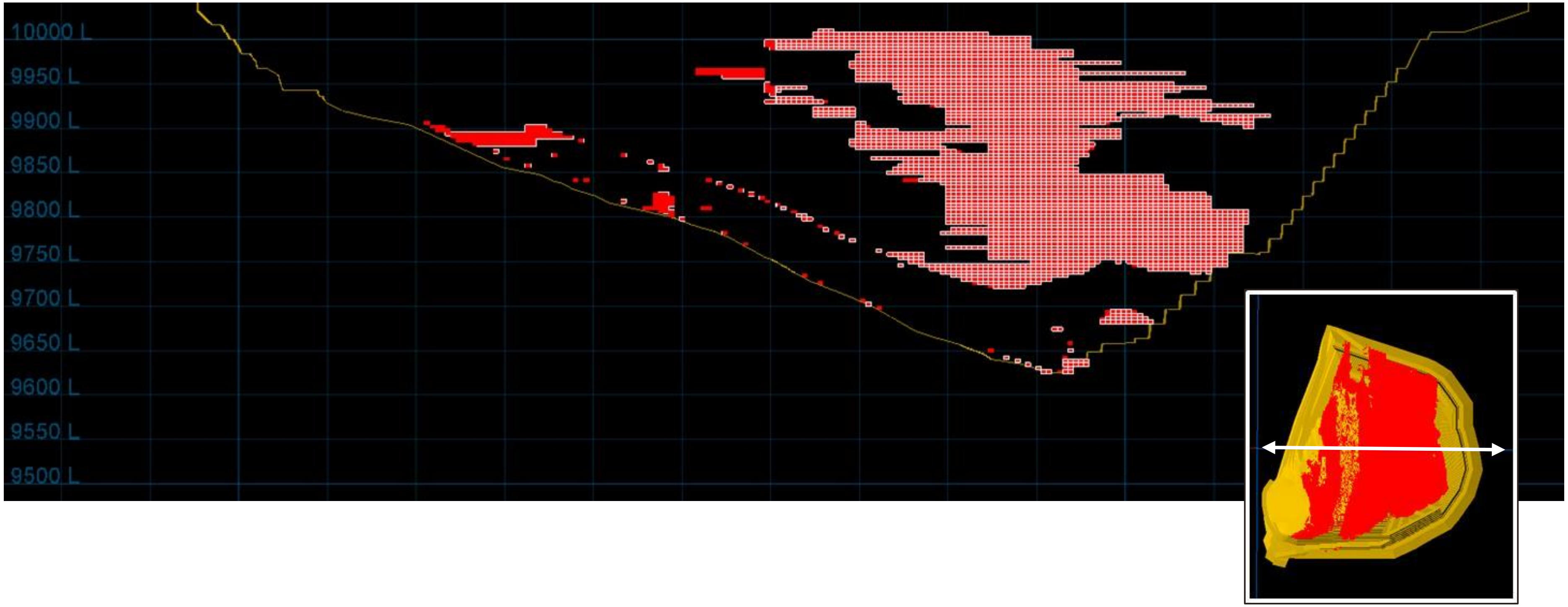


Figure 6-35 PAF(HC) Distribution in the Open Cut

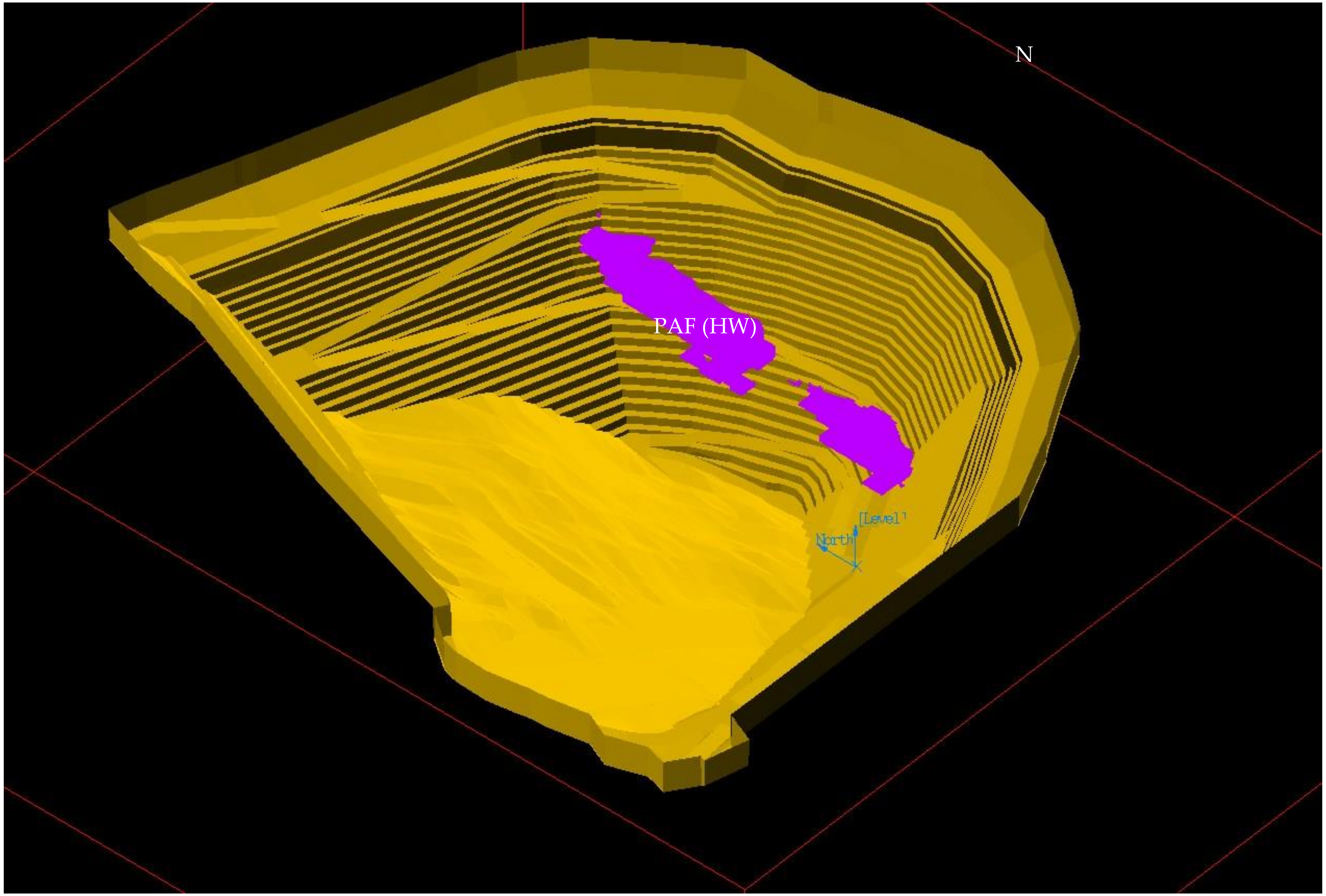


Figure 6-36 Distribution of the PAF(HW) in the Open Cut

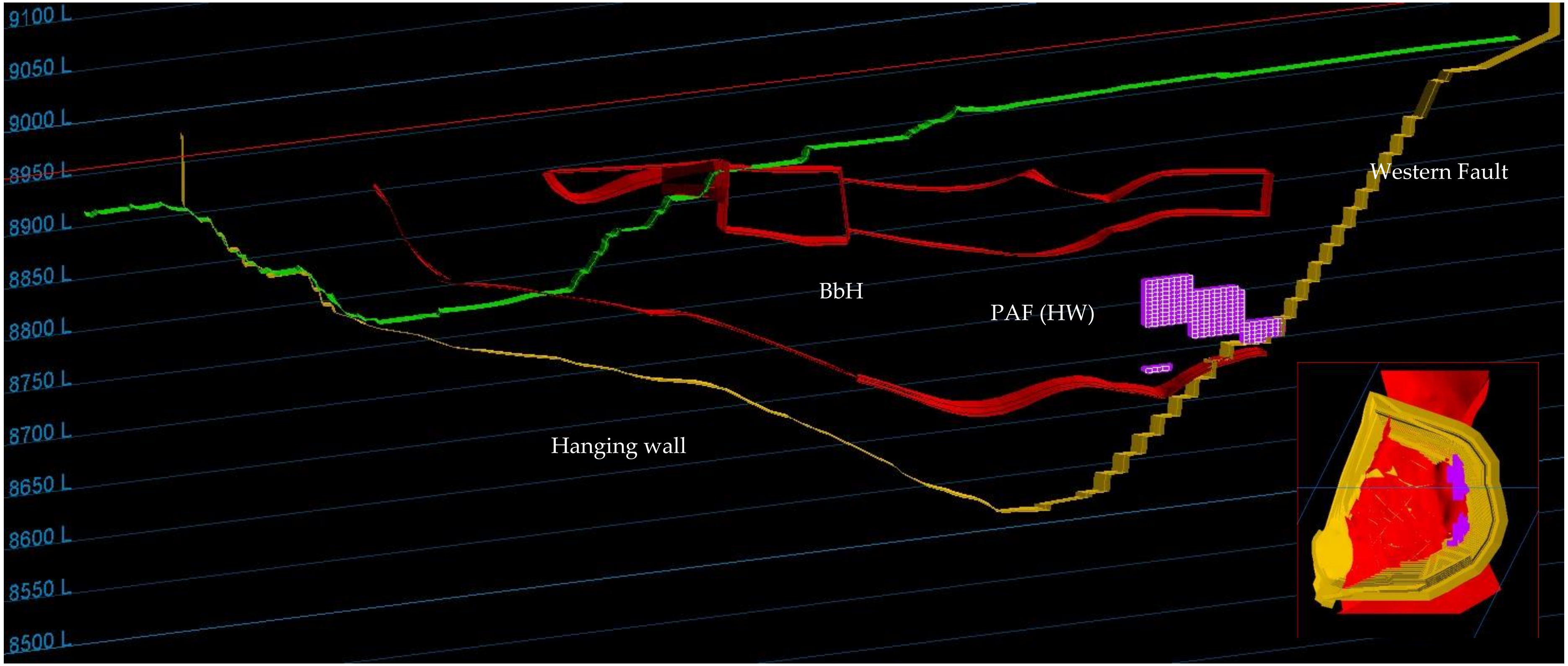


Figure 6-37 Location of the PAF(HW) Relative to the Orebody and Black Bituminous Shale

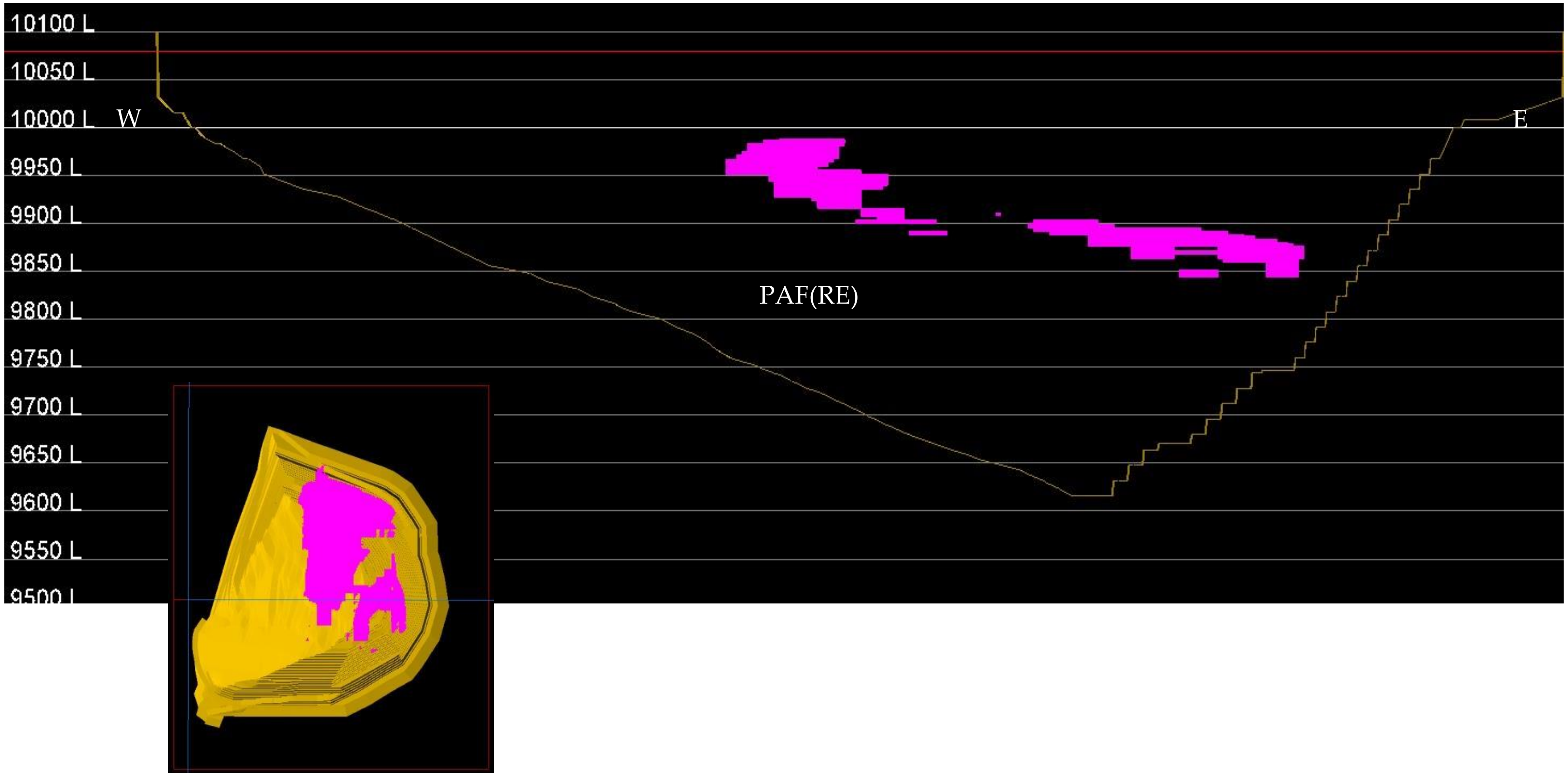


Figure 6-38 Distribution of PAF(RE) in the Open Cut

6.5.2.2 Indicative Material Quantities

The indicative material quantities to be mined for each year from 2018 to 2037 have been updated based on the proposed geological block model boundary criteria and the proposed mine schedule and are summarized in **Table 6-10**. The relative proportions are presented in **Figure 6-39**, together with the respective proportions of geochemical samples. Further information regarding the indicative production schedule is provided in **Chapter 3 – Project Description and Justification**.

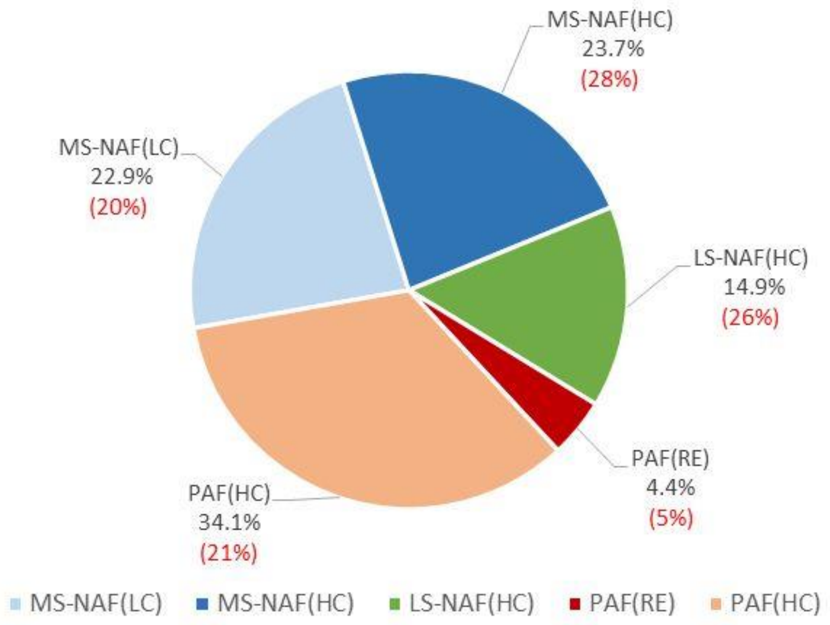


Figure 6-39 Overburden Proportions: Block Model (Black) and Geochemical Assays (Red).

The relative proportions of each overburden class from the reserve model are generally in good agreement with the proportions present in the geochemical sample population. It is important to note that there is no theoretical need for this to be the case, but a close agreement with similar proportions suggests that the sampling is relatively spatially uniform. The higher proportion of LS-NAF samples in the geochemical assay data reflects the targeting of LS-NAF material in the 2015 sampling program for the purpose of geochemical characterisation.

Historically, block model estimated PAF proportions were consistently lower than both what was suggested by the geochemistry and what was physically mined. This feature of the MRM resource model has been successfully corrected so that any future improvement on the model is unlikely to result in a significant change in ex-pit PAF quantities.

The PAF(HC) in-pit dump is a subset of the PAF(HC) class. It is the highest AMD generating material in the MRM overburden and represents only 5 million tonnes (Mt) and 0.8% of the material. This material will be placed back into the open cut at the end of mine life, following a brief period of surface storage (refer to **Chapter 3 – Project Description and Justification**).

Table 6-10 Indicative Ore and Overburden Production Schedule

Year	Ore (Mt)	PAF(RE) (Mt)	PAF(HW)[1] (Mt)	PAF(HC) (Mt)	MS-NAF(LC) (Mt)	MS-NAF(HC) (Mt)	Alluvium (Mt)	LS-NAF(HC) (Mt)	Yearly Total (Mt)
2018	1.3	0.009	-	3.0	0.9	6.7	16.5	3.1	31.5
2019	3.2	7.3	-	19.3	13.7	5.7	0.9	5.2	55.3
2020	3.3	0.06	-	9.5	12.9	22.2	5.4	3.0	56.4
2021	5.6	5.9	-	22.8	12.7	3.9	0.1	3.4	54.4
2022	5.0	0.001	-	5.4	17.5	16.5	6.9	3.0	54.3
2023	5.0	2.8	-	29.2	8.2	5.5	-	3.7	54.4
2024	5.0	0.9	0.002	18.5	16.8	5.8	4.8	2.5	54.3
2025	5.0	0.3	-	11.2	8.6	23.1	2.6	3.5	54.3
2026	5.0	2.5	0.2	15.4	12.6	16.9	-	1.7	54.3
2027	5.0	1.5	1.1	22.1	10.9	10.8	-	2.9	54.3
2028	5.0	4.3	0.8	17.9	9.1	13.2	-	4.1	54.4
2029	5.0	0.4	2.8	16.6	10.7	6.1	-	0.5	42.1
2030	5.0	-	0.01	-	0.6	2.2	-	2.2	10.0
2031	5.0	-	0.2	2.8	0.6	0.1	-	10.9	19.6
2032	5.0	-	-	1.7	0.2	0.03	-	1.8	8.7
2033	5.0	-	-	0.6	0.004	0.02	-	-	5.6
2034	5.0	-	-	0.4	0.003	0.02	-	-	5.4
2035	5.0	-	-	0.5	0.001	0.3	-	-	5.8
2036	5.0	-	-	0.3	0.007	1.1	-	-	6.4
2037	3.5	-	-	0.4	0.0002	0.5	-	-	4.4
Grand Total	**91.9**	**26.0**	**5.1**	**197.6**	**136.0**	**140.7**	**37.2**	**51.5**	**685.9**

1. A subset of PAF(HC) located in the open cut hanging wall. It has been classified differently for operational purposes rather than significant geochemical differences.

6.6 Overburden Class Descriptions

6.6.1 Low Salinity High Capacity NAF

6.6.1.1 Geological Units

Although a proportion of LS-NAF is present in most lithostratigraphic units (with the exceptions of the Upper Pyritic Shale and the Black Bituminous Shale), only four lithostratigraphic units are mined as LS-NAF(HC):

- Quaternary Alluvium;
- Upper Breccia;
- W-Fold Shale; and
- Teena Dolomite.

6.6.1.2 Geochemical Properties

LS-NAF(HC) is the least mineralised material class in the MRM classification. The materials are characterised by metal concentrations either comparable to crustal average values or with low level enrichment. The dominant ABA property is the very high net acid consumption capacity, and kinetic testing results indicate that the material will not leach sulphate or metals in concentrations likely to exceed site trigger values.

6.6.1.3 LOM Volumes

The total LOM volumes of LS-NAF include 51.39 Mt (8.7%) from the open cut and 37.2 Mt (6.2%) of alluvial materials outside of the open cut for a total of 81.59 Mt representing 14.9% of the total mined overburden. Alluvial materials located outside of the open cut footprint were identified through a site-wide investigation of shallow hydrogeology and benign material (alluvial) resources. The findings of this investigation are reported in **Appendix T – Groundwater Impact Assessment**.

6.6.1.4 Key Management Requirements

The LS-NAF(HC) is the only material class which is considered acceptable for stockpiling in environmentally sensitive areas. It is considered at low risk of generating AMD and therefore does not require mitigation management apart from standard sediment controls.

Contamination of the LS-NAF(HC) by metalliferous or saline NAF material will be avoided by mining only LS-NAF(HC) from two footwall units of the orebody. Only the clearly identifiable Upper Breccia will be mined as LS-NAF(HC) in the hanging wall.

6.6.1.4.1 Management Opportunities

As the only material class which is considered acceptable for stockpiling in environmentally sensitive areas, LS-NAF(HC) is a valuable resource for MRM. Its primary use will be for the construction of cover systems as well as levees, growth media and buttresses in environmentally sensitive areas.

6.6.2 Metalliferous Saline High Capacity NAF

6.6.2.1 Geological Units

The MS-NAF(HC) is abundant in the hanging wall sequence. It is the principal component of the following dolomitic units:

- Cooley Dolomite (92)%;

- Upper Dolomitic Shale (53%); and
- Lower Dolomitic Shale (68%).

The MS-NAF(HC) material also constitutes a substantial fraction (32%) of the Lower Pyritic Shale, largely corresponding to the dolomitic breccia sequence in the lower part of the Lower Pyritic Shale.

6.6.2.2 Geochemical Properties

The MS-NAF(HC) is weakly mineralised NAF, with concentrations of key elements such as zinc, lead, cadmium, arsenic, antimony that are enriched compared to crustal average values. Kinetic testing results indicate that the material has the potential to leach sulphate and metals at concentrations in excess of site trigger values. The material has a very high net acid consumption capacity which is similar to or greater than that of the LS-NAF(HC) class, providing a significant neutralization capacity to the MRM overburden material.

6.6.2.3 LOM Volumes

LOM volumes of MS-NAF(HC) are 140.57 Mt representing 24 % of the total mined overburden.

6.6.2.4 Key Management Requirements

Because of its high acid consumption capacity, the MS-NAF(HC) class is not considered at risk of generating AD. The MS-NAF(HC) materials, such as the Cooley Dolomite, have some of the highest neutralizing capacities of all lithologies on site. However, because of the potential for SD and NMD, appropriate management is required to minimize undesirable effects on drainage from the NOEF.

6.6.2.4.1 Management Opportunities

The high acid consumption and buffering capacities of the material are important properties that add significant value in the construction of the OEFs. MS-NAF(HC) is proposed to be preferentially used for construction of the halo, located between the PAF cells and the cover system, but has a number of useful applications. The segregation of MS-NAF(LC) from MS-NAF(HC) is unlikely to be practical most of the time and, therefore, the MS-NAF materials will typically represent a combination of high and low capacity materials (see **Section 6.6.3.4.1**).

6.6.3 Metalliferous Saline Low Capacity NAF

6.6.3.1 Geological Units

The MS-NAF(LC) material is present in minor quantities in most lithological units of the hanging wall sequence. It represents significant proportions of units dominated by pyritic shales, including the following:

- Upper Pyritic Shale (29%);
- Upper Dolomitic Shale (35%);
- Black Bituminous Shale (24%); and
- Lower Pyritic Shale (29%).

6.6.3.2 Geochemical Properties

MS-NAF(LC) is defined exclusively by the NPR values that are between 1 and 2. This material is characterised by a limited acid consumption excess and therefore its long-term properties are considered somewhat more uncertain than NAF(HC) with respect to the risk of developing AD. The material is also enriched in both sulphur and metals, and kinetic testing results indicate that it has the potential to generate neutral saline metalliferous drainage.

6.6.3.3 LOM Volumes

LOM volumes of MS-NAF(LC) are 136.12 Mt representing 23% of the total overburden and almost one-half of the total MS NAF.

6.6.3.4 Key Management Requirements

The MS-NAF(LC) has a potential to generate SD and NMD and has an uncertain potential to generate acid. Therefore, the MS-NAF(LC) requires mitigation to limit oxidation rates and the generation of soluble constituents. Contact waters also require management.

6.6.3.4.1 Management Opportunities

In practice, the segregation of MS-NAF(LC) from MS-NAF(HC) is unlikely to be possible most of the time. Both material classes have similar geochemical properties and will require mitigation, so this has little effect on the architecture of the NOEF. The principal reason for segregating the two classes is to quantify the proportion of NAF which has limited acid buffering properties in proportion to the total overburden.

6.6.4 High Capacity PAF

6.6.4.1 Geological Units

The PAF(HC) material is present almost exclusively in the hanging wall sequence, and is concentrated in three lithostratigraphic units, including the:

- Upper Pyritic Shale (60%);
- Black Bituminous Shale (37%); and
- Lower Pyritic Shale (24%).

Historically, the whole of the Upper Pyritic Shale and Black Bituminous Shale were mined exclusively as PAF, leading to an overestimation of mined PAF quantities compared to predicted quantities from the resource model. The lowest pyritic shale interval of the Lower Pyritic Shale has also had been mined as PAF.

6.6.4.2 Geochemical Properties

The PAF(HC) is defined exclusively by NPR values of less than 1. It is geochemically defined as PAF with sulphide contents greater than 7% sulphur. However, the kinetic results and high ANC values indicate that there will be significant delays before the onset of acidic conditions. Prior to acidification, the kinetic test results also indicate that the PAF(HC) material has the potential to leach sulphate and metals at concentrations in excess of site trigger values.

A subset of the most potentially reactive PAF(HC) has been spatially segregated for in-pit disposal at the end of mine life. This effectively segregates the highest sulphide material from the bulk of the PAF(HC).

6.6.4.3 LOM Volumes

The LOM PAF(HC) was estimated to be 203 Mt representing 34% of the total mined overburden of which, 5 Mt (0.8%) of high sulphide overburden has been segregated for permanent in-pit disposal.

6.6.4.4 Key Management Requirements

This material has the potential to generate AMD in the long term and neutral saline and metalliferous drainage in the short to medium term, prior to the onset of acid drainage. This material therefore requires mitigation to limit oxidation rates and the generation of soluble constituents. Contact waters also require management.

6.6.4.4.1 Management Opportunities

The segregation of the highest sulphidic PAF(HC) will enable the in-pit disposal of the most deleterious material, and while this represents a relatively small volume of material, it will effectively remove all the very high sulphide materials from the NOEF. The PAF(HC) materials will be placed within the core of the NOEF and protected by a halo of MS-NAF prior to the placement of the cover system, further removing the PAF(HC) from the outer surface of the NOEF.

6.6.5 Reactive PAF

6.6.5.1 Geological Units

The PAF(RE) material is present exclusively in the Black Bituminous Shale that also has elevated organic carbon contents. It is however only one component of the unit. The Black Bituminous Shale has substantial portions of other classes of materials, including:

- MS-NAF(LC) (24%); and
- PAF(HC) (37%).

6.6.5.2 Geochemical Properties

The PAF(RE) is defined by NPR values of less than 1, sulphur contents greater than 10%, and total organic carbon contents greater than 1%. It is geochemically defined as PAF and kinetic test results indicate that there will be substantial delays before the onset of any acidic conditions as a result of the very high acid neutralising capacity of the material. Kinetic test results also indicate that the material has the potential to leach sulphate and metals at concentrations in excess of site trigger values prior to the onset of acid conditions.

A distinct geochemical property of the material is its ability to self-heat and develop spontaneous combustion within days to weeks following exposure and/or placement on the NOEF and therefore requires management to prevent this outcome.

6.6.5.3 LOM Volumes

The LOM quantity of PAF(RE) was estimated to be 25.9 Mt or 4 % of the total mined overburden.

6.6.5.4 Key Management Requirements

The PAF(RE) material requires specific management to prevent spontaneous combustion. The specific controls that will be implemented by McArthur River Mining include the following.

6.6.5.4.1 Dedicated PAF(RE) Cells

The reactive PAF will be segregated from all other overburden in order to prevent the material from acting as a catalyst for otherwise less reactive material.

6.6.5.4.2 Low lift Construction:

PAF(RE) will be exclusively paddock dumped and compacted to limit oxygen ingress and avoid particle size segregation. This constitutes leading industry practice in the management of reactive material. The PAF(RE) cells will be built in maximum 2 m lifts, with 100 millimetres (mm) of compacted fine grained alluvial material above every lift.

6.6.5.4.3 Dry Season Mining:

In order to limit to a maximum the possible ingress of water into PAF(RE) cells, the reactive PAF will be mined primarily during the dry season over the LOM.

6.6.5.4.4 Wet Season Covers:

Prior to every wet season, a 1 m compacted fine grained alluvial material cover will be placed to enclose the PAF(RE) cells to limit both oxygen and water ingress into the cell. This will in turn be protected from erosion by a 1.5 m layer of MS-NAF.

6.7 Material Identification and Handling

6.7.1 In-Pit Grade Control - Classification Criteria

In-pit material classification is based on the same criteria as the material classification scheme. The direct measurements of sulphur, zinc, lead and the indirect estimate of NPR are used to classify the overburden into the five classes.

Because the NPR cannot be calculated directly using XRF results, the calcium and magnesium content are used as a proxy for ANC. The relationship between calcium and magnesium from ICP-MS results from MRM drill cores and the relationship between calcium and magnesium and ANC are presented in **Figure 6-40**. As presented on the figures, there is a strong linear relationship between calcium and magnesium consistent with dolomite being the principal carbonate mineral present in the sequence.

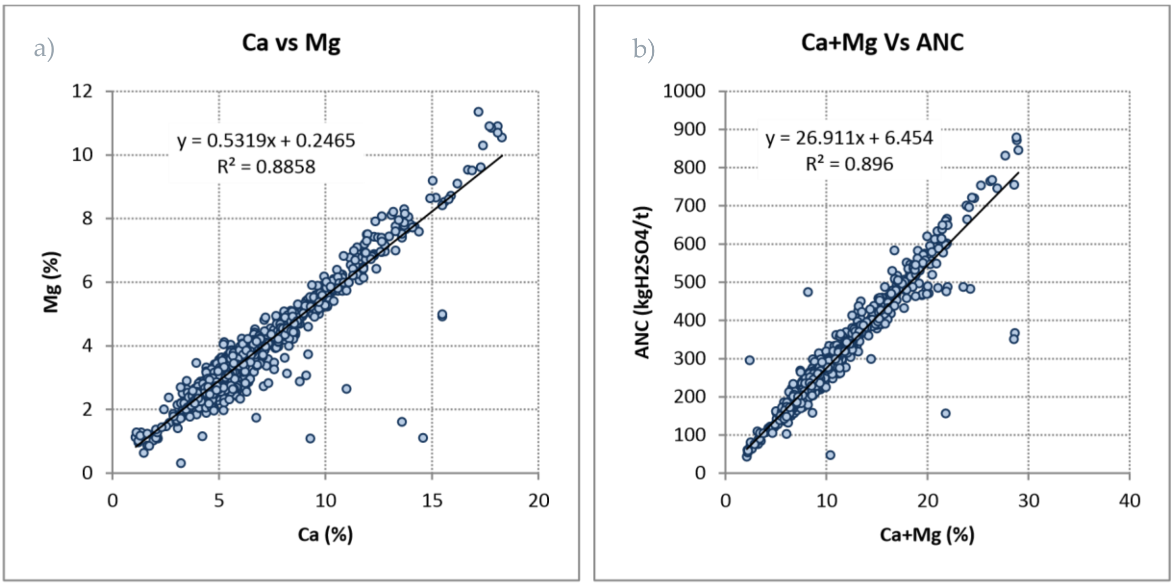


Figure 6-40 a) Calcium vs. Magnesium b) Calcium + Magnesium vs. ANC

The strong linear relationship between Ca+Mg and ANC indicates that Ca+Mg can be used in conjunction with sulphur to model the NPR:

$$NPR = \frac{ANC}{MPA} \cong \frac{Ca\% + Mg\%}{S\%}$$

When (Ca+Mg)/S is plotted against measured NPR (**Figure 6-41**), a very good linear relationship is observed (r^2=0.994) indicating that it is a very good proxy for NPR.

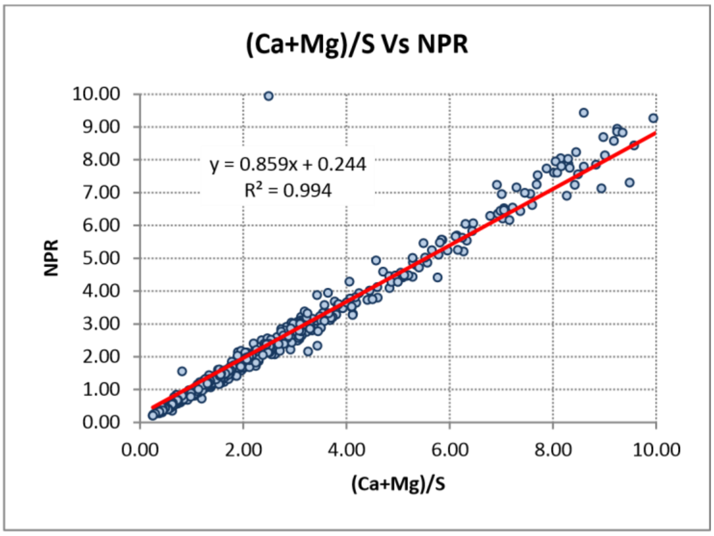


Figure 6-41 NPR vs. Calcium (Ca) + Magnesium (Mg) over Sulphur (S)

6.7.2 Portable X-Ray Fluorescence

Portable XRF (pXRF) has proved to be an effective screening and validation tool for determination of elements and has gained widespread use in the mining industry. Following a successful trial in 2013, its application was introduced at MRM in January 2014 and forms the basis for in-pit grade control of overburden units and mark-up procedures. Portable XRF analyses calibrated to ICP-AES results are used for confirming both NAF/PAF classification and for the identification of potentially metalliferous/saline NAF by screening for critical elemental abundances such as antimony, arsenic, bismuth, cadmium, chromium, copper, iron, lead, manganese, molybdenum, selenium, sulphur and zinc.

A known limitation of portable XRF analysers is the limited ability to accurately measure light elements. For overburden characterisation purposes, the ability to directly measure sulphur, calcium and magnesium is critical, and requires the use of a high end instrument.

The instrument used at MRM is a Thermo Scientific™ Niton™ XL3t GOLDD+ XRF analyser. This instrument is considered the current market leader in terms of accuracy for the purposes of environmental geochemical assessments. The instrument uses the Geometrically Optimised Large Area Drift Detector (GOLDD) technology, a proprietary technology specifically designed for optimising light element analysis (Mg, Al, Si, P and S) without the use of a helium purge (refer to **Figure 6-42,** emission spectra of a mineralised sample analysed with the Niton XL3t where the 0 to 8 kilo-electron volt range highlights the light element optimisation of the instrument).

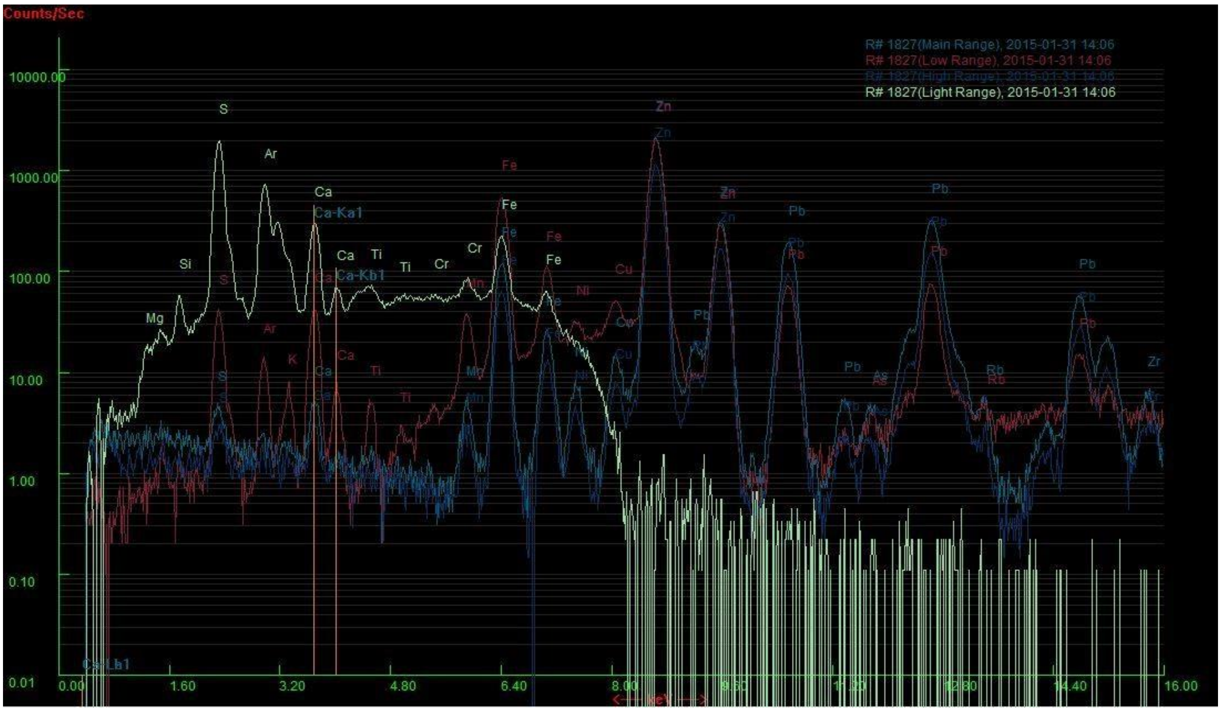


Figure 6-42 Emission Spectra of a Mineralised Sample Analysed by Niton XL3t

Figure 6-43 presents the correlation between the results from the portable XRF and the standard chemical analysis over the range of elements of interest. The exceptions to the correlations include aluminium and barium for which the pXRF does not seem to perform well despite relatively high concentrations of the elements in the sample. The lower performance of the instrument for cadmium and antimony is likely due to the low concentrations in the samples, close to the detection limit of the instrument of approximately 8 ppm.

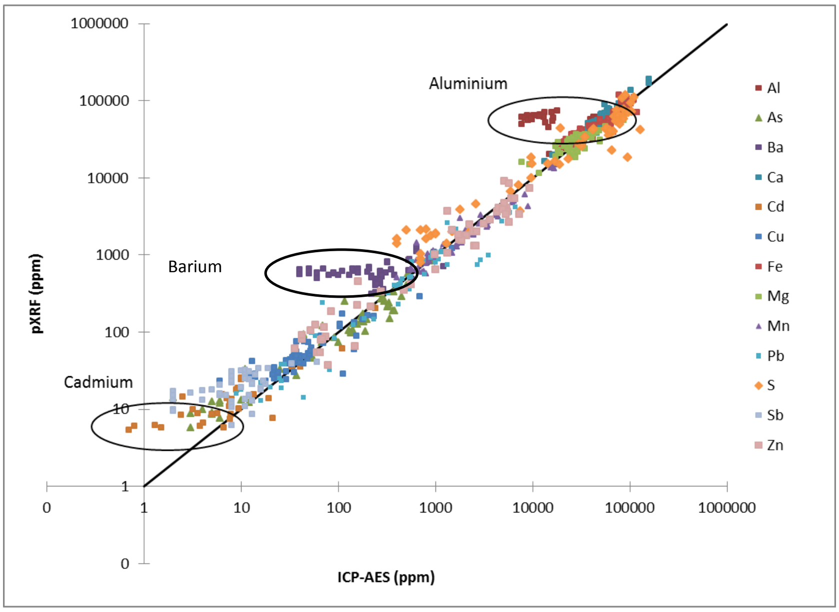


Figure 6-43 Comparison Between ICP-AES and pXRF for 13 Elements

To compensate for the expected variability in performance of the XRF for each element, the pXRF results are corrected using the ICP-AES results for each element rather than by using a global correction factor.

The results (**Figure 6-44**) show a strong correlation between the three data sets (drill core, ICP-AES and pXRF) and demonstrate that the portable XRF is a suitable technique for in-pit grade control, enabling a rapid and reliable estimation of elemental abundances in overburden.

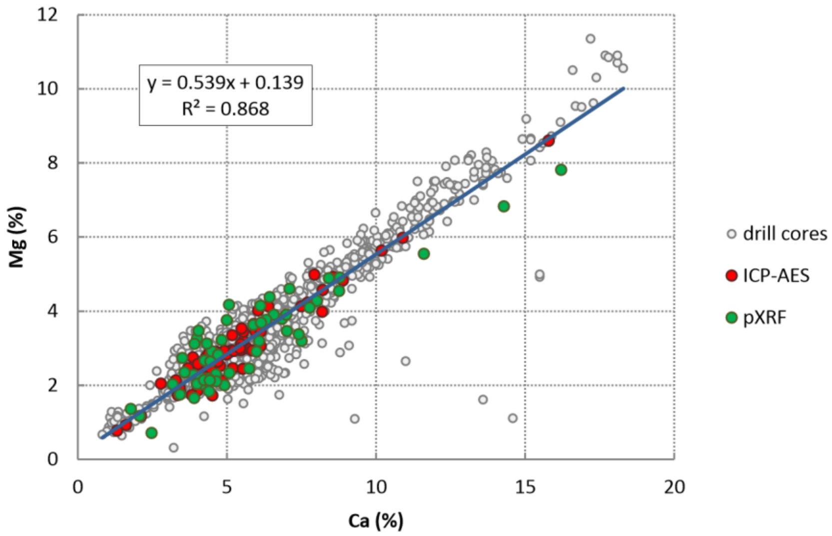


Figure 6-44 Calcium (Ca) vs. Magnesium (Mg) (pXRF, ICP-AES, Drill Core Assays)

6.7.2 In-Pit Grade Control Procedure

The in-field overburden class validation implemented at MRM is based on analyses of blast-hole cuttings. An average blast block consists of approximately 500 holes. Fifty drill holes are sampled for analysis per blast block (1 in 10 drilled). Of these 50, 10 % are selected for validation by laboratory ICP-AES analyses. A representative slice (spear) is taken from each sampled drill cutting mound or cone that forms around the drilling stem, then dried, ground and homogenised. Four sub-samples are prepared per drill mound for both intra-sample and portable XRF variability. The powder-like sub-samples are pressed into pellets by using a portable ThermoScientific™ pellet press in order to achieve a uniform surface and optimise the accuracy of the analysis. The sample pellet is then mounted in a sample stand and analysed for 90 seconds.

The analysis suite includes the following elements: zinc, lead, copper, magnesium, aluminium, silicon, phosphorous, chlorine, potassium, calcium, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, arsenic, selenium, rubidium, strontium, zirconium, niobium, molybdenum, palladium, silver, cadmium, tin, antimony, tellurium, caesium, barium, hafnium, tantalum, tungsten, rhenium, gold, mercury, bismuth, thorium and uranium.

Of these, the following elements are relevant to the classification and/or management of the rock: zinc, lead, copper, aluminium, chromium, manganese, arsenic, molybdenum, silver, cadmium, antimony and bismuth.

Once analysed, the samples are classified according to the five overburden classes and a map of the blast block is produced by the mine geologist for the mining engineers and production crews to plan and execute extraction and appropriate placement in the NOEF.

6.7.3 Overburden Tracking System

McArthur River Mining utilises global positioning systems to track haul truck movements from the open cut to the NOEF. The particular material type being mined is entered into the system along with the associated placement location for that type of material within the NOEF. The system sends alerts when a certain material type is placed within the incorrect area of the NOEF. Once identified, the material is removed and sent to the correct location.

6.8 NOEF Monitoring Programs

6.8.1 Geochemical Quality Assurance/Quality Control

Geochemical sampling of placed overburden is undertaken monthly at the NOEF as part of the broader NOEF monitoring and QA/QC program. From 2009 to 2013 inclusive, the sampling program has concentrated exclusively on the NAF stockpiles. The priority was to monitor for placement of PAF in the NAF fraction of the NOEF. Sampling was designed to detect incorrect placement resulting from incorrect classification, incorrect boundary identification in the pit, or accidental incorrect placement of PAF material by the haul fleet.

Since 2014, the program has been significantly expanded to include systematic sampling of PAF material as well as low grade ore on the OEFs, and includes elemental analyses as well as standard ABA sampling. The general structure of the program is presented in **Figure 6-45.**

Rock samples (10 to 26 samples of approximately 3 kg) are collected each month from the OEFs active placement areas by McArthur River Mining Geology personnel. Sample locations within each area are randomly selected in order to minimise sampling bias.

Sampling density is proportional to the amount of material movement and is based on international guideline recommendations (Price, 1997). The purpose of the monitoring program is for quality assurance and quality control and represents a final verification that materials are placed in the designated locations on the OEF.

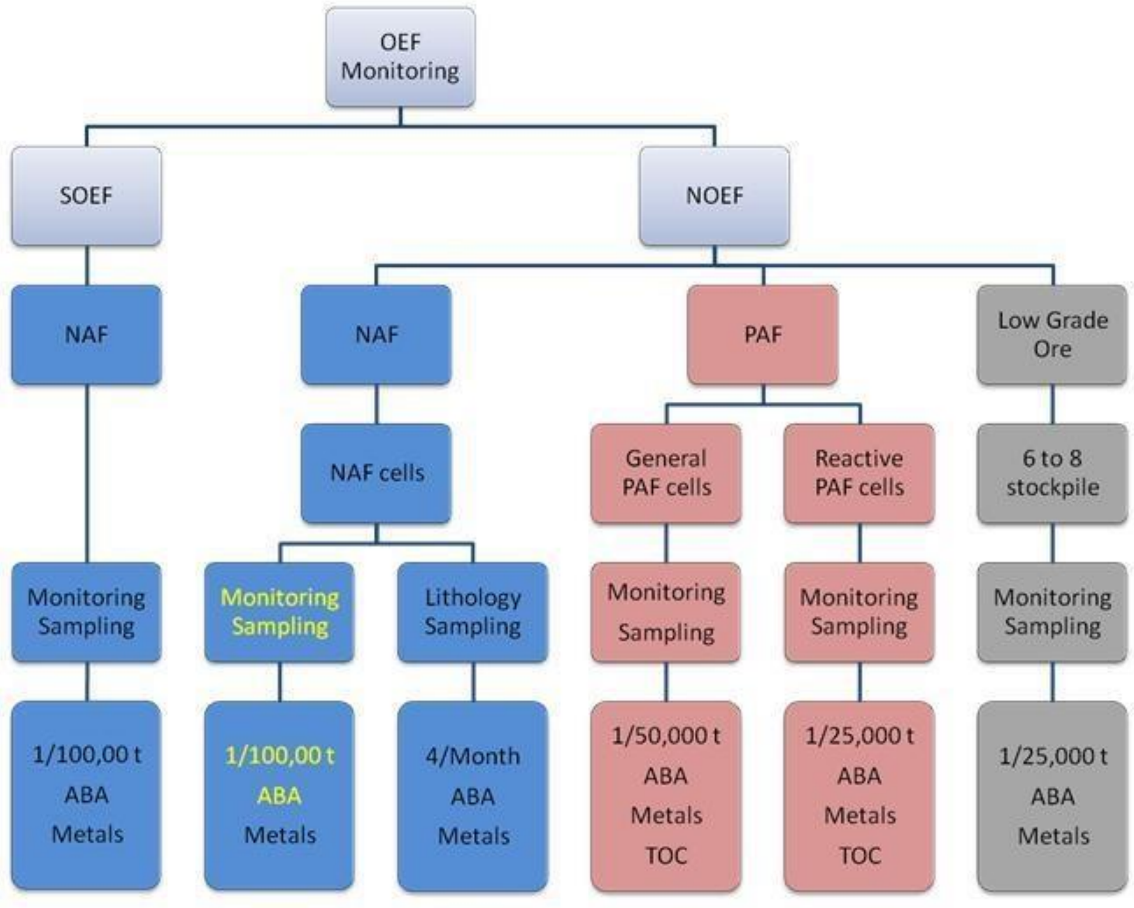


Figure 6-45 OEF Monitoring Program

6.8.2 Spontaneous Combustion Monitoring

Additional monitoring procedures are required for the identification of spontaneous combustion at MRM. Because spontaneous combustion is time dependent and represents a potential safety hazard, early detection and remediation is essential for its successful management. In addition to block model predictions, monitoring is conducted as outlined in the following sections.

6.8.2.1 In-Pit Monitoring

Thermal monitoring is undertaken prior to and during drill and blast operations enabling the early detection of potentially problematic material.

6.8.2.2 Daily OEF Inspections

Daily visual and thermal inspections are conducted by Mining personnel for early detection of reacting material. The aim is to identify areas showing early signs of increased reactivity (abnormal surface moisture, elevated temperatures, cracks, heaving, or efflorescent salts) prior to the onset of spontaneous combustion.

6.8.2.3 Gas Monitoring

Daily gas measurements including sulphur dioxide levels are undertaken on the OEFs to identify potential hazards and areas requiring remediation/intervention.

6.8.2.4 Hazard Maps:

Weekly hazard maps of the OEFs are generated showing areas of concern with regards to temperatures and gas levels. An example hazard map for the NOEF has been presented in **Figure 6-46**. The hazard maps indicate the areas where elevated sulphur dioxide levels could pose a hazard to personnel based on regular inspections.

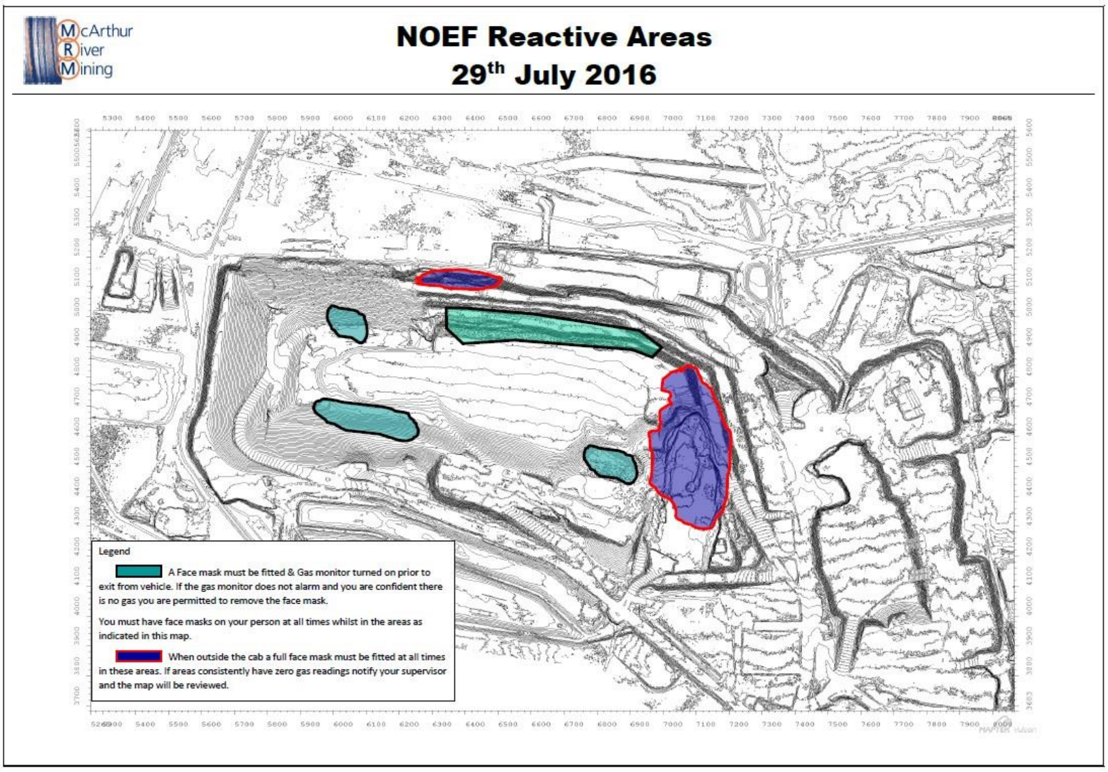


Figure 6-46 NOEF Hazard Map

6.8.3 Gas and Temperature

As part of the existing NOEF remediation program, a total of 29 monitoring bores were drilled into the NOEF in 2015 and 2016. Of these, 15 are used for groundwater monitoring and 14 are used for temperature and gas monitoring. The bores that extend through the full thickness of 40 m in the PAF cells are equipped with thermocouples and gas ports at different depths and enable gas sampling and the ongoing monitoring of internal temperatures within the NOEF. The locations of the monitoring bores are presented in **Figure 6-47**, and examples of temperature readings from five monitoring bores are presented in **Figure 6-48**.

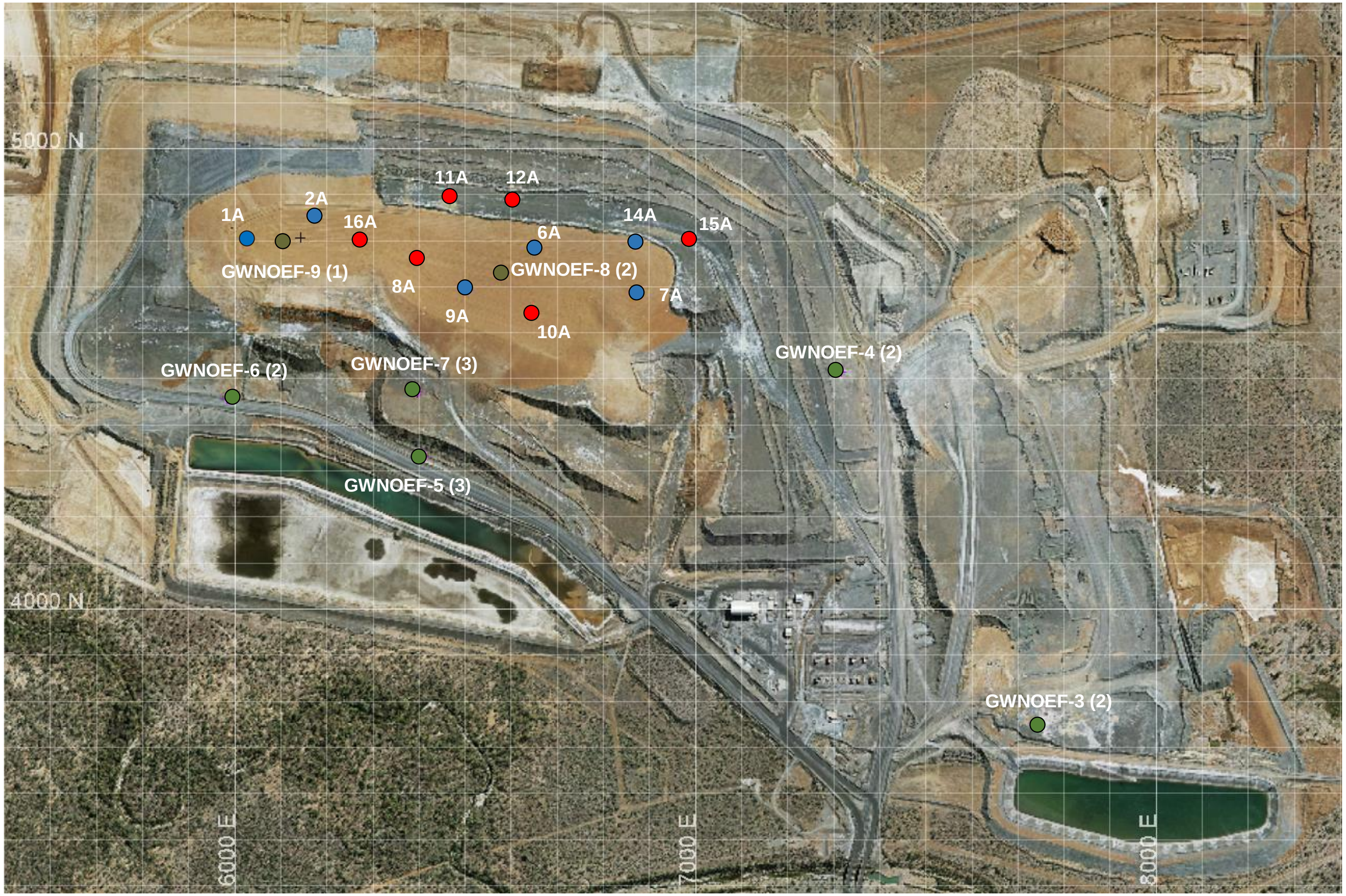


Figure 6-47 NOEF Monitoring Bores.

(Groundwater (green), gas and temperature (red for hot, blue for cool)).

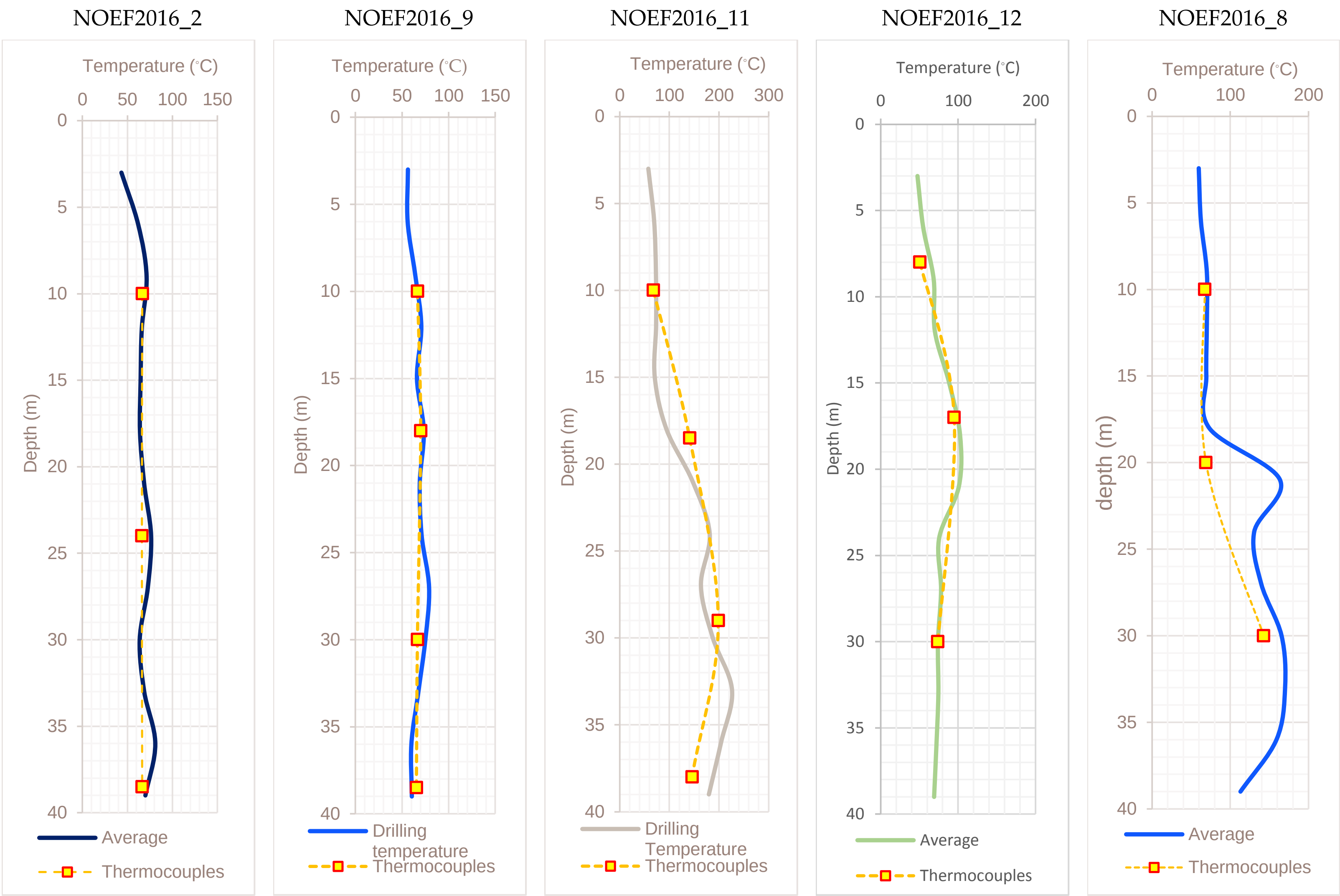


Figure 6-48 Examples of Temperature Readings (NOEF Monitoring Bores)

In **Figure 6-48** the drilling temperature curve indicates the measured downhole temperature at time of drilling, while the thermocouple temperatures represent the mean temperature from the thermocouple reading at that depth. As presented in **Figure 6-48**, temperature profiles are spatially variable within the NOEF, reflecting the presence of localised hot-spots within the existing PAF cells. Bores NOEF2016_2 and NOEF2016_9 are characteristic of half of the bores, showing a uniform temperature of approximately 65°C representing the general background temperature of the NOEF PAF cell. Bores NOEF2016_11, NOEF2016_12 and NOEF2016_8 show different patterns of elevated temperatures below 15 m, indicating greater heat production rates associated with sulphide oxidation at those depths.

The temperature bores will be important for monitoring the effectiveness of remediation strategies implemented to reduce oxidation rates and temperatures within the NOEF. This includes the long term effectiveness of the planned oxygen barrier layers (refer to **Chapter 3 – Project Description and Justification**).

6.9 Geotechnical Testing

Geotechnical testing is used to determine the physical properties of soils and rocks. For the EIS, field and laboratory Geotechnical testing was principally conducted to geotechnically characterise the overburden facility foundation, develop an understanding of the geomechanical performance of the material types to be stored in the NOEF, and establish quality control criteria for engineered materials that form important components of the facility such as CCLs.

All laboratory testing is completed by University (UQ or UNC) or NATA accredited laboratories to Australian and/or industry recognised standards. Field tests are completed by trained and competent geotechnical staff.

6.9.1 Geotechnical Tests

The range of material tests consists of, but is not limited to:

- particle size distribution (PSD) including hydrometer;
- mineralogy (X-ray Fluorescence);
- Atterberg limit tests;
- Emerson class number;
- pinhole dispersion;
- moisture content;
- compaction;
- hydraulic conductivity;
- organic content;
- large scale direct shear tests; and
- consolidated undrained triaxial tests.

6.9.2 NOEF Foundation

The natural foundation of the NOEF typically consists of alluvial clay predominantly low to high plasticity sandy clay to clay with a typical thickness of 0.6 to 1.0 m, with some zones up to 6 m thick (KCB 2014). Zones of localised sand and gravel have also been identified in a subsurface site investigation (KCB 2014).

The foundation will be prepared by removing topsoil and any organic material that may compromise the integrity of the foundation, such as decomposition of tree roots and stumps. In addition, any loose or weak materials identified after topsoil removal are removed and replaced with competent materials consistent with the surrounding material. This process will reduce the potential for significant differential settlement within the foundation of facility.

The materials forming the upper foundation will meet or exceed alluvial materials strength criteria outlined in **Table 6-15.**

Below the alluvial zone, a residual soil and weathered rock layer of up to 8 m thick exists, comprising generally of white and creamy white, extremely to moderately weathered dolomite or dolomitic siltstone. The weathered zone transitions to a weakly weathered to fresh high strength dolomite.

6.9.3 Compacted Clay Layer

An important feature of the NOEF is the CCL that will encapsulate the structure restricting the infiltration of rainfall and air into the mass of the structure. The CCL is engineered to follow specifications from selectively sourced materials onsite that conform to the criteria outlined in **Table 6-11.**

Table 6-11 CCL Geotechnical Specifications.

Property	Requirement
Size of largest particle	Not greater than 75 mm
Minimum % by weight passing 37.5 mm AS 1152 sieve	90%
Minimum % by weight passing 0.075 mm AS 1152 sieve	50%
Minimum plasticity index (AS 1289.3.3.1)	15%
Hydraulic conductivity (Ksat)	1×10^{-9} metres per second (m/s)

The materials used to develop CCLs must not be significantly dispersive, including under the effects of anticipated leachate waters. Uniformity of CCLs is important to its performance. To manage conformity, rigorous testing of both the source and material will be performed to the frequencies outlined in **Table 6-12,** and revised as an outcome of performance reviews.

Table 6-12 Geotechnical Testing Frequency for CCL Construction

Test Type	Clay Layer Borrow Area Frequency	Placed Clay Layer Frequency
Particle size distribution Atterberg limit, including linear shrinkage	1 test per 5,000 m^3 or Soil Material Change	1 test per 20,000 m^3
Emerson class Chemical analysis (exchangeable sodium percent and sodium absorption ratio) Pinhole dispersion	1 test per 10,000 m^3 or Soil Material Change	1 test per 20,000 m^3
Moisture content and dry density ratio		1 test per 500 m^3
Permeability/hydraulic conductivity		1 test per 10,000 m^3

In conjunction with the selection and preparation of CCL materials, a construction methodology will be adopted that forms a stable and uniform subgrade prior to placement of the CCL that is free of angular and oversized (< 0.6 m) particles and, levelled to be free of depressions or low points to a tolerance of +/-0.15 m. This will provide a stable and smooth base to accurately construct the CCL layer.

In addition to the CCL that encapsulates the entire structure (immediately beneath the cover system), a number of internal CCL style layers will be placed during development of the facility to limit infiltration of rainwater into the overburden during construction and impede the flow of oxidising gases within the facility upon completion. These layers are not built to the same criteria as the final cover CCL but will undergo mechanical and/or moisture conditioning to achieve placed air permeability of less than 10^{-3} m^2.

6.9.4 Shales

The term shale is used at MRM to describe well bedded siltstones and mudstones that preferentially shatter along bedding and jointing planes. They are typically fine grained, well bedded, jointed and fissile sedimentary rocks, comprised, primarily of dolomite, with bituminous material that has variable amounts of micro-crystalline pyrite laminae.

Mineralised overburden removed from the mine for storage within the NOEF consists primarily of material classified as shale including geological units; Upper Dolomitic Shale, Upper Pyritic Shale, Black Bituminous Shale, Lower Pyritic Shale, OB #2 to #8, HYC, Lower Dolomitic Shale and W-Fold Shale. These units contribute the majority of the NAF and PAF materials designated for encapsulation within the NOEF.

Geotechnical characterisation of the shale overburden by field or laboratory testing is difficult due to the size and range of the clast size and variable composition of clast material types. Historically material strength criteria has been based on industry experience with similar materials (URS 2008) with Mohr-Coulomb strength criteria applied as shown in **Table 6-13.**

Table 6-13 Shale Overburden Historic Strength Parameters (URS 2008)

Material	Unit Weight (kN/m^3)	Friction Angle (degrees).	Cohesion (kPa)
NAF Overburden	20	38	0
PAF Overburden	20	38	0

To improve the understanding large scale direct shear tests were completed at two university testing laboratories, University of Queensland (UQ) and University of Newcastle (UNC).

A range of materials to be stored in the NOEF were tested with both dry (UQ and UNC) and inundated (UNC) testing methods. There is a clear indication that friction angles in wet samples are slightly lower compared with those obtained for dry samples (University of Newcastle tests only). The difference between the dry and wet test results were, however, in most cases not significant. Tests completed by University of Queensland were on dry samples only.

Figure 6-49 summarises the UQ recommended Mohr-Coulomb shear strength parameters from the results of both UNC and UQ testing programs, and are also tabulated in **Table 6-14**. For the purposes of NOEF stability modelling, lower bound parameter have been adopted to identify areas of potential instability and conservatively allow for parameter uncertainty.

Table 6-14 Recommended Strength Parameters (UQ)

Application	Apparent Cohesion	Friction Angle
Near the surface	50±25kPa	40±3 degrees
Within the overburden facility	100±50kPa	35±3 degrees
Rock/CCL interfaces	20±10kPa	33±3 degrees

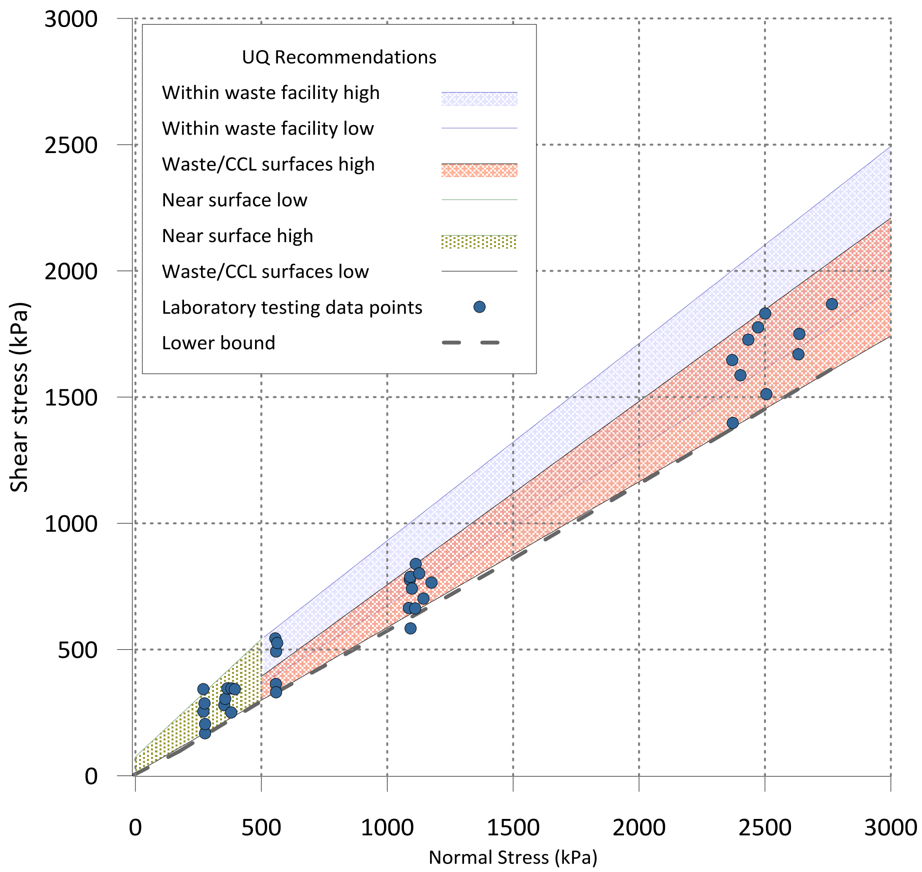


Figure 6-49 Strength Parameter Recommendations

(Source: University of Queensland)

6.9.5 Breccia

The term breccia is used to describe clastic sedimentary rocks composed of angular to sub-angular, randomly oriented clasts of predominantly dolomites and shales cemented in a carbonate matrix. The breccias constitute the hardest and most competent rocks in the MRM sequence. The results from the large scale direct shear testing (UNC) did not show a discernible difference between the shale rock and breccia rock. However the testing is expected to underestimate the material strength due to sample preparation where larger clasts are scalped or resized to fit into the apparatus. With a high proportion of large clasts, the results reported from Breccia samples are likely to be representative of a mid to upper bound strength. For stability modelling purposes, strength parameters for shale and breccia have adopted the mid bound strength envelope for shale material.

6.9.6 Summary of Geotechnical Parameters

Table 6-15 summarises geotechnical parameters adopted for overall NOEF stability assessments.

Table 6-15 Generic Geotechnical Parameters

Material	Geotechnical parameter						
	Unit weight (kN/m³)	Angle of friction (⁰)	Cohesion (kPa)	Undrained shear strength (kPa)	Yong modulus (MPa)	Poissons ratio	Permeability Ksat (m/s)
Foundation							
Alluvial clay	18	22	0		10	0.25	10^{-8} to 10^{-9}
Residual soils/weathered rock	20	32	0		20	0.25	10^{-6} to 10^{-8}
Bedrock (dolomite)	22	40	0				10^{-6} to 10^{-9}
Overburden							
Alluvial cover	20	30	5				$2x10^{-6}$
CCL	18	22	10	70	11	0.25	10^{-9}
LS-NAF(HC)	20	Lower bound strength envelope (**Figure 6-47**)					$2x10^{-6}$
PAF(HC) and PAF(RE)	20	Lower bound strength envelope (**Figure 6-47**)					$2x10^{-6}$
Breccia cover	20	Mid bound strength envelope (**Figure 6-47**)					$2x10^{-6}$

6.10 Tailings Properties

6.10.1 Previous Geochemical Testing

Several historical investigations have been conducted on the geochemistry of tailings, including both static testing and very limited kinetic testing. These are reported in:

- McArthur River Development Feasibility Study Northern Territory, Tailings Disposal and Water Management Studies; M.P.A. Williams and Associates PTY LTD., July 13, 1992;
- Report on McArthur River Mine Tailings Storage Facility; URS, March 29, 2010;
- McArthur River Mine Hydrogeochemical Investigation of the Tailings Storage Facility; Golder Associates, June 17, 2011;and
- McArthur River Mine: Tailings classification review; Klohn Crippen Berger, March, 2014.

In addition to the above reports, McArthur River Mining has conducted a monthly tailings sampling program since 2009. The data set consists of over 150 monthly composited samples collected for elemental analyses and ABA properties.

A monthly sampling program of Tailings Storage Facility (TSF) supernatant waters has also been conducted.

6.10.2 Current Geochemical Testing

Supplementary testing has been conducted as part of this EIS with the objectives of confirming that the properties of currently deposited tailings conform to the historical data, and complementing the available data set with additional analyses not routinely conducted.

Five in situ tailings samples were tested in addition to the monthly composited samples. The complementary analyses included X-ray diffraction mineralogy, sulphur speciation, kinetic NAG, ABCCs and SFEs.

Oxygen consumption testing was conducted on two composite samples to determine the reactivity of the material. Moisture content has a significant impact on oxygen consumption rates, so the tests were conducted at moisture contents ranging from fully dry to saturated. These tests aimed at characterising the material under the full spectrum of possible conditions and hence gaining a better understanding the material’s broad geochemical properties.

In addition to oxygen consumption testing, humidity cell testing was undertaken on two tailings samples as the available historic kinetic data from tailings was very limited. Samples originally tested by URS (2005) were discontinued early in the test program when the samples were deemed unrepresentative of the tailings being deposited in the TSF.

The results of the investigations are presented in the following reports and are summarised in **Section 6.10.3** below:

- McArthur River Mines 2015 EIS: Suitability of Tailings as a Liner, Klohn Crippen Berger, March 19, 2015;
- McArthur River Mine EIS Support: Tailings and Waste Rock Oxygen Consumption Rate Testing, Klohn Crippen Berger, February 01, 2016; and
- McArthur River Mine EIS Support: Tailings Geochemistry Report, Klohn Crippen Berger, July, 2015.

6.10.3 Geochemical Properties

6.10.3.1 AMD Properties

The MRM tailings have been consistently classed as PAF in successive investigations, a classification confirmed by all the geochemical testing conducted as part of this EIS. The material is classed as PAF(HC) in accordance with the MRM/KCB 2017 classification.

The tailings are characterised by total sulphur contents that are typically greater than 12% sulphur, of which 75% is in the form of sulphide, mainly in the form of pyrite with comparatively minor sphalerite and galena.

The high sulphide contents are somewhat offset by a high intrinsic ANC ranging from 140 to 200 kg H_2SO_4/t. The X-ray diffraction results indicate that the ANC is composed mainly of dolomite with lesser calcite, which provide buffering capacity. While the NAPP is positive (refer to **Figure 6-48**) and the NPR is less than 1, indicating that the material is PAF, the intrinsic buffering capacity can be expected to result in delays for the onset of acid generation should the tailings be exposed to oxidising conditions.

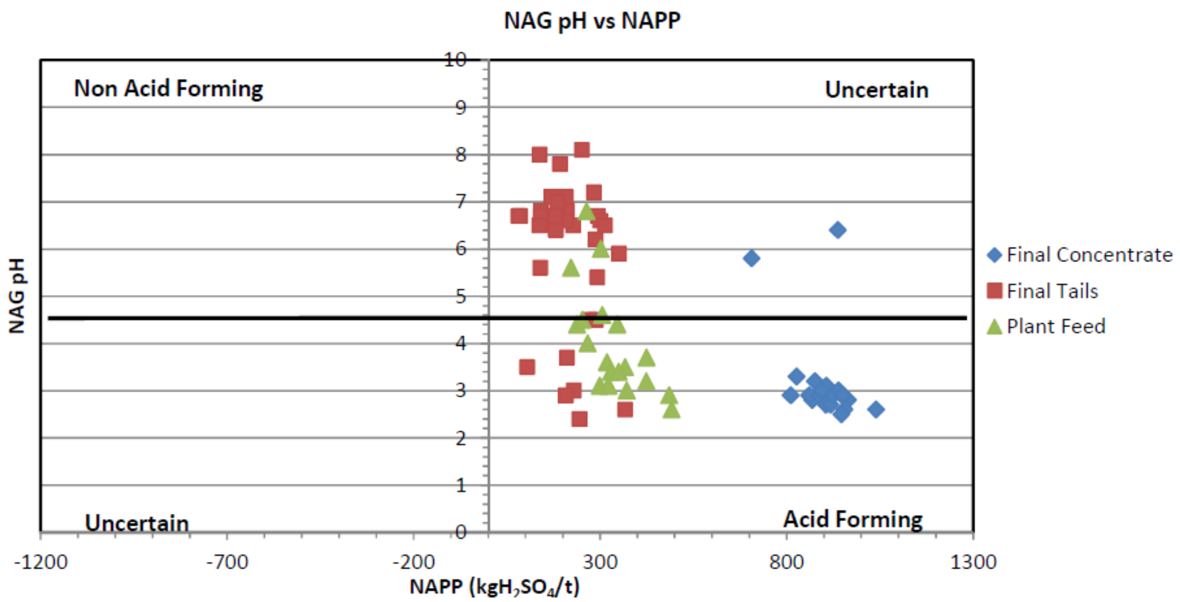


Figure 6-50 NAPP versus NAG pH

In **Figure 6-50,** the large proportions of final tailings classified as uncertain on a NAPP/NAG pH diagram are considered PAF, the uncertain classification likely reflecting the limitations of the single addition NAG pH determinations at high sulphur values.

In addition to pyrite, the static and kinetic testing indicates that the tailings elevated contents of a number of metals including arsenic, copper, lead, cadmium and zinc. Shake flask extractions and humidity cell results indicate that some of these (e.g. arsenic, copper, lead, sulphate, cadmium, cobalt, zinc) have the potential to leach at elevated levels under neutral pH conditions.

6.10.3.2 Tailings Reactivity

The reactivity of the tailings is broadly defined as the rate at which sulphide minerals, specifically pyrite, oxidise and produce sulphuric acid. More reactive material is represented by higher oxidation rates.

In order to determine the reactivity of the MRM tailings, oxygen consumption tests were conducted at a series of moisture contents. The reactivity is measured as OCR and expressed in kilograms of oxygen per kilogram per second (kg O_2/kg/s).

The OCR results show that the reactivity of the tailings is highly dependent on moisture content (refer to **Figure 6-51**). Saturated tailings have a lower reactivity at 2.84^{-11} kg O_2/kg/s, while dried tailings have a higher reactivity at 3.67^{-08} kg O_2/kg/s. Maintaining high in situ moisture content is key to reducing oxidation rates and long-term management of the MRM tailings.

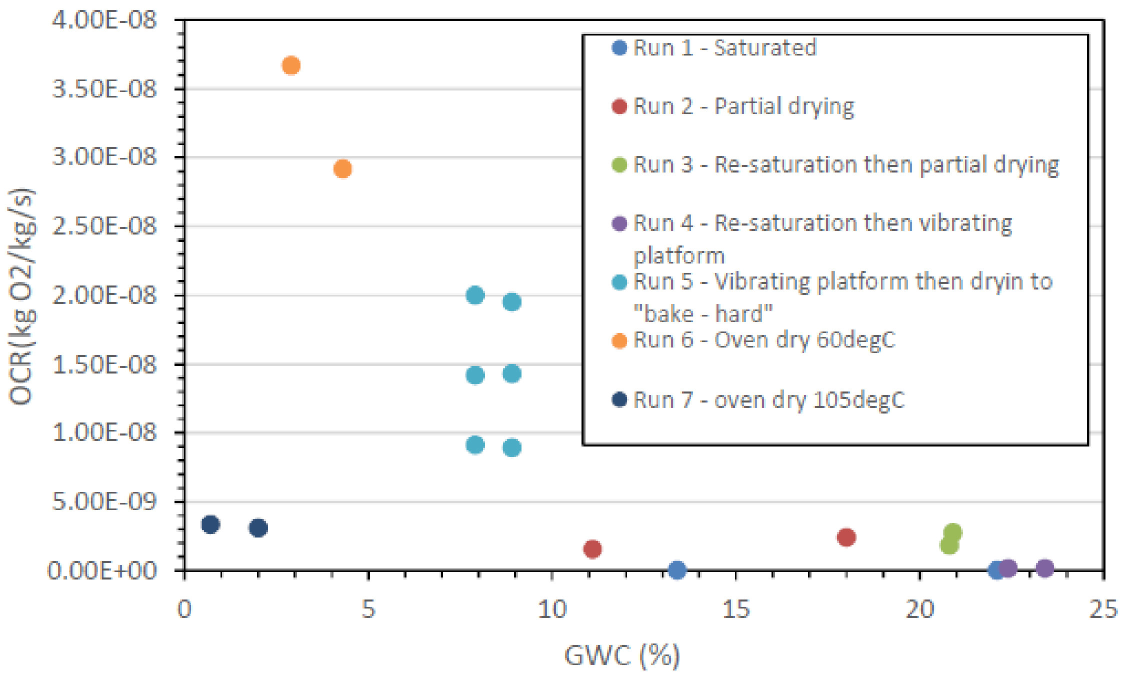


Figure 6-51 Gravimetric Water Content vs. OCR (Tailings)

Figure 6-51 presents the gravimetric water content versus oxygen consumption rate of MRM tailings (from KCB, 2016). Runs 1 to 3 are most likely to represent various in situ conditions: run 1 (saturated) represents deposition with supernatant water; Run 2 broadly represents a drying tailings beach; Run 3 represents a dry beach re-humidified by a new depositional cycle. Runs 4 to 7 are less likely to occur, and simulate the behaviour of the tailings under extreme conditions.

The results indicate that oxidation is unlikely to occur under fully saturated conditions, with the laboratory measured OCR values reflecting the residual moisture contents in the tailings. Increased tailings moisture content will control oxidation rates and therefore will control the potential for acid generation.

6.10.4 Physical Properties

Tailings physical properties have been investigated on a number of past occasions, and recently reviewed by GHD for the development of the TSF Life of Mine Plan (GHD, 2017).

Ore blends and mill processes have changed over time, so the properties of the tailings discharged to the TSF have also varied with time. Furthermore, tailings properties throughout the TSF will differ depending on the deposition method and distance from active spigots.

Nevertheless, the MRM tailings are characterised by a fine-grained texture. They are typically soft to very soft with some strength gain at depth. All tailings samples are classified as sandy silt to silty sand with differing clay content. Testing conducted in 2014 on two tailings samples reported a clay (particle size) content of 17% and 25%, with corresponding Plasticity Index of 9% and 8% respectively. Previous testing of samples reports non-plastic behaviour with minimal clay content and 30 to 50% silt. The tailings have an estimated in situ dry density of 1.7 t/m^3 and a saturated permeability of 10^{-6} to 10^{-8} m/s.