Using Geological Analogues and Proxies to Better Determine AMD Risk

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Abstract

We present initial results from a combined structural and geochemical assessment designed to improve AMD classification at the Martabe gold mine, Indonesia. Martabe conforms to a classic epithermal acid sulfate model displaying local variations in structure and geochemistry that are difficult to constrain using existing resource models. Fracture-controlled mineralisation and oxidation explains the observed irregular and incomplete "oxidation zones" in which Jarosite, a non-sulfide cause of AMD is found. Supported by outcrop analogues such as the Rodalquilar gold mine in SE Spain, these observations imply detailed grade control drilling is justified to improve model resolution and improve waste rock management efficiency.

Keywords: AMD, Structure, Mineralisation, Jarosite, Mine-Waste Characterisation

Introduction

Situated in Sumatra, Indonesia, the Martabe Mine Cluster (MMC) is an epithermal acid sulfate volcanogenic gold deposit developed using open pit mining. Accurately and efficiently classifying waste rocks to prepare a fit-for-purpose waste management schedule presents a challenge due to the complexity of the geological setting and considerable variation in the AMD characteristics of materials being mined at the MMC (e.g. Fig 1). Therefore, we have sought to investigate ways to increase the effectiveness of geological models, test generalised industry assumptions, and improve waste rock classification and processing streams.

Following initial assessments, waste rocks at the MMC are divided into six different classes of waste based on physical and geochemical characteristics which collectively determine relative and absolute AMD risk. Waste rocks are broadly categorised based

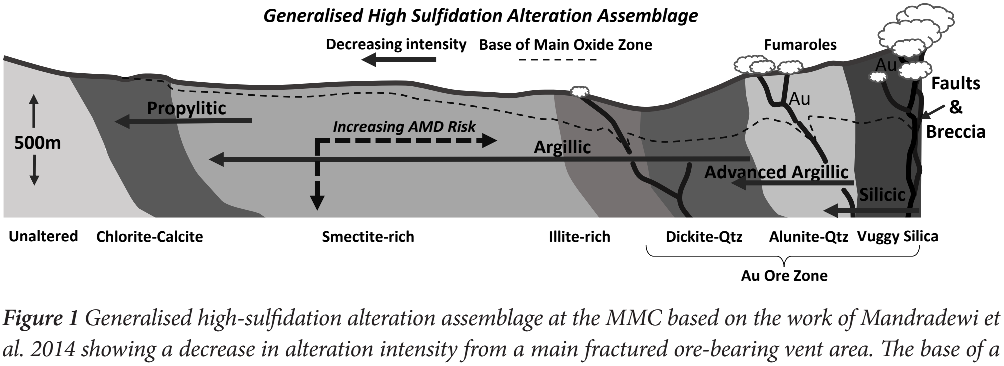


Figure 1 *Generalised high-sulfidation alteration assemblage at the MMC based on the work of Mandradewi et al. 2014 showing a decrease in alteration intensity from a main fractured ore-bearing vent area. The base of a supergene oxide zone is indicated with dashed line along with the approximate extent of alteration assemblages and common indicator minerals. AMD risk is generally assumed to increase towards the ore zone.*

on risk which include higher and lower risk *Potentially Acid-Forming* "PAF" materials, *Non-Acid Forming* (NAF) and material that is PAF but may have a lag time before acid generation occurs. Techniques such as encapsulation of PAF using sealing layers to reduce oxygen ingress are employed at the site to manage AMD generation as part of waste placement in an integrated waste and tailings storage facility. In general, low grade PAF and NAF waste is considered beneficial for use in an outer growth medium zone used to encase the completed integrated waste landform.

To date, waste rocks at the MMC are classified using acid base accounting (ABA) testing based on assay data and laboratory *Net Acid Generation* "NAG" tests undertaken as part of resource development and grade control drilling and sampling. An AMD risk block model based on PT Agincourt's 3D resource development block model is used to map out waste material by waste class and ensure correct identification of materials at an appropriate scale. AMD risk is largely governed by the assumption that sulfide content is the key factor in determining net acidity with buffering provided by carbonates. We investigate whether these simple analytical techniques are sufficient and whether it is appropriate to assume that AMD risk is connected directly to sulfide sulphur (SxS) and the mineralisation system in fig. 1. We seek to investigate scale variance of AMD risk factors and identify more efficient techniques to differentiate classes of waste material using broad proxies and practicable rules or protocols based on quantifiable rock properties in existing resource development models e.g. lithology, alteration type and routine assay metals.

A key area of interest is the possible link between subsurface permeability and oxidation state. We predict permeability and thus AMD risk could be directly linked and influenced by faulting, brecciation and alteration type which are defined in the existing resource development model but are not used directly to model AMD risk. Developing deposit specific AMD models based on a greater understanding of empirical geological and geochemical data can help us design appropriate drilling and laboratory testing strategies e.g. "what is the optimal spacing of grade control drilling?" and "are PAF materials prevalent everywhere or concentrated in certain structural, alteration or mineralogical zones?".

Methods

We used extensive borehole data from the site and analogue deposits to enhance our knowledge of the 3-D geometry and character of alteration zones, faults and mineralisation and determine how PAF materials such as sulfide and the sulfate jarosite are distributed within the MMC. Rodalquilar in SE Spain was identified as our primary geological and geochemical analogue. Rodalquilar was mined using traditional artisanal techniques supplemented by later localised mechanical excavation. In contrast to most modern mines around the world, the original structural fabric of the deposit is largely intact and retains sufficient outcrop to allow a thorough understanding of the 3D distribution and character of faulting and mineralisation. Our descriptions are based on visits to the mine, laboratory analysis and published literature.

To better constrain geochemical data, samples from grade control drilling were assayed and processed to determine sulfide sulfur (SxS) and standard NAG acidity. In addition to repeat QC testing, Paste pH and Rinse pH methods were also used to test whether estimations of net acidity derived from NAG tests require supplemental laboratory test data to define PAF characteristics.

Results

The plots in fig. 2 illustrate varying geochemical characteristics of two boreholes drilled in the Tor Ula Ala site at the MMC. Borehole APSD1879 shown in fig. 2a is drilled over a 130 m section revealing two notable excursions in NAG pH and SxS data indicating locally high-grade waste material. These zones also show elevated Au and Cu. We interpret these zones as being potentially fault controlled ore zones. The concentration of acidity data suggests PAF material might be concentrated in narrow metre or sub-metre scale bands rather than evenly distributed within the rock volume. Such narrow bands could easily be missed with widely spaced drillhole sampling, therefore the knowledge that such concentrated zones exist has potentially important implications for the resolution of drilling required to identify such features. It is further noted that less PAF waste could be characterised as high risk if the main ore body can be isolated along the fault and treated separately to the bulk waste surrounding it as would be the case in underground or artisanal mining. In fig. 2b borehole APSD2491 is cored over a longer 380 m section and whilst there are fewer obvious narrow excursions, the SxS and NAG pH trends show a marked step at 155 m with the remaining section showing consistently high SxS but rather variable NAG pH suggesting SxS is not directly proportional to NAG pH. Initial testing suggests some of the observed variability is due to calcite which provides a source of acid buffering ANC material, and alunite which returns a false positive from SxS testing.

Assay, XRD, SEM and thin section analysis data shows the main contributions to AMD risk at the MMC are sulfides e.g. pyrite, enargite and covellite. Sulfides are mostly concentrated in Siliceous (Si) and Advanced Argillic (AA) alteration zones, but also occur as patchy concentrations throughout the MMC including within localised pods and veins within the main oxide zone which is contrary to the simple AMD model proposed in fig. 1. This suggests permeability and access to oxygenated water are potentially important factors in determining the levels of sulfide oxidation. On further inspection, our laboratory studies led us to recognise a statistically significant disparity between expected rinse pH and measured sulfide content (SxS) derived from basic NAG testing. Jarosite ($KFe^{3+}_3(SO_4)_2(OH)_6$) has been isolated as the potential cause of the difference and is now recognised as a potential AMD risk factor at Martabe. The distribution and deportment of jarosite is, at present, poorly constrained; however, jarosite usually forms under acidic conditions in the presence of oxygen meaning it could be present wherever partial oxidation has occurred in the presence of acidic leachate

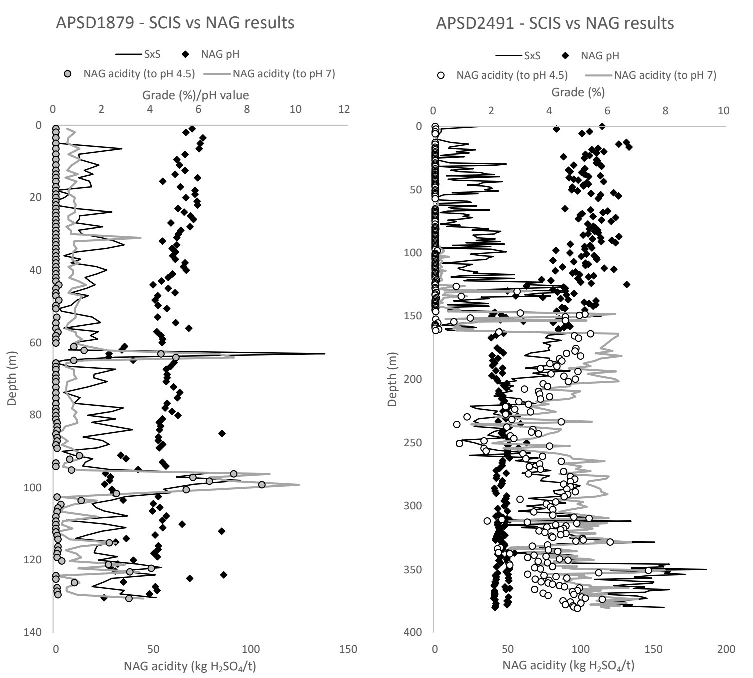
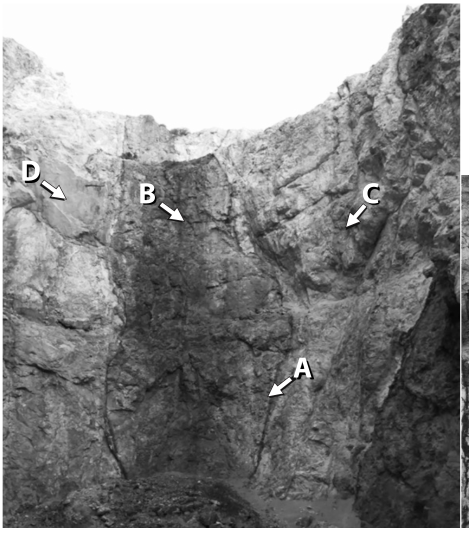


Figure 2a *Plot showing NAG acidity (pH 4.5 and pH 7.0) superimposed with Sulfide Sulfur (SxS) and NAG pH against depth in boreholes APSD1879 and* ***2b*** *APSD2491 at the Tor Ula Ala pit PT Agincourt Resources). Depths are measured depth along borehole.*

(e.g. Cunningham *et al.* 1994). Based on initial cross-plots of Jarosite and SxS, we provisionally conclude transitional SxS grades of 2.0–4.0% could signify higher likelihoods of encountering Jarosite e.g. between 120–140 m in APSD2491. Testing also indicated large concentrations of alunite ($KAl_3(SO_4)_2(OH)_6$) which affects the accuracy and precision of routine SxS readings. Alunite contains bound sulfur which is incorrectly counted as SxS during routine laboratory analysis leading to overestimations of SxS. Rinse pH and NAG pH tests are therefore required to measure jarosite and sulfide grade which are required to reliably calculate AMD risk.

To date, block and wireframe models of PAF material which are the basis for populating the AMD model show limited structural alignment with known ore bodies and suffer as a result of aliasing widely spaced sample points. To enhance the level of geological control, we identified the need to establish reliable rules of thumb and proxies to estimate sulfide and jarosite grade distribution within the MMC. Exploratory drilling suggests the MMC is crosscut by several generations of faulting which may be coeval with acid sulfate mineralisation. The interpreted fault intersections identified in fig. 2a suggest primary structures could be exerting an important influence on the distribution of PAF mineralisation. Field data collected using Analytical Spectral Devices (ASD) also supports a directional component to mineralisation and alteration assemblages at the MMC which appear to be aligned with primary faulting (e.g. Mandradewi *et al.* 2014). Introducing more structural control to the AMD block model using techniques such as Kriging could enhance the accuracy and reliability of the AMD model reducing the need for additional high resolution grade control drilling. Whilst our analysis shows existing modelling is broadly fit for purpose, we are aware of the scale-independent fractal nature of fractures and faults (e.g. Walsh & Watterson 1991) and therefore explored the detailed structural and geochemical character of our chosen analogue acid-sulfate deposit at Rodalquilar, SE Spain.

Rodalquilar is of comparable scale and relief to the MMC and is hosted in similar acid-intermediate host lithologies with a strong structural control on Au grades (e.g. Arribas *et al.* 1995). As with the MMC, Au is late stage at Rodalquilar, focused in quartz-pyrite veins, vuggy cavity filling quartz and complex banded and brecciated veins predominately in silicic and advanced argillic alteration zones (e.g. Saing *et al.* 2015, Rytuba *et al.* 1990, Hedenquist & Lowenstern 1994 and Foley & Hayba 1987). Alteration is observed to be of greatest intensity in highly fractured or brecciated host lithologies suggesting early-stage acid leaching of primary minerals and structural weakness facilitates higher permeability along which later Au and sulfide mineralisation is concentrated. As with the MMC, Rodalquilar displays characteristic decreases in alteration intensity grading outward in a concentric pattern from siliceous and advanced argillic central cores with abundant alunite. Looking in detail at the patterns of excavation artisanal miners have made, ore mineralisation at Rodalquilar is focused along sheet-like silicified faults, narrow silica veins and irregular breccia pipes. Calcite is concentrated in propylitic and unaltered rocks at Rodalquilar. Propylitic zones are comparatively less well developed at the MMT, but calcite appears concentrated in zones away from the more intense alteration zones at both locations. Fig. 3a shows a typical irregular shaped intact siliceous pipe surrounded by various alteration zones and intense localised fracturing. Our observations suggest far more complexity and fractal behaviour between interacting structures and alteration haloes than the generalised model shown in fig. 1 would predict. Complex interactions between irregular sheet and pipe-like 3D features helps to explain the step like behaviour of ore and SxS grades as well as irregular or repeating patterns of alteration mineralogy noted in boreholes at the MMC. Our work suggests routine testing based on widely spaced samples from resource drilling could provide misleading results therefore higher density 1m vertical sampling intervals used in grade control boreholes drilled at ≈10–15 m centres would be necessary to reproduce the types of features shown in fig. 3a in our AMD models at the MMC.



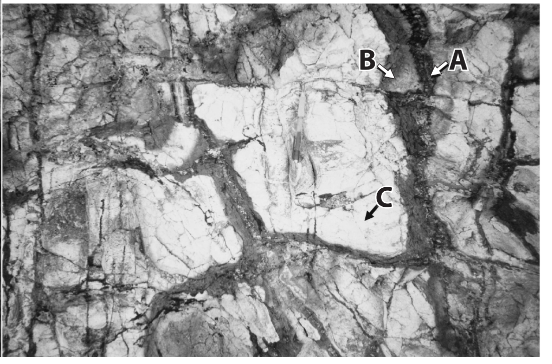


Figure 3a *Excavated gallery at the Rodalquilar gold mine, Almeria, SE Spain showing defined dark alteration margins at "A", a central silica-rich ore zone at "B", advanced argillic alteration rich in alunite at "C" and an isolated intact block of volcanic material at "D" which is relatively unaltered, possibly due to reduced permeability. Field of view is 20m (image: Timothy Wright).* ***Figure 3b*** *Volcanic breccia at the Rodalquilar gold mine, Almeria, SE Spain showing concentrated hematite, jarosite and goethite in the centre of a fracture at "A", with syntaxial development into lower concentrations of iron oxides at "B". Point "C" displays no visible iron oxides but some residual alunite along with kaolinite typical of argillic to advanced argillic alteration. Field of view is 1m wide (image: Timothy Wright).*

Both the MMC and Rodalquilar exhibit marked surface weathering and the development of oxide zones characterised by high concentrations of the stable iron oxides hematite & goethite. Jarosite has been identified together with hematite and goethite in freshly exposed road cut sections at Rodalquilar, e.g. fig. 3b, indicating the presence of iron oxides are on their own not sufficient to determine "low" AMD risk (i.e. absence of sulfides or acid sulfates). Routine testing of the "oxide" zone using the rinse pH analytical technique is advisable to detect jarosite, and sulfide sulfur analysis to detect remnant sulfides. We continue to search for suitable geochemical markers and proxies that can be used to quickly classify waste based on standard assay testing. Initial results indicate Cu and As grades (routine assay data) can be used as potential proxies for estimating SxS and jarosite presence. We also note that sulfide and base metal concentrations are not always directly linked, e.g. Cu and As may be concentrated or depleted in various transitional zones characterised by separate oxidation states to iron sulfides. The regular net-like patterns of concentrated metalliferous mineralisation observed at outcrop scale at Rodalquilar and shown in fig. 3 indicates conventional blasting could also result in preferentially separating and fragmenting higher AMD risk vein material leaving larger pieces of low-risk matrix intact (e.g. Pearce *et al.* 2019). As a result, opportunities are identified for mechanical recovery of resources that would otherwise have been not identified (due to grade weight averaging of "blocks" in modelling) and consequently, the removal of high-risk (high sulfide) material from otherwise inert waste rocks.

Discussion

Our work studying the Rodalquilar deposit has revealed many details of the sinuous, streaky, fracture controlled and brecciated nature of the ore zones and surrounding waste rocks that display fractal behaviour. We have discovered evidence that AMD risk is generally higher in the most intensely altered siliceous and advanced argillic zones due to a lack of acid buffering calcite, but we also note sulfides are present in lower intensity argillic alteration zones and also more generally defined "oxide" zones. Carbonates do not appear to be present in advanced argillic and siliceous zones, therefore it is true to say low risk material with higher acid buffering potential is more likely to be found in zones of argillic, propylitic and unaltered assemblages (but not assured).

The presence of hematite and goethite in ASD readings is commonly used to define the "oxide zone"; however, in the oxide zones at the MMC and Rodalquilar, there is still abundant sulfide and jarosite so it is incorrect to attribute low AMD risk to all rocks containing common oxide indicators at the MMC. Jarosite appears to be concentrated in zones rich in partially oxidised SxS and therefore might be of greatest concern as a source of acid in advanced argillic and siliceous zones. More research is required to confirm whether this is a quantifiable relationship. Quantitative evaluations indicate faults and breccia zones are generally more prone to hosting high risk material. For example breccia of the type found at the Barani pit in the southern area of the MMC has elevated jarosite suggesting permeability controlled by faulting and fracturing is a key risk factor. We therefore consider whether is it appropriate to abandon a simple oxide zone model and include fault planes and breccia pipes into our AMD model and define a high-risk zone to all material within a given distance of the fault or with potentially elevated permeability. In the case of the "340 vein" at Rodalquilar, anecdotal reports indicate approximately 560 kg of Au was recovered from a planar fracture-hosted zone of silicious material measuring a few metres in width suggesting any associated PAF material would be captured during ore processing with surrounding rocks yielding much lower sulfide grade and lower acidity forming potential. At Martabe (and most modern mines using open pit excavation), such a narrow vein will be treated as "bulk ore" and mined along with lower grade material.

Modern open pit mining is driven by bulk ore grade (using grade weighted averaging and block modelling approaches) negating the need for precision resource modelling and mining technique. Grade weight averaging over 10-20m blocks using single borehole validation will, on average capture sufficient details of the broad mineral system and the resulting resource model will be similar to the generalised model shown in fig. 1. Our research suggests sulfide tends to be focused in localised structurally controlled concentrations therefore small-scale variability could be missed with this block modelling approach which might mean that any given block could register as low-grade AMD risk but contain very high concentrations of AMD material, e.g. along sulfide veins in zones of lower permeability or jarosite pods and streaks in zones of higher permeability that are not intersected by drilling. Failure to consider such features could lead to incorrect classification of waste and deleterious environmental consequences. Anything that can be done within a commercial context to prevent extraction, incorrect classification and disposal of unnecessary material will result in greater efficiency and reduced environmental impact.

Our search for proxies is ongoing with promising indications that As and Cu concentrations could be potential proxies for acid sulfates such as Jarosite at the MMC. We are also considering whether it might be possible to use physical fragmentation characteristics and rock properties of certain classes of material to isolate high-grade waste that could constitute ore and be processed as ore thus reducing the high-grade waste load, or selectively recover higher grade sulfides based on particle size (as vein material tends to act as weak points for fragmentation during blasting).

Conclusions

We have shown that it is helpful to draw on geological analogues when seeking to predict and model AMD risk using integrated resource modelling at the MMC. The fracture- and permeability -controlled nature of oxidation and mineralisation observed in outcrops at Rodalquilar explains the observed irregular and incomplete "oxidation zone" observed at the MMC. We conclude the

MMC AMD model will continue to benefit from enhancements to adequately capture features such as the geochemical excursions noted (e.g. fig. 2a.) Scales of measurement and aliasing are important factors due to the fractal character of pods, streaks and fractures which contain substantial localised concentrations of sulfide and jarosite. We have developed improved modelling strategies which prioritise waste with the greatest AMD risk and reduce the amount of low-grade waste being classified as PAF.

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