CONSIDERATION OF GEOLOGICAL BLOCK MODELS AND ANALOGUES IN ARD ASSESSMENTS

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ABSTRACT

This paper presents results from a combined structural and geochemical assessment designed to improve waste rock 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 estimation and ARD classification methodologies in isolation. This paper demonstrates the challenges of converting geological knowledge into block models where conventional modelling based on sparse high quality data struggles to accurately represent real-world geology. Forming an understanding of structural, mineralogical and geochemical heterogeneity of sulfides, sulfates, alteration zones and oxide zones is shown to enable improved accuracy and efficiency during the block modelling and waste management processes. Potential improvements are delivered by separating waste using a practical logic-based approach. This paper outlines the detrimental effect of low-risk sulfate e.g., Alunite on standard Sodium Carbonate Irreducible Sulfur (SCIS) measurements of sulfide which are routinely used to guide block modelling, and shows how limited use of NAG testing can make better allowances for non-sulfide sources of sulfur whilst still accounting for the potential contributions to ARD risk attributed to acid sulfate e.g., Jarosite. Outcrop analogues demonstrate how geochemical proxies based on assay measurements and observations of colour and alteration type can provide improved control for the modeller and more realistic output models without compromising project efficiency. Fracture-controlled mineralisation and oxidation explains irregular and incomplete oxidation zones at Martabe. Our observations indicate a simple layer-cake model is insufficient to capture important aspects of the mineral system which affect ARD risk and resulting waste rock classification, therefore detailed grade control drilling and regular NAG testing is justified to improve ARD model resolution and improve waste rock management efficiency.

Keywords: ***ARD, structure, mineralisation, block model, waste***

1.0 INTRODUCTION

Situated in Sumatra, Indonesia, the Martabe Mine Cluster (MMC) is an epithermal acid sulfate volcanogenic gold deposit developed using open pit mining (e.g. Saing et al. 2015). Mine waste is routinely classified and segregated allowing low-risk mine waste to be used on site to construct infrastructure (haul roads) and large engineered structures e.g. tailings storage facility (TSF). Accurately and efficiently classifying waste rocks as part of routine resource modelling 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 ARD characteristics of materials being mined at the MMC. Waste rocks at the MMC are divided into different classes of waste based on physical and geochemical characteristics which collectively determine relative and absolute ARD risk. Properties used to characterise waste rocks include sulfide sulfur content (SxS) and net acid production potential (NAPP) which can be used as a guide as to whether the rocks are Potentially Acid-Forming "PAF", Net Neutral (NN) or possess Acid Neutralizing Capacity "ANC" and are thus potentially Non-Acid Forming (NAF). ARD management techniques such as lime addition and compaction of sealing layers to minimise oxygen ingress into placed waste are routinely used to manage acidity in higher grade PAF materials. Lower-grade NN, low risk PAF and NAF waste are considered beneficial and are separated to be used as part of progressively placed sealing layers and as a continuous outer growth medium zone to encase the completed TSF as part of closure risk management. Care is also taken to assess metal mobility in the full range of Eh-pH conditions encountered on site. Correctly classifying material is therefore imperative as part of the long term mine planning (and scheduling) of mine waste placement at the MMC site to ensure ARD management and closure goals can be achieved.

The MMC contains zones of advanced argillic and siliceous alteration which display varying concentrations of sulfides, typically <3% (mainly pyrite) and alunite ($KAl_3(SO_4)_2(OH)_6$) ranging between 0.5% to >50%. Alunite is a significant source of non-sulfide sulfur and has been found to yield elevated sulfide sulfur readings in standard SCIS based assay reporting because alunite is not dissolved using sodium carbonate. This phenomenon results in falsely high predictions of sulfide content, and thus implied acidity when translated directly into waste models. Falsely high values of acidity lead to more waste being treated as higher risk than necessary, greater waste management costs and reduced amounts of material being available for construction on site. This study seeks to understand the distribution of both alunite and sulfide and whether sulfur mineralisation can be predicted accurately within a block model using logical programmable measurements. This research also seeks to understand more about the presence of acid sulfate e.g., jarosite. In contrast to alunite, jarosite presents a quantifiable ARD risk due to the tendency to breakdown and generate acid in meteoric conditions. Such acid sulfate can be detected using NAPP in conjunction with rinse and paste pH tests to separate long term sulfidic sources of acid from short term acid generation from unstable acid sulfate. However, test data from these analysis methods are not present in high resolution in the resource model and a means to efficiently determine the presence of acid sulfate during modelling is required.

2.0 MODEL BUILD AND ARD ASSESSMENT METHODOLOGY

The key aim of the model architecture building exercise is to accurately represent geological structure and provide a framework in which all data types such as geochemical data can be compiled and referenced to. At the MMC, this framework model is the main development model used to map out ore zones and plan mining schedules. Structural framework input data typically includes borehole logs, surface grid maps and fault plane meshes. The coarse structural model is combined with more detailed models of host lithology, assay data and alteration grade to build the overall resource model. An assessment of the degree of geological reality represented in the structural framework model using qualitative visual assessment was undertaken at this stage to determine whether modelled geological boundaries displayed similar geometric characteristics to boundaries observed in pit outcrops.

The principal aim of the ARD specialist is to accurately represent geochemistry within the structural frame of reference of the development model such that waste materials can be scheduled in a similar detailed and comprehensive manner to ore. To constrain geochemical data, samples from resource and grade control drilling are assayed for key rock forming and precious element components and a routine and regularised selection are processed to determine SxS and Net Acid Generating (NAG) acidity. The resulting data are quality controlled and calibrated using repeat sampling and multiple analysis methods e.g. NAG test, paste pH and rinse pH to arrive at reliable estimations of NAPP. Inconsistent results are highlighted and investigated.

Data collected during laboratory analysis of rock core samples are used to build a series of ARD models reflecting NAPP and NAG acidity based on PT Agincourt's 3D resource development block model framework utilizing Surpac® and Leapfrog® software for model build and visualisation. Resource core samples are supplemented during pit development by higher resolution grade control (GC) drilling at spacings of between 5m and 25m.

To better understand and constrain the distribution of PAF and non-PAF material at the MMC and build realistic ARD models, methods have been sought to develop a better understanding of the fundamental geological setting and the 3D distribution of lithology, structures and alteration assemblages and their relationships to sulfide and sulfate sulfur distribution and therefore overall PAF character of the deposit and its host rocks. This has been achieved by looking at core, analysing assay data and using published examples and field outcrops to better understand the relationships between scale dependent heterogeneity in mineralisation and alteration patterns. Examples were noted where apparent aliasing was occurring where sampling frequency is too low to correctly replicate real world patterns of behaviour.

Increasing the data collection resolution of drilling and using complex laboratory analysis to enhance modelling and capture more geological detail to overcome aliasing has substantial cost implications. It was therefore considered beneficial to make extensive use of potential analogues to 1) enhance understanding of the 3-D geometry and character of alteration zones, faults and mineralisation, 2) determine how PAF materials such as sulfide and the acid sulfate mineral phases such as jarosite are distributed within the MMC, and 3) investigate how sulfide and alunite are distributed e.g. prevalent everywhere or concentrated in specific structural, alteration or mineralogical zones. The overall aim is to determine the best way to account for sulfur mineralogy.

Rodalquilar mine in SE Spain was identified as a primary structural and geochemical analogue for the MMC. Rodalquilar was mined using traditional techniques supplemented by later localised mechanical excavation, therefore 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 better understanding of the 3D distribution and character of faulting and mineralisation within the heart of the ore-bearing deposit. Descriptions are based on visits to the mine and reviews of published literature.

3.0 RESULTS

3.1 Review of block model input data

An initial investigation was undertaken to assess the various assay databases and existing ARD block modelling criteria to determine where accurate reliable data exist and where there is scope for improvement. Borehole assay based models, e.g. Au grade, which contains tens of thousands of data points can be used to build 6.25 x 6.25 x 5m block models. The resulting models are not only fit for ore mining purposes, but also demonstrate the ability to capture aspects of the underlying structural framework which can be used for waste rock models e.g. locating and defining lithology or alteration assemblage boundaries, mapping fault planes and defining mineralisation trends. The same applies to SxS data for which a similar number of data points exist. However, as has been noted in this paper, SxS derived from SCIS is not a suitable proxy for sulfide content because of the presence of alunite. The SxS block model looks geologically credible with similar trends and structural styles to Au; however, the SxS data in the Martabe mine database are misleading being based on methods which do not differentiate between sulfide and sulfate sulfur. Therefore zones which appear to be sulfide rich are potentially zones of elevated alunite concentration. There is no easy way to discriminate between "real" sulfide and "false" sulfide using SxS alone as the two forms of sulfur are often present together, therefore the model based on this "low quality" dense data is flawed and considered unreliable for classification purposes without further calibration and validation.

A second approach has been trialled using "high quality" NAG data which provides more accurate estimations of ARD properties where data are present e.g. usually only along boreholes or at sampled outcrop surfaces. Overall, such models are limited by the sparse resolution of high quality data. Examples of issues in the NAG block model built using sparse but high quality data are shown in Fig.1 where sharp unrealistic boundaries are noted at "A", irregular but unrealistic wedges of material at "B" are caused by interpolation between borehole data points with very different values, and broad zones with very monotonous character at "C" and "D" result from widely spaced data points with relatively large interpolation distances. Aliasing is commonly observed in the model when sampling increments are substantially greater than the scales of heterogeneity in properties being measured.

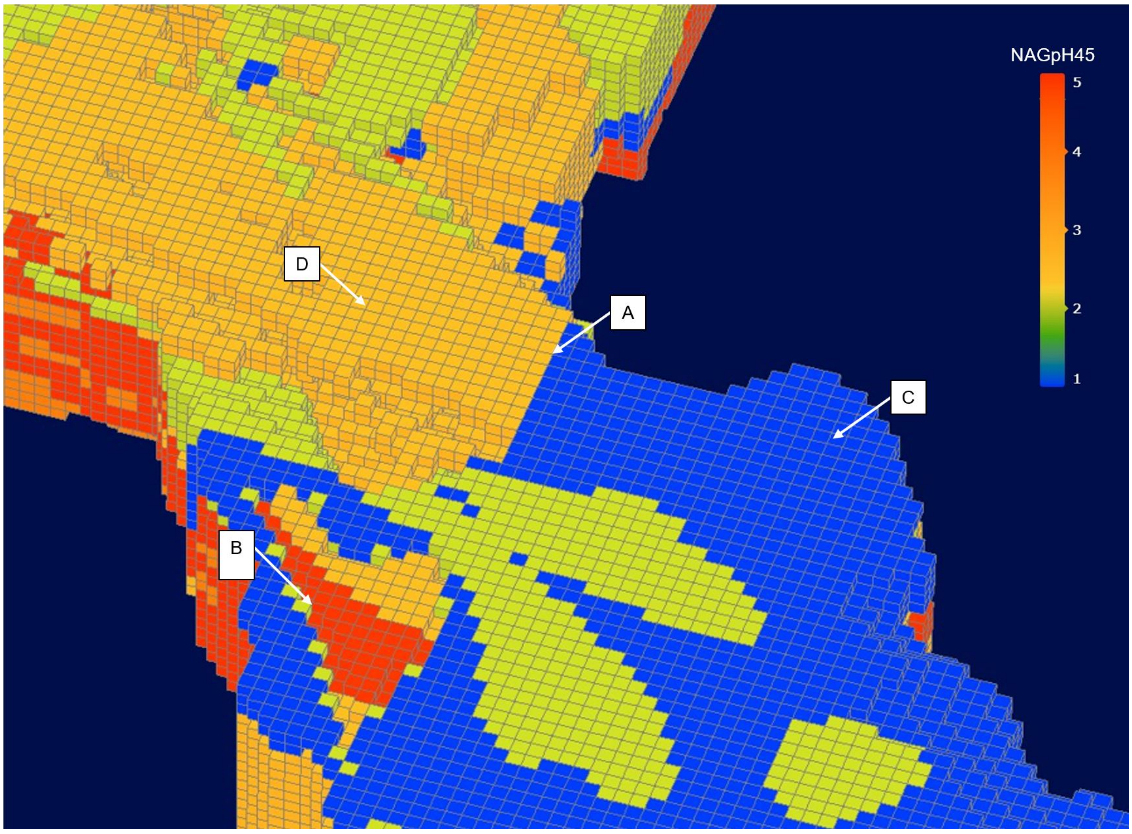

Fig.1. **Closeup of NAG based ARD model illustrating the limitations of a high quality sparse data approach**

Because of the limitations of the NAG model, attempts were made to generate a simple model from high resolution Analytical Spectral Device (ASD) data based on the premise that oxide zones are mostly found above sulfide zones, sometimes separated by a transitional zone e.g. Fig.2. The ARD model was generated from a simple set of parameters in a limited number of boreholes and yields sensible pit-scale models for MMC that agree with boreholes such as Bore APSD2491 also displayed in Fig.2.

Further looking in detail at geological models based on dense data sampling, evidence was noted of apparent heterogeneity in the model which looks "geological". From an ARD perspective, it was considered relevant to investigate whether this heterogeneity translated into important information regarding ARD character. In the example in Fig.3 (LHS) which is based on SxS, there are several instances where higher sulfide content e.g. at "X" is observed to be perched above oxide layers e.g. at "Y" which matches observations from outcrops e.g. Fig.3 (RHS).

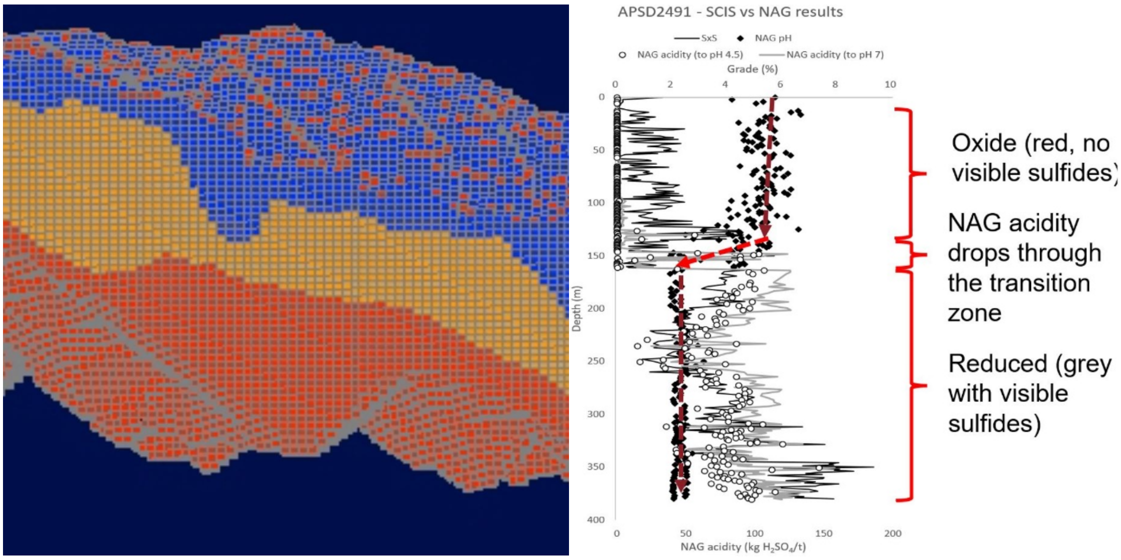

Fig.2. **LHS: Block model of oxide dominated zone (blue) above sulfide zone (red) with transitional zone (orange) based on oxide mineral assessment from high resolution ASD data. RHS: Zone where the classic model of oxide and reduced zones works well in borehole profile APSD2491.**

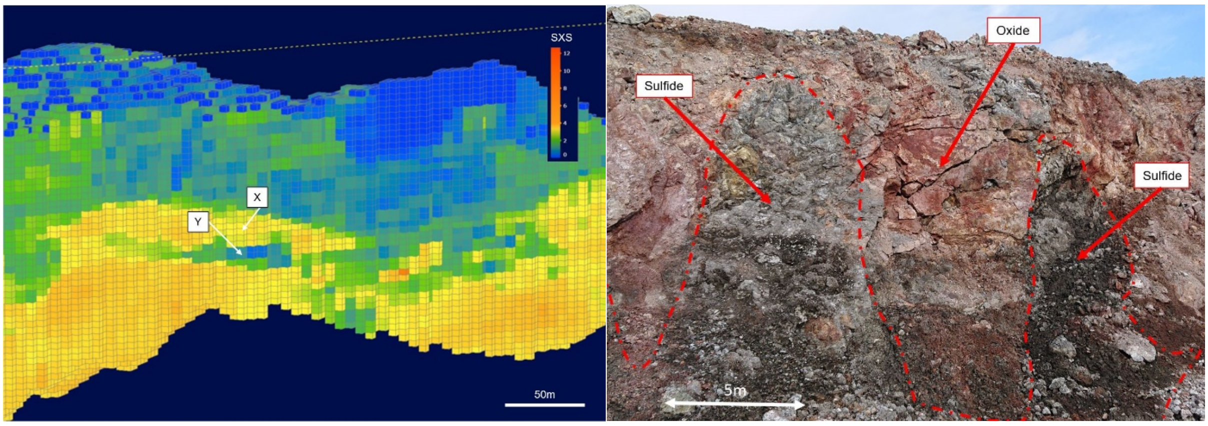

Fig.3. **LHS: Block model of SxS, RHS: photo in pit wall outcrop showing sulfide zones amongst oxide suggesting the SxS model is capturing realistic geology and the simple layer-cake model of oxide above reduced sulfide zone with a regular transition is possible**

3.2 Use of Core and Outcrop Data

Following initial investigations based on diamond core samples, the potential importance of scale and heterogeneity were considered in context of assessing and measuring PAF character. Examples shown in Fig.4 demonstrate heterogeneity seen in the MMC deposit with dramatic variations in sulfide content and structure observed over centimetre and metre scales. Many examples were encountered where sulfide bearing material is encapsulated in oxidised low-risk material and vice-versa. High densities of sampling e.g. the plots in Fig.2 and Fig.4 resolve metre-scale pods of PAF sulfide; however, such high resolution sampling has only been attempted on a limited number of boreholes. Many instances were also noted where an apparent transitional zone has developed where oxide and sulfide material is almost indistinguishable but for changes in colour. It became clear the scale at which the core was analysed e.g. point based or composite, centimetre or metre scale, greatly influenced the ability to correctly assign accurate geochemical character. Mine sampling cannot capture the detail of the complex heterogeneity observed, therefore testing and modelling strategies need to be adapted to capture "enough" data, and where possible, use simple but robust methods to extrapolate and upscale to pit-scale models.

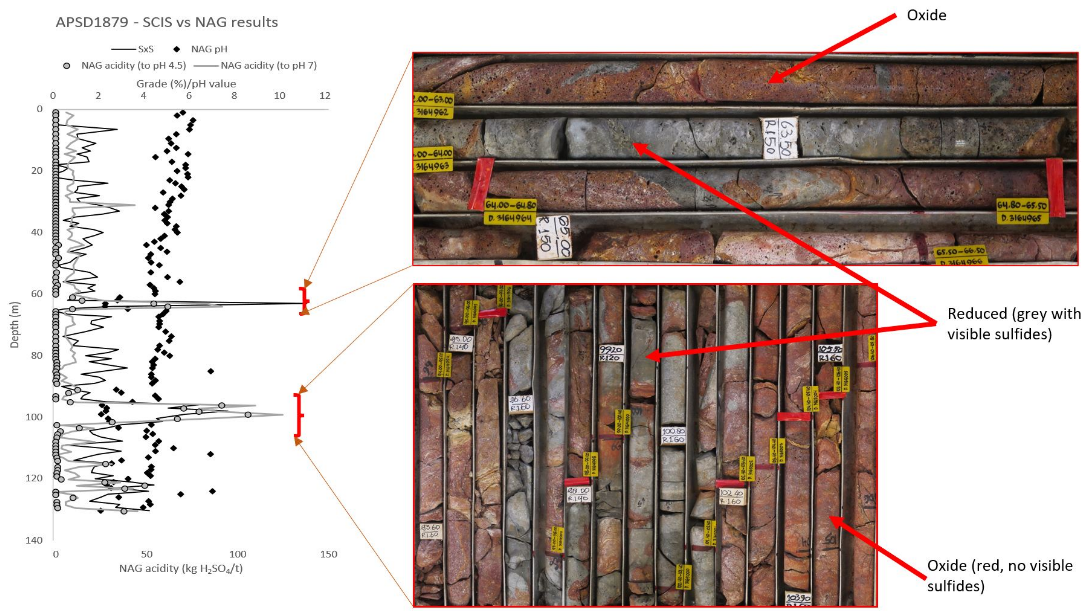

Fig.4. Examples of heterogeneity in borehole APSD1879. Transitions can be gradational or extremely sharp in the case of faulted boundaries. Oxide zones tend to be brightly coloured with no visible sulfide. NAG acidity drops through a brown and grey transitional zone until rocks become reduced with grey hues and visible sulfide.

3.2.1 Review of an analogue High Sulfidation Epithermal Systems

The historical Rodalquilar mine in southern Spain provides an opportunity to look in detail at a high sulfidation epithermal system of similar size, character and mineralogy to Martabe. Like the MMC, clusters of elongate ore bodies are associated with silicic cored argillic and advanced argillic alteration zones (e.g. Arribas et al. 1995 and Rytuba et al. 1990). Rodalquilar was mined using artisanal trenching and tunnelling supplemented with later mechanical extraction. The result is rare preservation of many lithological textures, structures and patterns of mineralization (e.g. Fig.5). Strong evidence was found of the controls on mineralization by structure, e.g. faults and fractures. Structure controls not only the main hydrothermal system and gold mineralization, but also oxidation which, like Martabe, appears to be permeability driven with evidence of sulfide depleted zones and oxidation deep in the Rodalquilar system focused on faults and fractures well below the main redox transition. At Rodalquilar and the

MMC, sulfide is retained within the oxide zone, typically in impermeable silicic materials. Jarosite, a potential source of ARD was observed in outcrop at Rodalquilar and is now recognized as a key secondary mineral at Martabe. Ongoing studies seek to identify Jarosite at the MMC and understand whether it is forming due to present day oxidation of exposed sulfides due to mining, or exists in the deposit as a relict of earlier naturally occurring acid alteration and oxidation.

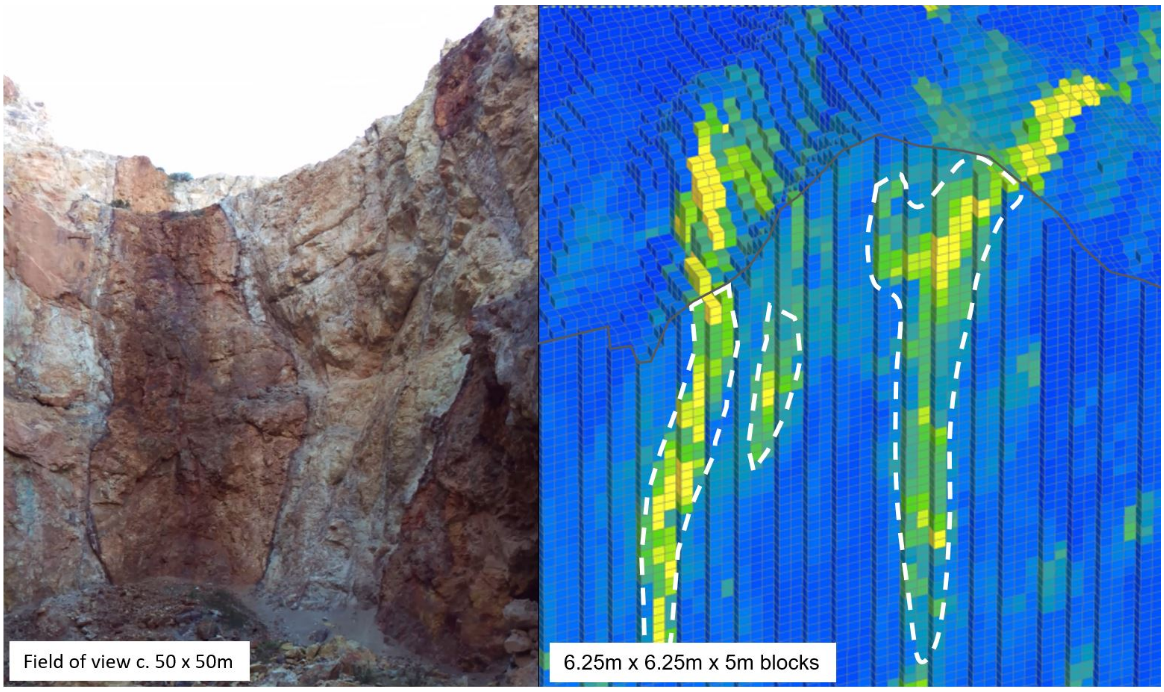

Fig.5. Comparison of transition zone breccia at Rodalquilar (left) with Martabe block model right coloured to highlight alteration at approximately same scales

A comparison of borehole sampling density and block size at the MMC suggests drill holes will not intercept all blocks based on typical drilling patterns and densities used for resource development not least because drill holes mostly target ore zones rather than waste rock. Therefore as demonstrated in Fig.1, ARD modelling is heavily reliant on interpolation which may be poorly constrained without appropriate geological validation. Regular GC drilling is therefore beneficial for waste management at Martabe due to the heterogeneous nature of the MMC deposits and requirement for rapid waste classification. Each waste rock block is assigned a waste category related to its ARD characteristics and marked-out prior to blasting and is placed in the onsite integrated waste storage facility.

3.3 Benefits of Separate ARD Modelling Approach

There are multiple potential benefits of a separate GC based ARD model and Reserve model approach. Firstly, the 25m reserve model spacing is shown to be insufficient resolution for an effective ARD model. The ARD model can be constructed at 6.25m or 12.5m in the GC model rather the 25m of the reserve model and with vertical 1m sampling intervals. Secondly, the reserve model does not contain sufficient ARD testing parameters. The GC drilling and sampling now used at the MMC allows addition of ARD tests such as NAG and ANC to better define ARD risk. At MMC, the aim is to operate with near real time NAG sampling and ARD model validation, currently yielding >20,000 NAPP datapoints. Comparisons are routinely made between the evolving ARD and resource models and calibrated with incoming GC, resource and blast hole geochemical data. The use of the growing core and assay database is maximized to investigate the structural and mineralogical relationships which influence ARD management strategy to provide appropriate controls and calibrations during each model build. Bespoke ARD testing and monitoring is used to challenge assumptions and provide constant improvements in efficiency e.g. adjusting liming rates to better match waste grading. The result is an evolving ARD model combining as much valuable data as possible e.g. Fig.6.

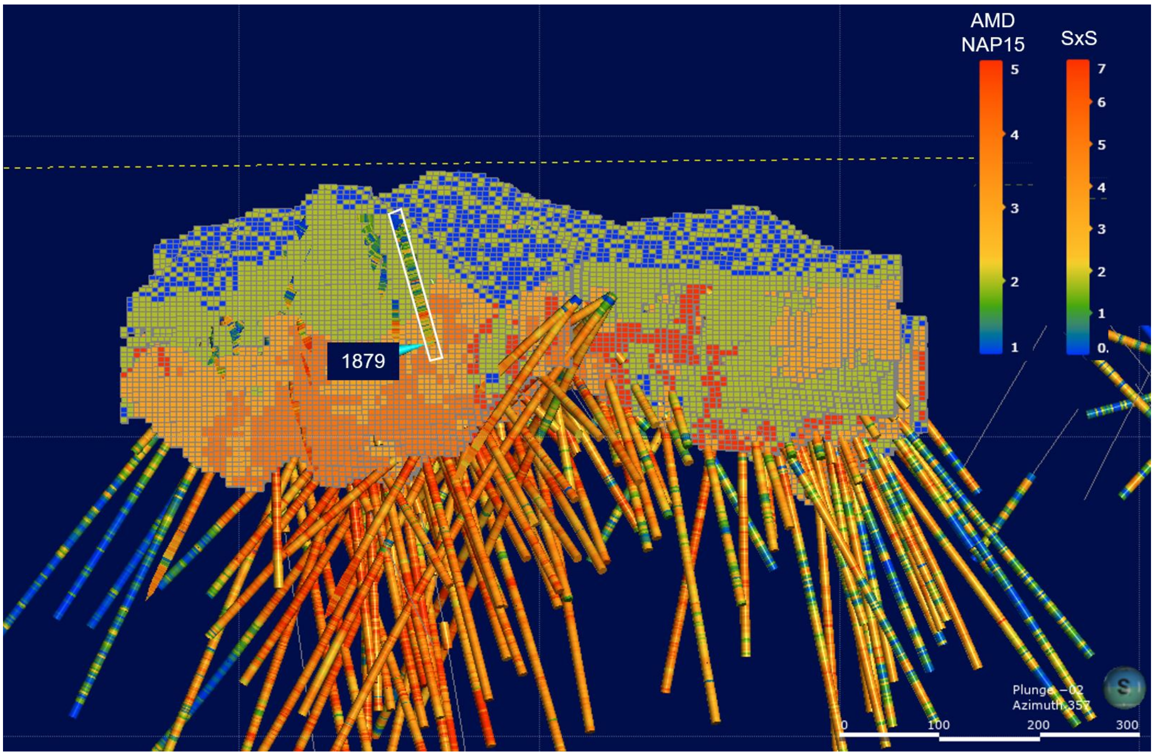

Fig.6. Borehole 1879 highlighted shows SxS acidity. Block model shows ARD based on NAPP with >20,000 data points.

3.4 QA/QC and Further Considerations for Waste Classification

When considered across the planned Tor Ula Ala pit subset of the MMC drilling database, there is a large-scale relationship between SxS and NAG pH and acidity with the SxS*30.6 acidity line offset by approximately 1.5% SxS. On a sample-by-sample basis however, there is no clear relationship due to interference from alunite and SxS cannot in isolation to reliably to classify waste in this deposit. It is therefore necessary to bridge the gap between raw data and interpretive modeling. The benefits of using SxS as the basis for ARD modelling were considered focusing on the benefits of high resolution sampling versus the recognised challenges of accounting for sulfides, alunite and jarosite already mentioned in this paper. As a distribution, over 75% of the samples down to 100m depth have NAG acidity of <5 kg H_2SO_4 t^{-1} (low level PAF), despite average SxS values of over 1%, indicating very low sulfide content on average, but with some localised sulfide pods observed. Between 100 and 150 m, over 50% of the samples also have NAG acidity of <5 kg H_2SO_4 t^{-1} (median), but many samples also have high acidity indicating very variable sulfide content yielding a wide range of interpreted ARD outcomes. Almost all of the samples below 150 m depth have NAG acidity of >5 kg H_2SO_4 t^{-1} and being sulfidic are classed as PAF.

QA/QC analysis using the chromium reducible sulfur method (CRS), XRD and NAG acidity testing was completed to provide comparative analysis data to compare sulfide sulfur (SxS) data obtained from the SCIS method. The results indicate that for grades of <3% SxS, where alunite is present >10%, CRS results are <0.15%, NAGpH >3.6 and NAG acidity <5 kg t^{-1} H_2SO_4. Taken together, the results indicate that the alunite rich material has very low to negligible sulfide content and has a low potential to release significant acidity. The results to date indicate that materials indicated from SCIS data to have sulfide grades of between 0.5-2%, alunite content from ASD and XRD data >10% and where NAGpH values of >4 were recorded, has a very low release rate of acidity or mobile metals. Oxitop testing indicates that samples of material which reported SxS results of between 0.5-2%, and where alunite content from ASD and XRD was >10%, also have low oxygen consumption rates <0.5 kg t^{-1} yr^{-1} O_2. These combined approaches indicate that reactive sulfides are not present at appreciable levels confirming apparent PAF risk may be routinely overestimated in zones rich in alunite.

Based on the validation work carried out for the reserve model parameters, practical GC validation criteria have then been developed that can be demonstrated to both accurately determine ARD risk and are able to be practically implemented into GC drilling modelling. Model estimation uses variography to average values between samples. Centres and composite samples are typically taken over 3m depth intervals for laboratory analysis. The practical implementation of ARD parameters into GC modelling is an important and often overlooked point because in many cases, geochemical validation criteria are developed based on geochemical test outputs that are not able to be successfully modelled as part of integrated ore/waste GC modelling. For example, although NAG pH has been identified as a suitable test to identify lower risk alunite containing material (where sulfur is present as alunite not sulfides), a pH value is not strictly suitable for estimation modelling purposes being a logarithmic scale. Whilst pH can be used if converted to mg of acidity, NAG, MPA/AP, ANC/NP and NAPP are all ratios therefore sulfur is considered to be the best overall reference except where alunite is >10% by weight. In recognition of the influence of deposit mineralogy over the ability to create accurate waste models in the reserve modelling process, a specific testing schedule tailored to each deposit at the MMC was initiated as part of development of GC assessment.

4.0 DISCUSSION

To date, waste rocks at the MMC are classified using laboratory NAG and NAPP tests undertaken on GC and blast hole samples; however, not all holes are sampled and NAG validation work indicates considerable scope for aliasing due to small-scale heterogeneity affecting point and composite samples. Compared to ore assay models based on many 1,000s of data points, initial ARD models based on fewer data points struggled to capture realistic geometries where NAG and NAPP sampling is sparse. The purpose of ongoing research is therefore to identify more efficient techniques to differentiate classes of waste material using broad proxies based on combinations of rock properties in existing resource e.g. lithology, alteration type. Doing so could reduce reliance on laboratory testing and lower mining costs. A key area of interest is the possible usage of colour to classify rocks into broad groups e.g. “oxide dominated”, “transitional” and “reduced” using digital colour mapping using the *Munsell* colour system (e.g. Kuehni, 2002). Doing so could rapidly identify pods of atypical material (e.g. “grey”) requiring further analysis. Based on the Rodalquilar analogue, it appears ARD risk could be directly influenced by faulting, brecciation and secondary alteration patterns which are defined in the existing resource development model at Martabe. Future work will investigate whether there are predictable relationships between mappable structure and geochemistry that can be used as the basis for the development of simple practicable rules aimed at improving ARD block modelling and improving waste processing efficiency e.g. within brightly coloured oxidised zones (blue in Fig. 2), the model should assume that if SxS is 2% or lower and rocks display advanced argillic alteration (known alunite host), sulfide content is likely negligible and material is assigned “LAPF” low PAF risk *otherwise* NAG test to confirm class where grey. Within the multicoloured brown-grey transitional zone (orange in Fig. 2), it is suggested NAG testing be used where many waste classes can co-exist in close proximity. In the grey sulfide zone (red in Fig. 2), it is recommended to use NAG testing to confirm if waste is PAF and whether waste is medium (MPAF) or high level (HPAF), assuming if SxS>6% waste is HPAF unless ANC>10 kg H_2SO_4 t^{-1}. Numerical classes can also be assigned e.g. HPAF is assigned “Class 4” in our models to enable simple digitization.

The ultimate aim of the recommended modelling approach is to assign ARD classification to rocks prior to extraction in the pit based on constantly updated GC and blast hole drilling. Identifying the datasets which yield the most valuable information is critical. To obtain maximum efficiency, sampling needs to be rapid and cost effective. An effective scheme can help to reduce waste management overhead costs and reduce misclassification. Having considered models at the MMC and outcrop geology at Rodalquilar, it is concluded using very precise testing on a limited number of samples is not as effective as using broader proxies. Provided calibrations and controls are in place, it is possible to build a robust waste classification scheme and practicable models using a series of routinely measured parameters such as lithology, rock colour, SxS concentration and alteration type.

5.0 CONCLUSIONS

The fracture- and permeability-controlled nature of oxidation, partial “transitional” oxidation and mineralisation observed in outcrops at the Rodalquilar explains the observed irregular and incomplete “oxidation zone” observed in diamond cores at the MMC. Scales of measurement, structural trends and aliasing are shown to be important factors affecting ARD character and measurement at both deposits due to the fractal character of pods, streaks and fractures which contain substantial concentrations of sulfide and acid sulfate bearing material. Elevated SxS using SCIS is noted in zones initially modelled as lower risk oxide domain which can reflect the presence of sulfide or sulfate in the form of alunite. ARD focused block modelling based on high resolution “low quality” assay data is demonstrated to be a valuable addition for waste classification and scheduling when enhanced through the addition of sparse “high quality” geochemical testing. Bespoke geochemical testing has been designed and used to produce “high quality” data that is required to calibrate and validate assay-based proxies, and help account for the presence of alunite and jarosite which can negatively impact standard measurements of sulfide sulfur. Using reliable ARD models to develop accurate liming strategies and practical waste classification can significantly improve waste management efficiency allowing more materials to be used beneficially on site.

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REFERENCES

Arribas A, Cunningham CG, Rytuba JJ, Rye RO, Kelly WC, Podwysocki MH, McKee EH, Tosdal RM (1995) Geology, geochronology, fluid inclusions, and isotope geochemistry of the Rodalquilar gold alunite deposit, Spain. *Economic Geology* **90**(4):795-822, doi.org/10.2113/gsecongeo.90.4.795

Kuehni RG, (2002) The early development of the Munsell system. *Colour Research and Application* **27**(1):20-27, doi.org/10.1002/col.10002

Rytuba JJ, Arribas A Jr, Cunningham CG, McKee EH, Podwysocki, JG Smith, MH Kelly WC, Arribas A (1990) Mineralized and unmineralized caldera in Spain; Part II, evolution of the Rodalquilar caldera complex and associated gold-alunite deposits. *Mineralium Deposita* **25** [Suppl.], 29—35

Saing S, Takahashi R and Imai A (2015) Characteristics of Magmatic Hydrothermal System at Southeastern Martabe High Sulfidation Epithermal Deposit, North Sumatra Province, Indonesia. Thesis Presentation, Graduate School of Engineering and Resource Science, Akita University, Japan