The Frieda River Project – a Novel Approach to Analysing Exploration Drill Core: How Broken is Broken?

D Bennett¹ and D La Rosa²

ABSTRACT
Exploration drill core provides for a number of standard measurements essential for determining the viability of a new mine or the extension of an existing one. Rock lithology and alteration can be visually determined and grade measured from the half core. Geotechnical parameters such as rock strength and structure can also be measured. Using suitable proxies, these metrics can then be used to estimate run-of-mine (ROM) particle size. In combination with comminution test results, these can subsequently be used to design comminution circuit configurations and estimate their performance.

The Frieda River Project drill core for the large Horse-Ivaal-Trukai copper-gold porphyry deposit was unusual due to a late stage gypsum-anhydrite stockwork event that overprinted much of the deposit. Above the base of the oxidised zone, which closely matches the water table, gypsum and anhydrite has been leached out, effectively removing the glue holding the rock mass together. As a result, much of the rock above this gypsum-anhydrite surface is fragmented and gravel-like in texture, while the material below this horizon is typically uniform and competent.

Large volumes of the orebody above the gypsum-anhydrite surface are expected to need minimal or no blasting for efficient excavation. In addition, the fragmented nature of much of the material was expected to reduce comminution specific energy as it already appears as though it has been crushed. While this was expected to have positive impacts to the operation, the lack of standard geological logging methods available to accurately define the degree of in situ fragmentation led to difficulty in gaining certainty over the ROM product and grinding circuit feed size distributions.

Using the extensive library of core photos for the project, a novel method using image analysis techniques to take both the intact core and gravel into account to predict ROM fragmentation was developed. In addition, existing point load test data was used to infer the strength of the rock and its impact on the blasting, crushing and grinding processes. The novel approach allowed development of ROM size distribution data and improved certainty in the results of comminution circuit designs.

This paper describes the methodology undertaken in detail, and discusses the results obtained.

INTRODUCTION
The Frieda River Copper-Gold Project is located in mountainous terrain within the Sepik River catchment on the northern slopes of the Thurnwald Range in Sandaun (formerly West Sepik) Province, close to the East Sepik provincial border in northwest Papua New Guinea as shown in Figure 1. Altitudes vary from approximately 50 m at the Frieda River to approximately 1200 m immediately west of the Horse-Ivaal-Trukai (HIT) deposit. The nearest major towns are Wewak and Vanimo, situated on the coast approximately 250 km to the northeast and north-northwest respectively. The project area is located 90 km north of the Ok Tedi mine and 175 km west of the Porgera mine, with no public infrastructure and services. Annual rainfall is between 8 m and 9 m with drainage controlled by steep, rapidly flowing mountain streams flanked by dense tropical rainforest.

The Frieda River porphyry system and copper-bearing sulfide mineralisation that included HIT was first discovered during a regional mapping program in the Frieda River area in 1966 and 1967 by the Australian Bureau of Mineral Resources. Exploration of the system commenced soon after discovery and major drilling programs were conducted in stages until 2012 to define the resource. The HIT deposit contains two billion tonnes of mineralisation at an average copper grade of 0.44 per cent and 0.23 g/t gold, at a copper cut-off grade of 0.2 per cent.

PanAust Limited acquired an 80 per cent holding of the project via its wholly owned Frieda River Limited (FRL) entity in August 2014, and is in a joint venture with Highlands Pacific Limited who holds the remaining 20 per cent.
FRL began the comminution design for the project in 2014 as part of a feasibility study for Frieda River, and it soon became apparent that the nature of the core shown in photographs available from the HIT drilling programs was unusual. In most drill holes, a distinct and narrow horizon was observed with a marked difference in structure above and below it. Much of the core above the horizon is almost gravel-like in texture, with the core below mainly intact. The horizon is usually located well below the surface, so this finer material potentially represented a significant amount of the material in the proposed open pit. A typical example of this is shown in Figure 2 (note that this tray is from a depth of 61 m).

As the gravel-like material visually appeared as though already crushed, it was anticipated that it may have a fine run-of-mine (ROM) size distribution and a significant influence on the comminution circuit design; in particular the specific energy requirements for the crushing and grinding processes. Standard ROM particle size distributions were considered to create a risk of overestimating coarse particle size specific energy requirements (for crushing and semi-autogenous grinding (SAG) milling) and underestimating the finer particle size specific energy requirement (for ball milling).

Significant diamond drill core logging and test data had been carried out and are essential to understanding ore characteristics for process design. Rock lithology and alteration data, grade assayed from the half core, rock strength determined from measurement of intact core pieces by point load and similar tests, and ore structure quantified by measures such as rock quality designation (RQD) and fracture frequency were all available. The strength and structure of the core, along with typical blast designs (burden, spacing, bench height etc), is normally used to estimate the ROM fragmentation and particle size distribution for new projects. This, along with comminution parameters such as the Drop Weight index (DWi) and Bond Ball Mill Work index (BWi) produced from tested samples, is particularly important when developing a comminution circuit design for a new concentrator.

In the case of HIT, however, none of the available logging or physical and chemical test data was determined to be useful in providing a meaningful indication of the size distribution of the in situ and ROM material, or the potential volume of the gravel-like material in the pit.

A Mine-to-Mill study for PanAust’s Phu Kham copper-gold operation in Laos as described by Bennett et al (2014) utilised image analysis of ROM material to measure the ROM particle size following blasting. Based on the results observed, and the failure to find chemical or physical proxy measures for gravel-like volume and particle size for HIT, image analysis from core photographs was suggested as a potential method for determination of ROM particle size and to estimate the proportion of gravel-like material in the total ore volume. In addition, the extensive data set of comminution parameters and logged core information could then be used to infer the strength of the rock in relation to blasting, crushing and grinding processes.

This paper describes the development of a method to predict the ROM fragmentation and particle size of the HIT material which incorporated image analysis of the core photographs. This, along with hardness data, was used to develop the comminution designs for the Frieda River Project.
HIT MATERIAL CHARACTERISATION

Rock characteristics

HIT exhibits porphyry alteration processes typical of Pacific island arc deposits, with approximately 30 per cent associated with potassic alteration and 50 per cent associated with phyllic alteration facies in the total ore tonnage. Late in the phyllic alteration sequence at HIT, there was extensive stockworking of anhydrite (CaSO₄) through the rock mass shown as light coloured veining in Figure 3.

During contact with water and low temperature fluids the anhydrite has hydrated to gypsum (CaSO₄·2H₂O), and the gypsum has subsequently dissolved, leaving a fractured rock mass, with the gypsum-anhydrite surface (GAS) representing the base of oxidation and closely aligning with the bottom of the water table. As shown in Figure 4 the GAS is well defined and the transition from fragmented and small particle material to competent rock in the third row of the core tray occurs in a very short distance. The term gravel is used in this paper to describe rock particles with both dimensions (length and width) that are less than the core diameter.

The material above the GAS has variable physical characteristics as measured by hardness, specific gravity and RQD. Below the GAS the material becomes relatively homogenous and is characterised by high hardness, specific gravity and RQD. Overall three main rock quality domains had been defined for HIT during earlier work (Scott, 2010):

Domain A: The weathered or weaker fragmented and blocky rock types found above the GAS, which includes the weathered and partially weathered material, and fresh phyllic microdiorite.

Domain B: Microdiorite, diorite porphyry, mudstones and volcanics found above the GAS, which is medium to strong rock, but highly fragmented to blocky.

Domain C: The rock mass below the GAS, which is found to be strong to very strong and predominantly massive.

Drill core photographs shown in Figure 5 indicate the rock quality domains and highlight the degree of fracturing and range of particle sizes in domain B.

The combination of intact core and gravel across the domains and how a diamond drill hole might intersect with them is illustrated schematically in Figure 6.

The gravel is indicative of volumes of the orebody that will need minimal blasting to allow efficient excavation and reduced grinding energy to liberate the minerals contained in the rock. While this will have positive impacts to the operation, it makes the prediction of ROM fragmentation and particle size difficult. Standard approaches to the estimation of in situ rock mass structure were not valid in this situation.

For the purposes of comminution circuit design, it was, however, considered to be critical to accurately quantify the expected ROM fragmentation.
Early geometallurgy modelling and comminution design work had attempted to find rock type, chemical or physical proxy measures of the gravel size distribution without success. Analysis of the geology database had determined that the method for measuring fracture frequency data during core logging had changed between different drill programs, and early fracture frequency data was not able to easily reconcile with later data. Logged RQD was not useful as it cannot discriminate between blocky (but less than 100 mm length) core and very fine gravel. There was no correlation discovered between any comminution hardness measures such as DWi, BWi or point load index with the gravel particle size.

In desperation, a manual logging exercise with a semi-quantitative core particle size ranking system was developed on a drill string core photograph set to determine whether it would be possible to estimate the core particle size for all drill holes and add the data to the geology database for volume modelling. The manual logging exercise was subjective and tedious, and although the data produced was considered likely to provide an estimate of gravel volume in the pit, it could not provide a definitive measure of particle size and therefore was unlikely to be very useful for comminution design.

Metso PTI had been engaged by PanAust during 2013 and 2014 to develop a Mine-to-Mill program for the Phu Kham copper-gold operation in Laos (Bennett et al., 2014). With their knowledge of the effectiveness of the Split system for coarse particle size measurement of ROM material during the program, Metso PTI were asked whether it might be possible to measure particle size from core photographs and estimate the ROM size distribution. Three HIT core images from a single drill hole were analysed using Split-Desktop®. These represented gravel, a mixture of gravel and larger blocky material, and rock from below the GAS horizon. The images and data obtained after the analysis are presented in Figure 7. The results were sufficiently encouraging to undertake a full program to develop ROM size distributions for HIT for the early years of operation when comminution design is critical to achieve design throughput and return on project investment.

**METHODOLOGY**

The complete Frieda River core photo set with matching comminution samples comprises more than 6700 images from 78 drill holes. Test results from comminution samples and grade data were also available to allow the measured material characteristics to be matched with the photographed core intervals. Therefore, the approach to the project required two components; data management and
image processing. The details of both of these important aspects are presented below.

**Data management**

While there was some structure to the naming convention of the core images available, there was not enough information in the image file name to determine the spatial location of each tray. For example, all that could be determined from the image 320XC09_Box 005.JPG was that it was the fifth tray in drill hole number 320XC09. In order to determine the 3D location of the tray, the collar coordinates of the hole needed to be known, plus the survey of the hole down to the tray, which was defined by the start and end distance of the tray. This latter information was stored visually in the image but not in a format that could be read automatically. Specialised software was specifically developed for this project, called CoreMS, to facilitate the management of this information and the interface is shown in Figure 8.

The main purpose of the software was to store all pertinent data in a central Microsoft Access database. This included diamond drill hole collar coordinates and survey data, depth_from and depth_to for the tray image, core diameter, drill hole name, mining period (year), and test comminution and rock characteristics data. Another function of the software was to allow the user to define the extents of the tray within the photo for image analysis using the Split Engineering Split-Desktop® Version 3. This minimised the amount of manual editing required by the Split-Desktop® users to remove irrelevant sections of the images.

The initial phase of the project required the processing of 400 images of core trays with material within the first six years of operation. These images were manually selected, then the tray extents were entered and each image cropped and exported, ready for processing in Split-Desktop®. Images were selected to match comminution sample intervals. In most cases this resulted in multiple images per comminution sample. The image analysis processing steps for each selected image are discussed in the following section.

**Image analysis**

The first step in the analysis was to analyse the cropped tray image with Split-Desktop®. The image was scaled using the tray length, processed and then manually edited to remove incorrect delineations, add missing ones and to remove the unwanted tray background. This resulted in an image similar to the one shown in Figure 9. The dark blue lines are the delineations and the light blue denotes areas not to be included in the final processing.

For the most part, all of these steps are the same as when processing an image from a stockpile or belt cut. The main departure between standard image processing and the processing of the core tray images is in determining the size distribution of the image.

When Split-Desktop® calculates the size distribution of an image it does so by making assumptions about the third, unseen dimension (coming out of the screen). Consider the particle schematic in Figure 10.

Internally, Split-Desktop® describes each particle by its minor and major axes, and then assumes that the third dimension to be proportional to: $\sqrt{\text{axis}_{\text{minor}} \times \text{axis}_{\text{major}}}$

This would not be an issue for the gravel in the core images; however, the longer core pieces would potentially be represented as unrealistically large particles. In addition, there would be no way of discriminating between larger gravel particles and some of the shorter core pieces. Therefore, a different approach had to be taken to determine the size and fragmentation characteristics from the drill core images.

Split-Desktop® allows the user to export the statistics for all particles in an image, and this functionality was utilised to determine how much of an image was ‘short core’, ‘long core’, or ‘gravel’. Definitions of these are shown in Figure 11.
The particle data for each processed image determined by analysis with Split-Desktop® was imported into the database using CoreMS. Additionally, the amount of fines in an image were also calculated by scanning the delineated image for red pixels (user defined areas of particles that were deemed too small to accurately delineate) and this was also stored in the database for each image. An example of this is shown in Figure 12. The particle data was then used in combination with blast fragmentation modelling to predict the overall ROM size distribution.

Run-of-mine prediction

Blast fragmentation

The main objective of the project was to develop ROM particle size distributions by annual mining period. These, in conjunction with comminution data from the same periods, were used to develop crushing and grinding circuit designs. To develop an overall size distribution, blast fragmentation size distribution estimates were required for the intact core, which was then to be added to the gravel and fines size distributions. These could then be applied according to the proportions of each determined from the image analysis and the mining schedule.

For the purposes of developing blast designs for the various strength and structure domains at Frieda River, a similar approach to that when conducting Mine-to-Mill process integration and optimisation projects was followed. Distributions of measured unconfined compressive strength (UCS) and fracture frequency (FF) from the image analysis were used to develop a simple \(2 \times 2\) matrix of rock hardness and structure. The UCS and FF frequency distributions obtained from samples which coincided with processed images are shown in Figure 13.

The domains were defined as detailed in Table 1.

Blast designs were then developed for each of the domains to minimise the variability in the final ROM size distribution. A default design was also developed to deal with those situations where UCS data was not available. The parameters that define the blast domains (UCS and FF extents) were stored in the CoreMS database, as was each associated size distribution. These were used when combining the measured gravel and predicted blast size distributions.
Combining tray image analysis with blast fragmentation

The first methodology considered for combining the image analysis results with the predicted blast fragmentation was to add the percentage in each histogram bin proportionally based on the amount of gravel in each image. This can be expressed as follows:

\[ C_i = \sum_{k=1}^{k} \left( G_i \times p_{gravel} + B_i \times p_{core} \right) \times 0.5 \]

where:
- \( C_i \) is the combined histogram
- \( k \) is the number of bins
- \( G_i \) is the gravel histogram
- \( p_{gravel} \) is the proportion of gravel in the image
- \( B_i \) is the predicted blasted histogram
- \( p_{core} \) is the proportion of core in the image, equivalent to 100 per cent - \( p_{gravel} \)

The calculated bin proportion is multiplied by 0.5 to normalise the final distribution to a total 100 per cent.

The resultant size distribution obtained with this technique had very little fine (-10 mm) material. This was a reflection of the lack of fines in the gravel size distribution. Figure 14 shows a typical histogram after image analysis, and it can be seen that there are very few particles in the -9.5 mm size fractions.

This is due to fine material possibly being washed out from the core, or limitations in the image analysis techniques which could not delineate very fine material and misclassified clay lumps for rock. The initial methodology assumed that blasting would only impact the solid core regions of the rock mass, whereas the rock mass around the blasthole will be reduced to fines regardless of whether it is gravel or intact rock, so the next method developed carried the blast generated fines through to the final combined size distribution, regardless of the proportion of core or gravel.

This next pass resulted in particle size distributions with a higher -10 mm fines content, however after benchmarking against other deposits, the overall distributions were still considered to be fines (-10 mm) deficient. Previous work during the manual core photograph logging and core size ranking had determined that core recovery percentage was a potential proxy for rock quality, as generally, the finer the particle size was, the lower the corresponding core recovery percentage.
recovery percentage. The rationale was that the percentage of unrecovered core was representative of fine particles that were washed out of the drill tube or that created high void space volumes during the drilling and recovery process. When processing the images with CoreMS, the unrecovered core percentage was added to the -9.5 mm size fractions. This resulted in a finer and more realistic combined ROM size distribution. This final methodology was used in the prediction of ROM size distributions by mining period.

RESULTS

As each image was processed, a particle output file (POF) and delineated image (JPG) was created. CoreMS imported the POF file contents into the central database, and calculated the percentage of fines in each image, which was also stored. The CoreMS software then analysed each image, calculating a number of parameters for each. These are described in Table 2.

These parameters were reported for each image and output as a comma separated value (csv) file. This file was then able to be analysed in Excel using pivot table techniques.

Gravel size distributions by period

The trends of the 20, 50 and 80 per cent passing (P20, P50 and P80) of the gravel and the proportion of gravel (per cent gravel) in the tray images for each period (1–6) from the analysis are shown in Figure 15.

These show the gravel getting progressively finer with year, almost linearly, with P80 reducing from an average of 88 mm to 63 mm over this time period. The proportion of gravel in each image shows a slight downwards trend over the same period. The data is shown in tabular form in Table 3.

The relationship between gravel P80 and elevation is shown in Figure 16 and illustrates the reduction of the gravel P80 with depth. The causes of reducing P80 gravel size with increasing depth are speculative but may be the result of more intense gypsum-anhydrite veining due to higher hydraulic pressures at greater depth.

The relationship between FF (calculated from the intact core in each image) with period until Year 6 showed that the rock is expected to become more fractured as the mine gets deeper until the GAS is reached. Gravel P80, which is calculated from the gravel in the image, shows a similar trend of getting finer (Figure 17).

Validation of the core image analysis method was conducted by comparing the calculated RQD with the geologist-logged RQD. The comparative data sets are presented in Figure 18, which shows a similar trend between logged RQD and calculated RQD. The calculated RQD data is consistently 20 per cent greater than logged RQD possibly because the logged RQD is a measure of the core centreline length whereas the calculated RQD is a measure of the major axis length. This result provided confidence that the techniques developed in the image analysis were representative of those practised by geologists in the core shed.

Combined results

ROM size distributions were predicted for Frieda River for each of the first six years of operation, as shown in Figure 19.
This was achieved by combining the image analysis data and predicted blast fragmentation according to the methodology described earlier. The raw data is presented in Table 4. The predicted ROM size distribution results were then benchmarked against numerous other operations in the Metso PTI database as an important reality check to ensure that the results made sense. With the development of the ROM size distributions combined with the comminution data, Mine-to-Mill modelling and comminution design was able to be confidently undertaken with determination of comminution stage specific energy for setting equipment sizes and circuit configuration to maintain throughput.

The ROM size distribution and comminution data was then applied as inputs to crushing models to develop SAG mill feed size distributions, which were combined with the measured DWi and BWi data for the same period to calculate SAG mill and ball mill specific energy requirements to achieve the optimum flotation feed particle size of 150 µm. The specific energy values were then used to calculate ball mill power requirements for selected SAG mill sizes to develop the comminution designs.

**CONCLUSIONS**

The Frieda River Project core image analysis project resulted in development of a number of innovative techniques for measuring core size characteristics and development of comminution design data using drill core tray images to match comminution data with predicted blast ROM size distributions. The development of these ROM size
distributions has been a very important step in development of mine and comminution designs for the Frieda River Project, with blasting, crushing and grinding designs able to be based on reasonably sound data rather than subjective and qualitative estimates. The results indicate that it is possible to develop reasonable relationships between geologist-logged and image analysis determined estimates of RQD.

The final combined ROM size distributions were used as input feed size distributions to various comminution equipment sizes and flow sheets and to determine process plant throughput during the first years of project operations. The ROM size distributions were included into comminution throughput models, which have been a key input into the HIT engineering block models for project design and economic evaluation.

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