Pre-concentration by screening – a cost-effective approach to testing and evaluation

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ABSTRACT

Preconcentration of run-of-mine subgrade and marginal ore by screening has the potential to substantially improve the economics of mining, particularly for large, low-grade orebodies, and to reduce environmental impacts. It has recently been the subject of a major research effort by a joint public-private research body, CRCORE. Yet despite this, there appears to have been only one fully commercial installation, at Bougainville Copper Limited in the late 1980s. Two reasons for the limited application are that not all ores have suitable properties and the economics of all pre-concentration processes on low-grade materials are highly sensitive to the precise balance of mass and value recovery and to the pre-concentration process cost, including materials handling. These factors make it imperative to have good test data on the process response of feedstock across the orebody. Collecting that data presents major challenges, which differ for green and brownfields operations.

This paper first discusses the approach to preliminary evaluation developed by CRCORE, which relies on testing of coarse rejects or drill chips available from exploration drilling programs. This method is an efficient first step in evaluating an orebody which is deemed geologically to be potentially amenable to screen upgrading, but it does have limitations and must be followed by larger scale work. A suite of methods have been developed by the authors as a result of test work since the 1990s on several projects, supplemented by published data, which aim to provide statistically robust data at lower cost than large scale bulk sampling tests.

For greenfields projects, the upgrade response measured on material crushed to -53 mm has been found to correlate closely with ROM ore, with no scale-up required for material with upgrade responses in the range of commercial interest. Large diameter whole drill core, such as PQ, is expected to be suitable for this method. As drilling such core is costly, the aim should be to establish relationships between upgrade performance and proxy measurements such as multi-element chemical or hyperspectral analyses. This approach was successful at the Gramalote gold project in Colombia. The method is not applicable for ores with thick vein material comparable with the crush size, but such material is not suitable for upgrading by screening and would be eliminated by the preliminary testing.

For brownfields projects where blasted material can be sampled, the upgrade response can be accurately measured by sampling only the finer fraction of the ore, selecting a top size which represents 30–50 per cent or more of the ROM size distribution. This is likely to be between 50 and 100 mm. The much finer size compared with the full ROM ore greatly reduces the sample mass required to achieve a given intrinsic sampling error and enables sample preparation to be undertaken with large-scale laboratory equipment rather than mobile crushing plant. The accuracy of the method can be improved by measuring the approximate mass of oversize rejected during sampling. Some ores do show a systematic deviation from the assumed model fit which results in this method slightly underestimating the upgrade response, and it would therefore still be recommended to take one or two full bulk samples to confirm results before a final investment decision.

INTRODUCTION

There has been increasing interest in recent years in methods of pre-concentrating ore by rejecting waste at coarse sizes, as reducing head grades have increased the amount of material to be processed. For much of the 20th century the main response to lower grades was increasing process plant throughput and using larger equipment, including mine trucks, tumbling mills and flotation cells. Carrasco *et al* (2014) showed that between 1960 and 2000 available mine truck payload increased from 35 t to 380 t, or more than ten times, leaving little scope for further cost reduction by this approach. The disposal of large quantities of fine process tailings with acceptable safety standards is increasingly difficult and costly (ICMM, 2021) and for large new mines in arid areas such as Western Australia, sourcing sufficient water at acceptable cost can be as critical as finding the orebody itself.

Pre-concentrating low-grade ore or mineralised waste by screening is a simple process that has the potential to markedly improve production economics. The process was operated at large scale (6000 t/h) at Bougainville Copper Limited (BCL) from January 1987 until mine closure in 1989 (Burns and Grimes, 1986). Run-of-mine (ROM) material that would otherwise have been categorised as waste was screened at 31–50 mm, recovering 60–70 per cent of the copper into 30–40 per cent of the feed mass in screen undersize, with an upgrade factor of about 1.8. Low-grade ore was also screened and upgraded. Overall, the same quantity of material was fed to the process plant but with higher grade and higher resource recovery.

A cooperative research centre was established in 2010 in Brisbane, Australia with the task of Optimising Ore Extraction (CRCORE) and a major focus was pre-concentration by screening, potentially enhanced by coarser blasting of waste (Rutter, 2017). CRCORE subsequently assisted with major trials at:

- Newcrest's Telfer mine in Western Australia (Bowman and Bearman, 2014).
- Anglo American's Los Broncos mine in Chile (Keeney *et al,* 2020).
- AngloGold Ashanti's Gramalote project in Colombia (Clarke *et al,* 2020).
- Sumitomo's Minera San Cristóbal mine in Bolivia (Adair *et al,* 2019).

In all of these cases, some ore types upgraded as effectively as the amenable ores at BCL but of the three operating plants, only San Cristóbal is known to have continued to operate screening plant for some time after the trials. Bowman and Bearman (2014) noted that it may be difficult to achieve the potential benefits when retrofitting screen upgrading to a brownfields operation and greenfields applications may be more promising. Another factor critically affecting economics of all pre-concentration processes is that additional costs are incurred for materials handling and additional processing, whilst some values are lost to the reject stream. Superficially attractive processes often prove to be uneconomic on further analysis. It is thus essential to have a reliable means of predicting upgrade performance in the planning stage for any pre-concentration project, and mapping it across the orebody.

PREDICTING PERFORMANCE FROM COARSE REJECTS

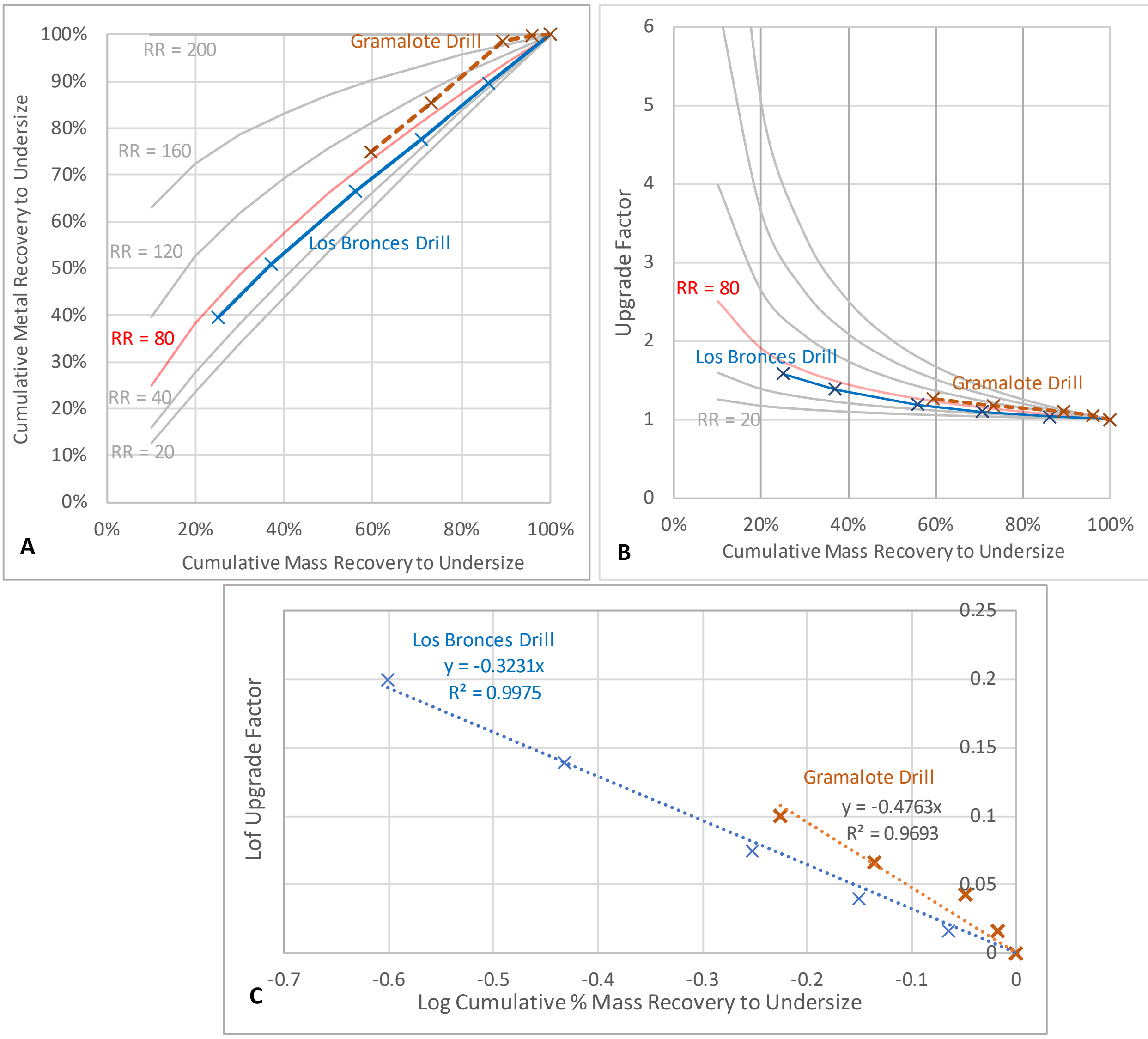
A key outcome of the work by CRCORE was the development of a relatively low-cost method to identify orebodies potentially amenable to upgrading by screening (CRCORE, 2014). The method relies on the fact that diamond drill core from mine exploration programs is usually split using a diamond saw, then the entire mass of half the core crushed to typically <3 mm, and a subsample pulverised and assayed. The remaining <3 mm material, termed the 'coarse rejects,' is stored and can be made available for further testing. Where reverse-circulation (RC) drilling is used, chips of similar size are also generated and stored and may be used instead.

The evaluation involves taking representative samples of coarse rejects for typically about 100 drill intercepts initially and screening to produce four or five size fractions. Where possible screen sizes are chosen to ensure a minimum of 10 per cent and a maximum of 30 per cent mass in each fraction (Adair *et al,* 2019) and the sample mass is selected to provide sufficient for assay in all fractions.

The cumulative metal and mass recoveries to undersize are calculated. Results can be presented either as plots of metal recovery versus mass recovery or an 'Upgrade Factor' (UF) can be calculated by dividing metal recovery by mass recovery and plotting against mass recovery (all as cumulative values). The product grade at any point on the curve is the feed grade multiplied by UF. Although the shape of the relationship varies with different ores, a good linear regression fit can generally be obtained by plotting the log of the UF against log cumulative mass recovery (BoBo *et al,* 2020). Since UF is 1 when 100 per cent of the feed reports to undersize, the log:log relationship can be forced through the point 0:0 and the constant is zero. The slope of the regression line then represents the comparative strength of the upgrade response. The best possible response is 100 per cent recovery of values to undersize at all mass pulls, which gives a maximum slope of -1. Multiplying the slope by -200 gives a Ranking Response (RR) number, which thus varies between 0 and 200 if upgrading to the fines occurs or could theoretically vary down to -200 where an ore upgrades into the oversize.

The approach is illustrated in Figure 1 using data from work on the Gramalote deposit (Clarke *et al,* 2020) and from the Los Bronces deposit (CRCORE, 2014). The data from the Los Bronces drill hole closely follows the log-log relationship, but the Gramalote data shows what has been termed a 'bird-wing' effect, where the response is strong at coarser sizes but relatively weaker at finer. This is seen most clearly when the data is plotted as metal versus mass recovery, in Figure 1a. The reason for this effect is thought to be that gold at Gramalote is strongly associated with pyrite and the average pyrite grain size is 2 mm, coarser than the crush size for the coarse rejects. However, this limitation is not relevant to upgrading at industrial sizes.

Despite this bird-wing effect and the occurrence of some samples which upgraded to the coarse fractions, overall the Gramalote ore samples had an average RR about 90, well above the RR 80 which CRCORE regarded as indicating a strong potential for pre-concentration by screening alone, without additional manipulation such as selective blasting. A conceptual study showed that this process had the potential to add substantial value to the Gramalote project and justified a further extensive study (Clarke *et al,* 2020).



Los Bronces Diamond Drill Data						Gramalote Diamond Drill Data DD59					
Sieve	Mass	Cu	Cum % to U/S		Upgrade	Sieve	Mass	Au	Cum % to U/S		Upgrade
mm	g	%	Mass	Metal	Factor	mm	g	g/t	Mass	Metal	Factor
2.36	152	0.37	86%	90%	1.038	1.70	284	0.013	96%	100%	1.040
1.70	170	0.37	71%	78%	1.096	1.18	454	0.029	89%	99%	1.105
1.18	164	0.36	56%	66%	1.189	0.60	1106	0.150	73%	85%	1.167
0.60	208	0.39	37%	51%	1.379	0.30	944	0.139	59%	75%	
0.30	132	0.46	25%	40%	1.583	-0.30	4092	0.230			
-0.30	276	0.76	0%	0%							
Total	1102	0.48				Total	6880	0.183			
Slope					-0.323	Slope					-0.476
RR					65	RR					95

Los Bronces data extracted from TR#080, 2014

FIG 1 – Example data calculation and presentation for analysis of diamond drill coarse rejects.

The Los Bronces raw drill hole data generally did not meet the RR 80 benchmark, but large-scale trials proceeded to investigate the full suite of Grade Engineering® techniques which includes methods of enhancing the natural response (Keeney *et al,* 2020).

Although testing of coarse rejects has been established by CRCORE as a useful technique for identifying orebodies or ore types potentially amenable to upgrading, the resulting upgrade response does not equate directly to the response on ROM ore and has to be scaled. This is illustrated in Figure 2 with Figure 2a showing data from the Gramalote project (Clarke *et al,* 2020) while Figure 2b shows published data for a copper porphyry mine (Carrasco *et al,* 2014).

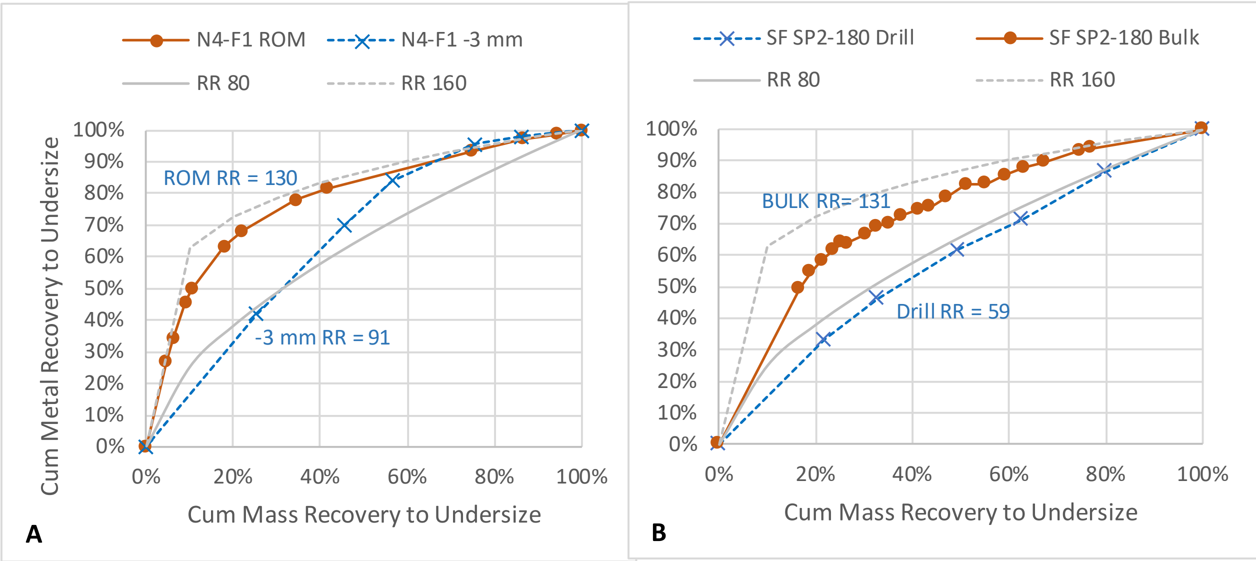


FIG 2 – Comparison of upgrade responses on ROM and -3 mm crushed ore for two deposits.

In these examples there is a large difference between the upgrade response on ROM ore (brown) and -3 mm crushed material (blue) for both ores. At a typical mass pull of 40 per cent, the difference on Gramalote ore is 80 per cent gold recovery on ROM ore versus 62 per cent on -3 mm crushed material, which is economically very substantial. The difference is not constant but varies with ore type and mass pull.

In Figure 2b the nominal -3 mm material is from crushed drill core while 'Bulk' is from testing of a sample of ROM ore. In Figure 2a however, both samples were derived from the same bulk ore sample mined from an underground adit. During testing for the Gramalote project, 18 bulk samples of about 17 t each were taken from the adit. Six cross-cuts were mined, located along the adit so as to provide good spatial and head grade coverage of the main orebody. At each cross-cut, three successive 1.6 m cuts were taken, thus providing a measure of short-range variability. Twelve of the samples were tested as received and also at three crush sizes. The finest crush size used the same final crushing procedure as used on diamond core. A progressive crushing technique was used, so all crushed products derived from the same head sample, thus eliminating the effect of sampling errors at ROM size. The overall sampling error for the coarsest fractions was estimated as ±10 per cent (Clarke *et al,* 2020). Figure 2a above shows that the -3 mm products showed the same 'bird-wing' effect as seen in the crushed drill core.

Figure 3 compares the upgrade response in the -3 mm and ROM materials for all samples. For this purpose, the gold recovery at 40 per cent mass pull to undersize has been read from manually fitted curves, as this allows a better fit to the -3 mm data than the log-log fit. A mass pull of 40 per cent is a likely operating point for Gramalote ores. Figure 3 shows that the average response estimated from the -3 mm material is a useful predictor of the **average** response of ROM ore but provides no information on variability.

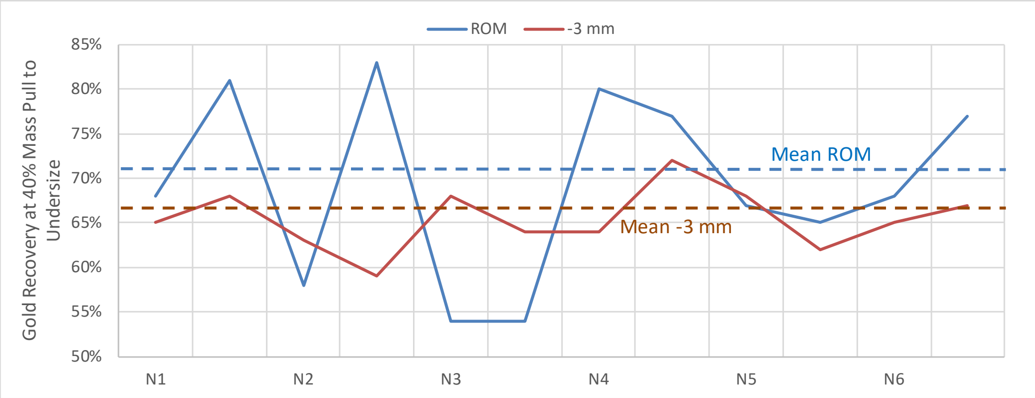


FIG 3 – Upgrade response in ROM and -3 mm material at six cross-cuts along an adit at Gramalote.

CORE BREAKAGE EVALUATION

The potential for pre-concentration by screening is entirely dependent on the way the ore breaks. Explosive blasting breaks ore by two mechanisms: breakage due to tensile waves which will tend to occur along planes of weakness and breakage in the pulverised zone close to the charge (Bauer and Crosby, 1990). In the pulverised zone softer minerals are preferentially broken which results in the practically universal upgrading of values in the fines for sulfide bearing ores. However, although the metal grades in the fines can be high, the mass of material involved is often small and by itself does not represent an economic opportunity. This was found to be the case, for example, in a preliminary study of the potential for screen pre-concentration at the Sunrise Dam mine of AngloGold Ashanti (Clarke, 2014).

For the cases discussed in this paper, economic opportunities for screen pre-concentration arise when:

- metal values are strongly vein-associated with minimal values disseminated through the rock matrix; and
- breakage occurs along mineralised fracture planes, or veinlets, which are more frequent in higher grade ore.

In such ores, higher grade material breaks finer (Burns and Grimes, 1986). A small-scale study was carried out at Gramalote (Clarke *et al,* 2020) to better understand breakage patterns in core and the approach is strongly recommended to ensure results of subsequent larger-scale programs are correctly interpreted and indeed worthwhile. It involved selecting 6 × 1 m lengths of core covering all the key alteration types, measuring and photographing veins or fractures and vein spacing and breaking with controlled hammer blows of increasing force while the core lengths were supported by the ends only. The process continued until all material was less than 50 mm (a typical pre-concentration separation size). The products were sorted into three categories: preferentially broken along mineralised planes, randomly broken and thick high quartz veins.

The work showed that not all veins were planes of weakness and some low and medium grade ore with average vein spacing about 50 mm nonetheless broke randomly with no upgraded fraction. Thick quartz veins could result in gold reporting preferentially to oversize. The overall strong upgrade response to the fines in this test resulted from one piece of core with only five fractures/m, but for which preferential breakage of the fractured section resulted in pieces assaying 9 g/t and carrying 90 per cent of the gold, while the randomly broken material assayed 0.1 g/t.

Coarse assay rejects at -3 mm cannot carry information on the effects of vein spacing, continuity and fracture resistance which affect large scale upgrading results. Crushing to -3 mm does however result in preferential crushing of softer vein material versus the rock matrix and therefore measures the amount of vein associated values and the potential for upgrading. Where vein material is hard, reverse upgrading will be observed. Where the values are vein associated but the veins do not break readily, fine crushing may overstate the full-scale upgrade potential whereas when veins break readily fine crushing will understate the potential.

Coarser crush sizes may correlate better with upgrade potential but as will be discussed below, it is likely that the crush size needs to be larger than the vein thickness, and probably than the average vein spacing, to achieve reliable results.

PREDICTING UPGRADE PERFORMANCE FROM CRUSHED DRILL CORE

It has been shown above that analyses of -3 mm coarse rejects provide a good preliminary indication of orebody amenability to preconcentration by screening, but do not directly measure upgrade potential or variability. For greenfields projects another method of evaluation based on drill core is essential.

The initial study into pre-concentration by screening at BCL involved taking 134 haul-truckloads of 140 t ore each from all accessible ore zones and subsampling by conveyor cuts or fractional shovelling to produce 1.5–2 t subsamples. The samples were screened at sizes from 152.4 to 12.7 mm and each fraction was stage crushed and split to produce 200 g samples of -1 mm material for assay (Burns and Grimes, 1986). The Bougainville ores were naturally highly fractured, with 95 per cent passing 150 mm in ROM ore (Paki and Koginmo, 1988), thus reducing sample preparation costs and intrinsic sampling errors. To enable prediction of upgrade performance in future ore sources, a diamond drilling campaign was completed. A short tumbling test was developed, testing 3 m lengths of drill core taken from every 30 m. The process was designed to break the ore along major weaknesses and so simulate the effect of blasting. Unfortunately, no details of the core diameter or test conditions used were published. To calibrate the drill core results, a hole was drilled through two mining benches and bulk samples taken from around the holes. Both tumbled core and the bulk sample were screened at 31.75 mm, resulting in similar masses to undersize at 34.5 per cent for core and 32.5 per cent for the bulk sample. Both copper and gold recovery to the undersize were substantially higher for the bulk sample, at 64 per cent versus 59 per cent for copper and 67 versus 60 per cent for gold. For planning purposes the drill core results were scaled up by the difference.

Gramalote project

For the Gramalote project, as discussed above, bulk samples were mined from six cross-cuts along an exploration adit. Of the three successive 17 t cuts at each of the six locations, two processed the full 17 t using a progressive crushing approach that resulted in upgrade curves at ROM, -53, -24 and -3 mm crush sizes. The third cut was used for a preliminary program which processed a 1 t subsample at two sizes, ROM and -53 mm, again using a progressive crushing approach. The preliminary program was intended to provide an early indication of feasibility as well as detailed sampling error and particle size information which could be used to design the full program. In practice, the results of the preliminary program were not significantly different to the results of the subsequent more comprehensive testing.

There were several reasons for testing at different crushed sizes, but one was to investigate if crushed drill core could be used to measure upgrade response and map it across the orebody. The results at -3 mm would be ideal but the limitations were discussed above. Next preferred would be a nominal 24 mm crush size as it is achievable with half-core of typical routine diameter (eg NQ or NTW), but -53 mm would be feasible, albeit quite costly, using purpose drilled whole PQ or HTW core.

Figure 4 shows the relationship between the RR values on crushed material and on ROM ore, with ROM ore on the X-axis and Crushed Products on the Y-axis. It shows that RR values on -53 mm material (blue) are strongly correlated with ROM material, with a correlation coefficient (R^2) of 0.93. The grey line shows a 1:1 relationship for comparison and the responses on ROM and crushed material are practically identical above RR 100, but on lower response ores the -53 mm crushed material slightly overestimates the ROM response. In practice it is the higher response ores which would justify installation of screening.

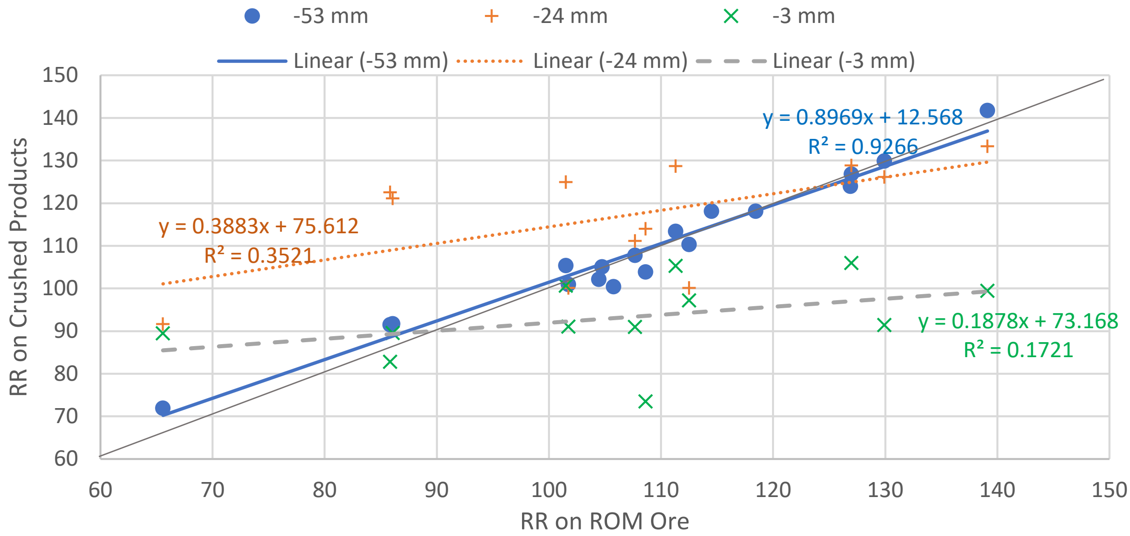


FIG 4 – Ranking responses for ROM and crushed Gramalote samples.

The RR values on crushed -24 mm material (brown) correlate poorly with the ROM ore, with R^2 0.35. The relationship is far from 1:1 so presents the same problem as coarse rejects, that the results require calibration by tests at coarser sizes over a range of ores with different responses. Crushing to -24 mm does substantially improve the upgrade response on lower response ores, as seen to a much lesser extent with crushing to -53 mm, but the improvement would not justify the cost of crushing.

The RR values on -3 mm crushed material confirm the lack of a relationship with ROM ore that was seen in Figure 3, with R^2 0.17. The fine crush size reduces the upgrade response across all ores except for the single sample with ROM RR<70.

Gold recoveries at 40 per cent mass pull have also been read from manually fitted curves for all samples and are shown in Table 1.

TABLE 1

Mean gold recoveries at 40 per cent mass pull to undersize.

	Au Recovery %			
	ROM	**Crush**	**P(T<=t) 2-tail**	**No. of pairs**
Crushed -53 mm	70.2	70.6	0.51	18
Crushed -24 mm	69.3	74.7	0.03	12
Crushed -3 mm	69.3	65.4	0.24	12

Table 1 shows that at 40 per cent mass recovery the gold recovery on nominal -53 mm crushed material is only 0.4 per cent higher than on ROM ore and this difference is not statistically significant using a paired t-test at 95 per cent confidence interval. Crushing to -24 mm does significantly increase average recovery, by 5.4 per cent, and crushing to -3 mm reduces average recovery by 3.9 per cent, which is however not statistically significant.

Los Bronces

Test work at the Los Bronces mine also explored the effect of crushing on upgrade response (Keeney *et al,* 2020) using pilot plant test work at tonnage scale. There was no significant effect from crushing over the range from 200 mm to 37.5 mm. Three ore samples were tested and were subject to a progressive crushing procedure with all size fractions derived from a single head sample. The samples were sourced from an open pit, but it was assumed upgrading would be practiced on primary crushed ore or finer, hence the coarsest size examined simulated primary crushing to -200 mm. This work supports the conclusion that crushed material down to 37.5 mm can be used to evaluate the upgrade response of ore.

Kalgoorlie Consolidated Gold Mines

A major investigation into preconcentrating by screening was carried out at Kalgoorlie Consolidated Gold Mines (KCGM) in 1992–1993 (Clarke, 1993). The project started because three samples of -100 mm material taken from subgrade material dumps for heap leach test work had much higher grades than expected from block modelling. It was considered that the high-grades could either be due to natural upgrading in the finer fractions, or imprecision in modelling and material routing. In either case, there was a large potential financial benefit from an investigation. The test program included processing one entire nominal 10 000 t subgrade block through the small Paringa plant; processing 15 samples of -100 mm material through a purpose-constructed 1 t/h Mini-screening and crushing plant; for each of three blocks from the 15, processing four replicate subsamples of 130–200 t each through a mobile crushing and screening plant and then processing selected products from that plant through the Mini-plant; and finally testing an additional eight selected subgrade samples through the Mini-plant.

The final conclusion from the project was that although 19 of the 26 samples tested did upgrade to the fines, in no case was pre-concentration by screening more profitable than direct treatment. However, the project led to the development of much useful knowledge for future screen upgrading studies and to improved methods for block delineation and hence material allocation.

For the three blocks treated through the mobile crushing plant, all samples were first passed over a 100 mm grizzly and the oversize and undersize were separately crushed and sampled. Sample masses were determined by a weightometer, by bucket counts and by stockpile survey. The most reliable procedure was found to be the survey. The crushing plant consisted of a primary jaw crusher followed by a screen in closed-circuit with a cone crusher. The final product was about 80 per cent passing 11 mm. Four replicate subsamples were taken of this product for both oversize and undersize for each of the four replicate subsamples from each block. Each subsample was assayed in duplicate for a total of 64 assays for each oversize and undersize product, so the degree of upgrading into the -100 mm fraction could be measured and the errors could also be assessed.

For all three blocks, separate samples of uncrushed -100 mm material had previously been sized and assayed using the Mini-plant, so the ROM upgrade response curve could be determined. Additionally, for all three blocks the -11 mm crushed product was sized and assayed and for two of the blocks the primary crusher product was sized and assayed. Thus, upgrade responses were measured on material crushed to 80 per cent passing 70 mm and 11 mm. The upgrade responses are reported in Figure 5 using the CRCORE method of calculation.

The RR determined on -100 mm ROM material will be discussed in a later section. Figure 5 shows however that for KCGM ores RR values from neither primary crushed nor fine crushed material correlate with RR values determined from ROM ore. The average value on fine crushed ore does provide an indication of the average value on ROM ore but provides no information on block-by-block variations. This is similar to the situation with -3 mm crushed material on Gramalote ores. The size-by-size data on primary crushed ore is very erratic, as can be seen by comparing results for samples A and B but it nonetheless appears that crushing has suppressed the block-by-block variation in response.

The results from KCGM do not negate the concept of estimating RR from suitably crushed drill core, but they do show the importance of preliminary coarse reject and core breakage studies to understand the nature of the ore and its amenability to screen upgrading before undertaking larger scale work. Figure 5 shows the low upgrade response of fine crushed ore, averaging RR 27, which would have ruled out further work had the preliminary evaluation techniques discussed above been available at that time.

Block	RR Calculated from:					
	ROM	ROM	Primary Crushed			Fine
	All	-100 mm	Mean	A	B	Crushed
140217 #1	48	56	ND			26
15004	30	37	3	10	-6	38
150021 #4	22	43	3	14	-14	17
Mean	33	45	3	12	-10	27
P(T<=t) 2 tail	NA	0.12	0.11	0.23	0.01	0.55

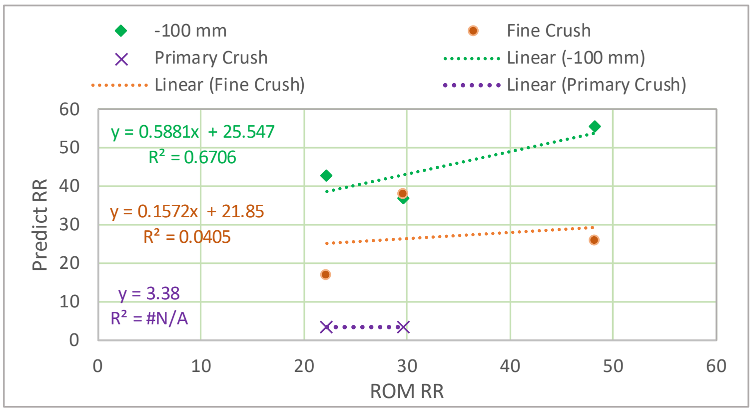


FIG 5 – Effect of crushing on upgrade response rank for KCGM subgrade ore.

ROM ORE TESTING – A LOWER COST PROCEDURE

For a brownfields project some bulk samples should be tested as part of an evaluation of pre-concentration by screening. However, in practice it is very difficult to carry out a ROM bulk sampling program and achieve reliable and reproducible results as the usually coarse size distribution requires large samples. The problem is exacerbated for gold ores containing either coarse gold grains or large gold clusters. In these circumstances investigations become primarily an exercise in reducing sample errors to the point where it is possible to draw conclusions. However, it was discovered during the investigation at KCGM (Clarke, 1993), discussed above, that the upgrade response measured on the -100 mm fraction of ROM ore appeared to be a close estimate of the response on ROM ore, probably within the accuracy of the ROM estimate. This approach has since been tested on data from three other orebodies:

- Underground ore from various shafts operated by Gold Mines of Kalgoorlie in the 1950s.
- Published data from BCL.
- Gramalote.

In all these cases full ROM samples were taken, sized and assayed. From the data, the upgrade response has been determined for the full ROM data and for various undersize fractions. For this paper the upgrade responses have been re-calculated using the CRCORE RR curve fit.

KCGM data

For KCGM open pit ore, the data is shown in Figure 5. Based on three ore samples treated through an industrial mobile crushing and screening plant, with sizing of the -100 mm material through a Mini-plant, the RR for the -100 mm material averaged 45 compared to the ROM material 33. The difference is not statistically significant. A regression analysis showed a useful correlation coefficient (R^2) of 0.67. Although this is not statistically significant, with only three data points, it led to the subsequent investigations. The 95 per cent passing size for the ROM material averaged 1260 mm and for the -100 mm fraction it averaged 93 mm. The -100 mm fraction contained 30–40 per cent of the weight in the full ROM size distribution.

The sampling theory of Gy is widely accepted for estimating sampling errors. The original form of this equation (Pitard, 1989) predicted that the sampling error was proportional to the cube of the coarsest (95 per cent passing) particle size and used a fixed liberation factor based on the ratio of the gold grain size to the particle size. Experience showed that this equation greatly overestimated actual errors on gold ores. For the test work at KCGM the estimation of sample error was based on the estimated maximum particle grade for the respective product:

$$\sigma_{FE}^2 = \left(\frac{1}{M_s} - \frac{1}{M_L}\right) \times d^3 \times f \times g \times \left(\frac{a_{max}}{a_L} - 1\right) \times RD^1)$$

Where:

σ_{FE}^2 is the fundamental sampling variance

M_s	is the sample mass (g)
M_L	is the lot mass (g)
d	is the particle diameter in cm, taken as the 95 per cent passing size
f	is the shape factor (f × d^3 = volume)
g	is the size distribution factor, which corrects top size to average size
a_{max}	is the maximum particle grade (decimal fraction) of mineral for particles of diameter d
a_L	is the lot grade as a decimal fraction of mineral

$RD^1 = \frac{RD_{Au} \times RD_g}{RD_g \times a_{max} + RD_{Au} \times (1-a_{max})}$ which is the density of a particle at maximum grade

Where:

RD_{Au}	is the relative density of gold
RD_g	is the relative density of gangue

In this equation the sampling variance is still proportional to the cube of the particle diameter but is moderated by the reduction in maximum particle grade in coarser products. It is impractical to exactly determine the maximum grade of 1 m lumps in ROM ore and so the maximum grade was estimated from the measured coefficient of variation of replicate assays at finer sizes, using a hierarchical analysis of variance. It was found that there was a good relationship between particle size and maximum particle grade, of the form:

$$\text{Log}_{10}(a_{max}) = 4.33 - 1.77 \times \log_{10}(d)$$

for which $R^2 = 0.63$

Extrapolating above 200 mm using this relationship, the estimated maximum particle grade for the top size in ROM ore is 4.2 g/t. In the -100 mm fraction it is 421 g/t. The total quantity of ROM ore treated in the mobile plant for each block was about 500 t while the Mini-plant treated 4–5 t of the -100 mm ROM fraction. With these quantities, the estimated coefficient of variation on the head grades, based on maximum particle grades, is ±7 per cent for ROM ore and ±13 per cent for the -100 mm fraction. The error on the -100 mm fraction could be reduced to 7 per cent by treating 20 t samples, or just 4 per cent of the tonnage to be treated at ROM size for the same error. Moreover, whereas large scale on-site equipment is needed to establish the grade of ROM ore, -100 mm material can be processed at some commercial testing laboratories. Of course, the actual sample size that needs to be tested depends on the ore characteristics.

Gold mines of Kalgoorlie data

During the course of the investigation at KCGM some reports dating from 1955 were located, which investigated the variation of gold grade with particle size in underground ores at Gold Mines of Kalgoorlie (GMK) (Coles, 1955). At that time, it was the practice to take grab samples, literally a hand-full, from every underground truck and reconcile with plant recovered grade. The samples were taken only from the fines. Up to 1952 agreement was good but after that time underground sampling showed erratic high-grades which were not reflected in plant recovered grade. The problem correlated with increasing amounts of telluride rich gold ore. As tellurides are soft, it was thought they might report preferentially to the fines. Two initial rounds of test work were carried out which confirmed that high-grade friable material did preferentially report to the fines. A more extensive investigation was then carried out, taking 16 full 1 t truckloads from eight different shafts in the GMK stable and sizing and assaying the size fractions using eight repeat samples for every size fraction. The largest screen used was a rectangular 125 × 63 mm and this retained an average of 42 per cent of the mass but varying from 17–80 per cent for the different sources. The ore was slabby and the top size in a truck with 57 per cent oversize was measured as about 125 × 70 × 63 mm, indicating a narrow size range for the oversize material.

The Response Ranking for both the ROM material (total truck contents) and the -63 mm fractions are shown in Figure 6.

	Response Rank		Corr Coeff R^2		%<63 mm
	ROM	-63 mm	ROM	-63 mm	
Oroya 15L 1505 Stope	65	66	1.00	1.00	42.9
Oroya 6L 617 Stope	14	40	0.57	0.99	58.7
Iron Duke 9L Sec 22 OHW	10	12	0.87	0.86	82.5
Iron Duke 13L Hinchcliffe	7	26	0.37	0.98	61.7
Paringa S Shaft 1000L (a)	70	66	1.00	1.00	43.9
Paringa S Shaft 1000L (b)	105	80	0.98	0.99	48.6
NNB 4L 623 Series	36	32	0.98	0.91	20.1
NNB 7L 1160 Sec	47	58	0.99	0.97	47.7
Perseverance 9L LVN	36	17	0.93	0.94	63.8
Perseverance 22L Bell Stope	6	3	0.80	0.75	53.3
Enterprise 17L Sec 9-10 N	3	0	0.93	0.14	65.6
Enterprise 22L Greenhill	15	-15	0.46	0.54	40.8
Hainault 6L 606 Stope	35	36	0.99	0.98	85.7
Hainalt 5L Bin bulk	17	23	0.84	0.92	72.1
South Kalgurli 4L 310 Stope	27	26	0.98	0.98	73.9
S Kalgurli 2180L 8 N Stope	44	43	0.97	0.95	64.6
Mean	34	32			57.9
Probability (T <=t) two tail	0.70				

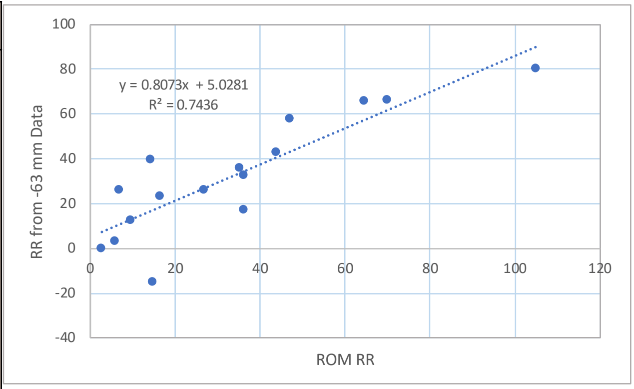


FIG 6 – Response Rankings for Run-of-Mine and -63 mm material from 16 mine trucks at GMK.

There is no significant difference between the average RR_{ROM} and RR_{-63}, which are 34 and 32 respectively. The two are also highly correlated, with R^2 0.74, which is statistically highly significant. Figure 6 also shows the correlation coefficients for the individual log-log fits used to derive RR values. In four of the six cases where the RR values differ substantially for the ROM and -100 mm fraction (highlighted in yellow), the correlation coefficient on the RR estimate for the ROM ore is low. Thus, the main factor reducing the correlation between RR_{ROM} and RR_{-63} is probably sampling errors on the oversize in the ROM ore.

Bougainville Copper Limited data

The investigation into pre-concentration by screening at BCL was discussed above. Burns and Grimes (1986) reported average size by grade and size analysis data for two ore types with a good upgrade response. The data has been extracted from the graphs and used to calculate RR values for ROM ore and for various size fractions of ROM ore. The 95 per cent passing size for ROM ore is about 150 mm, which is quite fine for open pit ore due to the highly fractured nature of the deposit, also key to the good upgrade response. The results are summarised in Table 2.

TABLE 2

Response rankings for Bougainville Copper Limited ROM ore and fractions.

	Response Rankings				Corr Coeff R^2 for RR Estimate				% Undersize		
	ROM	-152 mm	-76.2 mm	-50.8 mm	ROM	-152 mm	-76.2 mm	-50.8 mm	-152 mm	-76.2 mm	-50.8 mm
Gold											
BCL KD	115	114	109	111	1.00	1.00	1.00	1.00	98%	75%	53%
BCL PS	128	126	127	127	1.00	1.00	1.00	1.00	94%	73%	53%
Mean	122	120	118	119							
Copper											
BCL KD	88	86	82	84	1.00	1.00	1.00	1.00	98%	75%	53%
BCL PS	121	118	118	117	1.00	1.00	1.00	1.00	94%	73%	53%
Mean	104	102	100	100							

Table 2 shows very close agreement between RR values calculated from ROM ore and all size fractions. It is notable that the BCL results give a practically perfect correlation in the plots of data used to estimate RR, which doubtless contributes to the good correlations between RR for the ROM ore and size fractions. The RR values estimated from the -50.8 mm fractions are the best to compare with the other sites as the undersize in this fraction is 53 per cent of the ROM sample.

Gramalote data

Data from the Gramalote project has also been used to investigate the relationship between the upgrade response of ROM ore and of the -53 and -106 mm size fractions. The calculated RR values are shown in Table 3.

TABLE 3

Upgrade responses for Gramalote ROM ore, -50 and -100 mm fractions.

	Response Rankings					Mass% of ROM	
	ROM	-106 mm	Sim ROM -106 mm	-53 mm	Sim ROM -53 mm	-106 mm	-50 mm
N1F1	111	105	106	107	108	59	36
N2F1	86	88	89	89	89	61	42
N3F1	66	64	65	62	61	58	34
N4F1	130	126	130	114	127	75	42
N5F1	102	98	103	95	102	78	50
N6F1	102	96	99	89	94	69	51
N1F2	113	102	106	82	84	78	45
N2F2	109	97	102	69	67	44	27
N3F2	86	95	96	98	101	91	60
N4F2	139	140	143	136	142	82	43
N5F2	108	103	106	96	101	89	64
N6F2	127	125	127	117	124	72	54
N1F3	105	105	106	104	101	67	37
N2F3	106	102	107	103	113	73	45
N3F3	104	100	103	96	101	87	61
N4F3	115	109	100	117	103	82	52
N5F3	118	116	118	118	123	91	70
N6F3	127	123	127	119	118	87	60
Mean	108	105	107	101	103	75	48
t-test prob. chance		0.0104	0.3716	0.0132	0.3708		
Slope		1.001	0.970	0.737	0.745		
Intercept		3.08	4.30	34.25	28.38		
R^2		0.96	0.95	0.78	0.89		

Table 3 shows that RR_{ROM} and RR_{-106} correlate closely, with R^2 0.96. Moreover, the relationship is practically 1:1 with no scale-up factor required although the small difference is statistically significant due to the consistency of the data. This is perhaps not surprising however as on average 75 per cent of the ROM ore was in the -106 mm fraction, so a better comparison with a typical open pit situation may be the -53 mm ROM fraction, which carries 48 per cent of the mass on average. In this case the correlation coefficient is 0.78 and the mean RR for the set is 101 versus 108 calculated from the ROM ore. This is still a strong relationship, but it is worth examining why the RR from the -53 and -106 mm fractions underestimates the true RR for most samples. Sample N2F2 may be taken as an example.

GRT-N2-F2				
Sieve Held, mm	Cum % Pass	Au g/t	Au % Pass	UF
+175	100		100	1.00
175	82.1	0.01	97.04	1.18
125	65.7	0.02	92.08	1.40
75	44.0	0.02	85.63	1.95
53	28.9	0.06	72.96	2.52
39.8	18.7	0.12	56.33	3.02
23.8	11.6	0.19	38.87	3.34
19.8	10.1	0.17	35.41	3.51
12.3	7.5	0.14	30.50	4.09
9.8	6.4	0.18	27.99	4.35
4.7	4.9	0.22	23.58	4.81
2.8	3.4	0.31	17.22	5.11
-2.8	0.0	0.39	0.00	
Total		0.08		

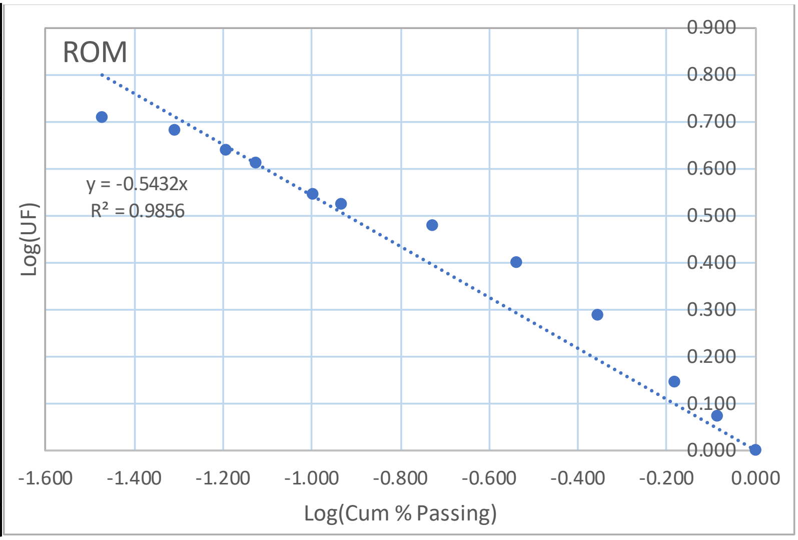


FIG 7 – Size-assay distribution for Gramalote ROM sample N2F2 and RR estimation plot.

Figure 7 shows the variation in gold grade with particle size and the resulting log Cum per cent Passing versus log UF plot. The data table in Figure 7 shows a sharp decline in the gold grades above 40 mm, which results in a systematic deviation above the line for the first five points in the log-log plot. This systematic deviation also means that the log-log curve fit underestimates the benefits of upgrading by screening at mass pulls of around 40 per cent. For that reason, evaluation of screen upgrading for the Gramalote pre-feasibility study was based on plots of raw data, not the mathematical curve fit (Clarke *et al,* 2020). There is no way to overcome this problem without the additional cost of sampling the top-size material, but as can be seen in Table 3 the impact is effectively some additional conservatism in the economic evaluation.

It is possible to improve the correlation with RR_{ROM}, particularly for the -53 mm fraction, by reconstructing an approximate ROM sizing. This refinement of the method requires that the mass percentage of the +50 mm material is measured during sampling, but not the assays. The geometric mean size of the +50 mm material also needs to be approximately known, which can be determined using image analysis. The work would be most economically carried out by a small excavator or backhoe fitted with a sieve bucket and weighing instrumentation. The largest rocks may exceed the machine's capacity and are pushed aside and counted. The remainder of the material is weighed in the sieve bucket then sieved with the undersize being collected in a skip-bin or bulk bags. The oversize is discarded. The undersize is subsequently also weighed, then sent to a sample processing plant for screening, then crushing and subsampling of the individual size fractions. The assay of the +50 mm material is estimated by plotting the known size fraction grades against the geometric mean fraction size and extrapolating using a power curve (or other suitable form) to the mean size of the +50 mm material. Table 3 shows the results, labelled Sim ROM -106 mm and Sim ROM -53 mm. There is little benefit from applying the approach to the -106 mm material, but for the -53 mm it improves both the estimate of average RR and the correlation with ROM material with only a small amount of extra effort. The method could equally well be applied at an intermediate size, such as 75 mm.

EFFECT OF PARTICLE SIZE ON SEPARATION SIZE

An important question when designing a screen pre-concentration plant for a greenfields project is whether the optimum separation size remains the same with scale-up to ROM material, or the mass pull remains the same. If the separation size is controlled by vein spacing, that would suggest that the separation size should remain the same and the mass pull vary. However, both the Gramalote and Los Bronces test work shows that the RR value remains the same over a range of coarse crush sizes. This implies that it is the optimum mass pull that remains the same and the separation size that varies. Nonetheless, it would be wise to allow for some fine-tuning of the separation size in any greenfields plant design. The BCL data does not provide any guidance on this question as the 80 per cent passing size of ROM ore was fine, at about 90 mm, and the drill core was tested by tumbling rather than crushing and resulted in a similar separation size on core and ROM ore.

CONCLUSIONS

The results of the studies reported here show that size-by-assay studies of the coarse rejects from drill core, or RC drill chips, are a cost-effective means of determining whether an orebody is potentially amenable to pre-concentration by screening. The results do not however correlate with variable responses across the orebody and must be calibrated by large scale test work. The reason is that fine crushing measures the proportion of metallic values which is vein associated rather than disseminated, but suppresses all information on vein thickness, spacing or breakage characteristics. A study of the breakage characteristics of drill core selected to cover all major alteration types is a low-cost way to supplement the coarse reject information and guide subsequent studies. Pre-concentration by screening is likely to be effective when high-grade sections of core break relatively finely (eg <50 mm) to produce high-grade particles while lower grade sections break randomly to produce larger and lower grade particles. If a substantial proportion of the values is in veins which are thick compared to a likely separation size, then screening is unlikely to result in consistent upgrading. High values in thick and hard quartz veins are likely to result in upgrading to the coarser fractions.

It is advantageous to evaluate pre-concentration as part of a greenfields project design as this allows for mine planning and plant location to be optimised for the entire process. However, greenfields projects may have little or no access to bulk samples and planning must be based on drill core. It has been shown for two projects evaluated that the upgrade response measured on coarse crushed drill core correlated very well with the response of blasted ROM ore with little or no scale-up factor required. A third project (BCL) required a scale-up factor to be established by bulk sampling (but used tumbling rather than crushing) while for a fourth project (KCGM) the upgrade response of crushed ore did not correlate with ROM ore. The reason in this last case is likely to be that the gold at KCGM occurred in veins which were thick compared to the crushed sizes used and so the response was suppressed. Application of the preliminary evaluation techniques developed since that work was done would have shown that the KCGM ore was not amenable to upgrading.

The cost of large diameter core drilling for upgrading studies across a deposit would be large. However, for Gramalote it was shown that the upgrade response could be correlated with chemical or hyperspectral databased on a moderate number of samples (Clarke *et al,* 2020; Guerrero *et al,* 2020) and then proxy data used to map the response in more detail.

For a brownfields site, the most effective means of study is sampling material from operating benches. However, sampling the full ROM size distribution is costly and difficult due to the typically large top-size, consequent large sample masses required to control intrinsic sampling errors and the cost of processing that coarse material. Test work at four sites has shown that instead of sampling the entire size range, samples can be taken only of the -100 mm material, or finer depending on the ROM top size. This can greatly reduce the sample size required for a given accuracy, in one case by a factor of 25 times. The samples can also be screened and prepared for assay using equipment available at larger commercial testing laboratories. All four sites showed a strong correlation between the upgrade response of selected size fractions and the ROM ore. It has also been shown that the correlation can be improved by measuring the oversize and undersize fraction weights at the time of sampling and deriving a simulated ROM distribution. This can be done with relatively little extra effort. For the Gramalote project the upgrade response measured from finer size fractions is biased a little low, due to the coarsest fractions having consistently lower grades than expected from the modelled relationship. However, the difference is not enough to materially change the economics and provides some additional conservatism.

Although the methods described here will greatly reduce the cost of studies for either green or brownfield projects, while providing high quality data, in all cases it is likely that at least one ROM bulk sample would need to be sourced and tested before proceeding with final approval and engineering. It is also recommended that any screening plant should be designed to allow some flexibility in the separation size in operation.

ACKNOWLEDGEMENTS

The work reported here has involved many people, but the guidance and encouragement of Doug Halbe at Kalgoorlie Consolidated Gold Mines was key to the successful completion of that project.

The assistance of Eugenio Gatto of Northern Star Resources Ltd, current owners of KCGM, in reviewing the paper and giving permission to publish the KCGM and GMK data is gratefully acknowledged. The Gramalote upgrading by screening project could not have happened without the support and encouragement over many years of V Chamberlain and R Sanhueza and the hard work of the on-site teams. Approval by AngloGold Ashanti, B2Gold and the Gramalote JV to publish the Gramalote data is gratefully acknowledged.

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