CRC ORE White Paper

Grade Deportment by Size

Initial characterisation of deposits in the Western Australia Gold Fields at the small scale

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CRC ORE
Optimising Resource Extraction

KALGOORLIE-BOULDER
MINING INNOVATION HUB

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Abstract

CRC ORE's Grade Engineering® covers a suite of technologies aimed at gangue rejection as early in the process as possible. Key among this suite is grade deportment by size, the inherent propensity of metal value to concentrate in a particular particle size fraction. The Kalgoorlie-Boulder Mining Innovation Hub (a node of CRC ORE) has obtained diamond drill core and reverse circulation (RC) drilling samples from a variety of sites in the Western Australian Goldfields to crush, screen and assay to develop a snapshot of responses to this approach.

Samples were crushed (where necessary) and screened into five to six size fractions, a finer set of screens was used for the RC samples to accommodate the difference in particle size distributions. Gold samples produced varied data with the majority of sites producing low to moderate upgrades on average. The RC samples generated greater variation and often decrease in grade at the finest size fractions, likely due to being below liberation size. This creates issues with the RR fit. Nickel produced far more consistent behaviour with all sites producing moderate to high responses for both nickel and cobalt. While for some samples the nickel and cobalt RRs matched well, in others the nickel upgraded significantly better.

Introduction

The primary drive in recent decades to maximize profitability of operations has been to mine and process as much material as possible to exploit economies of scale. This has led to bigger equipment, higher throughput plants and greater production but not necessarily efficient use of resources. Coupled with the concerns of declining grades, more difficult ores, greater haulage distances – both from mine face to surface and mine to mill, higher energy costs and water usage any approach that can alleviate the impact of these issues is highly desirable.

Grade Engineering is a system-based methodology developed by CRC ORE designed to reject low value material early in the extraction value chain and pre-concentrate processing plant feed. An important part of Grade Engineering, and the focus of this project, is the preliminary characterisation of preferential deportment of grade by size. An understanding of the relationship between ore grade and size fraction in an orebody after blasting and crushing (known as natural deportment) will help support the decision by a mining company to progress the Grade Engineering methodology to reduce processing unnecessary material.

Small scale testwork has been carried out to significant extents on individual projects as it represents a far more efficient manner of characterising a large number of samples from a deposit than using bulk samples at ROM or primary crusher size. This then allows for a more detailed assessment of the deposit and a better understanding of how the various zones/rock types/etc. within the deposit respond with respect to grade by size. Such testwork is generally conducted on drill core and follows a consistent protocol as outlined in the Methods section, but other sample sources such as coarse rejects from assaying that have an appropriate particle size distribution are also useful. While testing at this scale will not necessarily provide the correct magnitude of response as conducting screening at a bulk scale, a positive result is indicative of positive response at larger scale.

The primary output of the analysis from grade by size testwork is the Response Ranking (RR), which is an index that describes the propensity of metal in a given ore to deport to particular size fractions. These are calculated via a series of manipulations of the mass and grade data producing Response Factors (RF) describing the proportion of upgrade in a given fraction and then fitting them to the standardised RR function. This process is detailed in Carrasco et al. (2014 & 2016).

A key component to quantifying a valid RR value, is that the metal is preferentially deporting to the coarse or fine component of the sample. Traditionally this is a positive RR (i.e. the metal is deporting progressively towards the fine component). Alternatively, a negative RR is where the metal is deporting to the coarse fraction. A positive response is relatively simple and straightforward to calculate assuming the sample masses of each fraction are not vastly different, or any one fraction contains an abnormally large (e.g. 50%) or small (<10%) portion of the mass. This is more important for the laboratory drillcore testing as it attempts to define a “relative amenability”, rather than an absolute response.

Negative RR values are not as straight forward to calculate as positive RR values, and greater investigation and analysis needs to be taken to determine whether it is a valid RR (i.e. genuine inverse deportment) or is simply a function of assay precision or non-predictable metal deportment and hence cannot be represented as a valid RR value.

The objective of this project is to undertake initial representative sample testing to determine natural deportment RR at a range of deposits in the Kalgoorlie-Boulder region.

1 Background to Grade Engineering

A focus on throughput as the main driver of revenue has led to a bulk average mentality with respect to in-situ cut-off grades (Walters, 2016). In many cases, average grades used to define bench or stope scale processing destination decisions such as mill, dump leach, waste, etc. include significant sub-volumes of material outside cut-off specifications. An averaging approach ignores potentially exploitable grade heterogeneity below the scale of minimum mining unit even though significant localised grade heterogeneity is a dominant characteristic of many base and metal deposit styles and ore types.

Localised grade heterogeneity is typically overlooked in favour of maximising extraction rates and loading efficiency. This is coupled with a desire to blend ROM and produce steady state feed in terms of grade and physical properties to optimise and maximise recovery of saleable product particularly in crush-grind-float operations. Grade Engineering® recognises that in many cases out of specification sub-volumes assigned to destinations based on bulk averages can be removed using efficient coarse separation techniques in the 'dig and deliver' interface. Coarse separation (~10-100mm) can be used on a range of particle size distributions ranging from ROM to SAG discharge (Bearman, 2013). The earlier this occurs in the conventional dig and deliver mining cycle the higher the potential net value of removing uneconomic material (Bamber et al, 2006 a and b, 2008).

Every handling and size transformation interface in the dig and deliver cycle should be considered an opportunity for applying coarse separation (Rutter, 2017). ROM and post primary crushing are obvious intervention points with opportunity for separation conditioning during modified blast design. The decision to intervene is a function of grade heterogeneity in each parcel of material; the yield-response of a separation device at a specific size reduction point; the ability to change a destination decision for one or more of the new streams following separation; and the net value of the new streams after handling costs.

Grade Engineering® outcomes do not create 'new' metal but rather exchange metal from separated components between existing destinations to create improved net value after cost of exchange is considered. This involves exchanging a component of separated mill feed with other destinations such as mineralised waste, stockpiles or dump leach with low recovery. The aim is to bring metal forward from destinations that are not delivering maximum current value and reduce overall costs per unit metal produced.

Natural Preferential Grade by Size Deportment (PGS) is the propensity for some ores to exhibit preferential breakage leading to concentration of minerals into specific size fractions. This typically involves an increase of valuable mineral phases in finer size fractions, or less commonly to the coarser fraction in some geological settings.

The geology and mineral association of base and precious metal deposits is typically complex with many overprinting paragenetic events contributing to the creation of potentially mineable reserves. This is evident in features such as multiple vein events; different mineral associations and intergrowths; varying alteration styles and mineralogy's; metamorphic overprints; banding; discrete lenses and replacement textures. Preferential grade deportment is an interaction function of these rock mass properties, texture, ore paragenesis and mineralogy at a range of scales.

There is typically no relationship between magnitude of response and head grade, with the main control being textural rather than absolute abundance. Physical separation is a function of screening employed after blasting or primary crushing.

The drillcore scale testing undertaken in this project is a laboratory test that is aimed at determining the "amenability" of a material type to Grade Engineering and may not represent true metal deportment rates or size fractions at a production scale. In CRC ORE's experience, results from laboratory scale testing are traditionally underestimated compared to bulk response. The scale up factor between laboratory testing and ROM scale has been measured at a number of operations and has varied between 0 and > 2 (commonly 1.2 to 1.6), with the scale up depending on geological and mineralogical controls.

The objective of this project is to undertake initial representative sample testing to determine natural deportment Response Rankings (RR) at a range of deposits in the Kalgoorlie-Boulder region. It provides an introduction for industry participants to Grade Engineering and an indication of potential opportunities that grade by size may present.

2 Materials and Methods

A standard method for conducting sizing at this scale has been determined by CRC ORE (CRC ORE, 2015). This involves crushing the material to 100 % passing 3.35 mm and screening the product into 5 fractions: nominally: -3.35 +2.36, -2.36 +1.70, -1.70 +1.18, -1.18 +0.60 and -0.60 mm. An additional fine split at 0.30 mm can also be made if sufficient material presents in the smallest size fraction. The quality control governing the sizing is that no less than 10 % and no more than 50 % of the mass should report to any individual size fraction, ideally with roughly equal quantities reporting to each.

Three different sample types were provided that could be successfully tested with this procedure: diamond drill core (generally 1/2 core), coarse assay rejects – which are the remainder of core samples crushed to -3.35 mm for subsequent split assaying - and small grab samples of moderate size particles.

RC drilling sample sets were not able to be tested via this procedure due to a lack of material at the coarser end of this scale. In this case no further particle size reduction was used and the samples were screened so to achieve 5 or 6 size fractions of similar mass distributions. Given a variety of particle size distributions for RC material were provided the screen apertures were selected to be appropriate for all between samples provided.

3 Results and Discussion

The various results obtained have been separated in this section by commodity (Ni and Au ores) and sample type (diamond and RC drill product).

3.1 Gold

Previous work conducted by CRC ORE has generated a large database of gold diamond drill core testwork on samples from international sites that shows a wide range of responses with the majority in the moderate positive response (moderate preferential deportment of gold to the fines) (fig. 1). Such a vast range is primarily influenced by the geology and mineralogy associations, as well as particle size within individual gold deposits. This is also one of the reasons why greater numbers of samples and assays are often required to create confidence in the outcomes and thus why duplicate assays were used in the course of this study.

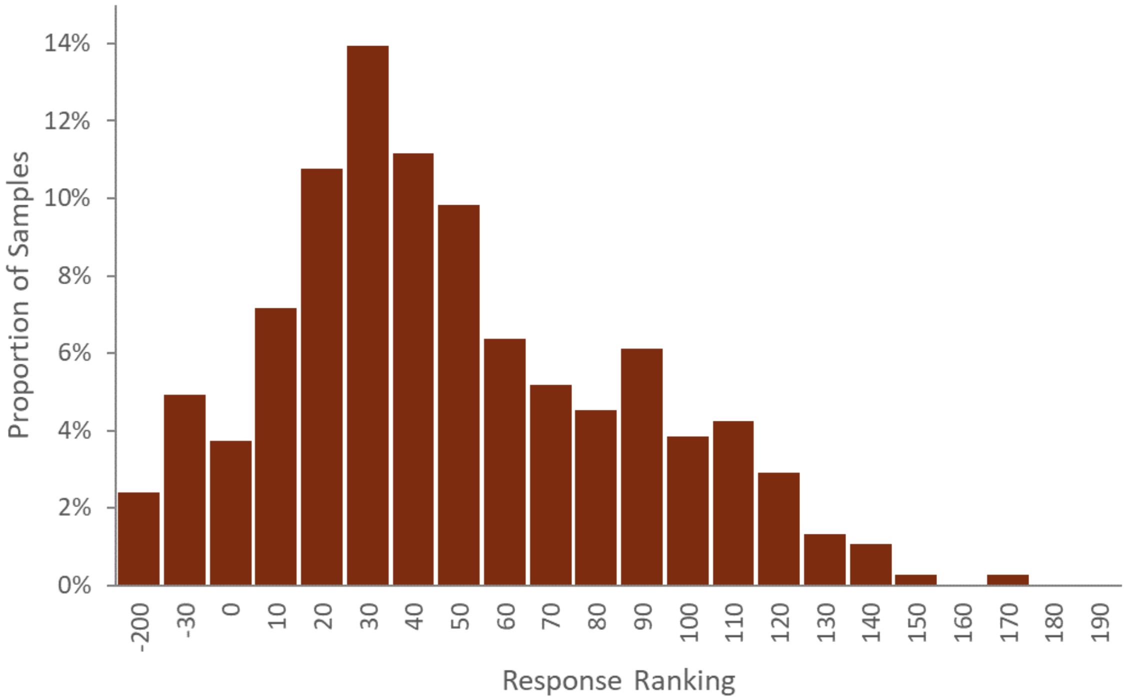

Figure 1: Sample RRs returned from extensive CRC ORE testing on gold drill core.

Response rankings allow for the deportment of grade by size in a sample to be described by a single calculated value. While % metal vs % mass retained relationships provide the same basic information, this becomes cumbersome as soon as larger sample numbers are obtained and the data is to be used for modelling or forecasting. By determining a single number per sample this can be easily manipulated for large sample sets and utilised for modelling purposes. The RR is calculated as described in equations 1 to 3. The response factor (RF) and response… (RS) are calculated cumulatively for each size fraction (i) in the sample, the average of the RS values for the sample is then calculated and multiplied by a factor of 200 to obtain the RR.

$$RF_i = \frac{\% \, metal}{\% \, mass \, retained} \quad (1)$$

$$RS_i = \frac{-\ln(RF_i)}{\ln(\% \, mass \, retained)} \quad (2)$$

$$RR = \left(\frac{\Sigma(RF)}{n}\right) * 200 \quad (3)$$

Where n is the number of size fractions within the sample.

This section will only treat the samples with particle sizes suited to the drill core protocol (full, ½ or ¼ core, coarse rejects, other small geological samples). Samples were submitted from six sites (designated Sites 1-6) in the Northern and Eastern Gold Fields, some from multiple mines/locations on the same or adjacent leases (designated as Site 1A, B, etc.). A list of samples provided is presented in Table 1. Some of the sample numbers are below ideal levels for statistical accounting due to provision of these samples as well as RC material from the same location/zone.

Site	Deposit Type	Sample Number	Sample Type
1A	Banded Iron Formation (BIF)	10	Core
1B	Intermediate Volcanoclastic	10	Core
2	Porphyritic Felsic Intrusive	6	Core
3A	Sediments / Volcanoclastics	4	Core + Geo
3B	Volcanoclastics	3	Core + Geo
3C	Mafic Volcanics	3	Core + Geo
4	Tonalite	7	Core
5	Unclassified Archean Greenstone	17	Core
6	Volcanoclastics	11	Coarse Rejects

Table 1: List of gold samples provided that were suitable for standard drill core test protocol.

The relative masses occupying the size fractions was relatively consistent across the samples with small differences noticed that corresponded well to the hardness of the rock. The grade deportment varied significantly as did the fit of the data to the RR equation. The validity of the RR that is generates is determined by the standard deviation calculated from the curve fit. An acceptable level is generally 0.1 for base metals but higher at 0.2 for gold given its high variability and thus generally poorer adherence to a particular trend. A standard deviation above the acceptable level is the definition of the QA/QC failure described herein. Therefore, it does not relate to the validity of the data obtained from the sample, but the accuracy of the RR to describe the metal deportment. The higher the standard deviation, the further the data is from standard RR behaviour and thus the number is a poorer representation of the exact sample response. Figure 2 provides examples of data that fit well and poorly.

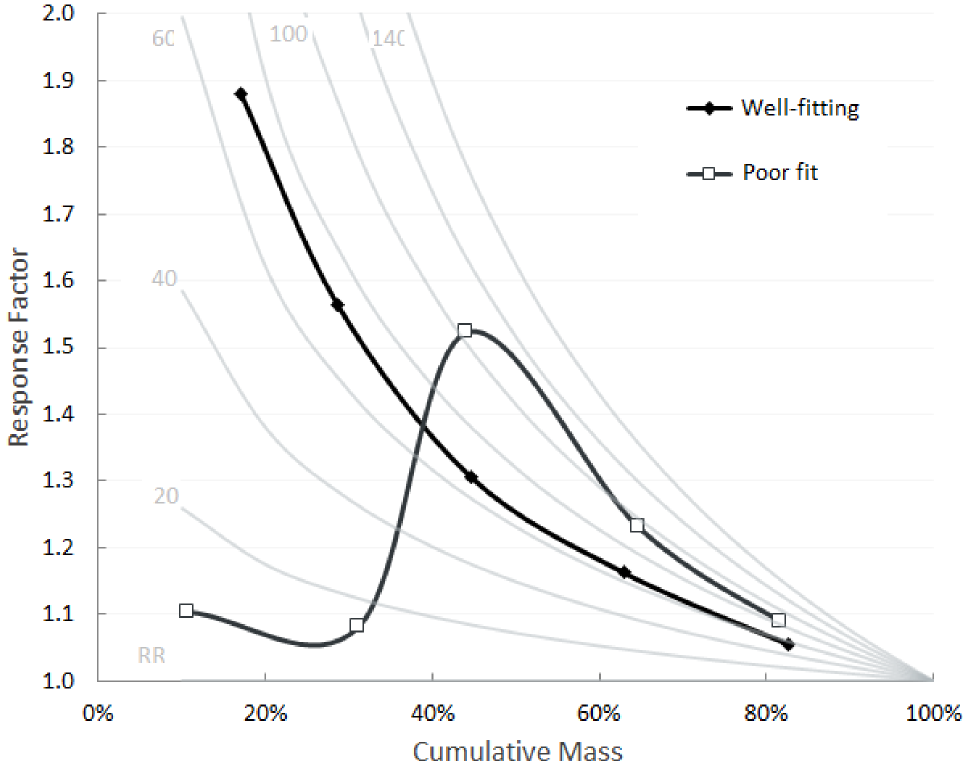

Figure 2: Examples of well and poorly-fitting curves to the response ranking function.

A summary of the RRs collected for each set of samples is presented in Table 2 and a distribution of all of the individual sample RR values are presented in Figure 3.

Site	Ave Head Grade (ppm)	Average RR	RR Range	% Passing QAQC
1A	1.93	8	-28 to 61	50
1B	1.70	32	-62 to 82	90
2	3.03	27	-15 to 67	100
3A	26.48	14	-17 to 34	100
3B	86.95	0	-18 to 37	100
3C	28.34	37	5 to 53	100
4	0.61	46	-18 to 139	86
5	3.86	35	8 to 60	88
6	3.44	33	16 to 67	90

Table 2: Data obtained from the sample sets detailed in Table 1.

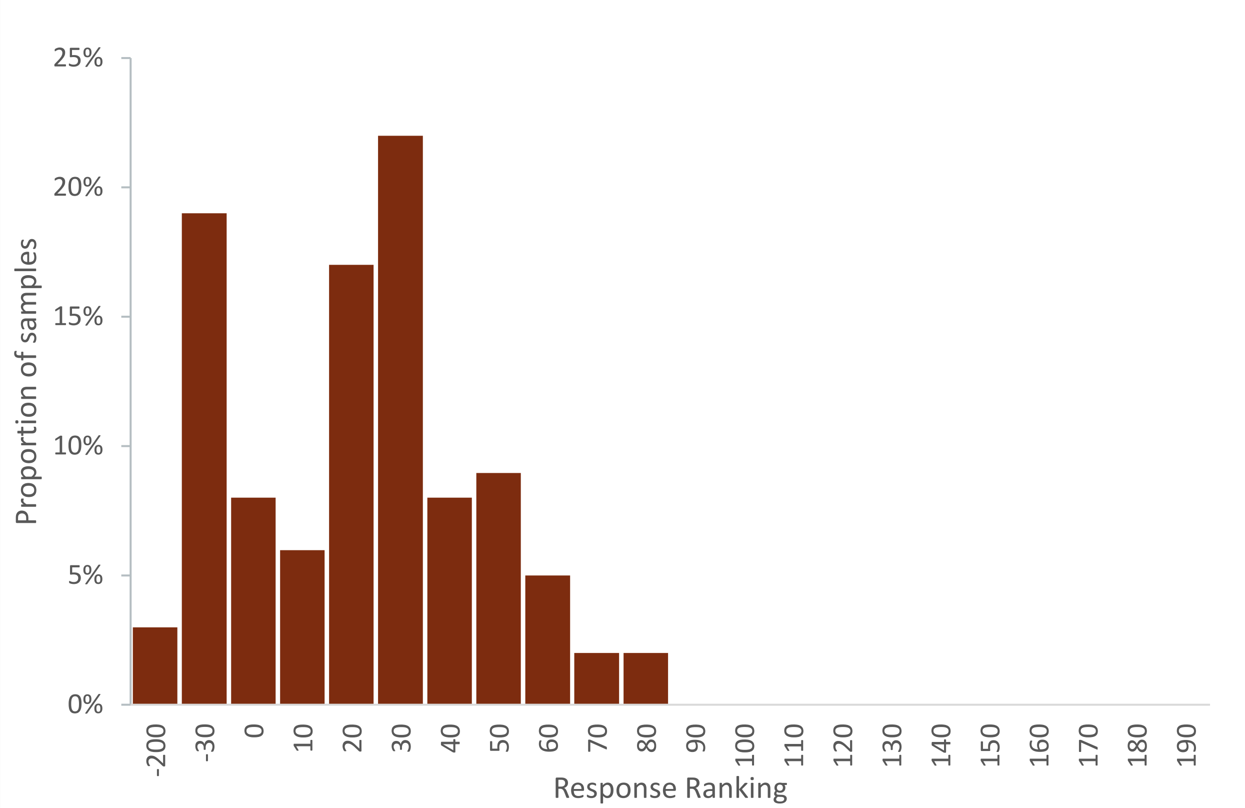

Figure 3: RR values obtained from gold samples treated via the drill core protocol.

Several generalisations can be made across the data, such as the fact that the majority of negative RR values return standard deviations above acceptable levels. There are several different reasons for negative RR values, however the only one that will still fit relatively well with the curve fitting is preferential deportment to the coarse fraction thereby having progressively lower grades in finer fractions. The majority of the results with negative values displayed somewhat random distributions in grade between size fractions suggesting little or no preferential deportment in either direction. As expected, none of these present valid RR values.

CRC ORE's experience elsewhere in both base metal and precious metal deposits has indicated no definitive relationship between grade and Response Rankings. If an ore type displays a propensity to respond to natural deportment, it may do so irrespective of head grade. However, context of the geological sample and submitted for testing is important. This is best considered by utilizing 2 idealistic end members as an example;

- Sample A: Coarse rejects from a broad low-medium grade shear zone's or stockwork's
- Sample B: Coarse rejects from Narrow discrete high grade "lode" (e.g.: 1m) and barren or semi barren country rocks → Uncomposited
- Sample C: Coarse rejects from Narrow discrete high grade "lode" (e.g.: 1m) and barren or semi barren country rocks → Composited

For Sample A, if the material displays a propensity for deportment, this may occur equally at 0.5 g/t or 5 g/t. The key driver for deportment is the geology and mineralisation. For Sample B the key driver is still geology and mineralisation (lode = gold, country rock = no gold), but the context of the coarse reject sample submitted for testing may drive the Response Ranking (illustrated in Fig. 4). If the coarse reject was for example barren footwall it will have a low RR as there is no metal to upgrade (Fig., comps 1, 3, 4 & 6). However, if the sample consisted of lode material only (example core cutting cut strictly to geological boundaries) then this may or may not have a significant RR (Fig. 4, comp 2). Sample C (composited mineralization and country rock) may reflect a more realistic mining scenario with minimum mining constraints and dilution (Fig. 4, comps 5, 7 & 8). In this case the “grade” may simply be the ratio of lode in the sample, but Grade Engineering RR will also be driven by the ratio of the rheological contrast that may be present. Hence whether the actual head grade of the composite is 0.5 g/t or 5 g/t, it is the broad context of the geological or mineralogical setting that is important in this case.

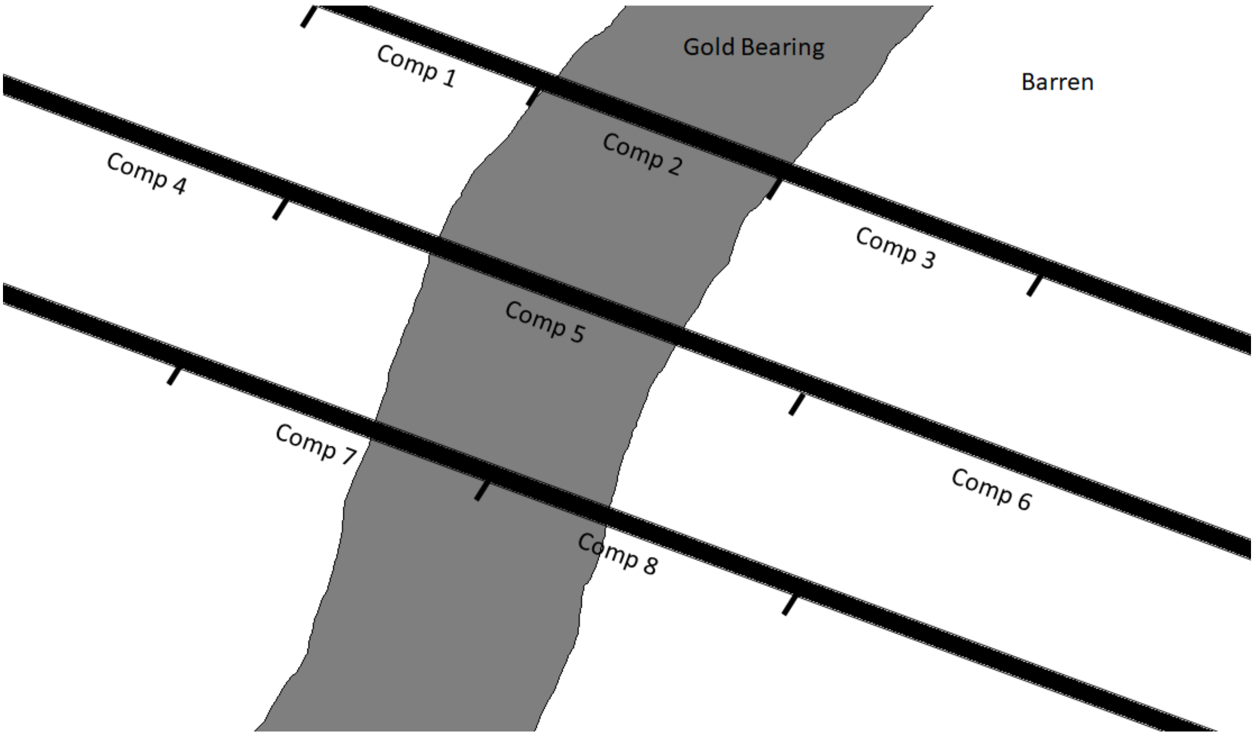

Figure 4: Simplified illustration of potential composite for sampling.

Consideration also needs to be taken for deposits with known coarse to very coarse free gold. This may cause issues with a RR at the drillcore lab testing stage but is less of a concern at meso or production scale testing. Specific lab scale drillcore RR testing protocols may be required for these sample types.

The operational reality is probably a full spectrum of all these cases, and individual sites will have greater understanding of context of the samples submitted. The Kalgoorlie-Boulder Mining Innovation Hub has made general assumptions or comments on the Response Rankings without full knowledge of sample providence which may lead to some incorrect observations.

3.2 Nickel and Cobalt

There is limited Grade Engineering information in the public domain regarding grade by size testwork on nickel ores, however there is significant anecdotal evidence to suggest many ores tend to upgrade in the finer fractions. Samples were collected from three sites in the region, one from the Northern Goldfields, one from Kambalda area and one from the Flinders ranges, these are designated Sites 7, 8 & 9 respectively (outlined in Table 3).

Site	Deposit Type	Sample Number	Sample Type
7	Kambalda Style Komatiite	4	Subsample
8A	Kambalda Style Komatiite	7	Subsample
8B	Kambalda Style Komatiite	6	Subsample
9	Differentiated Mafic Intrusive	10	Core

Table 3: List of nickel samples provided that were suitable for standard drill core test protocol.

As with the gold program there were fairly consistent mass splits among the size fractions across the samples. However, the response distributions were far more consistent both within the sample sets from individual sites and across the sample sets. All samples displayed a very predictable Response Ranking with a high quality fit to the Natural Deportment model.   No sample failed the curve fitting QAQC for either nickel or cobalt. A summary of the RRs collected for each set of samples is presented in Tables 4 and 5 and distributions of all of the individual sample RR values are presented in Figures 5 and 6.

Site	Location/Zone	Average Head Grade (%)	Average RR	RR Range	% Passing QAQC
7	-	1.79	46	40 to 61	100
8	A	4.72	78	63 to 99	100
8	B	2.85	62	57 to 73	100
9	-	3.40	40	14 to 64	100

Table 4: Nickel data obtained from the sample sets detailed in Table 2.

Site	Location/Zone	Average Head Grade (ppm)	Average RR	RR Range	% Passing QAQC
7	-	536	35	31 to 36	100
8	A	586	42	36 to 52	100
8	B	915	51	39 to 71	100
9	-	1105	41	13 to 78	100

*Table 5: Cobalt data obtained from the sample sets detailed in Table 2. *Co not assayed for Site 7.*

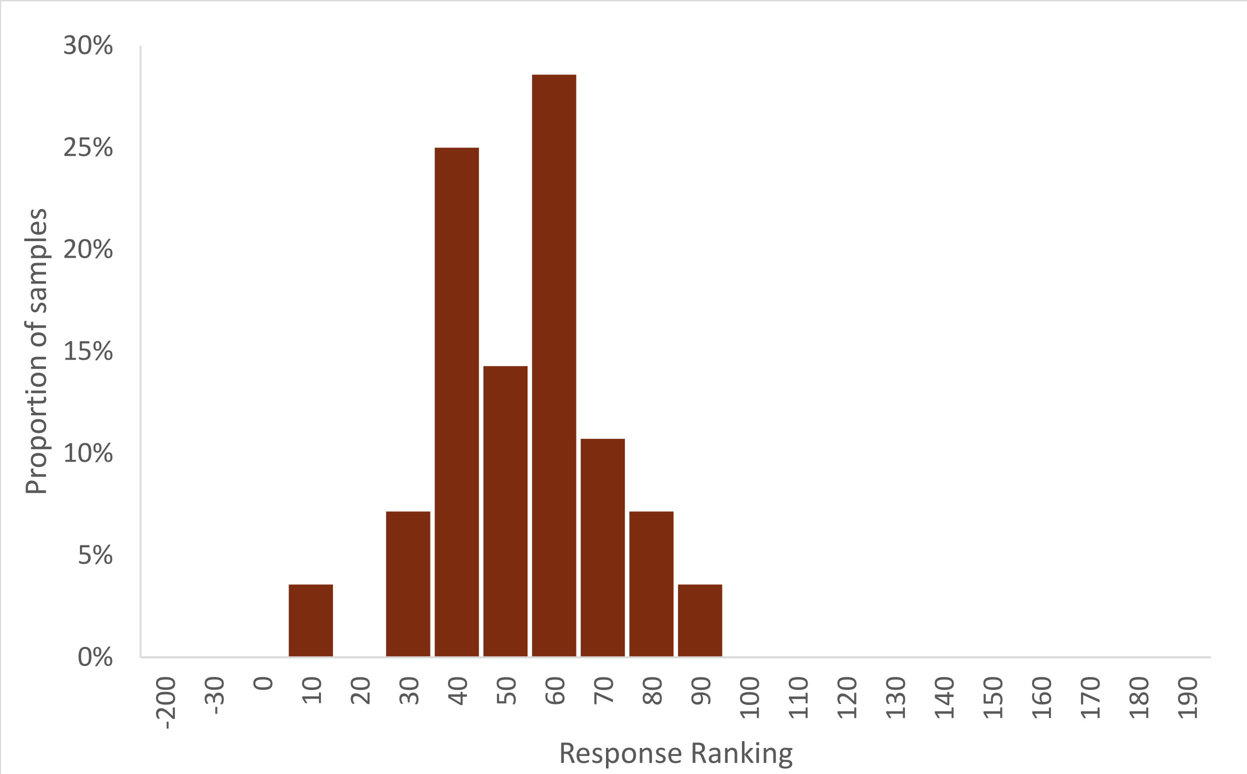

Figure 5: RR values obtained from nickel samples treated via the drill core protocol.

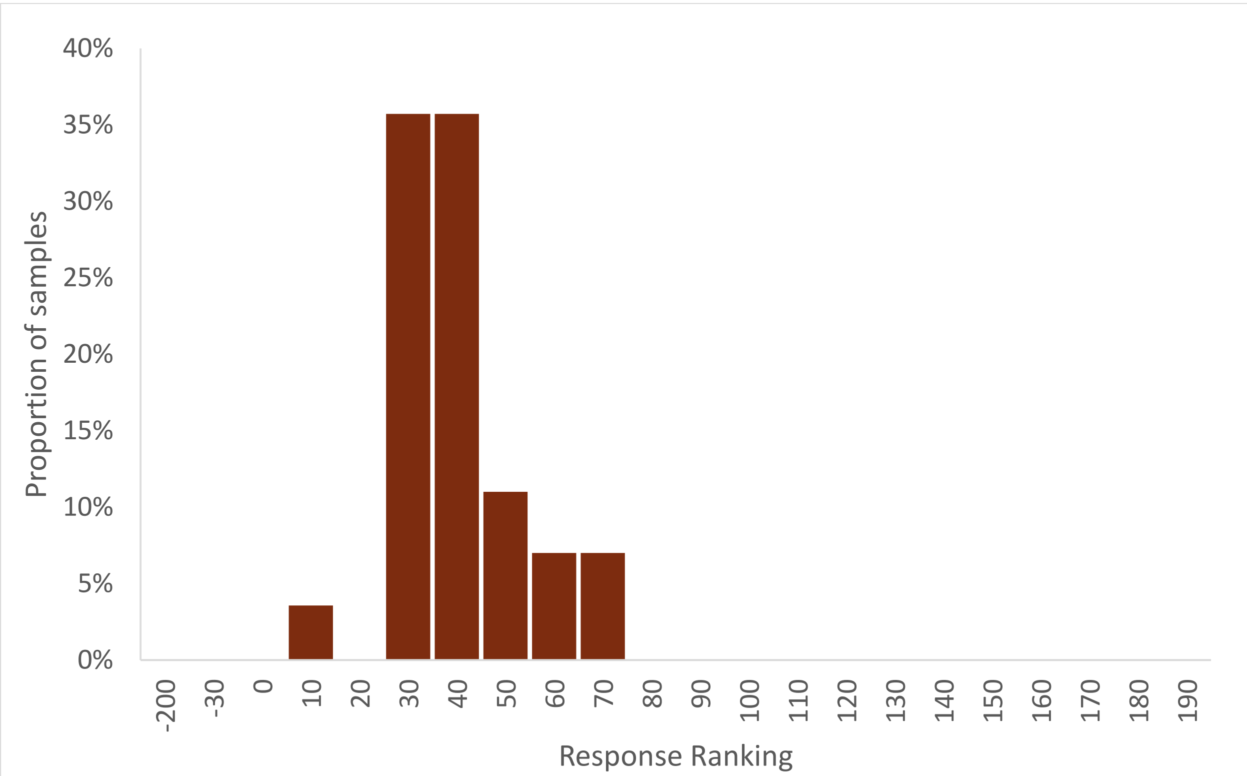

Figure 6: RR values obtained from cobalt samples treated via the drill core protocol.

The tighter ranges of RR values obtained and overall closer distribution for all samples within each set gives much greater confidence in the results. With respect to nickel, both zones from Site 8 reported RRs higher than the other two sites with 8A performing the best. While the Ni grade in the finest fraction was still relatively high (>1%), as discussed in section 3.1 the drillcore testing is an amenability test only. Production scale responses are commonly significantly improved.

As discussed previously in section 3.1 regarding geological sampling, providence and context of the samples are important. For example, the RR may be higher for traditional narrow "Kambalda Style" deposits if the sample contains hard footwall basalt with a narrow ore zone. The same Kambalda style may also show a lower RR if the sample only contained the massive/matrix sulphide zone.

It is a similar discussion for disseminated komatiites or layered intrusives. The inclusion or not of massive or semi massive sulphides with disseminated ore needs to be analysed separately. Likewise, the possible impact of serpentinization to mafic and ultramafic components.

Similar to the nickel response, cobalt RRs are tightly grouped in the distribution, in fact even more so than nickel values. Interestingly, the average values from Site 8 are comparable to Sites 7 and 9 even though the nickel RRs are almost double in the case of 8A. This is not consistent across all samples as the average cobalt value for Site 9 is effectively the same as for nickel. This behaviour is illustrated in Figure 7, which shows a distribution of samples in various RR zones and the comparison between the nickel and cobalt upgrades. The samples from Sites 7 and 9 are generally centred in the Ni=Co region with moderate RRs while the Site 8 samples are predominantly in higher RRs and Ni>Co region.

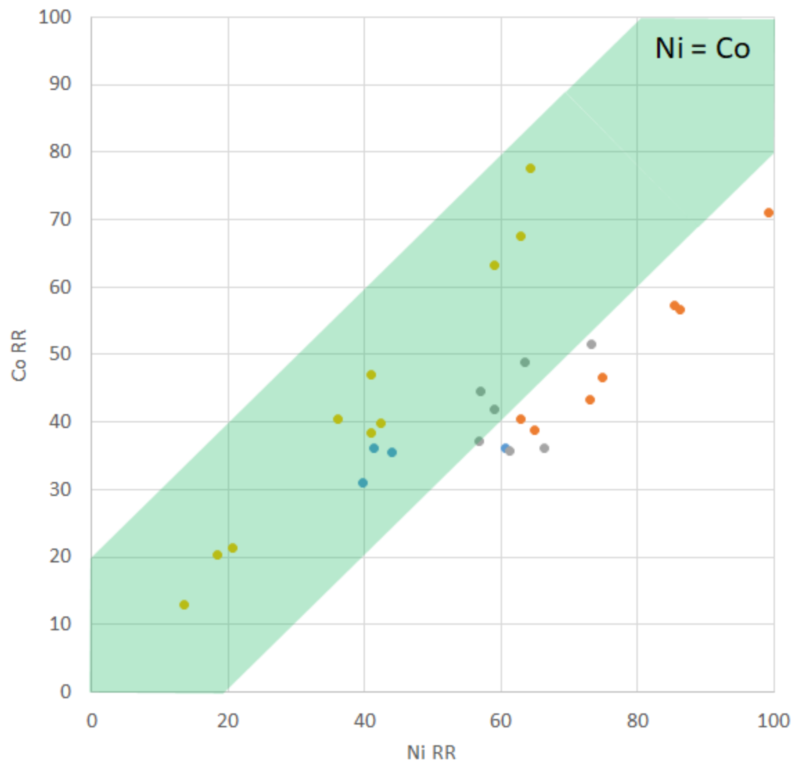

Figure 7: Relationship of Ni and Co RR values across individual samples.

3.3 Reverse Circulation (RC) Drill Product

Given the prevalence of RC drilling for exploration in the region, testing was conducted on RC samples both to test if they were a suitable source material for grade by size work and to provide information on sites that do not have available drill core. Three sites provided RC samples (designated Sites 4, 10 & 11), all of which are gold operations from the Kalgoorlie-Boulder. Site 4 provided both drill core and RC samples as described in section 3.1. The samples provided are detailed in Table 6.

Site	Number	Type
4	3	RC (& drill core as above)
10	10	RC
11	10	RC

Table 6: RC samples provided for testing.

Given the finer particles generated in RC drilling than crushing drill core, a different set of screens was required to provide useful data (Fig. 8). The difference in mass distribution increases at finer particle sizes. The P40 (40 % passing) value for the drill core and RC samples were 0.75 and 0.14 mm respectively. Testwork was conducted to select an appropriate screen set to use as a standard protocol for this material. The sizes selected were 1, 0.5, 0.212, 0.106 and 0.053 mm. While particle size distributions vary more between sample sources (likely based on ore softness among other influences) these screens provide satisfactory mass distribution between the size fractions from all of the samples tested (Fig 9). The variation in PSD between samples dramatically increases in the finer size range with the P40 value of the softer material decreasing to 0.053 mm from 0.18 mm in the hard ore. The selection of screens must thus be appropriate for all to minimise the bias in metal distribution between hard and soft material.

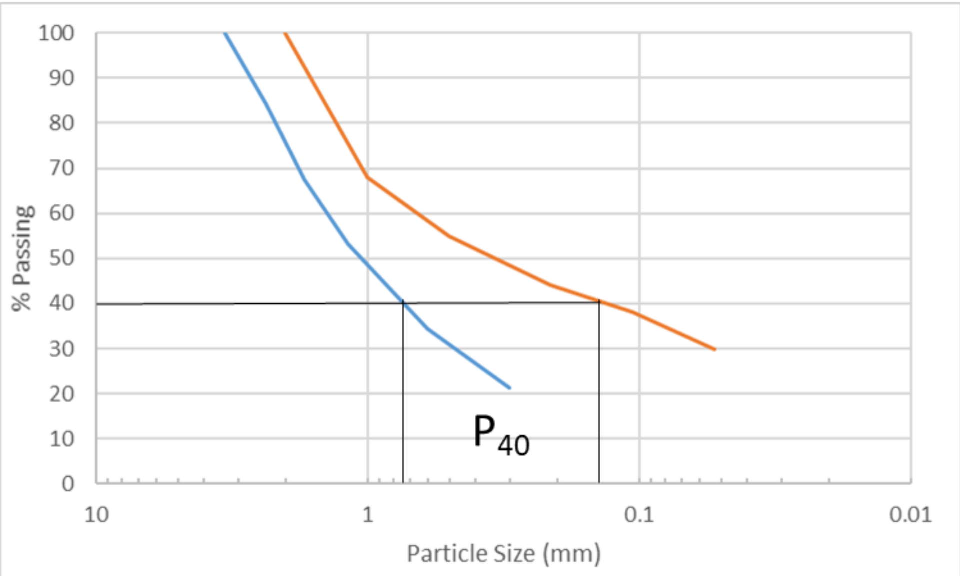

Figure 8: Comparison of the PSDs from a sample of crushed diamond drill core and an RC sample from similar ore types.

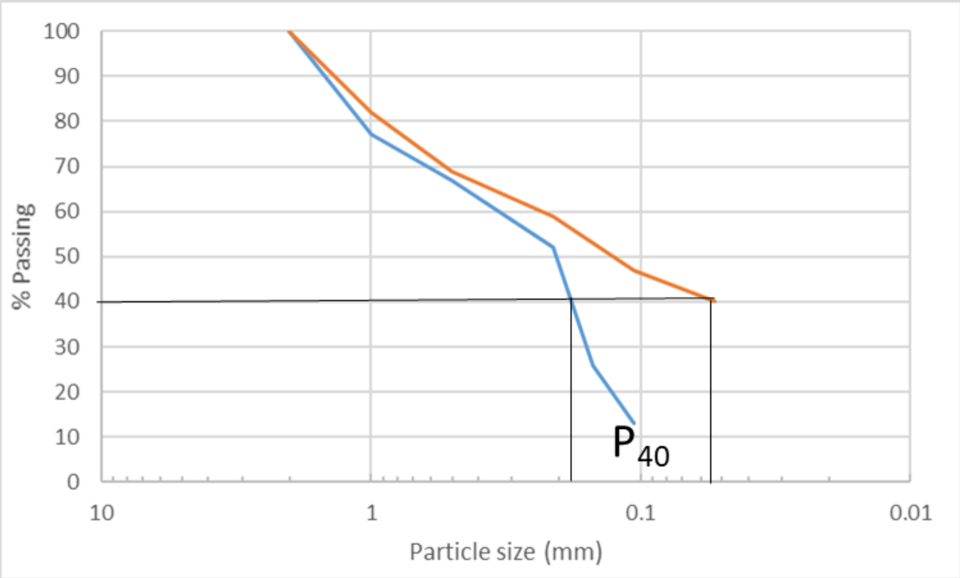

Figure 9: Comparison of the PSDs from RC samples of ores of different hardness.

The average RR values obtained from the samples described in table 6 are presented in table 7, and the distribution of individual sample RRs as well as a selection of curve fits are shown in figures 10, and 11.

Site	Commodity	Average Head Grade (ppm)	Average RR	RR Range	% Passing QAQC
4	Au	1.49	100	50 to 139	33
10	Au	2.76	-99.4	-600 to 4	30
11	Au	1.38	34	-83 to 98	30

Table 7: RR values obtained from the samples detailed in Table 5.

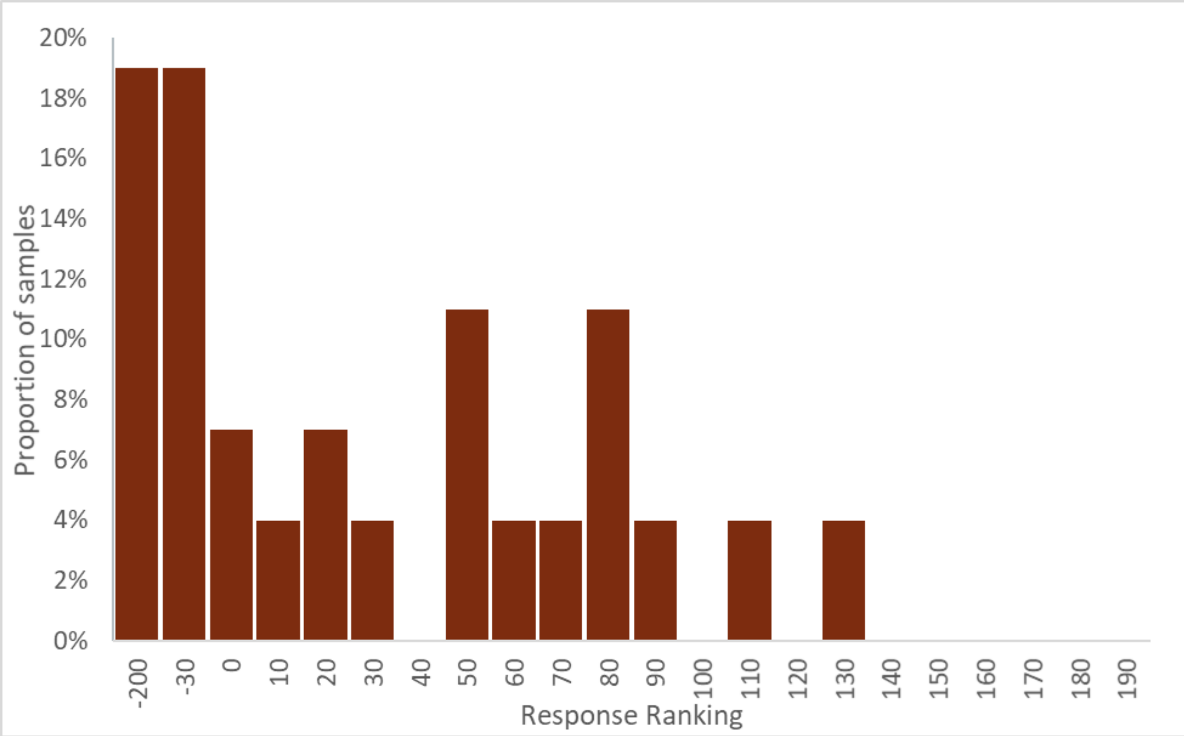

Figure 10: RR distribution for RC drill samples.

A significant proportion of the RRs provided negative numbers, which from a basic perspective indicates preferential deportment to the coarser fraction. Given the fine particle sizes considered here, this may be due to the finer sizes being below the liberation point of the valuable mineral and thus not indicative of what would occur at larger scales. Such results then beg the question as to whether these values are indicative of the behaviour of the material or artefacts of the fine particle size distribution. The fact that the majority of the negative values are from site 10 and some samples from sites 11 and 12 provided strong positive values suggests there is potentially some legitimacy in the values.

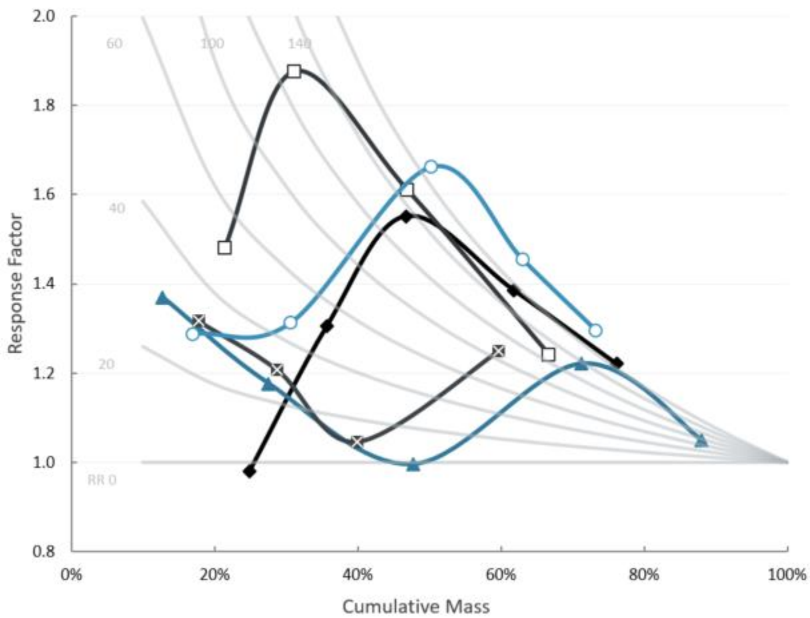

Figure 11: Example curve fits from RC samples.

As can be seen in several of the examples above, there is an initial increase in grade (roughly following correct curve fitting) followed by a decrease below a certain size range. This has been observed in previous CRC ORE drill core testwork and may indicate that the particle size is below the level of metal liberation, which may induce an incorrect analysis as it creates an artefact of apparent reduced metal deportment. This is indicated by the bird-wing shape RF vs mass retained plot as shown in the example in Figure 12. For these samples there was a lower limit of effective upgrade between 0.1 and 0.05 mm. A significant proportion of the material from these samples were below this level.

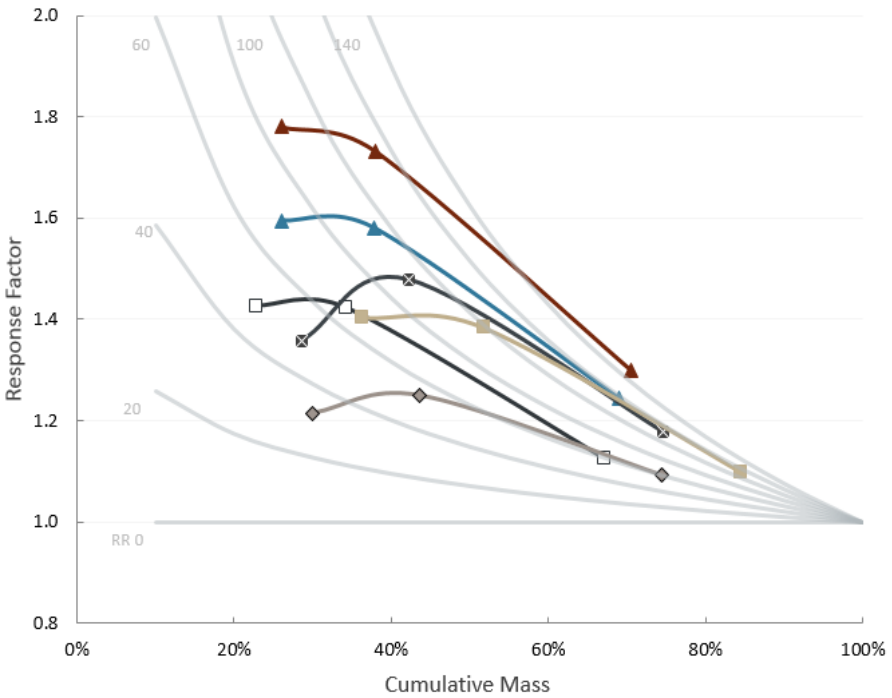

Figure 12: Example of samples displaying the 'bird-wing' curve shape.

Currently, we have isolated information regarding RC drill material in that there is no corresponding drill core or larger scale testwork to directly link the values obtained to a trusted indicator or actual bulk outcome. It can thus not be concluded one way or another whether this sample source is a viable material for this testwork or whether the outcomes from any given site are reliable. It must be considered that while these may be a legitimate indication of real deportment for some sites, it may not be suitable for all sites. Therefore, a larger sample set is necessary and comparable larger samples must also be tested to determine whether they display similar characteristics.

Conclusion

Several sites within the Western Australian Goldfields show significant potential for separation by size to provide value their operations. This is particularly the case where either marginal grades are present or growing distances from face to surface and/or mine to mill are vastly increasing transport costs. Gold sites displayed significant variation in response as expected, while all nickel sites tested showed significant upgrade in the finer fractions of both nickel and cobalt. RC samples are a compelling sample option due to their prevalence and self-preparation for screening, however, there remains a question as to the legitimacy of the results they generate.

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