CRC ORE White Paper

CRC ORE - Grade Engineering and GE View

Author: Jon Rutter

Curtin University

mriwa
Minerals Research Institute of Western Australia

CRC ORE

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Optimising Resource Extraction

White Paper: CRCORE - Grade Engineering and GE View

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Jon Rutter[1]

1. CRC ORE

Name of project: GE View

Project leader: Jon Rutter

Enquiries and additional copies:

Cooperative Research Centre for Optimising Resource Extraction (CRC ORE)
Queensland Centre for Advanced Technologies (QCAT)
1 Technology Court, Pullenvale QLD 4069, Australia
PO Box 403, Kenmore QLD 4069

07 3161 6657 | crcore@crcore.org.au | www.crcore.org.au

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1 Who is CRC ORE

CRC ORE is an Australian not for profit organisation funded by the global minerals industry and the Australian Federal Government. It is a collaborative research centre (CRC) responsible for furthering research to optimise resource extraction (ORE). The organisation's key objective is to ensure that it delivers significant economic, environmental and social benefits to Australia. CRC ORE aims to transform the minerals sector by deploying innovative world-class technology to effect a step change in value across the whole-of-mine system. It will assist to 'Optimise Resource Extraction' through site implementation of innovative technology and applied research to improve overall productivity.

Its prime directive is to identify and implement innovative solutions that can improve operational value and reverse the marked trend of declining productivity over the last decade. CRCORE aims to achieve this through applied innovation, technology development and technology transfer focus rather than undertaking fundamental research. This is based on the view that there is abundant existing and latent technology already available which has not been integrated on mining sites or needs to be accessed from other sectors.

CRC ORE is focused on radically improving the productivity, energy and water signatures of our mining operations. We are also dedicated to reversing the 'conventional wisdom' of grade decline through new gangue rejection techniques. CRC ORE research projects investigate all elements of the mining process, seeking opportunities to optimise the system through better understanding of the processes and the synergies between processes. This includes ore body characterisation, geometallurgy, blasting, comminution, mine planning and economic evaluation.

CRC ORE commenced in mid-2010 and after its initial 5-year funding term, was awarded a further 6-years of funding until July 2021. CRC ORE has achieved support of over $110m in investment to achieve critical mass and capacity. This includes $34.4m in federal funding, with the remaining investment through Mining Companies, METS and Research participants.

1.1 The Industry Changes

The 'Millennium Super Cycle' from 2003-11 was an unprecedented period of growth and investment resulting in increased throughput and development of lower grade resources to meet demand (Downes et al, 2014; Sheehan, 2015). The urgency to bring production to market quickly stretched people, project and management resources.

Now prices have declined the industry is left with a legacy of high costs, declining ore quality and less efficient operating practices (Pease et al, 2015). For example, the average grade of copper ore mined in 2020 will be half what it was in 1990. Along with other challenges (less efficient site logistics, higher stripping ratio, treating more complex ores, etc.) it will take more than twice the activity to produce each tonne of metal (Pease et al, 2015). This is particularly evident in Australia where multi-factor mining productivity has dropped 50% over the last decade (Syed et al, 2015).

The overall trend of decreasing feed grades is shown in a comparison of normalised Cu grades for a selection of world-class Chilean Porphyry Cu operations between 1999 and 2012 (Figure 1). This shows relative feed grade decline of 25-50% over the last decade which is projected to continue over time under current mine planning and scheduling concepts. Over the last 20 years the average head grade for Anglo American platinum operations has decreased from ~5.5 g/t to just below 3 g/t (Rule et al, 2015).

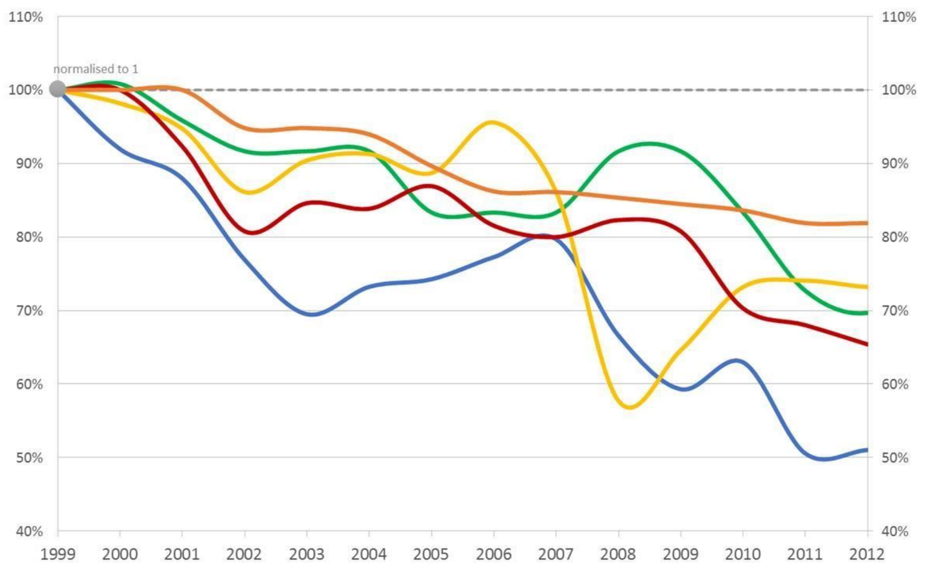


Figure 1: Comparison of normalised Cu feed grades to the concentrator for a selection of world-class Chilean Porphyry Cu operations.

There are many factors contributing to overall productivity on large mining operations. These can be divided up into supply chain and value chain influences. The supply chain represents the costs of goods and services. During the boom cycle hyperinflation contributed to a significant loss in productivity. This has been addressed by a return to more normal pricing and by structural reforms in major mining companies often involving reduction of skilled workforce. Value-chain factors relate to the quality of ore mined and the overall efficiency of mining and mineral extraction in generating a saleable product. Increasing scale of operation is widely regarded as a key driver of productivity (Mudd, 2004; 2009). While this generated significant benefits in the 1990's as the size of individual units such as trucks, SAG mills and overall material movement increased, the benefits diminished during the boom.

This reflects a reliance on multiple rather than larger units (more trucks, additional concentrators, etc.), increased complexity, reduced operator skills, and poor integration across unit operations which has resulted in declining equipment productivity indices. During the boom quantity became more important than quality with throughput the key metric. This was accompanied by a general trend of decreasing feed grades across all commodities which was offset with higher production volumes. Simply increasing the scale of operations can greatly increase cost, which in turn may have negatively impacted the feasibility of many projects.

Current industry perception is that declining feed grades are an unavoidable consequence of ore deposit geology and mass mining technologies for increasingly mature mining operations (West, 2011). In typical crush-grind-float operations value recovery only takes place at ~100micron particle size involving 3-4 orders of magnitude size reduction compared to primary feed. For increasingly low grade deposits the cost of energy and capital intensity required to process and reject worthless material at micron scale drives poor productivity.

An alternative is to deploy a range of coarse rejection technologies. Grade Engineering® is an integrated approach to coarse rejection (~10-100 mm) that matches a suite of separation technologies to ore specific characteristics and compares the net value of rejecting low value components in current feed streams to existing mine plans. The outcome for many base and precious metal operations is a significant increase in ROM feed grades that can be used to counter over reliance on throughput as the only available option to drive value.

2 Grade Engineering

2.1 Introduction 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. 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. ROM and post primary crushing are obvious intervention points with opportunity for separation conditioning during modified blast design (Figure 2). 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.

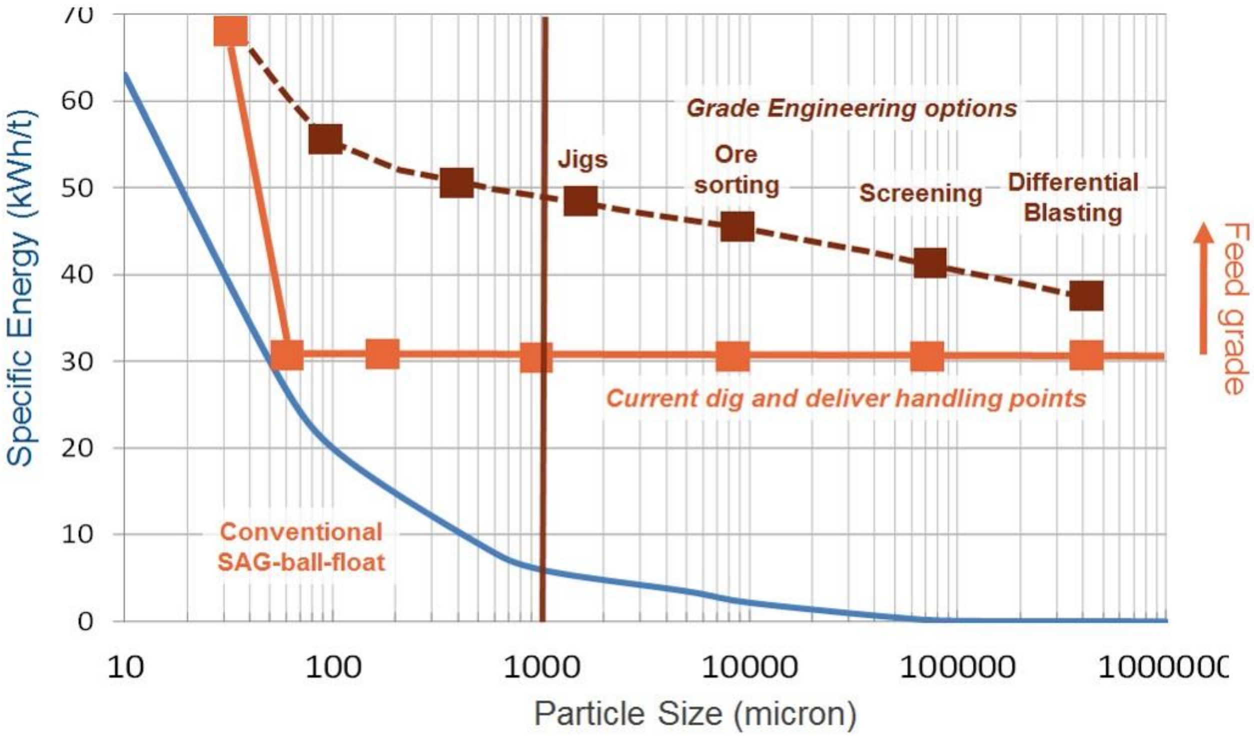


Figure 2: Schematic illustration of opportunity for Grade Engineering® intervention across all handling and feed transformation points relative to energy required to generate the size distribution.

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.

The concept of coarse separation or pre-concentration is not new and has been practiced from the beginning of mining as hand picking (Wills and Napier-Munn, 2015; Salter and Wyatt, 1991; Wotruba and Harbeck, 2010). For example, the propensity of some ores to break preferentially during blasting and crushing leading to an increase of valuable phases in finer fractions has also been widely known but rarely exploited at production scale (Bowman and Bearman, 2014). A notable exception was pre-concentration carried out in the 1980s at the Bougainville Copper Limited Panguna Cu-Au mine in Papua New Guinea (Burn and Grimes, 1986; Paki and Koginmo, 1988). This involved a screening plant to upgrade marginal low grade ROM ores (0.22% Cu, 0.18 g/t Au) that exhibited preferential grade deportment into fines. The plant had a capacity of 35 Mt p.a. at a <32mm screening size, which produced a 50% Cu-Au upgrade in 38% retained mass.

Although there are examples of coarse pre-concentration generating value for some base and precious metal mining operations, there is no coherent system-based industry approach or standard methodology to assess optimal configurations for selecting specific technologies or equipment to deliver maximum value for specific ores and operational constraints. Grade Engineering® is the first large-scale initiative to focus on integrated methodologies to deliver maximum operational value (Pease et al, 2015).

Within the Grade Engineering® methodology developed by CRCORE, five technology options or 'levers' are utilized (Figure 3). Different levers respond to different rock properties. Grade heterogeneity and gangue liberation at a range of scales linked to the physical properties of specific ores define which lever will give the best return (if at all) and the optimal upgrade and mass pull opportunity.

Levers 1 and 2 involve size based separation and are typically exploited at ROM and primary crushing stages using screening. Levers 3 and 4 involve sensors diverting material at truck or conveyor scale. Lever 5 is typically used after secondary crushing using DMS or jigs.

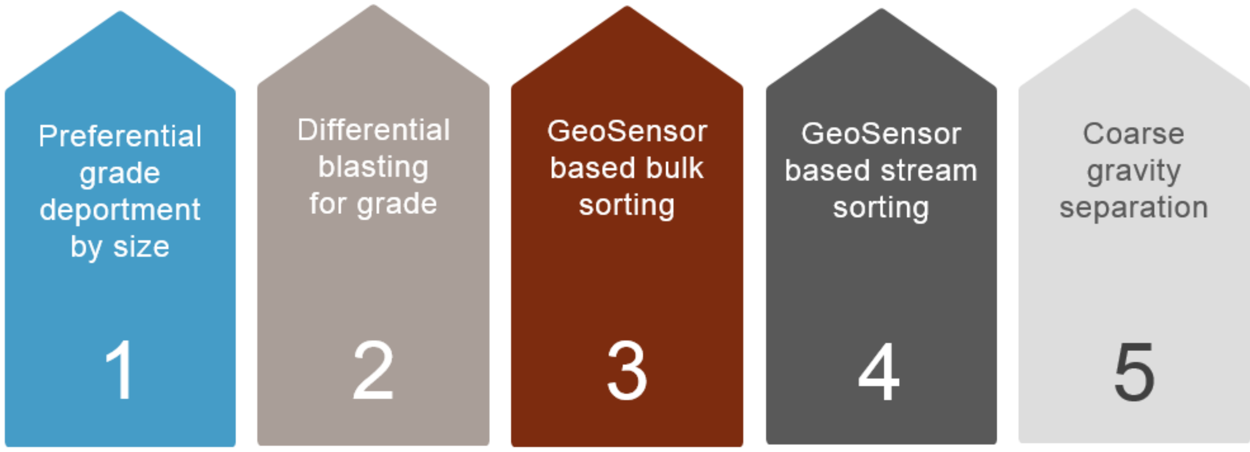


Figure 3: CRCORE's Grade Engineering coarse separation levers

2.2 Preferential Grade Deportment by Size

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.

Grade by size testing involves screening or sieving of a particle size distribution resulting from sampling production scale blasting (+/- primary crushing) material, or from crushing drill core using a defined protocol. A minimum of four size fractions are recommended to calculate a statistically meaningful grade by size response curve. The sampling and testing protocol is generally readily capable of being completed by most onsite laboratories, or any commercial laboratory of a sites preference.

Figure 4. displays preferential grade by size deportment is evident where there is a systematic change in grade across size fractions. CRC ORE has developed a methodology for transforming raw sizing and assay data into a set of cumulative responses that can be used to rank and compare magnitude of preferential deportment. CRCORE refers to these as a Response Ranking (RR). The Response Ranking is a function that can be passed into simulation and modelling packages to optimise circuits and develop a Grade Engineering business case.

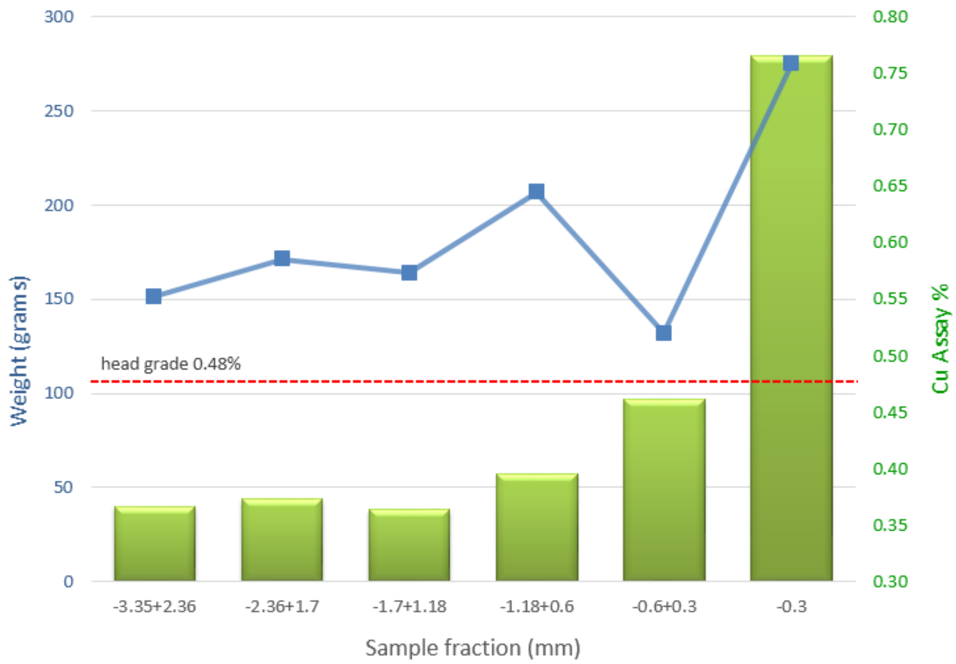


Figure 4: Example of raw grade by size assay and fraction mass data

Examples of grade by size Response Curves based on six size fractions for drill core coarse residues testing are shown in Figure 5, together with reference curves that represent the fitting function. Curve fits generate Response Rankings from 0-200 representing a theoretical preferential grade by size deportment maxima.

The Response Factor on the vertical axis of Figure 5 represents the upgrade of the metal, at that particular point of the cumulative mass, relative to the head grade of the sample. In Figure 5, Sample 3 has a Response Ranking (RR) of approximately 50, and the finest 25% of the sample mass has a Response Factor (RF) of 1.4. This indicates that this 25% mass, is 1.4 times the head grade of the entire sample. The Response Ranking refers to the average fit of the entire curve and does not change for the same sample. However, its Response Factor is variable, according to the selected cumulative mass.

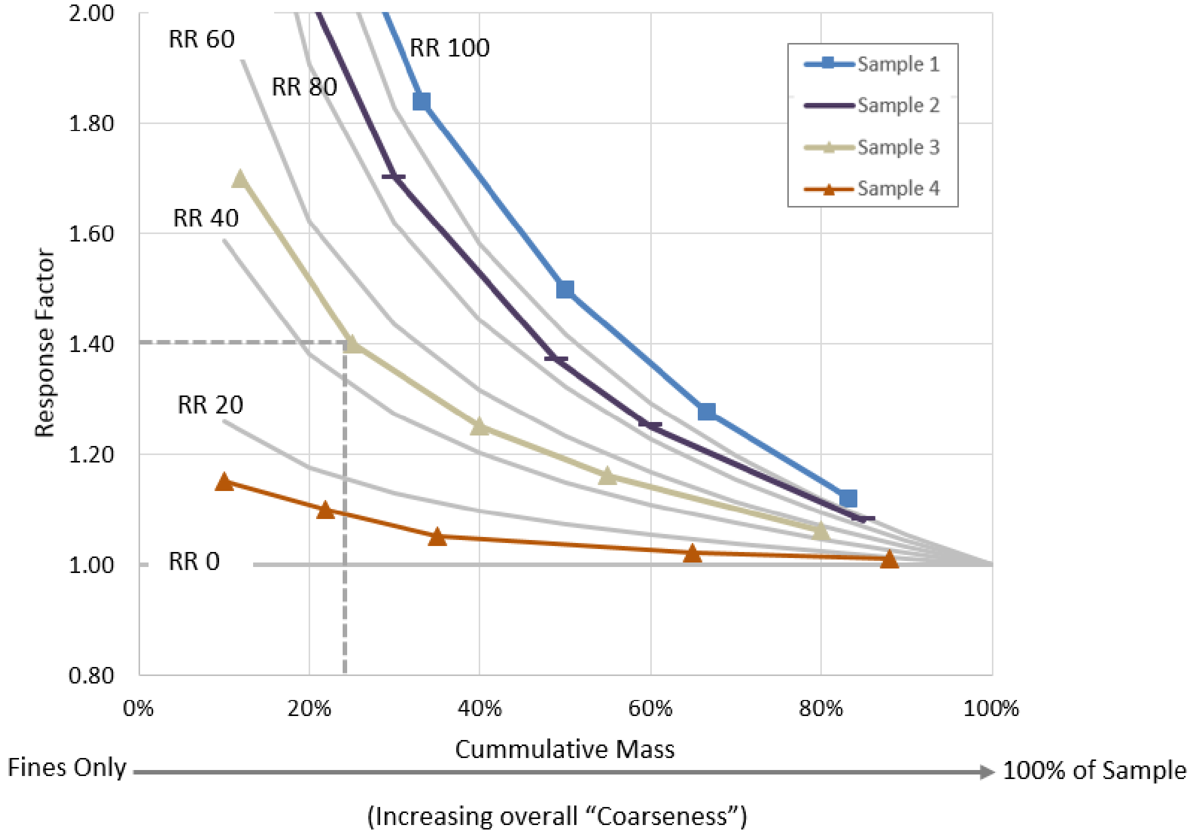


Figure 5: Example of calculated grade by size Response Curve for drill core testing. Pale grey curves are reference lines for Response Rankings.

2.3 Differential Blasting for Grade

Differential Blasting for Grade (DBG) involves conditioning of sub-volumes of material at bench or stope scale using customized blast designs that generate imposed size distributions with higher grade, concentrated in the finer fractions. This is referred to as Differential Blasting as it leverages the application of differential charge energies to different blastholes to achieve the desired result. Its amenability is a function of exploitable grade heterogeneity at blast/charge hole scale linked to the ability to impose and control different energy distributions within a blast design. As for Lever 1, physical separation is a function of screening.

DBG is designed to exploit in-situ grade variability for material that is currently "grouped" or assigned to a single destination at a typical grade control stage (eg: waste, low grade stockpile or mill feed etc). Figure 6 graphically displays an example of this variable grade distribution that may be targeted by DBG. The aim of differential blasting for grade is to apply significantly more blasting energy into high grade material to induce metal deportment into a finer particle size distribution (PSD). Low grade material is lightly fractured to create a low grade coarser PSD.

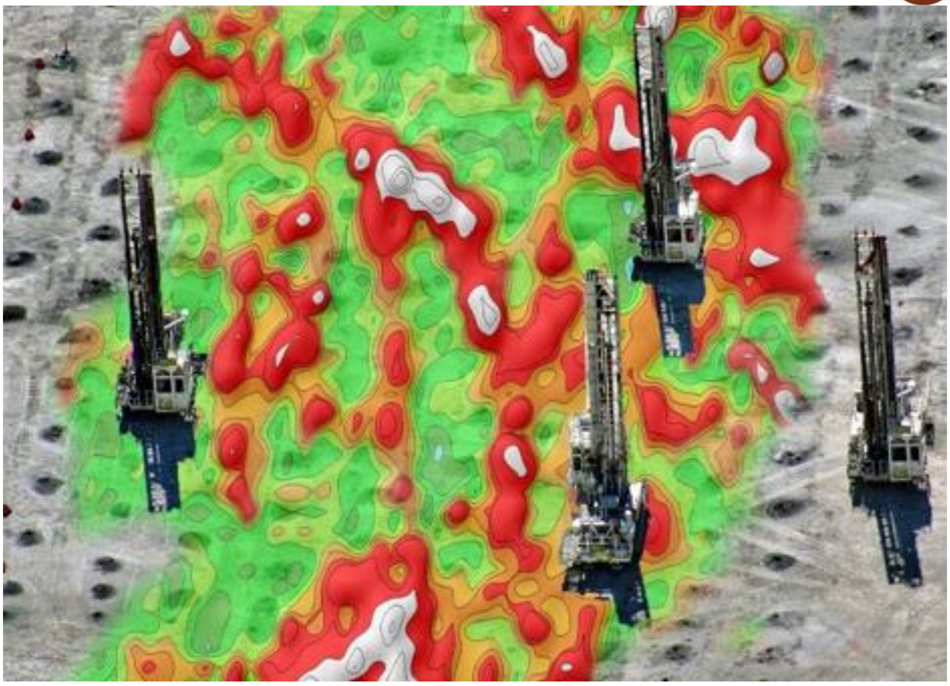


Figure 6: Example of grade variability that maybe exploited via Induced Grade by Size Deportment

The resulting generally bimodal grade by size distributions (Figure 7) can subsequently be separated using screening. Blast energy distribution is controlled by varying powder factor, explosive type, stemming intervals and in some cases blast hole spacings/designs.

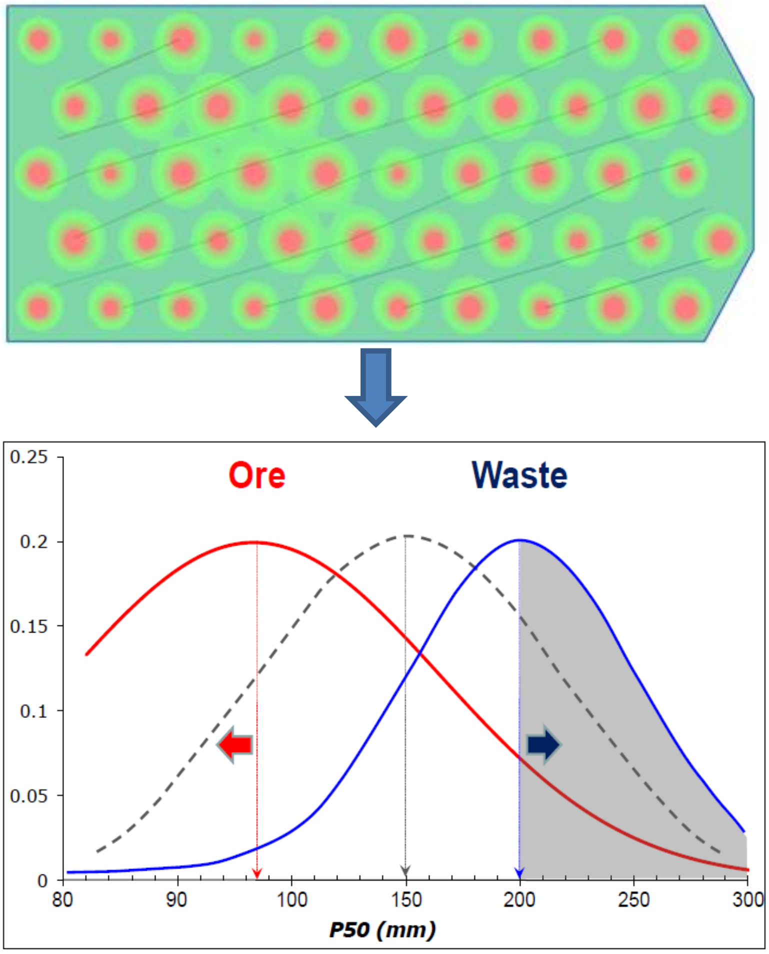


Figure 7: Differential Blasting Concept Diagram. High and low energy blastholes in the blast pattern (top) generate a bimodal Particle Size Distribution (bottom).

The efficiency and magnitude of upgraded screen feed is a function of in-situ spatial grade variation and optimal energy distribution involving discrete blasthole charging, with screen sizing typically in the order of 20-200 mm. Controlling particle size distribution to generate maximum Grade Engineering separation efficiency requires a new approach to integrated blast design which has been the focus of CRCORE.

Differential blasting for grade can be regarded as a more value-driven derivative of Mine to Mill drill and blast techniques developed over the last 15 years to increase comminution throughput. CRC ORE has developed blasting simulation software and undertaken initial bench scale trials on participant sites to validate the potential of this approach.

2.4 Sensor Based Bulk Sorting

There are many variables involved in determining what sensor or combination of sensors can add value to Grade Engineering coarse separation. This is a function of the nature of sensor-rock interactions; designing measurement geometries for optimal sampling statistics; short time to decision; operational detection limits: and production economics of coarse separation decisions.

A focus on specific sensor technologies potentially fails to recognize that heterogeneity of grade is typically accompanied by heterogeneity of rock attributes which affect sensor-rock equipment interactions and outcomes. Grade Engineering emphasizes that value must be fitted to specific domains based on coarse separation attributes and separation options. In this context a 'one size fits all' approach to coarse separation sensor technology is not appropriate.

Several key features of bulk sorting include;

- Bulk diversion at either Run Of Mine or Coarse Ore Stockpile sized material
- Scale of separation commonly in order of 100 to 1000's of tonne units
- Potentially applied to shovel, truck or conveyor environments
- Capable of dealing with the fines component of a rock mass
- Capable of handling large volumes; and
- Commonly senses on the metal/element or mineral directly

Coarse separation involves a yield-response relationship between grades of accept/reject versus mass splits that is common to all Grade Engineering levers. A small mass 'pull' typically results from setting an aggressive separation threshold which generates highest upgrade. For sensor-based sorting mass 'pull' is an outcome of sensor settings as a function of user-defined signal thresholds or a multi-component signal algorithm. This can be a direct measure for example as a primary PGNAA spectral peak for Cu or a discriminant function based on proxies that correlate with the element or phase of interest (e.g. XRT attenuation as an indicator of dense phases).

Since most on-line coarse sensors provide semi-quantitative low resolution data, these thresholds are established by laboratory testing and calibration and are often matrix dependent. Testing can be a tedious and costly process that discourages extensive comparative evaluation between sensor technologies for ore type variability. Lab testing outcomes can also be difficult to scale up given that on-line coarse sensing is potentially sensitive to attributes such as dust or poor sampling statistics.

Diverting feed volumes based on bulk grade sensing at truck or belt section scale is highly attractive if there is sufficient heterogeneity in current destination assignments to support separation.

Establishing if a sensor technology is technically capable of informing this coarse separation decision point is a relatively routine laboratory calibration process. However, predicting and propagating bulk sensor-based grade pod-scale separation into the resource block model is much more challenging. In many respects this is an issue of grade variability versus discrete separation volumes such as shovel or truck loads, or belt intervals of feed conveyors. It is essential that sufficient heterogeneity at the appropriate scale (shovel, truck or conveyor "pod"), delivers or maintains different grades to warrant coarse separation/diversion.

This cannot be established by lab testing and requires a simulation and modelling approach around in-situ grade, and subsequent validation. This requires information on yield-response embedded in the resource model to optimise outcomes. Bulk sorting and differential blasting are to some extent competitive and alternative Grade Engineering levers. While sensor-based bulk sorting would be expected to have a more precise and sensitive sensor-rock interaction than differential blast design giving superior yield response, this will be reduced by mixing of in-situ grade heterogeneity by material movement during blasting and digging

Sensor-based bulk sorting opportunity should be viewed in the same context as other Grade Engineering levers and decisions. It is as essential, if not more essential, to establish the value of deploying bulk sorting technology into specific operation types, than trying to accurately determine the technical merit of individual sensor technologies in what is a complex METS supplier landscape. Added to the requirement of determining the financial value of bulk sensing, is the reality that sensor-based sorting is only one potential Grade Engineering lever not a single point solution. Net value will only occur in specific domains based on grade heterogeneity and efficiency of sensor/ore type interaction, and is unlikely to be suitable to the entirety of a deposit.

CRC ORE is continuing to develop systematic and routine integrated methodology to establishing ore type specific Response Rankings for sensor based bulk sorting / separation potential.

2.5 Sensor Based Stream Sorting

The initial impetus for particle sorting was industrial waste recycling and food processing, and these were the major driver for initial sensor technology development. It was subsequently modified and adapted for application to the minerals processing industry.

Several key features of particle sorting include;

- Requirement to pre-screen material into specific size fractions
- Mechanical or air jet ejection of selected particles
- Inability to incorporate or sort the fines fraction
- Small or modest throughput rates (generally low 100's of tonnes/hr); and
- Commonly senses via proxy attributes rather than metal/element directly

Many particle sorting applications involve individual air jet or mechanical ejection of many sensed particles on conveyors or in falling streams (Figure 8). Scaling and adapting existing sorting equipment and recycling-driven concepts for the bulk mining industry has so far failed to generate widespread uptake, though this is changing as new technology has evolved in recent years.

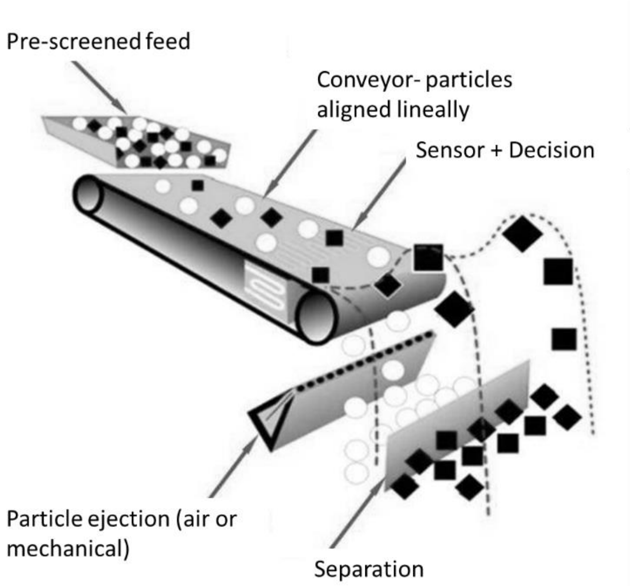


Figure 8: Schematic of key components of particle sorting

Value opportunity for stream based particulate sorting shares similar Grade Engineering characteristics to preferential grade deportment by size, in that grade selectivity is below any existing data collection resolution (eg: drill assay data). This generally means that new data generation or testwork needs to be completed. Hence, defining the opportunity for particulate sorting requires laboratory test work and standard protocols. These protocols can be combined with preferential grade by size testing given they share a common screening component.

It also means that the two levers can act together by operating on screened size ranges and textures. As particle sorting leverages the metal deportment into specific particle size ranges, it is important to consider that optimising or 'pre-conditioning' the particle size delivered to a sorter will optimise the financial value of the technique. This can be achieved through either optimising the metal and mass deportment with the most appropriate screen size via Preferential Grade Deportment by Size, or conditioning the particle size distribution to deliver the most appropriate particle size.

There is a compounding value to this pre-screening or pre-conditioning decision when the relatively low throughput rates of particle sorters is considered. Rather than the traditional mining metric of "tonnes / hour", a better metric for particle sorters is "particles / hour". Hence if the selected pre-screen or conditioning is optimised to the metal deportment, larger "net tonnages" may be achieved with the combined levers of upgrading via screening, and subsequent particle sorting of the targeted fraction. The Response Ranking generated by the multiple levers may be additive and this must be taken into account during testing programs.

Particle sorting commonly measures thresholds are often based on single or multivariate discriminant functions that may utilise proxies for the element or phase of interest which are present at higher abundance levels. The simplest example is using optical sensing as a proxy for gold. These functions are set up using lab scale calibrations but care must be taken to ensuring they are effective for the full range of ore types and domains targeted.

2.6 Coarse Gravity Separation

Gravity separation is one of the oldest methods of ore treatment and is widely applied in the industry. The challenge is to extend gravity methods into coarse separation and integrate opportunity with the other Grade Engineering levers.

Gravity separation involving dense media or jigging is well known and proven. One of the most significant examples is use of dense media to 'wash' coal and remove non combustible impurities. The use of coal washability curves to represent and value this upgrading approach are well documented. The Grade Engineering challenge is to extend gravity separation into coarser sizes to provide an additional competitive lever in the 'dig and deliver' interface before secondary crushing.

Dense medium separation (DMS), also known as heavy medium separation (HMS), is an established gravity separation technique of mineral beneficiation that utilizes a nonsettling dense medium (or "heavy liquid") to separate valuable mineral and the unwanted waste mineral based on distinct specific gravity (SG) difference in a sink-float process. The other requirement for DMS to be feasible is that the valuable mineral must be adequately liberated (broken free) from the unwanted waste mineral during the crushing phase. DMS utilizes the difference in material density between liberated particles as the separation mechanism.

The separation in a dense medium strongly depends on density differences between light and heavy particles, their size and the stability and rheology properties of the medium. The density differences have a similar relationship to inter-grade deportment within size fractions, currently assessed and exploited through Grade Engineering® techniques. The dense media can cut or separate, on density similarly to how a screen cuts on size to produce mineral value separation.

Essentially when an ore is introduced into the dense fluid medium some mineral particles will be denser (heavier) than the dense medium and will sink, while other particles will be less dense (lighter) than the medium and will float on top of the medium. While there is no absolute answer to the precision of the separation capability (as it is often dependant upon specific ore types and the dense media liquid selected), separation points at 0.1 to 0.2 SG increment units is feasible.

Effective separation by DMS depends largely on three factors:

1. • Suitable degree of liberation and intergrade deportment based on size fractions
2. • Settling rate of particles; and
3. • Difference in Specific Gravity when
    - compared against the medium in which they are being separated

The application of DMS preconcentration, and its success, is very site- and ore-specific. Theoretically, HMS /DMS can be applied to an unlimited size range. In practice, the ore's mineralogy (mineral liberation sizing) and economic considerations determine the feed top size. The feed top size for an ore is the coarsest size with economically acceptable mineral losses to the tailings within the materials handling size limit of the process equipment. Top sizes above 300 mm are unusual. The bottom size is dictated by the economics of media recovery (usually 28 to 35 mesh).

Potential benefits attributed to HMS /DMS application include;

4. • produce a finished concentrate and a final waste product in one operation
5. • reject a waste product at a coarser size, thereby saving grinding costs
6. • achieve separation at a low operating cost with low maintenance costs
7. • make relatively sharp separations
8. • operate continuously
9. • tolerate feed with wide size distributions, and
10. • produce a consistent product for further processing

Potential disadvantages attributed to DMS application include;

11. • increased circuit complexity
12. • coarse particle sampling difficulties leading to increase potential error in reported plant metallurgical balance, and
13. • security risk for coarse particle high gold content concentrates

In Line Pressure Jig (IPJ) technology efficiently pre-concentrates ore particles using gravity separation, mechanics and fluid dynamics (Figure 9). IPJ uses less power and lower water than traditional jigs. The technology has been successfully employed on a number of diamond, base and precious metal operations and typically generates up to 30% of feed mass as a concentrate. IPJ can handle a top size up to 30mm and operates optimally between 10 mm and 200 microns.

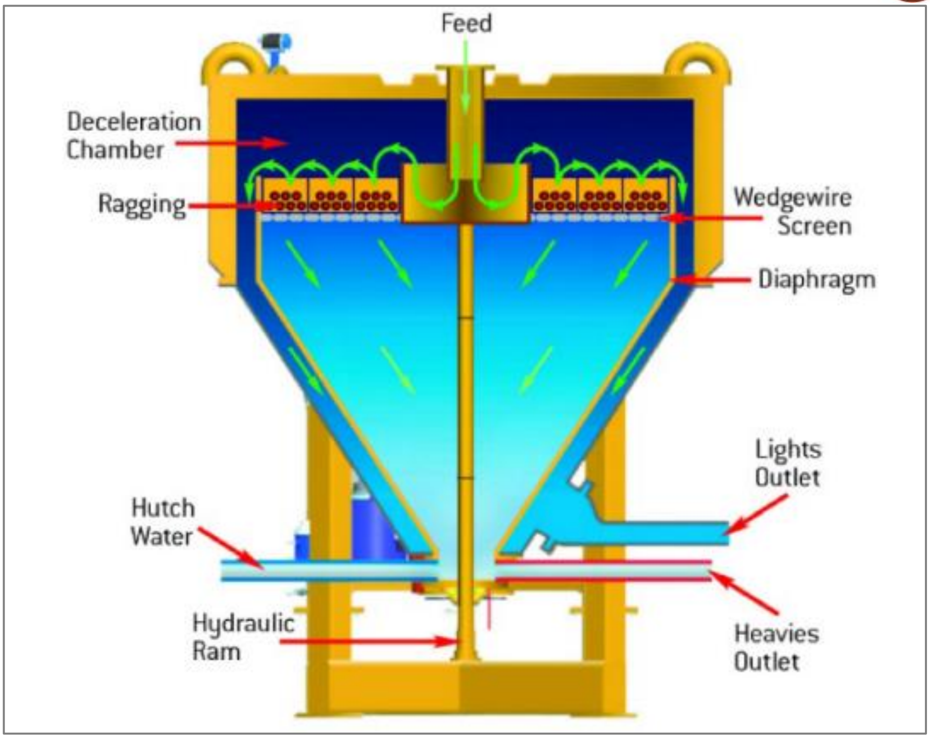
14. 

Figure 9: Schematic of key components of an IPJ

Use of IPJ requires secondary and tertiary crushing to prepare feed with a fines bypass, and relies on gangue density differential and liberation of some clean gangue at coarse size. A range of operating parameters can be used to change or fine tune performance in response to ore type variation.

Similar to DMS technology, the challenge in CRC ORE is to integrate the opportunity and value for IPJ as a potential Grade Engineering lever as part of an integrated comparative assessment.

2.7 Economic Exploitation

While high RR's drive opportunity, magnitude of RR is only one component in determining if there is improved value in exploiting coarse separation within a mine schedule. As noted the key aspect is that one or more of the separated streams has a new grade value that changes the destination decision and net value of the original bulk volume destination. For this reason maximum economic Grade Engineering® impact occurs through operational application of coarse separation around existing cut-off destination grades. This is illustrated schematically in Figure 10 which shows change of destination opportunity around a given gold cut-off grade as RR values increase (response) and mass retained (yield) is varied based on a simple binary waste or mill decision.

The box and whisker type plots indicate feed grade and resulting separated grades for a range of RR's and the area of opportunity where one of these products is amenable to a different destination. While area of opportunity enlarges with increasing RR there are still defined grade limits which constrain operational decisions. For high grade ores, for example, even with high RR there can be no change of destination decision if both separated streams are still mill grade with no economic rationale for intervention. As mass retained is dynamically manipulated this changes grade limits for intervention typically increasing with low yields. Yield manipulation is a function of changing feed conditioning; equipment settings such as screen apertures for levers that generate size differences; or changing sensor activation thresholds. This generates a dynamic interplay between separation functions with implications for advanced process control in Grade Engineering® circuits (Carrasco et al, 2016).

Like other variable rock property attributes, it is important that RR's are populated into the resource block model using a combination of physical laboratory, bulk scale testing and simulation using geometallurgical concepts. This provides an additional set of assigned block values and functions that can be dynamically manipulated for both grade and mass using Grade Engineering® compared to a traditional fixed block grade attribute.

The resulting Grade Engineering® value opportunity is only optimised after rescheduling to exploit new block model attributes linked to user-defined operational constraints such as equipment sizing, digrates, NPV, etc.

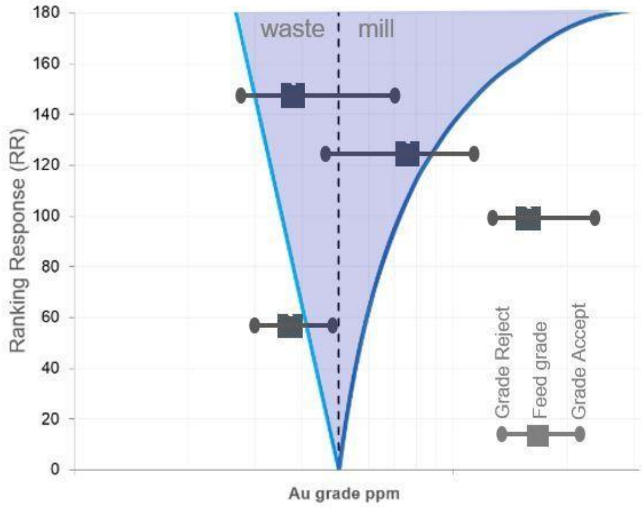


Figure 10: Change of destination opportunity around a given cut off example. As RR increases (the response) for a set mass yield, the opportunity to generate different products becomes apparent.

3 GE VIEW.WA PREOJECT

A key driver for coarse separation is the concept of grade heterogeneity – variability of grade below conventional minimum mining unit but within coarse separation scale. Resource drilling data can be used to assess first order Grade Engineering opportunity by defining localized grade heterogeneity typically smoothed in current resource estimation and mine planning. This smoothing approach, traditionally used in many operations, ignores potentially exploitable grade heterogeneity below the scale of minimum mining unit even though significant localized grade heterogeneity is a dominant characteristic of many gold and base metal deposit styles and ore types.

CRCORE in conjunction with support from MRIWA, is completing a research project to;

- Develop a heterogeneity/variability index method
- Defining deposit styles better suited to exploitation with Grade Engineering assistance
- Development of a Kalgoorlie-Boulder Mining Innovation Hub

3.1 Minerals Research Institute of Western Australia

The Minerals Research Institute of Western Australia (MRIWA) is a statutory body established by the Western Australian Government under the Minerals Research Institute of Western Australia Act 2013 to stimulate minerals research to support investment in, and operation of, a globally competitive minerals industry in Western Australia.

MRIWA's primary function is to provide and administer funding grants to carry out minerals research. The Institute collaborates with local, Australian and worldwide research and scientific institutions and is also able to undertake and procure minerals research itself.

GeoVIEW WA is an online public-domain GIS-based portal that allows users to view, query, and map various geology, resources and related datasets for Western Australia that provides unprecedented access to information from both producing and historical mines and prospects. This is developed and hosted by the Dept of Mines, Industry Regulation and Safety within the WA Sate government (http://www.dmp.wa.gov.au/GeoView-WA-Interactive-1467.aspx). Figure 11 is an example of the GeoVIEW. WA platform.

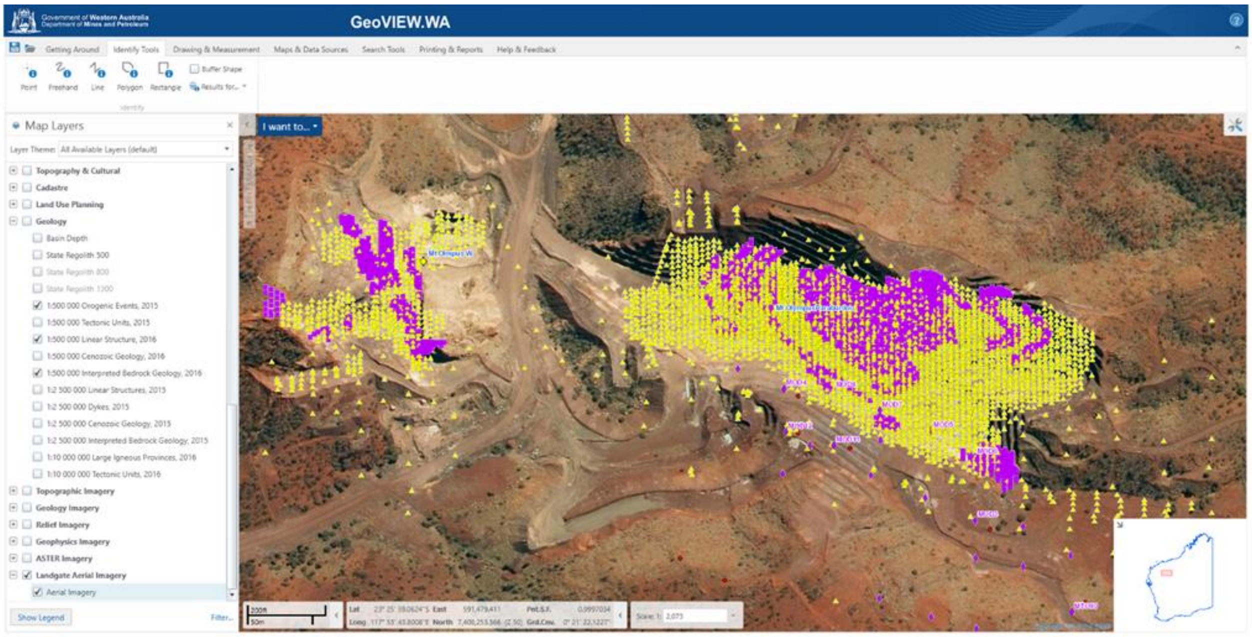


Figure 11: An example of drilling data from GeoVIEW.WA

Access to significant digital resource definition drilling information makes GeoVIEW WA a unique data resource compared to other States and Territories within Australia. CRCORE and MRIWA undertook a development project to show the feasibility of utilising GeoVIEW WA information into a database and using this to filter and potentially qualify Grade Engineering opportunity across a range of commodities and deposits in WA.

The ultimate aim is apply a new Grade Engineering lens on existing mining operations in WA to extend their Life Of Mine, re-invigorate operations on care and maintenance or unlock stalled feasibility projects, and to provide examples or opportunities of how these may be applied on WA deposits.

This has project was termed the 'GE.VIEW.WA' proposal with 'GE' denoting Grade Engineering, and 'VIEW.WA' referencing the world class Geoview.WA database developed by the Western Australian government.

3.2 Grade Engineering Levers and GE VIEW.WA

There are several key concepts within Grade Engineering that cannot be directly correlated to datasets that are sourced primarily from ***drilling assay data***. This can be summarised as;

1. Preferential Grade Deportment by Size → Drill scale assay grade or variability independent
2. Differential Blasting for Grade → Drill scale assay grade or variability **dependent**
3. Sensor Based Bulk Sorting → Drill scale assay grade or variability **dependent**
4. Sensor Based Stream Sorting → Drill scale assay grade or variability independent
5. Coarse Gravity Separation → Highly scenario/site specific

PGS currently requires a simple but specific characterisation laboratory test. Variability of grade is not a definitive measure of its amenability to Grade Engineering, and nor does PGS amenability correlate to head grade. While sensor based stream (particle) sorting does effectively utilise grade, it is at a scale that is not represented by regular or standard drilling data intervals. Specific scale relative (particle) testwork is required to evaluate this GE lever. While Coarse Gravity Separation does commonly have some significant correlation to grade, once again it is not necessarily at the same scale as drilling data. It is also commonly highly specific to mineral and site specific scenarios. However, both Differential Blasting for Grade and Sensor Based Bulk Sorting have a GE opportunity that can be initially reflected by the drilling assay variability.

*Coarse Gravity Separation in the context of this discussion regarding Grade Engineering, **excludes well established and utilised techniques such as coarse gold separation via cyclones, spirals and gravity tables etc.***

As only 2 of the 5 Grade Engineering levers currently have a preliminary ranking or amenability assessment from open file drilling data, CRCORE has developed a probabilistic Grade Engineering matrix based on its experience in evaluating various deposits and mineralisation styles (Figure 12). The amenability matrix is not geologically comprehensive, and does not attempt to incorporate all geological styles and models.

Geological Style	Mineralisation Style
Mesothermal	Vein Stockwork
VMS / Stratabound	Stockwork Massive / Semi Massive
Porphyry	Vein Breccia Disseminated
Laterite	Matrix/Disseminated
Differentiated Intrusive	Massive / Semi Massive Disseminated
Komatiite	Massive / Semi Massive Matrix Disseminated
Sedimentary Replacement	Stockwork Massive / Semi Massive Disseminated
Epithermal	Vein Stockwork Breccia
Pegmatite	Vein

Figure 12: Grade Engineering probabilistic amenability matrix utilised for 3 preliminary Grade Engineering Levers

Once a selected geological style is chosen, a limited mineralisation style relative to that choice is then selected. This generates a probabilistic amenability for PGS, Sensor Stream Sorting and Coarse Gravity Separation (Figure 13).

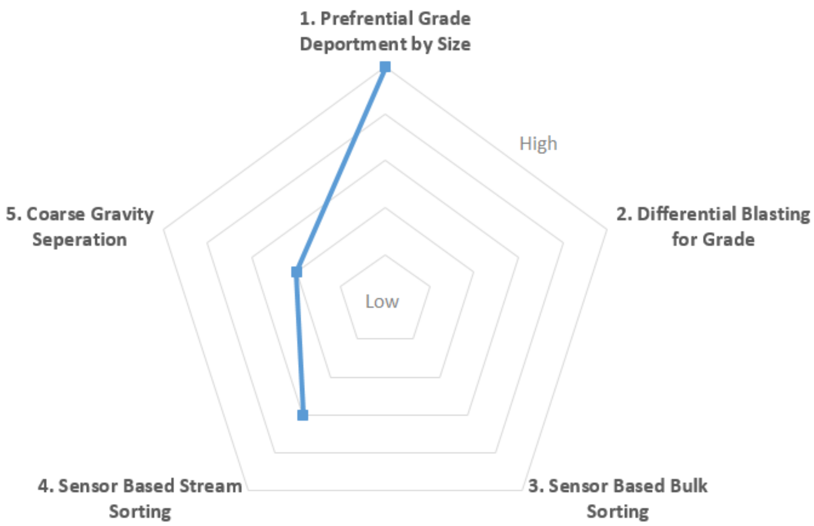


Figure 13: Probabilistic amenability

The probability matrix provides a preliminary assessment of the 3 GE levers that may be suitable to the selected geological environment and mineralisation style. The additional 2 levers (DBG) and Bulk Sorting) undergo a preliminary assessment by utilising drilling datasets (eg: resource drilling). A heterogeneity analysis (Rf25) utilising the drillhole assay data completes the preliminary Grade Engineering opportunity as described below.

3.3 Methodology and Heterogeneity Analysis

GeoVIEW WA is an online GIS based mapping tool with numerous geoscientific fields included. The data is submitted from exploration and mining companies. The WADMP has collated much of the available data and is now in a standard format for a GIS system. A key component for the 'GE.VIEW WA' program is to use this base data and import into a 3D system for spatial analysis.

3.3.1 Heterogeneity Analysis - "RF25"

A key characteristic for 2 Grade Engineering levers (Differential Blasting for Grade and sensor/sorting applications) is local grade variability/heterogeneity, particularly when defining variability at a local separation unit scale. Variability within this local range indicates opportunities for Grade Engineering whereas variability between mining units is exploitable through conventional methods (eg: standard grade control).

A distinction is required between variability/heterogeneity and exploitable heterogeneity. Exploitable heterogeneity implies the analysed area provides added value when combined with a cut-off grade and taken through a separation stage as opposed to a planned or accepted "ore plus dilution" direct processing routes (Figure 14). For early opportunities, all analysis is conducted on local grade variability. Further assessment including additional testwork or site specific information will be required for sites that show potential.

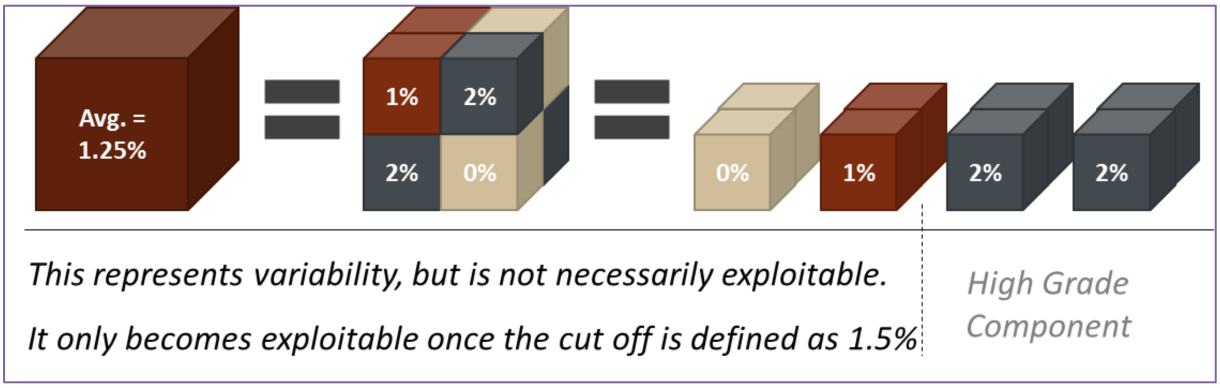


Figure 14: Example of exploitable heterogeneity

3.3.1.1 Compositing of Data

Compositing of data was conducted using sequential down hole sets of records. This allowed for a statistical based analysis of data sets providing an independent view of drilling variability given the unavailable project specific information generally required. Each assay was taken as a single data point with no weighting of intervals.

Each drill hole was composited into sets of 11 sequential records (Figure 15), allowing for ten separation points (including an accept 100% point). Where gaps existed (e.g. Figure 15 'Comp5') composites cover an increased length and contain missing data points. There is a requirement to "keep it simple" in the GE.VIEW WA project as it attempts to cover a wide range of geological models and supplied datasets. Hence a simple set of QA/QC filters are utilised to cover any geological dataset issues.

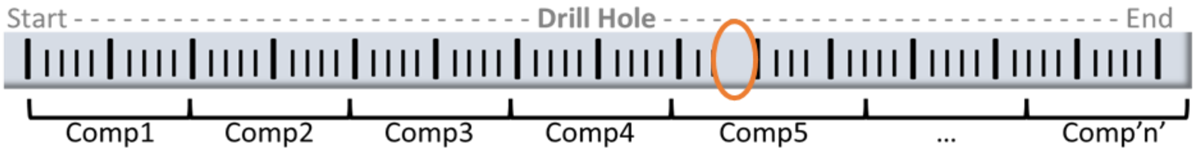


Figure 15: Example of drillhole compositing

3.3.1.1 QA/QC Filters

QA/QC steps (Table 1) were designed to filter out those composites that contained issues relating to the supplied "as is" data in GeoVIEW.WA and the analysis method. Each step was designed to deal with a specific problem noted in the datasets. It attempts to handle the most common type of data presentation problems. While it is not a comprehensive fix for all data issues, it is adequate to provide a relatively clean dataset that is suitable for use in the project. More comprehensive data clean ups would be required for specific projects.

As the number of records could potentially be low (generally at the start/end of holes) the first step ensured composites had a count of larger than 5 samples. Gaps in length where caused by missing sections of drilling and as such caused the assessed composite to cover a wider range. To minimise the effect of this on the results only those where >90% of total length was present were accepted. Composites with missing assays where only accepted when there was a single assay missing. The average grade filter was simply used to remove zones of barren or back ground host rock from further analysis.

Table 1: QA/QC Filters

QA/QC Step	Rule
# of Records	Minimum of 6 records
Gaps in Length	>90% covered
Missing Assays	Maximum of 1 missing assay
Average Grade	>0.10

Application of these rules allowed for the generation of adequately clean deposit data sets which, considering the open source nature of the input data, is a significant outcome. Deposit data sets consisted of summary composite data along with assessed response factor and QA/QC parameters with an associated pass or fail (Table 2).

Table 2: Example Data Output Format

Comp No.	Grade	R25	Length (Data)	Length (Samples)	Sample Count	Usable Count	QAQC	*Comment*
1	0.03	1.77	11.0	11.0	11	11	0	*Failed - Low Grade*
2	0.19	2.46	11.4	11.4	11	11	1	
3	0.67	2.36	9.0	9.0	11	11	1	
4	0.51	3.03	11.0	11.0	11	11	1	
5	0.26	3.03	40.8	35.0	11	11	0	*Failed - 6m gap*
6	0.89	1.70	11.2	11.2	11	11	1	
7	1.41	2.85	11.0	11.0	11	11	1	
8	0.21	2.17	2.0	2.0	3	3	0	*Failed - Only 3 samples*
9	2.60	1.82	26.0	26.0	11	11	1	
10	6.39	3.01	10.0	10.0	11	11	1	
11	0.37	2.02	11.0	11.0	11	8	0	*Failed - Missing 3 assays*
…	…	…	…	…	…	…	…	

3.3.1.2 Response Factor

A key concept across Grade Engineering is Response Rankings (RR) which are representations of the propensity of a material to concentrate, generally in the finer fractions, across the complete range of mass pulls. A precursor to calculating Response Rankings is the determination of Response Factors, which are the ratio of a new accept stream grade over the feed grade (Equation 1) at a specific mass pull. For this variability analysis composite grades were ordered from highest to lowest with the top quarter of grades taken as the accept stream. This assessment quantifies those composites where there is a significant portion of material at a higher grade than the average composite grade.

$$Response\ Factor\ (RF) = \frac{Accept\ stream\ grade}{Feed\ grade} \qquad \textbf{(1)}$$

An arbitrary fixed 'mass' pull of 25% was selected to provide an indicative measure for 2 GE levers – Differential Blasting for Grade and Bulk sense/sort amenability. Scope exists for adjustments to the specific mass pull however due to the generic "industry wide opportunity" scale of this project, analysis of the datasets at this selection was deemed appropriate.

Where there is no grade variability within a composite, the Rf_{25} equals 1, indicating no potential upgrading Response Factor.

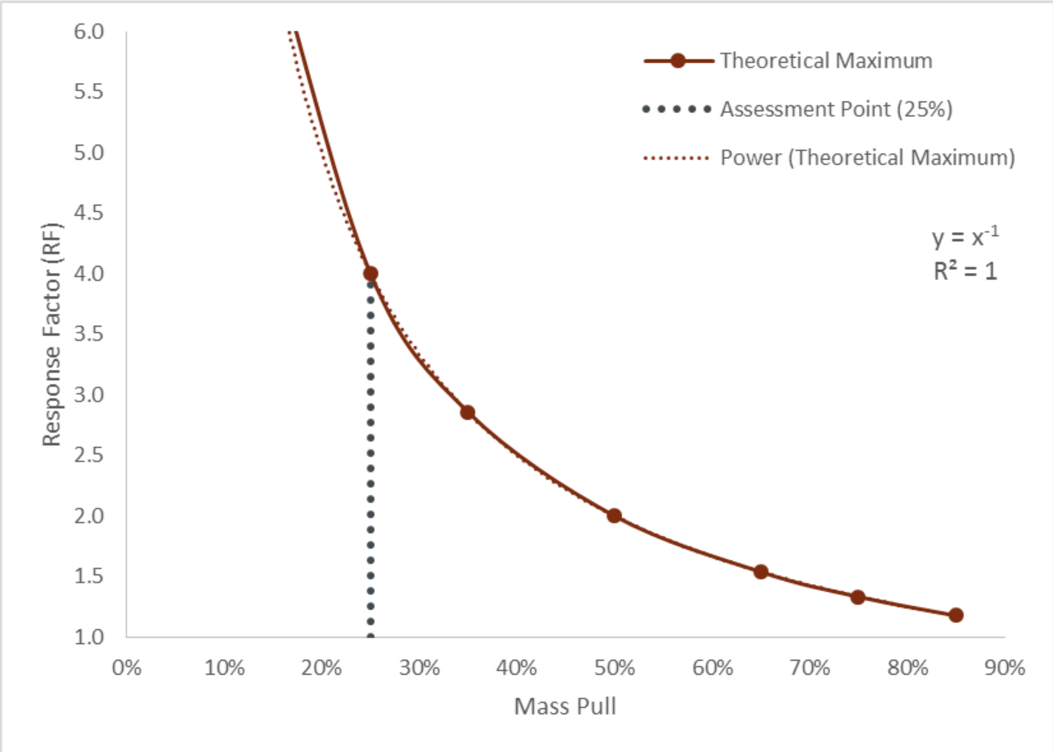


Figure 16 - Theoretical Maximum Response Factors across Mass Pull Range

3.3.2 Output Formats

A compiled output file can then be made using those intervals that passed all QA/QC steps for each individual project. There are three dominant data output values that are used to present data. The simplest of this is using the average variability (Rf_{25}) of the supplied datasets across projects as a single point marker, and is useful for rapidly ranking a deposits variability in relation to a large range of other results (Figure 17). Figure 18 shows a more detailed form of results of all the Rf_{25} within either a single or multiple projects, and is designed to represent the variability in relation to grade. This is useful for comparing a limited selection of projects or elements within a project.

As an example in Figure 18, the highest density of sample composites are indicated by the warm red/magenta colours, while low density sample counts are the cool colours (blues/greens). In this example, the highest density count occurs with the highest Rf_{25} (approximately Rf_{25} 2.7 to 3.2), and within a grade range of approximately 0.4 to 1.8 g/t Au. This may indicate this mineralisation, may be well suited to potential Grade Engineering techniques such as DBG or bulk sorting in these grade magnitudes. Conversely, if the heat map indicated the highest sample composite density was at a low Rf_{25} (eg: 1.5), and was also at a grade significantly above economic interest, then it would be less suited to these techniques. Hence a user can determine if the grade heterogeneity is at a grade range that may be of interest in their own operational environment.

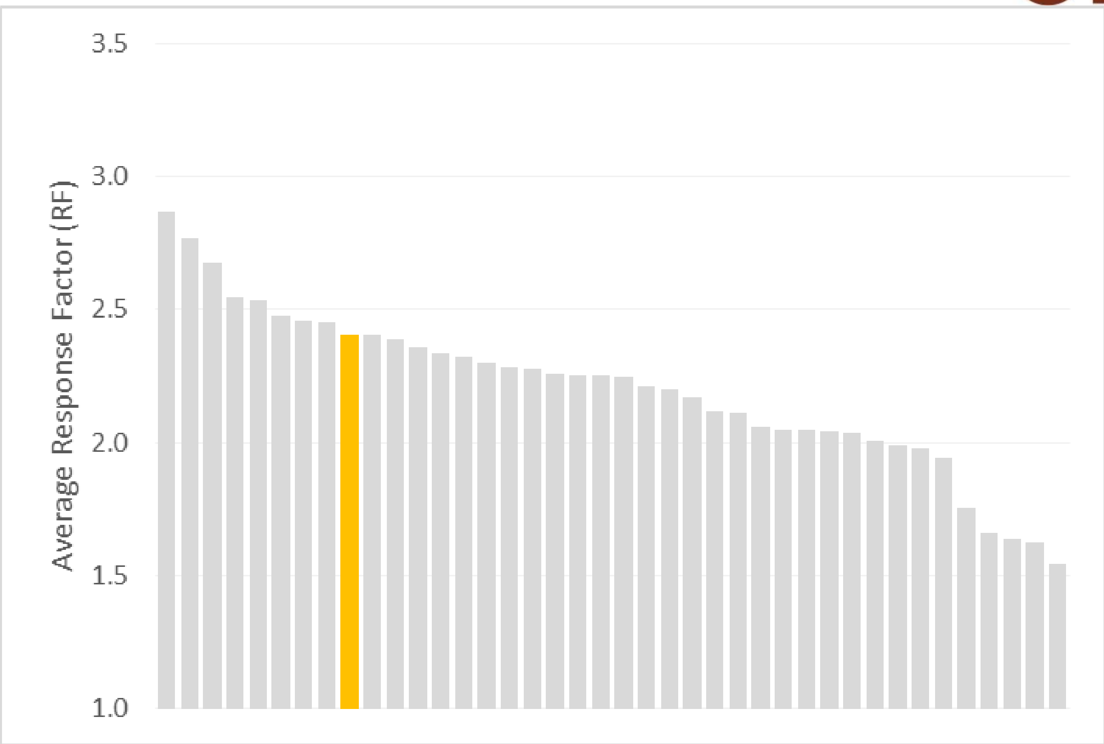


Figure 17: Example Ranked Project Output

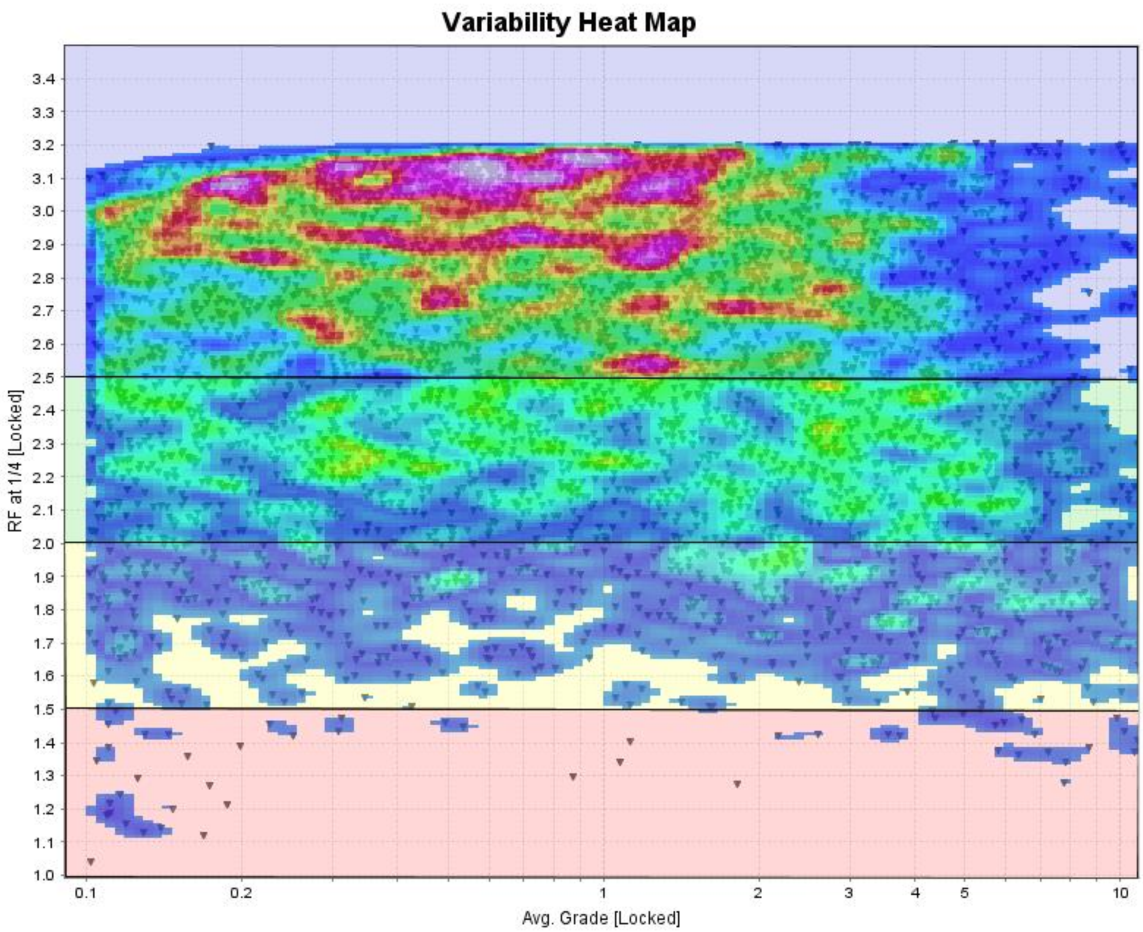


Figure 18 - Example Heat Map of Project Variability Results

3.4 GE VIEW.WA Online Web Portal

An online web portal is available to introduce the key concepts of Grade Engineering (https://www.crcore.org.au/ge-view). The portal is designed in 2 parts. The first part provides 5 case study examples sourced from the Western Australian Geoview application that steps through the initial Grade Engineering introduction, and incorporates a live 3D drillhole interactive viewer (Figure 19), and the preliminary analysis of the Grade Engineering opportunity.

The second part of the Web Portal allows the generation of a private user area that will allow the user to import their own data and complete a preliminary Grade Engineering assessment on their own dataset. The user is required to import 3 mandatory data files in a fixed csv template format (collar file, downhole survey file and assay file), and an optional 3D dxf file. The 3 data files are de-surveyed into standard 3D drillhole traces and can be viewed in a 3D viewer with their assays as supplied. An Rf_{25} is calculated and displayed both on the drillhole trace and as a summary graph of the entire dataset. While the viewer does not link directly to GeoVIEW WA, the drillhole files can be extracted from the GeoVIEW platform and subsequently be imported via the csv import to evaluate the deposit or dataset in the context of a Grade Engineering assessment. The interface also allows the user to select the broad geological and mineralization style as described earlier.

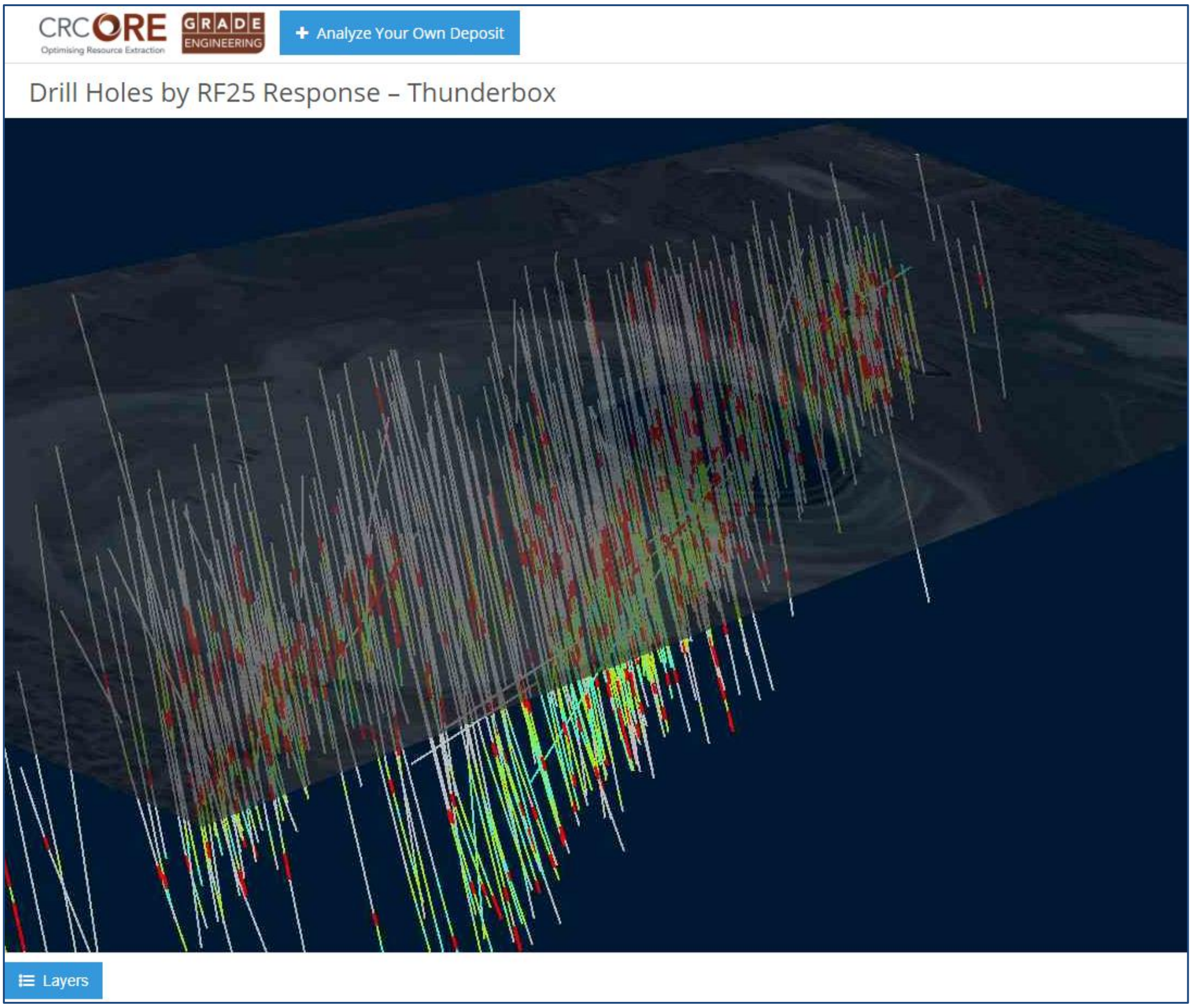


Figure 19: Image of Web Portal interactive drillhole viewer with Rf25 displayed on drillhole traces

4 Grade Engineering Assistance

CRCORE has recently announced the opening of a new Mining Innovation "Hub" that is located in Kalgoorlie-Boulder, Western Australia. This new initiative will bring together some of Australia's best scientists, engineers and mining experts on collaboration projects to innovate and add significant value to the minerals industry. The Hub is supported by critical foundation partners, including CRCORE, Curtin University's WA School of Mines (WASM), the Minerals Research Institute of Western Australia (MRIWA), METS Ignited (an Industry Growth Centre funded by the Australian Government), Chamber of Minerals and Energy, Central Regional TAFE and the City of Kalgoorlie-Boulder. The Hub will initially operate as a node of CRCORE for a period of 2 years, and then transition into a longer term self-managed independent entity. The Hub will be able to provide the initial contact point for mining operations wishing to evaluate the potential for a Grade Engineering evaluation of their project or mine.

The Kalgoorlie-Boulder Mining Innovation Hub can be contacted at;

Email: info@kalhub.com

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