

The Devil is in the Detail - Extended Abstract

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Abstract

Progressing process plant projects from studies to construction and operations requires process design work, preliminary engineering and metallurgical studies to prove up an economic flowsheet and plant layout. This work has a reliance on basic sampling, ore characterisation, and metallurgical testing to a standard that supports sound decision making. Often overlooked and underappreciated is the role of collaboration and multidiscipline approach employing best practices and attention to detail play to maximise the economic extraction of metal.

This paper will present examples of sampling practises often observed for copper development projects and compare these against sampling practises considered the best, with supporting evidence. Some of the benefits and pitfalls of domaining practises and tests used for comminution and flotation characterisation will be discussed for a selection of copper case studies.

Copper projects developed by Sedgman using these best practises have demonstrated a substantial uplift in NPV by domaining of ores by different comminution and flotation characteristics. The details of one such project will be presented that yielded a 27% increase in the size of the resource and 29% increase in project scale. The domaining also resulted in significant changes to the comminution and flotation circuit design, maximising the economic extraction of metal. A second case study details the importance of comminution and flotation sampling in combination with geospatial considerations. These considerations enabled a new operating schedule to be proposed which resulted in a 34% uplift in copper production over the first 4 years of the project, significantly increasing the overall project value.

The case studies presented demonstrate the importance of best practise with respect to sampling, ore characterisation, domaining and metallurgical testing to support the design basis, and technical and economic viability of copper development projects.

Introduction

Often in mining project development the terms “fast track”, “no time for detail”, “project acceleration” or even “skip a stage” are used aiming to accelerate project development. The goal of this acceleration is to advance project development as to get into operation as fast as possible, initiating cash flow for the project. An example of this was the “Standard Concentrator” approach to copper project development employed by a Tier one miner between 2007-2013. Antapaccay and Las Bambas were the only two “Standard Concentrator” projects commissioned. These projects are metallurgically unique compared to the portfolio of copper projects held at the time which also included El Morro, El Pachon, Tampakan and Frieda River. “Fast tracking” or similar concepts didn’t help with development of these later projects. Progressing from studies to construction and operations requires significant trade-off studies and process design work to prove up an economic flowsheet and plant layout which are often driven by site or ore specific requirements.

The basis of this work is a reliance on sampling, ore characterisation and metallurgical testing to a suitable standard. Often overlooked and underappreciated is attention to detail and the benefits in best practices to maximise economic extraction of metal. The basic aim should be to optimise key technical levers to maximise the economic extraction of metal. The key levers include defining the:

1. Flowsheet Design
2. Production Strategy
3. Production Rate
4. Production Efficiency
5. Resource Scale

Sampling

Ore sampling often does not attract the attention it deserves. It is a key initial step for project development and identifying the pathway for maximum economic extraction of metal. Sampling practises should consider many things such as geological and mineralogical variation, mine schedule, sample representation, test methodology and extraction methodology. We will consider some of these focus areas in this paper and show how following what we consider best practise can lead to maximise the economic extraction of metal.

The JK Drop Weight test is a single particle test and was developed at the Julius Kruttschnitt Research Centre in the early 1990s to characterise ore according to its resistance to impact breakage. The test was an improvement over sourcing of bulk samples for pilot mill tests. These bulk samples were generally accessible ore samples, rather than representative samples. The test involves breakage testing of five particle size ranges from 13.2 mm to 63 mm at three target specific energies. The test typically requires >70 kg of rock to complete the required testwork procedure. This amount of material is considered difficult to obtain by diamond drilling due to the competing demands for material for resource confirmation and other characterisation and testwork programs. An adit is often suggested but they don’t typically provide representative sample. RC chips are of no value because the survivors of the RC drilling process are hard materials (Way et al 2021). For diamond drilling using PQ size we need >5 meters of continuous core at high recovery and competency to provide enough material for testing. From experience, >10 meters is normally required to provide enough sample of the required particle size and mass. This amount of core and cost of the test meant

that few tests were completed which did not support practitioners to define hardness variability.

This led to the development of the SMC test by Dr Steve Morrell which is another single particle test (Morrell 2004 and 2008). The SMC test requires ≥ 20 kg of diamond drill core and this sample mass and lower test cost supports larger quantities of samples for testing to define hardness variability. The test considers one particle size range (preferred size fraction is $-31.5 +26.5$ mm) tested at five target specific energies. In all, one hundred discrete particles in the target size range are tested to provide the hardness characteristics. It is most important that practitioners understand the origin of these one hundred particles before assigning spatial hardness parameters to a block model.

Sedgman regularly receives data from bulk samples or master composites, which were collected with the aim to establish an average performance of the ore and/or save on project development costs. This paper will attempt to demonstrate via two case studies how these practices can limit maximum economic extraction of metal. Consider the examples below for comminution characterisation testing which presents two examples of bulk or master composite samples and multiple continuous intervals of drill core that are tested independently.

Figure 1 is an example of multiple sub-samples gathered from a spatially broad area to form a bulk or master composite sample. The composite sample is likely to originate from across multiple years of production and provide an average SMC test result. However, if any of the discrete sub-samples are ≥ 20 kg then it is possible that the SMC test sample could originate from one sub-sample. The most likely case is that the results will represent a weighted average of a few unidentified areas once samples are mixed. Unfortunately, this means that the result is omitted or is of secondary value in the database. It is important to note, the typical procedure for sample selection for single particle comminution tests can result in unintentional sampling bias toward selection of most competent rocks (i.e. avoid soft-crumbly rock). Other tests such as SAG Power Index (SPI), SAG Design, Bond Ball Mill Work index (BBWi) and flotation tests using this sampling methodology will likely present weighted average results for the sampled areas and may not have any resemblance to ore characteristics expected in the process plant.

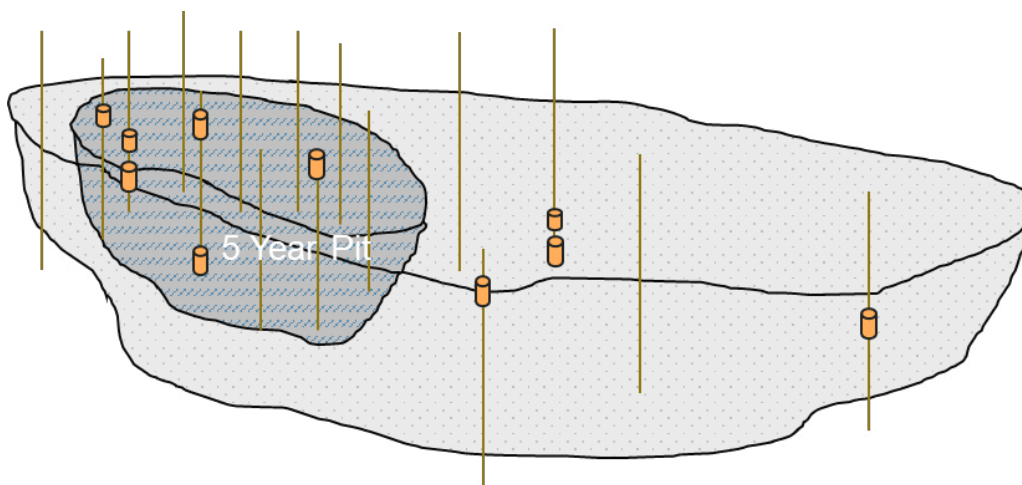


Figure 1: Example of multiple sub-samples gathered from a spatially broad area to form a bulk or master composite sample.

Figure 2 is an example of a continuous bulk sample gathered by combining a long continuous intersection of drill core (i.e. ½ HQ core from 70 meters of continuous drill core). This sample is likely to present ore characteristics across multiple years of production (i.e. ≥5 mining bench heights). For single particle comminution tests, the particles could originate from either end or any location along the drill core. Spatial representation of the test result is lost. Other tests such as SPI, SAG Design, BBWi and flotation tests will likely present weighted average result for the sampled area and again may not have any resemblance to ore characteristics expected in the process plant.

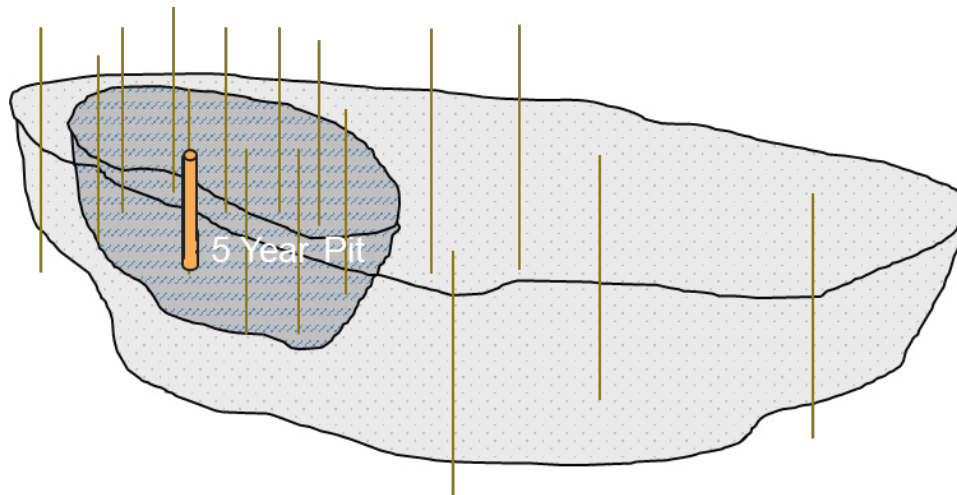


Figure 2: Example of a continuous bulk sample gathered by combining a long continuous intersection of drill core.

Figure 3 is an example of multiple samples of 40kg – 70kg. Each sample is formed by combining discrete continuous intervals of drill core from spatially representative areas. The continuous intervals are no greater than the proposed height of the mining bench. Individual characterisation and testing of samples enables test results to be spatially representative in a block model. After individual testing these samples is complete, they can be combined to form bulk, production or master composites for flotation testwork. An approach the authors use specifically for SMC testing is to assign a maximum of 25 kg - 30 kg of continuous intersection for each test. This approach forces the laboratory to use a limited set of particles and if sufficient material cannot be identified as suitable for testing, then the intersection is likely very soft and/or highly fragmented. This is a good result because an understanding about the ore variability is gained and there should not be a cost for not being able to run the test. Test results for SPI, SAG Design, BBWi and flotation tests using this sampling methodology are more representative of how the ores are mined and processed according to a production schedule.

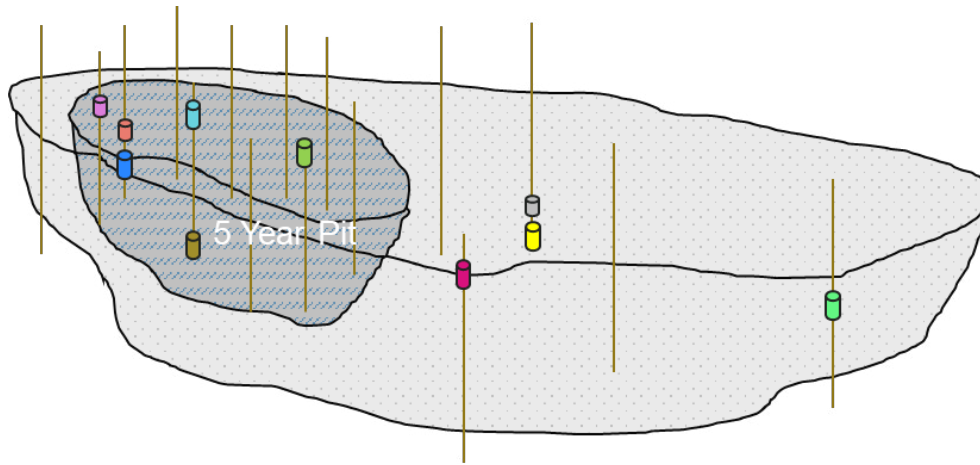


Figure 3: Example of multiple samples of discrete continuous intervals of drill core from spatially representative areas.

Methodology

Two case studies of copper development projects that Sedgman was involved in are presented as examples of the importance of sampling and a methodical assessment of results. Some of the benefits and pitfalls of ore domaining practises and tests used for comminution and flotation characterisation testing will be discussed using two copper development projects that were undertaken by Sedgman.

Case Study A

This case study considers a small to medium copper-gold project containing separate oxide, transition, and sulphide materials. The original processing schedule was developed to treat a blend of the materials in the early payback years of the project. The resource includes a couple of open pit and underground mines.

The ore domaining for comminution identified into the following three categories:

- Oxide
- Transition
- Sulphide

Figure 4 presents comminution results for sulphide ores and shows that they can be interpreted in two ways, and it demonstrates the importance of collecting significant variability samples. Broad assumptions, such as “ores get harder with depth” do not always hold. The data identifies some early throughput rate opportunities if ores can be defined and mined selectively.

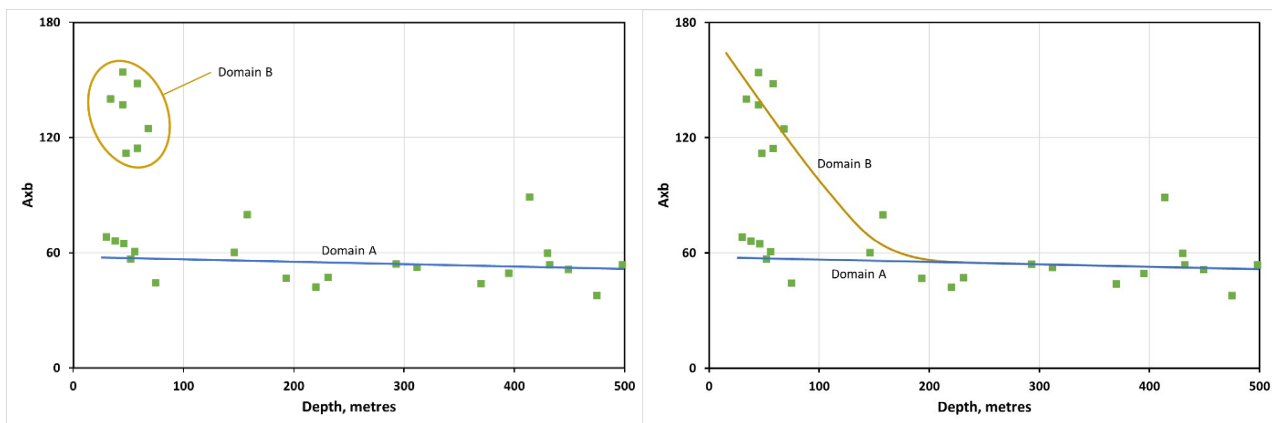


Figure 4: Case Study A comminution data interpretation (left) Domain B as a separate softer zone in RL > 100m. (right) Domain B trends towards domain A and >200 m RL they are inseparable.

For flotation the domaining methodology was altered from the original concept which considered all materials of equivalent flotation performance. Figure 5 presents the historical data with the Copper recovery versus copper head grade data and curve of best fit. The copper recovery was determined with a normalised copper concentrate grade of 27% Cu. Sedgman reassigned the results according to the domains identified for comminution characterisation. The separation of samples into domains was based on copper solubility in citric acid which was available but previously never used. Sedgman also omitted flotation results for blended ore domains. Figure 6 presents flotation results for the separate domains according to the three key categories identified and the new low-grade sulphide samples. It was found that most of the lower grade and poorer recovery results were associated with oxide and transition ore samples.

Definition of samples into separate domains also showed that there was insufficient testing of sulphide domain samples near the cut-off grades for open pit and underground sulphides, and the copper recovery relationship with respect to copper head grade was unchanged across the copper head grade range tested. Additional low grade samples were targeted from core samples available and flotation tested to determine the sulphide copper recovery relationship to lower copper head grades. These results showed a slow decrease in copper recovery occurring at <0.8% Cu. This work shows how definition of ores into separate flotation domains resulted in $\geq 24\%$ increase in copper recovery at cut-off grades. Sulphide ores cut-off grade is 1.0% Cu equivalent for underground and 0.5% Cu equivalent for open cut ores.

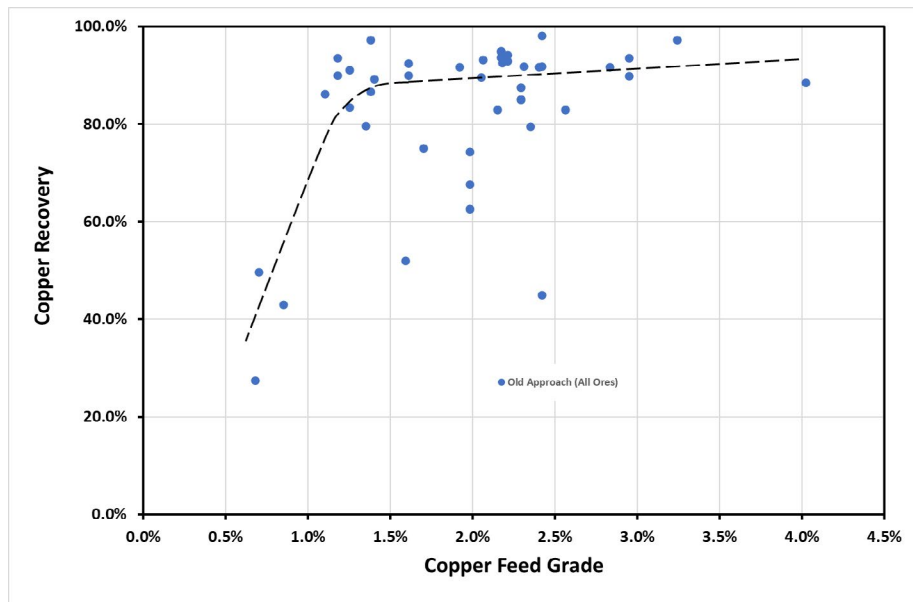


Figure 5: Case Study A flotation data interpretation employing the historical domaining approach with curve of best fit.

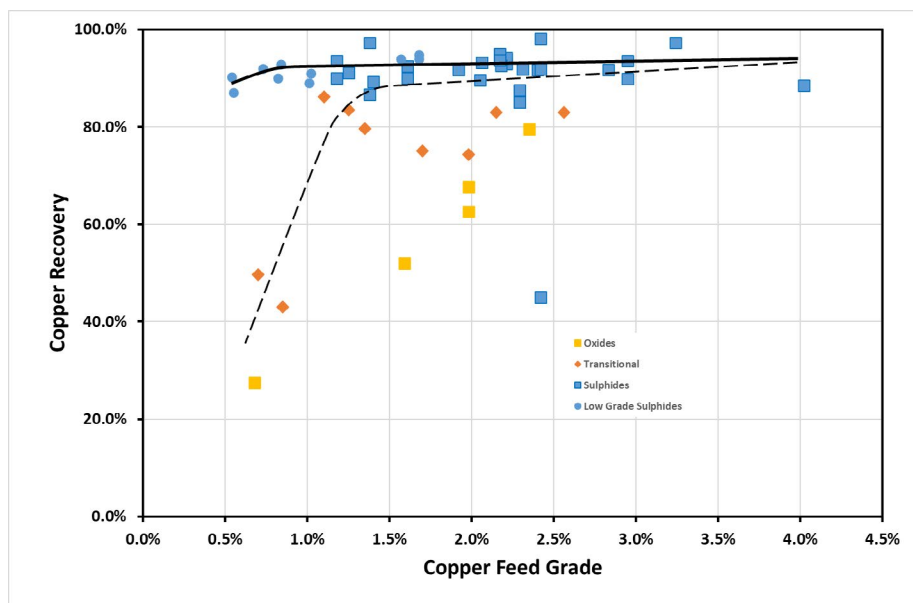


Figure 6: Case Study A flotation data interpretation employing the new domaining approach using the three categories (oxide, transition and sulphide) and addition of low-grade sulphide samples with curves of best fit for sulphide domains versus the historical prediction for flotation performance.

The new interpretation of results and filling in gaps in the results caused the production schedule to change. Prior to this work the sulphide ore (ore domain with highest recovery at the target concentrate grade) represented 96% of the processing schedule, whereas after this work it was 99% of the schedule. The sulphide domain increased because lower grade ores could be justified for the production schedule due to the improved copper recoveries. Transition and oxide domains with poorer recovery of copper decreased and only the highest head grades of these materials can be economically justified for production.

Table 1: Summary of key changes realised from implementing proper ore domaining practises for Case Study A.

Parameter	Change/Grade, %
<i>Original Resource</i>	
Oxide	3
Transition	3
Sulphide	94
Open Pit Cut-Off Grade, Cu	0.5
Copper Recovery Improvement	+63
Underground Cut-Off Grade, Cu	1.0
Copper Recovery Improvement	+24
<i>New Resource</i>	
Oxide	0.5
Transition	0.5
Sulphide	99
Increase Size of Resource	+27
Increase Scale of Project	+29

Overall, the resource scale increased by 27% and the throughput rate was able to be scaled up by 29%, significantly maximising the economic extraction of metal. Table 1 presents the breakdown changes with respect to content of domains, copper recovery improvement and overall effect on project strategy and economics. This project is a good example to highlight the importance of domaining and detailed procedures, and the effect that these can have on assessment on project viability.

Case Study B

This case study considers a medium to large copper-gold project containing separate sulphide and native copper deposits. The original processing schedule was developed to treat sulphide and native copper ores at a controlled blend ratio. The resource includes numerous open pit mines but early production (>6 years) is expected to come one or two deposits only.

All native copper ores are soft. All relevant sulphide comminution data is presented for this project. The Drop Weight index (DWi) data is presented against depth and again there is no correlation between hardness and sample depth, showing that the anecdotal saying that ore hardness increases with depth doesn't always hold true. Although the two comminution testing methods test different properties, the DWi was compared against BBWi and a broad linear relationship is observed which can potentially lead to BBWi being used as a proxy for DWi in future ore characterisation testwork (see Figure 7).

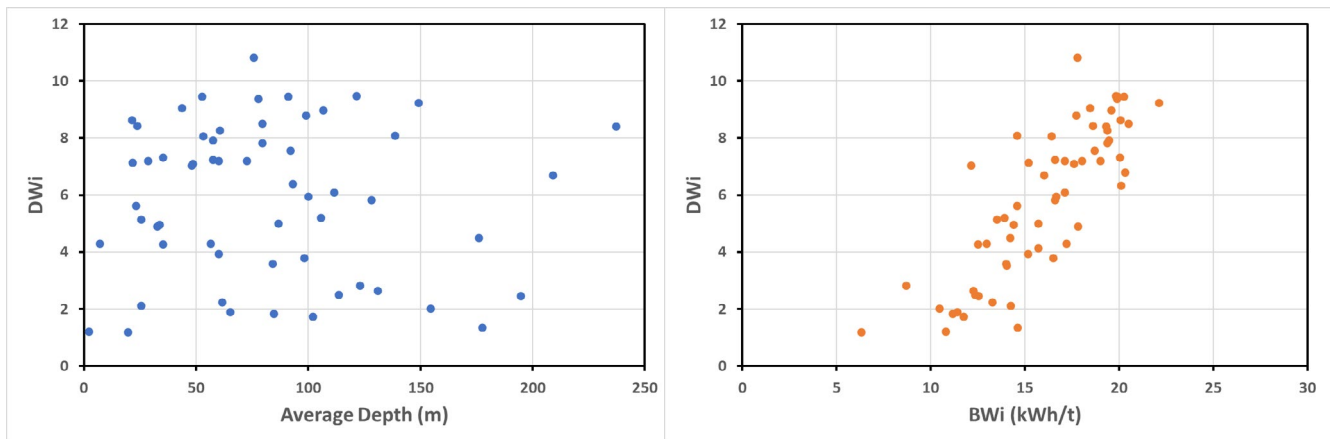


Figure 7: Case Study B comminution data assessment (left) DWi versus average depth showing DWi is highly variable at all depths (right). DWi versus BBWi showing a broad linear relationship between the two separate comminution parameters.

The frequency of DWi data is presented in Figure 8 for DWi ranges covering soft, soft-medium, medium-hard and hard. Interestingly, plotting the frequency distribution this way shows almost equal number of samples characterised for each of the hardness categories. It is not surprising the comminution circuit was designed with a 75th percentile hardness DWi of approximately 8.0.

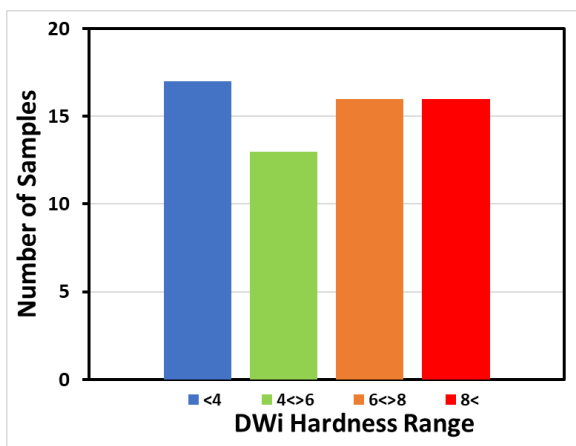


Figure 8: Frequency distribution of Drop Weight Index (DWi) results for comminution samples

Due to the high variability in samples characterised, Sedgman requested that each of the samples be spatially mapped in the project block model with colour coding to represent each of the four hardness categories, shown in Figure 9. This assessment revealed that all the hardest sample to be located at one end of the deposit and the softest samples at the opposite end. The medium hardness samples were in the middle. Considering that the ore grades are very similar across the entire deposit and the overburden depth is consistent too, this information opened the way for significant project optimisation during the initial financial payback years.

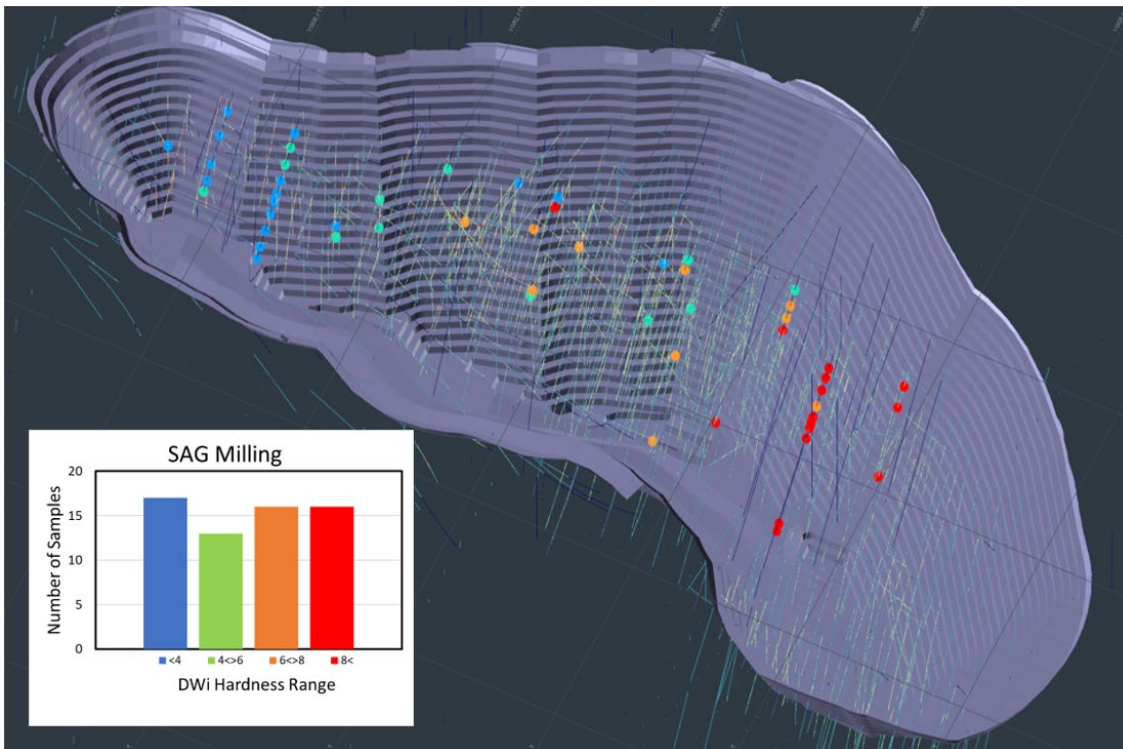


Figure 9: Spatial representation of the ore hardness variability across the proposed pit shell with the frequency distribution for hardness shown in the bottom left.

For this project it is particularly important to comment on the mineralogy and key characteristics of the different materials for treatment. The native copper ore is dominated by metallic copper (>85% of the copper content) and is coarse grained with a P80 $\geq 100 \mu\text{m}$ for the mineral. It needs to be pointed out that native copper mineral is malleable and ductile which means that during comminution the mineral concentrates into the coarsest size fractions, which is contrary to sulphides. The sulphide minerals are typically between 18-40 μm P80 and easily liberate at coarse target grind sizes due to being soft and brittle. The head grade of the native copper ore is 15% higher than sulphide ore and was considered higher value on that basis.

A high-level summary of the concentrate grade against primary grind size for various ore domains and blends is presented in Figure 10. Native copper samples consistently upgraded to $\geq 25\%$ copper grade in concentrate with a primary grind of 75 μm P80. At primary grinds $\geq 100 \mu\text{m}$ P80 this copper grade in concentrate was not achievable. Sulphide samples were optimised for flotation and locked cycle tested at coarser primary grind sizes of 180 μm and 250 μm P80. The results are consistent with $\geq 28\%$ copper grade in concentrate at recoveries $\geq 95\%$.

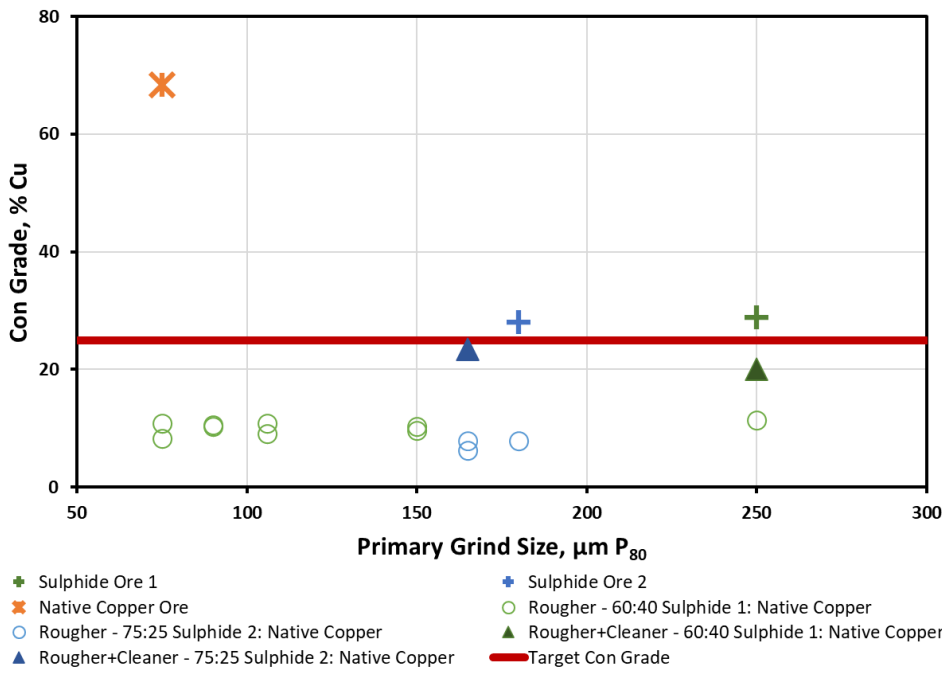


Figure 10: Concentrate grade against primary grind size for ore types and blends, with the target concentrate grade shown via the red line.

The production strategy to blend the sulphide and native copper ores was derived so that sulphide ore dominated the feed to the concentrator flowsheet. The sulphide: native copper ores were tested in blends of 75: 25 and 60: 40 to cover the most likely production scenarios. They considered that such blends would provide a softening of the feed blend and that the blended head grade of the native copper ore would naturally produce a weighted average flotation P_{80} performance of the individual domains.

Figure 11 shows the anticipated blended recovery targets by the blue and green lines. None of the laboratory flotation testwork could support this expectation and in fact, all blended testwork fell short in terms of concentrate grade target and $\geq 13\%$ recovery at primary grinds of 165 μm and 250 μm P_{80} shown in Figure 10. The reasons for this under performance is related to the lack of liberation of native copper in the blend at these target grind sizes and the difficulty in achieving optimum flotation performance for the individual domains once blended.

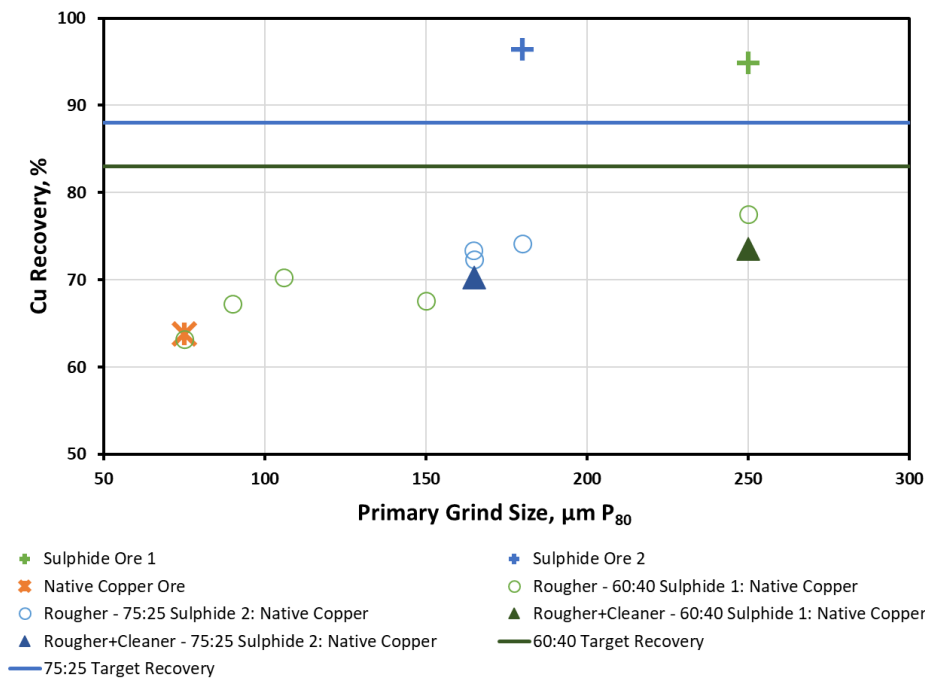


Figure 11: Copper recovery against primary grind size for various ore types and blends, with green line showing 60:40 sulphide:native copper target recovery and blue line showing 75:25 sulphide:native copper target recovery.

Sedgman's assessment resulted in a production strategy change and a change in key equipment selection. The overall benefits realised a 34% increase in metal production compared to the base case by end of year 4, as shown in Figure 12. Focus changed to be on batch processing of the different domains to maximise their respective recoveries. Treating the softer sulphide ores first (higher value ores) provided higher throughput rates at coarse primary grinds and higher copper output (throughput rate and recovery driven).

The soft native copper ores were delayed for the end of mine life and could utilise a cut down version of the comminution circuit and still achieve a primary grind of 75 $\mu\text{m P}_{80}$ and maintain the target throughput rate, due to their soft comminution properties compared to the sulphide ores. Overall, these strategies delivered significant value to the project and resulted in the change of production strategy to enable this early value generation.

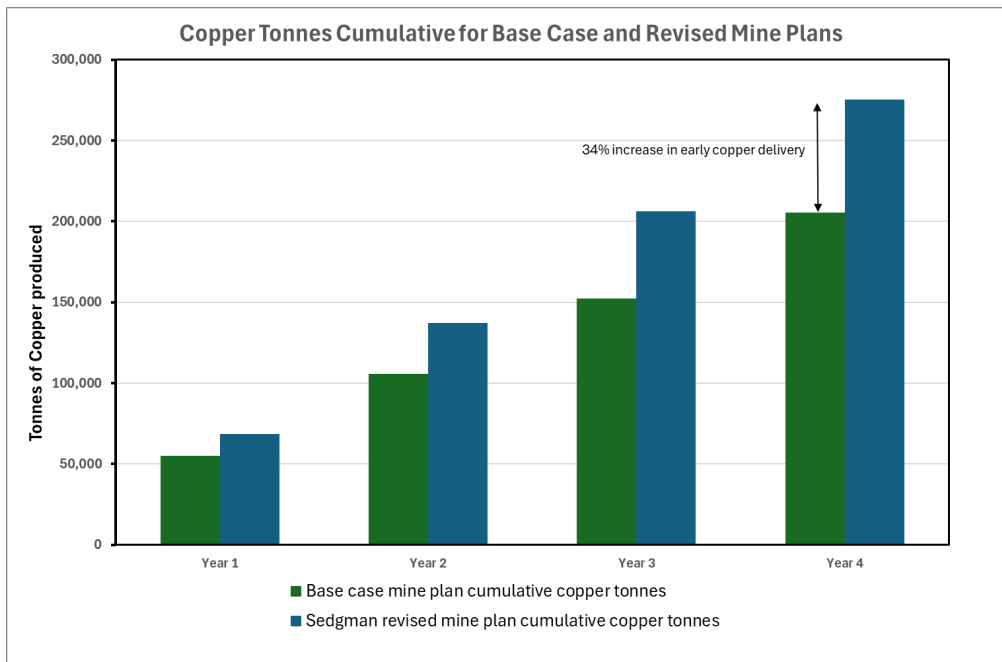


Figure 12: Copper production cumulative over production years 0 – 4 for the base case and revised mine plans

Conclusion

The case studies presented demonstrate the importance of best practise with respect to sampling, ore characterisation, domaining and metallurgical testing to support the design basis, and technical and economic viability, of copper development projects.

Case Study A presented an overall resource increase of 27% thereby making the project economically viable. This increase was enabled by better definition of flotation domains, separate testing and analysis of individual domains and targeted testing of low-grade samples aimed at improving metal recoveries at cut-off grades. A lack of domaining led to poor and confusing testwork results until the performance of individual components were understood. The best performing domain (sulphides) increased in overall content from 96% to 99% off the resource. The remaining 1% of the resource was originally considered important for the initial production years but now is divided between high-grade transition and oxide domains that were delayed until late in the mine life.

Case Study B provided an overall benefit of 34% increase in metal production (and value) compared to the base case by end of production year 4. Although slightly higher head grade than sulphide ore, the recoverable copper content of native copper ores is significantly lower which resulted in the strategy and plant design to change. Focus changed to be on batch processing of the different domains. Detailed assessment of comminution samples and spatial 3D mapping in the block model supported softer sulphide being the early priority to maximise project value. Sulphide ores were found to have substantial soft ore available in the early production schedule, they are liberated for flotation at much coarser primary grinds and despite a lower head grade, the copper and gold production rates are higher due to much higher metal recoveries compared to native copper ores.

References

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