srk news
Metallurgy and Mineral Processing

Understanding ore characteristics: new pathways to processing

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New pathways from the geological block model to saleable products and tailings byproducts

This issue presents metallurgical and mineral processing perspectives from our global consulting work, covering advances in ore characterization and recovery, sustainability and tailings management for traditional and emerging commodities, and impacts on studies, flowsheets, operations, and long-term performance.

This issue centres on pre-concentration and particle sorting, outlining lab protocols, simulation approaches, and XRT-based pebble sorting to unlock ore value early in the flowsheet. We also examine the economics of pre-concentration and ore variability, highlighting the need for upfront characterisation to inform early design.

Other articles span a wide range of metallurgical and mineral processing challenges, from improving testwork programs and evaluating alternative flowsheets to extracting value from complex ore bodies and existing tailings. They reflect both traditional and emerging commodities, and the growing influence of sustainability, market conditions, and project risk on processing choices.

Together, these pieces outline how new technologies, processing options and technical data are being applied to support project decision-making, operational planning, and longer-term resource strategies, helping organisations respond to change while optimising operational performance.

Case study in grade heterogeneity

For pre-concentration evaluations, SRK conducts two types of heterogeneity analyses – Composite-Sample Relationship and Heterogeneity and Scale. Heterogeneity analyses were performed on a polymetallic underground operation to assess the potential for pre-concentration as part of a broader economic evaluation. More than half a million sample intervals were analyzed, constrained within geological and mining domains.

Using the Composite-Sample Relationship method, composites were analyzed on 30 m vertical intervals with mine-specific value parameters to classify ore and waste. Heterogeneity measures quantify the proportions of Waste in Ore (below cut-off material within ore composites; see figure) and Ore in Marginal (above cut-off material in sub-economic composites). These heterogeneity measures were used to assess potential pre-concentration strategies and served as direct inputs to SRK's pre-concentration economic models.

Across the operation, Waste in Ore averaged 30–40% within existing stopes, with slightly higher proportions in low-grade zones. Outside the mined stopes, the trend reversed—there was more below-cut-off material within ore but less above-cut-off material in marginal areas. Marginal zones exhibited approximately 30% Ore in Marginal, with the grades of above cut-off material sufficiently high to justify pre-concentration. Overall, mining areas exhibited different trends in heterogeneity measures, possibly leading to different pre-concentration strategies.

The analysis confirmed that significant internal dilution occurs, even within mined stopes, and that meaningful upgrading potential remains both inside and outside current mining areas. These findings demonstrate how heterogeneity measures guide pre-concentration strategy selection—highlighting zones suitable for waste rejection versus those better suited for reserve extension.

The results will feed directly into SRK's Size the Prize evaluation to estimate the economic potential through pre-concentration. Subsequent test work will refine recovery assumptions and integrate revised grade distributions into pit and stope optimizations.

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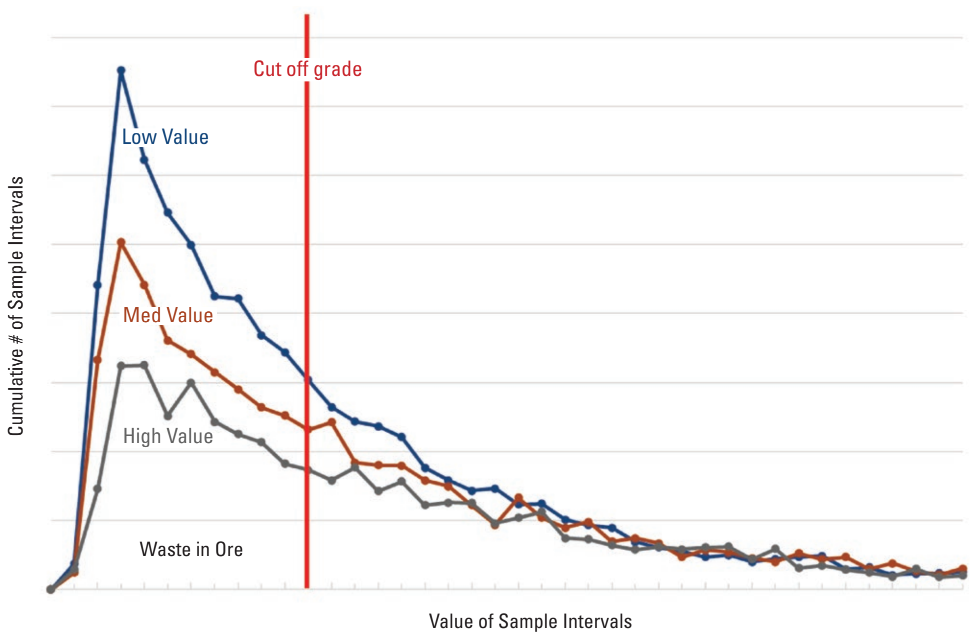
Composite-Sample Relationship for Ore Composites



Pre-concentration—broadly defined as the rejection of waste before conventional processing—requires a tailored approach to economic evaluation. Multiple implementation strategies are possible, and effective evaluation must account for both these strategies and the outcomes of heterogeneity analysis and laboratory testing.

Typically, three strategies are commonly applied in pre-concentration:

1. Upgrade feed by rejecting waste from mined ore, thereby increasing the grade of material sent to the mill.
2. Extend reserves by processing marginal, sub–cut-off material that would otherwise be classified as waste.
3. Maintain mill throughput by increasing mine production to offset material rejected by pre-concentration.

Strategy #1 can allow downsizing of the downstream processing facility—an advantage for greenfield projects where reduced capital expenditure improves project economics. For existing operations with spare mining capacity, however, Strategy #3 may be more compelling, as expanding production combined with pre-concentration can yield strong economic returns.

Strategy #2 lowers the processing cut-off grade, effectively turning waste into ore. In open pit mining, marginal material can be identified during grade control and sent to a pre-concentration plant. Alternatively, new pits, pushbacks, or underground stopes that would otherwise be uneconomic can be incorporated into the mine plan.

Pre-concentration evaluations use several distinct cut-off grades:

Pre-concentration evaluation economics

Can pre-concentration improve the economics of your project? (AI-generated image)

BOB MCCARTHY

Bob is a professional mining engineer with over 30 years of experience in mine operations, mine planning, asset management, technology development, and consulting. He has worked across multiple mine departments in both technical and management roles. His expertise includes project evaluation, mine and project reviews, and technology implementation. Bob is particularly specialized in In-Pit Crushing and Conveying (IPCC) assessments and pre-concentration evaluations using various approaches. Recognized as an open-pit specialist, he is a Qualified/Competent Person for mineral reserves under NI 43-101 and JORC.

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- Mill Economic Cut-off Grade (COGE): The conventional threshold separating ore from waste.
- Marginal Cut-off Grade (COGM): A lower threshold defining material that may become economic with pre-concentration.
- Sort Target Cut-off Grade (COGT): The upper grade limit for pre-concentration; higher-grade ore bypasses sorting and thus is not subject to potential losses in the sorting process.

Evaluations typically vary the COGM and COGT to test the three strategies. The optimal approach defines the grade range fed to pre-concentration—bounded by COGM below and COGT above. Material below COGM is waste and that above COGT bypasses sorting for direct processing. In an underground mine, with well-defined stopes and abundant reserves, marginal material may be excluded by setting COGM equal to COGE.

Laboratory tests further refine the evaluation by relating mass pull (the fraction accepted as ore) to metal recovery (the fraction of valuable metal recovered). Because these relationships vary, different mass pulls correspond to different recoveries. In sensor-based sorting, higher sensitivity settings typically increase recovery but also mass pull. SRK also assesses fines bypass—material below the minimum sortable size, usually less than 10 to 25 mm—and metal deportment within that fraction. The fines bypass and metal upgrade (or downgrade) are inputs to the economics.

SRK's economic evaluation follows two stages:

1. Size the Prize: A preliminary assessment conducted before laboratory results are available, using heterogeneity measures (Waste in Ore, Ore in Waste, and metal deportment) and assumed separation efficiencies to estimate potential value.
2. Detailed Evaluation: Incorporates laboratory test data and refines the analysis. This may involve only integrating test results or, in a more rigorous approach, re-optimizing the mine plan through pit optimizations or including additional underground stopes made economic by pre-concentration.

Both instances test the sensitivity of economic outcomes, typically NPV (Net Present Value), across ranges of COGM, COGT, and mass pull to identify optimal pre-concentration strategies.

Pre-concentration is not a one-size-fits-all solution but a flexible lever that can upgrade feed, extend mine life, or increase metal throughput depending on its application. A structured economic evaluation grounded in heterogeneity analysis and test data enables mining teams to identify the strategy that best fits their resource and operation. As analytical tools and test methods advance, these frameworks will continue to refine where pre-concentration delivers true step-change gains in project value.

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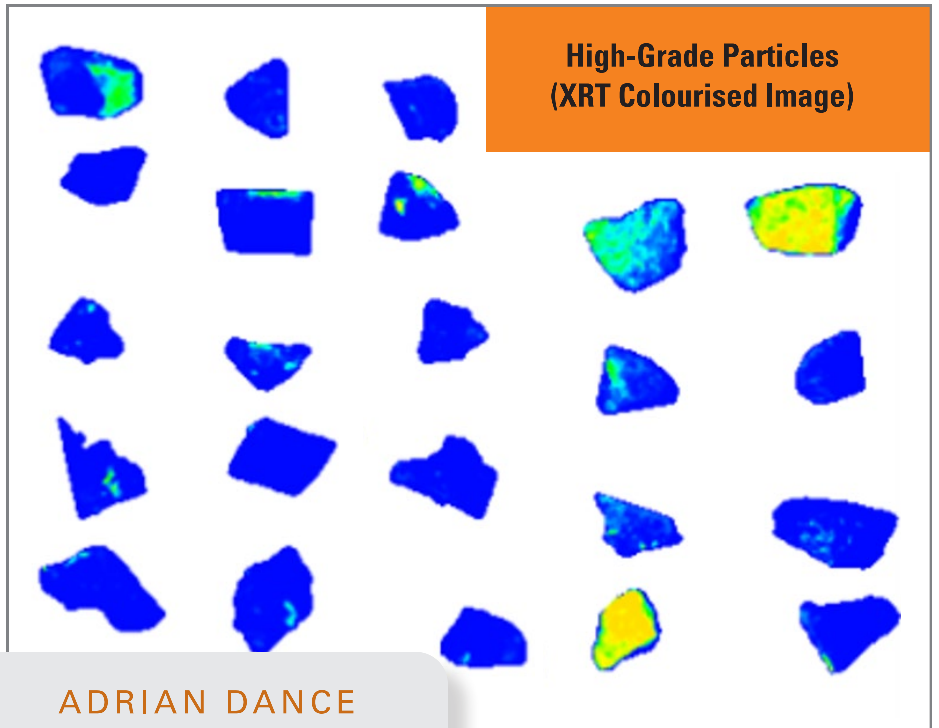
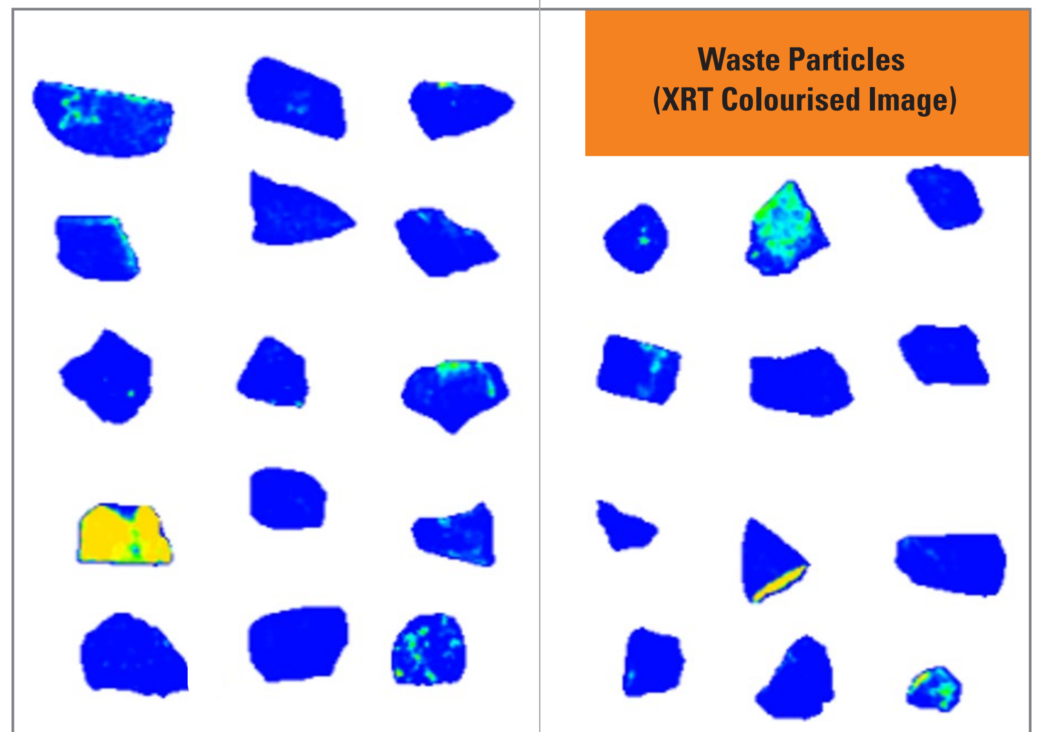
SRK pre-concentration lab test protocol





ADRIAN DANCE

With over 30 years of experience, Adrian is a recognized authority in comminution circuit operation and applies a proven methodology for delivering improvements through Mine-to-Mill optimisation. His expertise includes geometallurgical modelling, pre-concentration solutions, laboratory and pilot-plant testwork, and flowsheet design. Adrian holds a PhD from the JKMRC (Australia), has both industrial and consulting experience, and has worked in Australia, Canada, and Peru. He now integrates his operational expertise into greenfield and brownfield projects, developing mill-forecasting and geometallurgical models to enhance performance early in the mine life.

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Pre-concentration is increasingly being assessed in both early-stage projects and existing operations to determine whether it can add value. Pre-concentration is applied when plant material is still coarse, dry and can be conveyed—or hauled by truck. It exploits the natural heterogeneity of the orebody, provided it persists after being blasted and crushed. Rejecting waste before it reaches the mill reduces energy and water use during downstream processing, preventing a significant amount of waste from being ground and sent to tailings.

For a greenfield project, evaluating pre-concentration can be challenging due to the lack of standardised testing methods and sample top-size constraints. This is compounded by current testing practices, where metallurgical sample preparation typically involves stage-crushing down to a manageable size — eliminating the opportunity to evaluate coarse beneficiation methods. To remedy this, SRK has developed a laboratory protocol that can be performed on small masses of ½- or even ¼-core.

The laboratory test requires only 30 to 50 kg of material and measures metal deportment by size at various levels of impact breakage, simulating primary and secondary crushing. By combining this test protocol with an established comminution test, it can be integrated into existing metallurgical testwork programs with minimal disruption. The test is kept cost-effective by limiting the number of assays.

To observe how target metals occur in coarse particles, SRK uses a dual-energy, X-ray transmissive (XRT) sensor, which scans each particle to identify areas of higher atomic density. While not the only sensor technology available, it is particularly useful for characterising samples that display heterogeneous properties.

SRK provides independent evaluations of pre-concentration before committing to the cost and sample mass requirements of performance testing by manufacturers. The results characterise coarse particles in terms of preferential breakage and amenability to XRT sensor response — all from 30 to 50 kg of ½-core, including hardness testing. Because coarse liberation sizes can yield variable results, SRK recommends testing multiple samples to quantify this variability.

In addition, standardised testing like this will support project benchmarking and development of pre-concentration indices, which can be used in geometallurgical modelling.

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Pre-concentration circuit simulations

As part of SRK's assessment of pre-concentration for clients, different mine plans under a range of scenarios are evaluated to determine how rejecting waste ahead of the plant can add value. Is it through reduced dilution, lowering ore transport costs, increasing mineable reserves (by including marginal-grade material) or reprocessing low-grade stockpiles to recover additional value?

A novel output of SRK's laboratory testing protocol is the full characterization of coarse particle heterogeneity based on a number of selected samples (quite often adjacent mineralized and unmineralized zones and will be mined together). This enables simulations of different circuit configurations. For example: single versus two-stage crushing, screening at various sizes, and bulk sorting followed by particle sorting. Tonnes and grades can be estimated for each flow, providing detailed inputs that engineering firms need when evaluating pre-concentration circuits.

This work opens opportunities also for dynamic simulation. SRK's Discrete Event Simulation team, based in Sudbury, Canada, has developed a dynamic pre-concentration model using ARENA software. This model is used to assess changes in circuit operating practice as well as logistical factors, like equipment shutdowns (planned or unplanned) and scheduling ore transport when feed rates vary from the pre-concentration circuit. Conventional benefits of Discrete Event Modelling include optimising fleet sizes for truck haulage and concentrate handling, and estimating stockpile capacities upstream and downstream of the pre-concentration circuit.

As companies advance towards implementing pre-concentration, SRK provides ongoing support to engineer these circuits for each orebody and optimise their performance.

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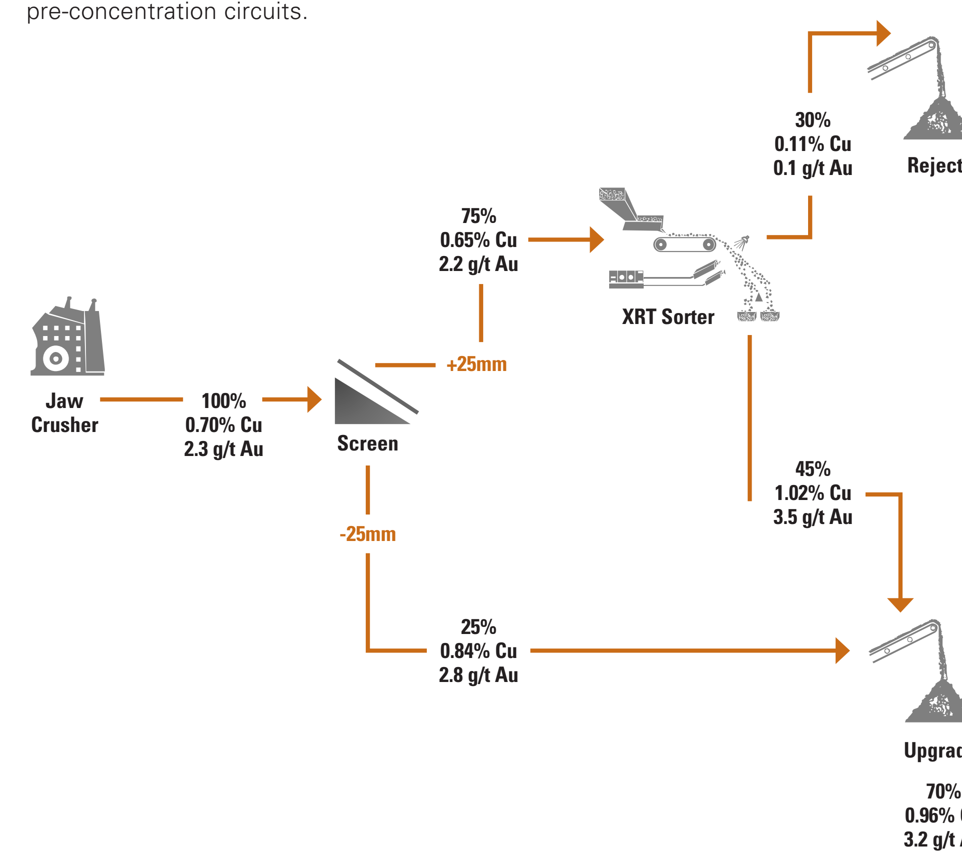

Pebble sorting with XRT sensors

The discharge from any autogenous grinding (AG) or semi-autogenous grinding (SAG) mill consists of coarse particles that recirculate back to the mill feed as ‘pebbles’ or ‘scats’. Sometimes these pebbles are crushed, while other times they are returned intact and considered a natural consequence of primary grinding.

Increasingly, the impact of pebble recycle is being recognised by operations processing competent feed. This includes the negative effects on overall circuit efficiency, mill and pebble crushing capacity. Operations are moving to finer feed conditions, more akin to primary ball milling circuits, so why are we not assessing the impact of pebble recirculation? Have pebbles not already proven themselves competent and resilient—and, in fact, worthy of a higher cut-off grade than the remainder of the ore?

SRK Canada recently evaluated a number of AG and SAG mill pebble samples from North American copper operations for their hardness, grade distribution, and suitability for detection by X-ray transmissive (XRT) sensors. Following SRK’s laboratory protocol, the pebble samples showed a remarkable range of metal grades, which could be detected using the XRT sensor.

As pebble streams are prime candidates for particle sorting —due to their limited size range and presentation on a recycle conveyor belt —these results support rejection of the low-grade portion of pebbles. Test results found pebbles were consistent in hardness and grade across the narrow particle range. However, XRT sensing was able to identify 80% of the valuable metal in only half of the pebbles. The economics of pebble rejection, as well as pebble sorting, were found to be highly attractive for large-scale copper porphyry operations.

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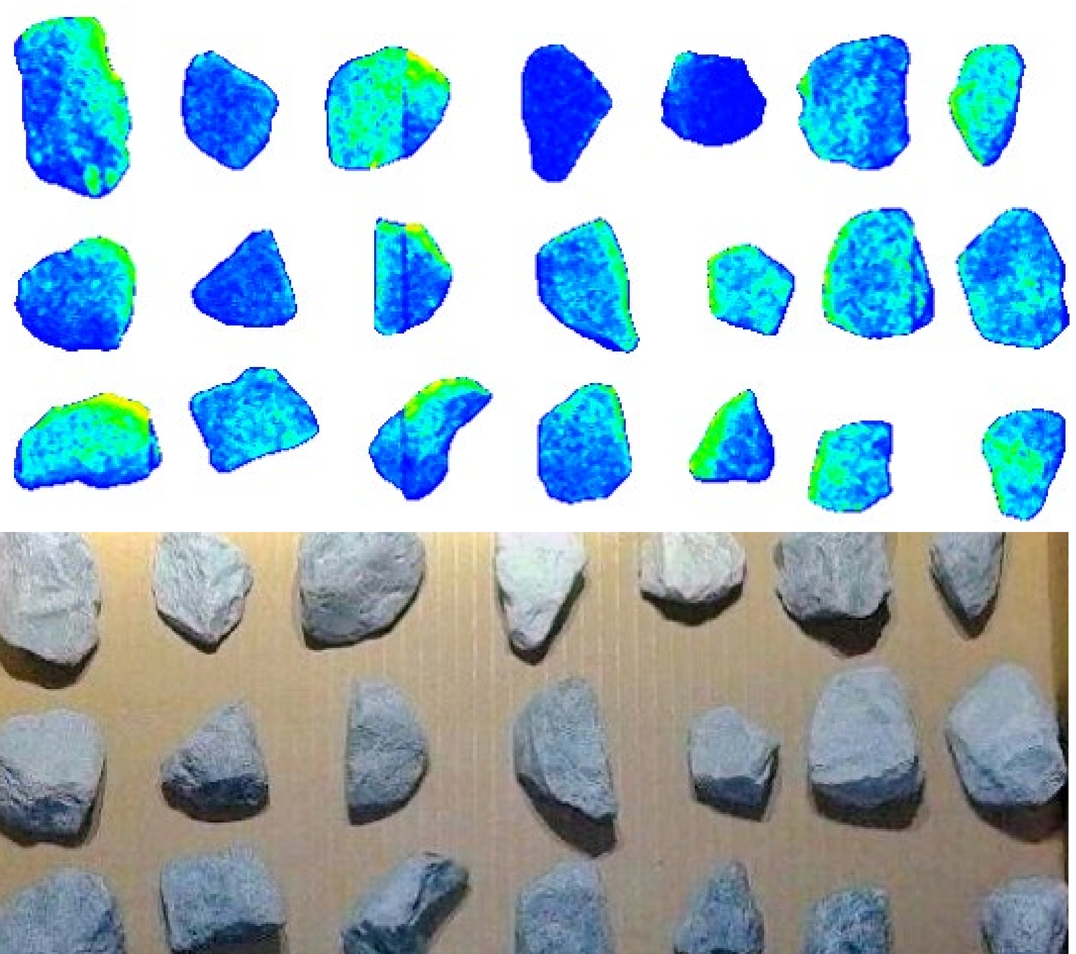

Mill pebbles (upper: XRT scan, lower: particle images)

Primary sulphide leach developments

Hydrometallurgy has long been used in mineral processing, leaching metal ions into solution that can be then refined into high-purity metals. Early successes were mainly achieved with oxide mineralisation and secondary sulphide minerals. Hydrometallurgical treatment of primary sulphide minerals has traditionally required an initial pyrometallurgical step to reduce sulphides to oxides using a roaster or kiln. The conventional route from sulphide concentrate to refined metal involved smelting the entire concentrate and releasing the oxidised sulphur as SO_2 gas in the process.

A fully hydrometallurgical approach for treating sulphide concentrates could deliver significant benefits. Refining can be performed on a relatively small-scale as part of on-site processing, enabling a mine to achieve vertical integration at a single location from extraction to final metal production. Moreover, producing metal without smelting or roasting eliminates the generation of SO_2 gas, offering a cleaner and potentially more sustainable processing route.

Over the past forty years, numerous hydrometallurgical processes have been developed, though few have reached commercial implementation. Commercial-scale success has been achieved with pressure oxidation, used for processing refractory gold ores. This technology has also been applied to base metal concentrate refining, with notable operations at Mt Gordon (Australia, now closed), Sepon (Laos), Kansanshi (Zambia), and Freeport’s Bagdad and Morenci mines (USA). Glencore have deployed several plants utilising the Albion Process™, while reagents- or catalyst-based systems such as the Jetti and Ceibo processes have found use in low-grade, heap leaching applications.

A hydrometallurgical plant of the future (AI-generated image)

Two pioneering sulphide leach processes have been developed to pilot scale in southern Spain. First Quantum’s Cobre Las Cruces (CLC) operation initially processed the secondary mineralisation cap on a polymetallic deposit through leaching. When this cap was exhausted, the mine transitioned to primary sulphide ore. To maintain on-site refining through copper cathodes, CLC developed the in-house Silver-Catalyzed Atmospheric Leach (SICAL) process, which was successfully piloted on a bulk copper-lead-zinc concentrate from a conventional crush-mill-flotation circuit. The mine is currently on care and maintenance pending permitting and capital approval. Meanwhile, at the Atalaya mine, Lain Technologies’ E-LIX™ process has been advanced to industrial scale to treat polymetallic ores, reportedly capable of producing 10,000 tonnes per annum of copper cathode and currently undergoing commissioning.

Several halide-based leach technologies have also been piloted but not yet commercialised. These include Cominco’s CESL process (which employs fine grinding); the Kell process (which uses an autoclave); and the Halion Loop™ (commonly referred to simply as the “Loop process”), capable of extracting copper, silver and other co-metals without high pressure or noxious gas emissions.

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Liam is a Principal Consultant in extractive metallurgy and mineral processing with over 25 years of international experience. His expertise spans hydrometallurgical processes, process-plant design, laboratory and pilot-plant testwork, and the construction, commissioning and operation of minerals processing facilities. Prior to joining SRK, Liam spent 24 years with an international equipment supplier involved in mining projects from feasibility studies, detailed engineering of mineral process, and project delivery. At SRK, he focuses on process-plant evaluation, technical reviews, audits and due-diligence assessments across Europe, Africa, the Middle East, Asia and Australia.

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Reprocessing mine tailings: unlocking hidden value

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Dmitriy has over 30 years of experience in processing and metallurgy, gained through operational management, engineering, capital-equipment supply, and consulting roles. His expertise includes comminution circuit design, base-metal flotation, gold metallurgy, uranium leaching, tailings reprocessing, and iron-ore beneficiation. He has managed operations as Processing Director for 12 plants producing over 1 Moz of gold annually. Dmitriy also has extensive experience in flotation, gravity and hydrometallurgical processes, pilot-plant campaigns, laboratory testwork, plant commissioning, and mining studies from scoping to FEED across Russia and the Commonwealth of Independent States (CIS).

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JOHN WILLIS

John is a Principal Consultant with SRK and has over 30 years' experience in the minerals industry covering industrial R&D, technical services and consulting. His expertise lies in the development and management of metallurgical testwork programs, geometallurgy, flowsheet development, plant auditing, due diligence and plant design. John has a PhD from the JKMRC and has worked out of Australia and the UK in commodity areas including gold, base metals, iron ore, and critical minerals including lithium, REEs and nickel.

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Are there valuable metals stored in tailings ponds? (AI-generated image)

Tailings from mineral processing plants account for large volumes of mining waste yet often contain residual valuable minerals. Rising metal prices, advances in extraction technology, and modern environmental standards are making tailings reprocessing an increasingly viable option. The depletion of high-grade mineral deposits has led to the processing of lower-grade and more refractory ores, reducing overall feed quality. While legacy tailings and waste dumps may contain higher metal concentrations than most new deposits, modern technology, equipment, and operational experience now enable their transformation into economically attractive projects.

Several methods are used to recover material from tailings storage facilities, depending on their physical state, moisture content, and accessibility. Hydromechanical mining uses high-pressure water jets (hydraulic monitors) to break down tailings, creating a slurry that is pumped through pipelines to the processing plant—an approach suited to saturated or partially consolidated deposits. Dredge mining employs specialized machinery to recover submerged tailings directly from ponds or flooded impoundments, while dry mining relies on conventional surface mining equipment such as excavators, loaders, and trucks to reclaim desiccated material. Finally, combined methods integrate elements of the above, often beginning with dewatering or drainage followed by mechanical loosening, hydrotransport, and secondary recovery stages.

Unlike primary ores, tailings require no crushing, though grinding may be used to expose fresh mineral surfaces. Feed preparation typically involves dewatering, screening and debris removal. Because most tailings are fine-grained, they are suited to flotation, gravity concentration and leaching. Given the large volumes and low grades involved, processing must be highly selective and cost-efficient.

Modern reprocessing applies advanced extraction techniques to recover metals once considered irretrievable:

Gold-bearing tailings: ultrafine grinding mills and high-pressure slurry ablation systems increase particle liberation. Centrifugal concentrators (for example, Knelson, Falcon, and ITOMAK) can enhance recovery of micron-sized free gold, while improved flotation reagents and intensified cyanidation reduce losses and lower cyanide use. Sulfide oxidation methods further release encapsulated gold particles.

Copper tailings: new flotation reagents, chloride-ion leaching, and other extractive techniques are available to improve recovery of partially or fully oxidized copper minerals. Automation and online analyzers now allow precise process control, reducing variability and minimizing losses.

Tailings reprocessing offers significant environmental benefits by reducing waste volumes and the mining operation overall footprint; yet it also carries risks. Water-saturated facilities require detailed geological and geotechnical assessments to ensure stability during reclamation. Heterogeneous materials and potential contamination with hazardous elements such as mercury demand a thorough, preliminary investigation and careful environmental management.

As a growing opportunity for gold and copper producers, this approach is driven by technological innovation and shifting economic conditions. Project success depends on selecting appropriate extraction technologies and integrating them into efficient, environmentally responsible operations. With sound planning, reprocessing can unlock hidden value from legacy waste while advancing long-term sustainability goals.

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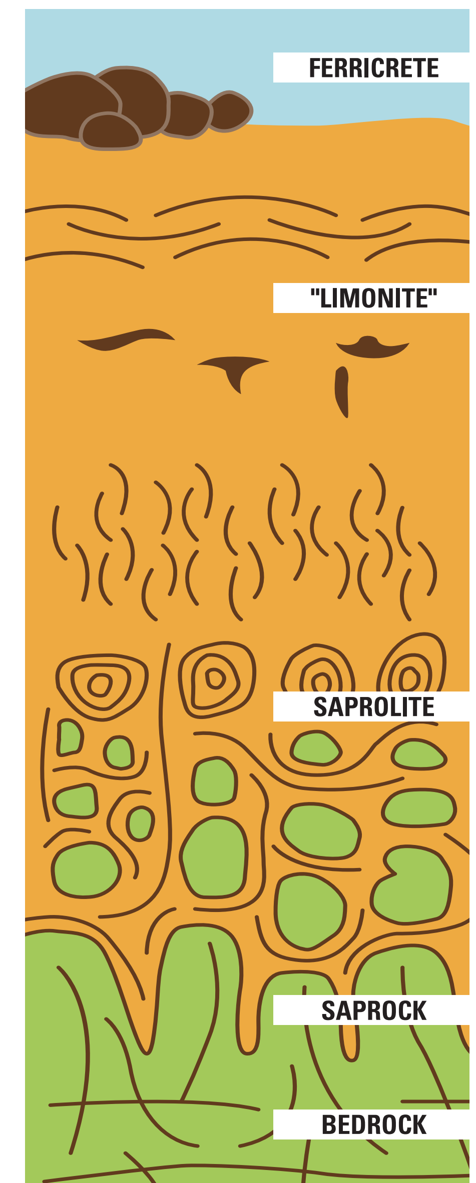
Processing options for nickel laterite ores

The diagram shows a typical weathering profile for a nickel laterite deposit, developed through the intense tropical alteration of ultramafic rocks. From a processing perspective, the two key zones are limonite and saprolite.

Their contrasting geochemical characteristics largely determine the preferred processing route.

Saprolite ores are typically treated by a pyrometallurgical process known as RKEF (rotary kiln–electric furnace),



producing an iron-nickel metal alloy such as ferronickel (20-40% Ni) or nickel pig iron (<15% Ni). The process relies on the saprolite's lower iron content but yields only "Class 2" nickel—suitable for stainless- steel production yet unsuitable for batteries without further refining. In some operations, sulphur is added at the end of the process to form a nickel sulphide matte, which can be refined directly into "Class 1" (battery-grade) metal. The RKEF route, however, carries a high carbon footprint, mainly due to the large electrical-power demand of the furnace, where the power supply is often generated from fossil fuels.

As for limonite ores, they are usually processed by High-Pressure Acid Leaching (HPAL), a hydrometallurgical method that dissolves nickel and cobalt using acid at elevated temperatures (~200 °C) and pressures to maximise recovery and minimise reaction time. Although HPAL plants can be fully integrated to produce Class 1 metal or battery-grade nickel sulphate, they often generate an intermediate product that is sent elsewhere for further refining. This process is less sensitive to iron content but highly sensitive to magnesium, which consumes significant amounts of acid. While HPAL generally has a lower carbon footprint than RKEF, both methods remain capital-intensive and are therefore best suited to large, long-life ore deposits.

More recently, heap leaching has emerged as an alternative to HPAL for processing limonite and, in some cases, saprolite. Although recoveries are slightly lower and reaction times longer, these drawbacks are offset by significantly lower capital cost. Heap leaching is also more flexible and better suited to smaller orebodies.

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Needles in a haystack: the search for critical metals

The global transition to renewable energy infrastructure is driving rapid growth in the demand for critical raw materials), including rare earths, gallium, germanium, cobalt, nickel and many other elements.

One challenge with these critical materials is their key components often do not form their own mineral hosts. Instead, they occur as trace elements within other minerals making identification of the host-phase challenging. Identifying and concentrating these minerals can be as difficult as "finding a needle in a haystack", following the old English proverb.

A good example is the rare earth elements can form carbonate and phosphate minerals but typically are found in minerals such as monazite (a phosphate), eudialyte (a complex silicate) or clay minerals in weathered deposits.

Another example is the production of the important elements gallium, germanium and indium for the electronics industry. Gallium has similar chemistry to aluminium and present in trace amounts in some bauxites. More commonly, all three elements tend to be enriched in higher abundance in sulfide ores, where they are hosted within minerals such as chalcopyrite and sphalerite as trace components.

Separation and concentration of these minerals are focused on the host-phase rather than the target elements. To aid successful separation, substantial mineralogical information is essential. Advanced mineralogical analyses are used to characterise critical metal mineralogy and inform process flowsheets, supporting the optimisation of target mineral separation and concentration.

Figure 1 shows a thin section of ion-adsorption clay ore showing up to 200 ppm Nd and 60 ppm Pr associated with opaque iron-rich phases. Goiás State, Brazil.

Figure 2 shows a Söhngeite ($Ga(OH)_3$). Named in 1965 in honor of Gerhard Söhnge, former Chief Geologist of the Tsumeb Corporation, Namibia, and professor at Stellenbosch University. One of the few known Ga minerals, it is extremely rare and found only from its type locality.

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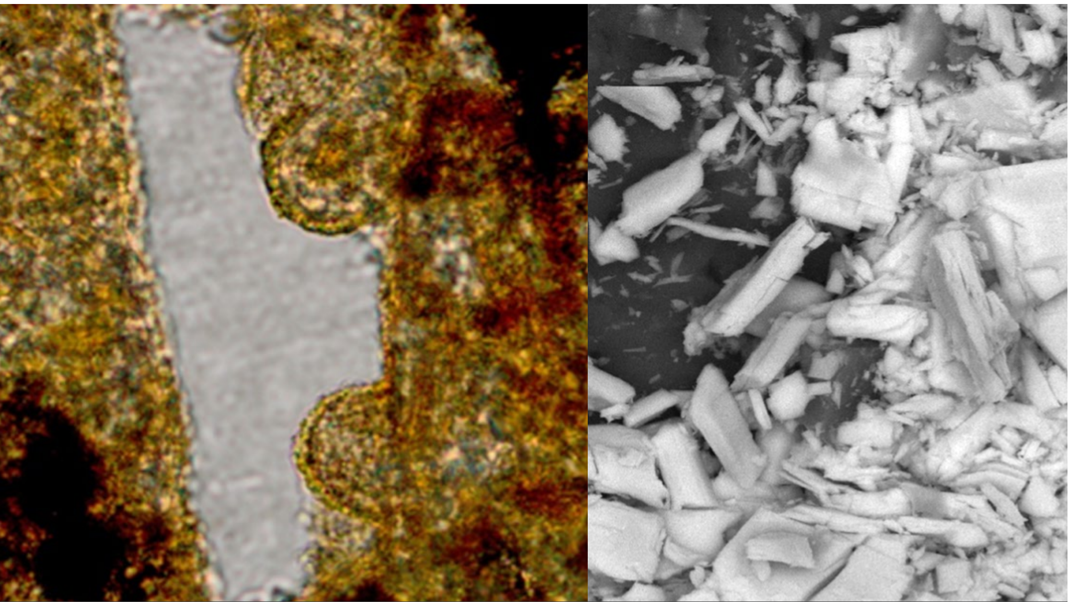

Figure 1: Ion-adsorption clay (left), Figure 2: Söhngeite (Ga(OH)3) (right)

The strategic role of tailings reprocessing

The mining industry faces many challenges, including declining ore grades, increasingly stringent environmental regulations, and at times, political agencies opposed to mining. Nevertheless, the sector has responded to these pressures with a growing commitment to technological advancement and the pursuit of truly sustainable operations.

This focus has placed tailings storage facilities (TSFs) at the forefront of sustainable mining practices. New regulations now require not only the geotechnical stability and operational safety of these structures but also the creation of positive environmental outcomes in their surrounding areas.

What was once considered as mining waste is now being revalued as a potential resource. With advances in processing technologies and favorable market prices for key metals—particularly gold and silver—tailings have become a potential secondary reserve.

Tailings reprocessing thus becomes strategically important, offering the industry two fundamental opportunities:

- Value recovery: enables the recovery of residual metal content, avoiding the full costs of primary mining and extending the economic life of the operations.
- Risk mitigation and environmental improvement: offers the possibility in transforming liabilities into assets. Reprocessing supports construction of new TSFs built to higher engineering standards, with improved safety and reduced environmental impact.

However, reprocessing can present inherent complexity. The initial phase of excavating an existing tailings structure involves significant geotechnical challenges. In many cases, historical data on composition and compaction are incomplete, leading to an underestimation of the work required. It is essential to recognize that excessive loading, vibration, or improper mining methods can trigger structural failure and compromise safety.

At the metallurgical stage, reprocessing often requires ultra-fine regrinding technology to achieve efficient metal liberation from small particle sizes. This process demands a thorough analysis of the physical and chemical behavior of the reground tailings. When particle size is reduced substantially, not only are the valuable metals released, but other species may be liberated, potentially altering the material's behavior in its new, secure storage facility.

Ultimately, successful reprocessing depends on careful attention to safety and integrity at every project stage. It represents a critical opportunity to transform existing TSFs into safer, more sustainable structures and leaving the environment in better condition.

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Tailings reprocessing underway using hydraulic mining

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Rob is a corporate consultant in geochemistry with 38 years experience in the mining industry applying mineralogy and chemistry to solve engineering issues. He has worked on many commodities with a particular interest in the process chemistry and geometallurgy of Cu, Zn, Ga, Ge, In, U, REE, Li, B, Br, Be and industrial salts.

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Héctor has over 14 years of experience in the design, operation, and optimization of metallurgical processes. He specializes in beneficiation plant design, plant operation and optimization, and value recovery processes for gold, silver, lead, and zinc. He also has experience implementing and operating tailings management systems. His work focuses on improving efficiency and safety through advanced technologies and innovative practices. Héctor's broad technical background has enabled him to excel in tailings deposition facility management and to support mining projects through sound process design and operational insight.

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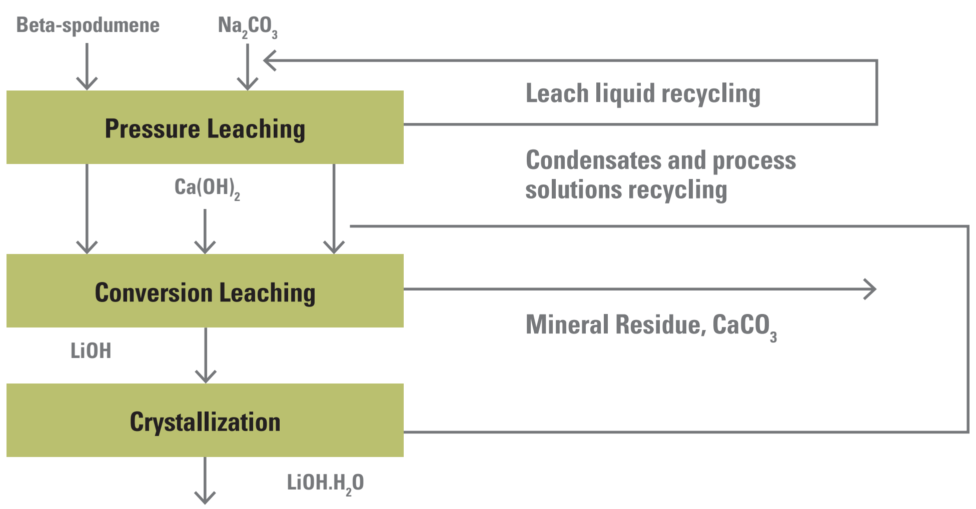
Implementing novel technology

Sibanye-Stillwater is advancing the Keliber lithium project in Central Ostrobothnia, western Finland and is in the latter stages of construction with scheduled for completion in H1 2026. SRK UK has been engaged since 2018 as Lenders' Independent Engineer for the project.

The Keliber lithium project is vertically integrated, with mines producing spodumene ore that will be upgraded at the company's concentrator close to the mine sites, which will then be upgraded to battery grade lithium hydroxide at the Keliber lithium refinery located in the port city of Kokkola. As the expected life of the refinery exceeds that of the mines, the refinery will have the capacity to process third party spodumene concentrates following cessation of integrated mining and beneficiation.

The Keliber lithium project has adopted Metso's proprietary Alkaline Leach Process (ALP) for the refinery, instead of the conventional "acid bake" process. The ALP process, for which Keliber lithium project will be the second to enter production, is expected to have advantages over the conventional alternative in the areas of carbon footprint and operating cost, as well as producing a benign solid waste stream that has potential downstream use in the construction industry.



Metso's development timeline for the ALP has spanned almost 20 years, building on earlier work out of Canada. Much of the process development has been undertaken using Keliber lithium project's spodumene concentrate produced from laboratory and pilot scale beneficiation testwork.

SRK's initial involvement in the project was in the Feasibility Study stage, and has followed the project's progression through Basic Engineering, Detailed Engineering and Construction. SRK influenced the Keliber lithium project's decision to commission Metso to run a 1:2500 scale pilot plant of the refinery flowsheet – fully continuous and with all recycle streams. The pilot ran in early 2020 and provided valuable data to support Detailed Engineering, further de-risking the project.

Introducing novel technology to the traditionally conservative mining industry requires persistence and long-term thinking. SRK looks forward to continuing to support Sibanye-Stillwater's partners as the project progresses closer to its moment of truth.

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Keliber lithium refinery, Kokkola, Finland

Metallurgical development for different project study phases

Mining project assessment typically progresses in stages—from preliminary economic assessment (PEA) and prefeasibility study (PFS) to feasibility study (FS) levels —with each stage delivering greater engineering detail and cost accuracy. SRK provides metallurgical development support for a wide range of commodities including gold, silver, copper, lead, zinc, iron, tin, tungsten, molybdenum, lithium, rare earth elements and various industrial minerals. At each study level, SRK assists with the preparation of metallurgical sample composites, laboratory selection, coordination and management of testwork, and preparation of final metallurgical reports and technical sections.

A PEA metallurgical program is designed to be cost-efficient, relying on limited sampling and, where available, existing material. Typical testwork includes head and mineralogical analyses, comminution testing, and bench-scale tests for process characterization.

The results provide an early indication of achievable metal recoveries using generalized test procedures appropriate to the ore type being evaluated and support the development of an initial conceptual process flowsheet.

A PFS metallurgical program provides a more detailed evaluation of process requirements and supports the development of preliminary design criteria and process flowsheet. Building on the findings from the PEA, it is typically conducted on selected core intervals to prepare one or more master composites representing the deposit and identified ore types. Testwork commonly includes head and mineralogical analyses, comminution testing, bench-scale tests across a range of process parameters and thickening and filtration studies. Initial tailings characterization is often conducted to generate data for early-stage environmental permitting.


Hydrometallurgical pilot plant (source: www.SGS.com)

An FS metallurgical program provides definitive process design criteria and finalized flowsheet. Building on PFS findings, it is based on master and variability composites prepared from selected core intervals representing the deposit main ore types. Variability samples are tested across grades, lithologies, and ore zones to assess response to optimized process parameters developed from master composites. For this program, testwork includes head and mineralogical analyses, comminution and bench-scale testing and thickening and filtration studies. Locked-cycle flotation tests evaluate the impact of recycling intermediate products and process water on recovery and product grades, while pilot testing is undertaken where new processes or large intermediate product quantities warrant further downstream evaluation. Detailed tailing characterization is also generally completed at this stage in close coordination with environmental teams responsible for project permitting.

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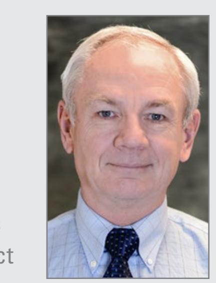

Eric has over 40 years of experience in the minerals industry with extensive consulting, plant operations, process development, project management, and research and development experience with base metals, precious metals, ferrous metals, and industrial minerals. Mr. Olin has served as the general manager and plant superintendent for several gold and base metal mining operations. Additionally, Mr. Olin has been involved with numerous third-party due-diligence audits and preparation of project conceptual, prefeasibility, and feasibility studies.

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Geometallurgy: benefits of early – stage implementation

As ore grades have declined in recent years and deposits have become more mineralogically and metallurgically complex, geometallurgy has gained recognition as an increasingly valuable exercise in the development of mining projects. By integrating mineralogical, geochemical, and metallurgical data into a single data set, geometallurgy enables a more comprehensive understanding of ore variability and its impact on processing performance. When implemented early in the project development stage, this approach serves as a powerful risk management tool, helping reduce risks associated with process plant design.

One of the key benefits of early-stage geometallurgical work is the ability to characterize ore domains based on both geological and metallurgical attributes. This allows project teams to identify potential processing challenges—such as variable hardness, mineral liberation characteristics, or unusual water demand—well before detailed design or operational decisions are made. The outcome is a more realistic and confident forecast of metallurgical recovery, throughput and operating costs; improving the accuracy of financial models and risk assessments.

From a process design perspective, early geometallurgical input supports more representative sampling and testwork. Rather than relying on a limited number of composite samples, testwork programmes can be structured around defined ore domains to ensure a deposit's metallurgical variability is properly represented. This approach leads to more comprehensive and informed process designs, optimized circuit configurations, and more accurate equipment selection and sizing, ultimately improving capital cost estimation.

Incorporating geometallurgical data into mine planning and ore blending enables the development of production schedules that consider not only grade but also process response. This integration supports smoother plant performance and more consistent recoveries, throughput and metal production.

Geometallurgical modelling is a valuable tool for both new and operating mining projects. Identifying favourable as well as metallurgically-challenging ore domains helps to inform decisions on process routes and capital allocation, benefiting overall project performance. Early-stage implementation aids project development by associating geological characteristics with metallurgical performance, enabling more reliable forecasts, and reduced technical and financial risks throughout the life of mine.

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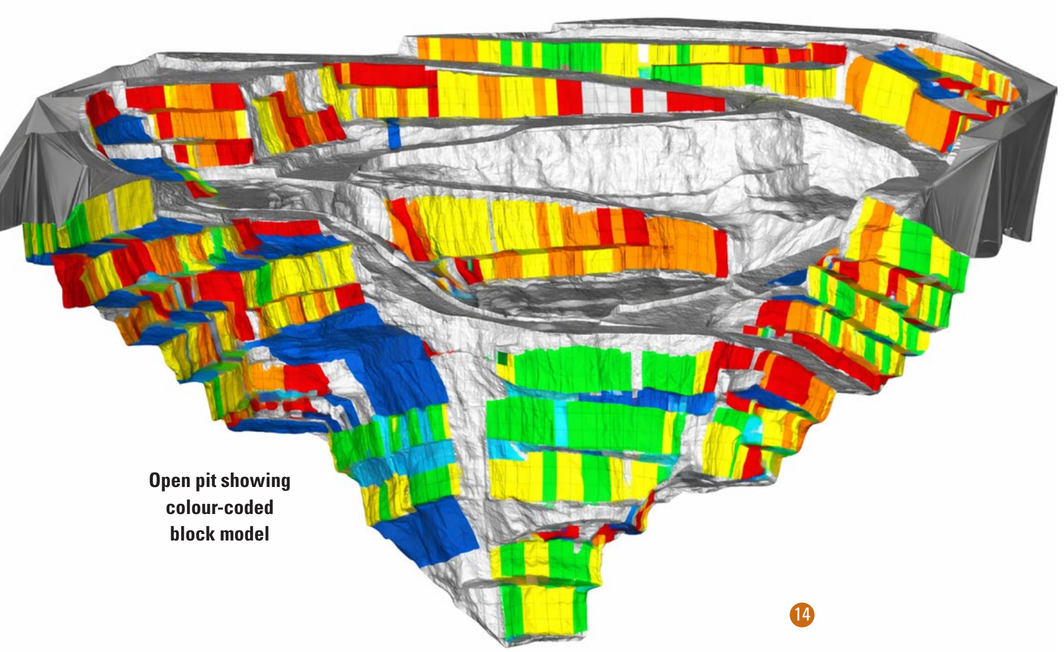
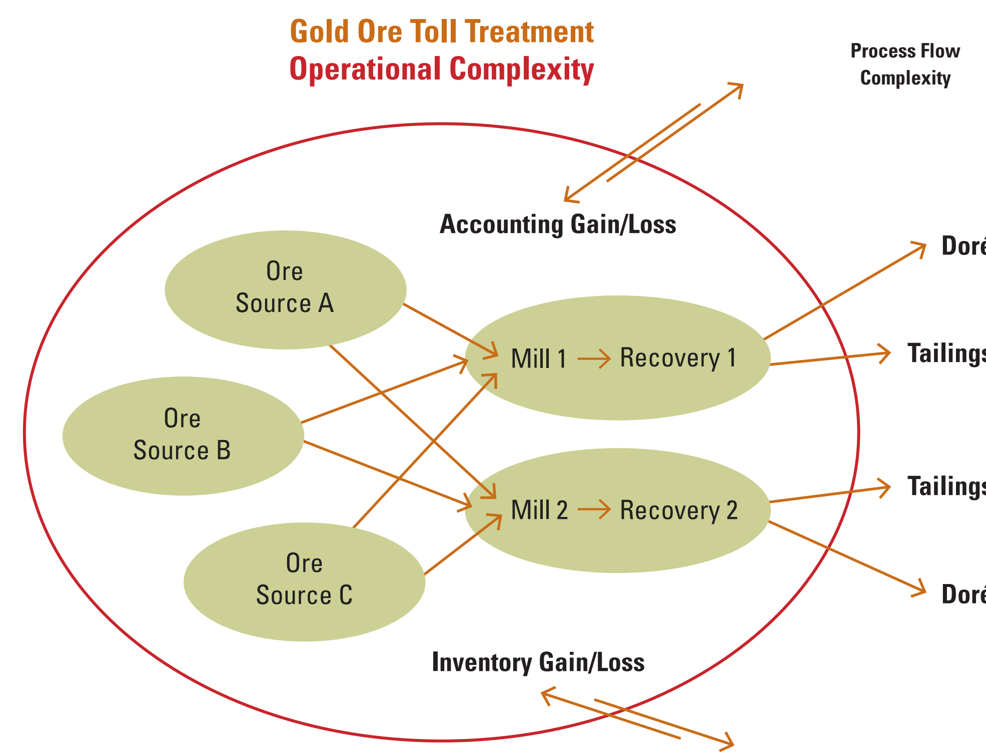


Open pit showing colour-coded block model

Gold ore toll treatment – potential sampling challenges



Ensuring metal accounting practices meet the requirements of modern corporate governance requires codes of practice, standard operating procedures and planned task observations. AMIRA International facilitated the development of AMIRA P754 (Ref 1), a standardized Code of Best Practice for metal accounting and reconciliation.

Meeting the AMIRA Code and Theory of Sampling principles in a self-owned processing facility is often challenging in itself. But how can these principles be applied in a third-party toll treatment facility treating multiple ore sources in a continuous blended feed rather than in campaigns?

Through its 10 core principles, the AMIRA Code addresses critical aspects of metal accounting, from data collection and validation through to reporting and auditing. A key principle is the metal accounting system must be based on accurate measurements of mass and metal content across defined 'Check-in Check-out' boundaries using best practices as defined in the Code. In a typical Carbon in Pulp (CIP) or Carbon in Leach (CIL) gold plant, such accounting boundaries might include mill feed, leach feed, leach residue, elution circuit feed and gold bullion produced.

Accurately determining the metal content of delivered run-of-mine (ROM) ore is a key challenge given ore sources with varying characteristics are blended and must be separately accounted for at the coarse delivery size (e.g. primary crushed).

Wet solid flowrates are readily measured via weighbridge or conveyor weightometer, subject to approved calibration procedures. Dry mass determination requires measurement of moisture content of ore on delivery (at best, rough estimates).

Stop-belt sampling and automated cross-belt sampling are two techniques used to collect primary samples of ROM ore for head grade determination; both have strengths and weaknesses. Stop-belt sampling interrupts ore flow, while automated cross-belt samplers do not. Automated cross-belt samplers, however, are more prone to yield biased samples if the complete size range is not quantitatively recovered. In both cases, samples should be tonnage rather than time-based. This results in the generation of large primary samples that need to be crushed and split to yield representative aliquots for laboratory analysis.

Given the blended feed, recovered gold is typically allocated in proportion to the expected recoverability of each ore source. This allocation is based on the delivered feed content and a leach factor derived from bottle roll tests, which account for varying leach characteristics among ore sources. It is essential the bottle roll procedure is aligned with the actual plant process; for example, with/ without carbon in leach, similar grind sizes, cyanide concentrations and leach times.

Finally, full disclosure of metal accounts must be stated in the toll treatment agreement, while maintaining the confidentiality of other participants.

Ref 1: AMIRA International; P754: Metal Accounting; Code of Practice and Guidelines: Release 3; February 2007

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Vic is a mineral processing specialist with over 40 years' industry experience, spanning operating, management and consulting roles, in South Africa and internationally. Vic's expertise covers a wide range of commodities, including precious metals, base metals, uranium, ferrous minerals, industrial minerals, battery metals and rare earth elements. His professional skills encompass metallurgical and mineral processing consulting, technical and economic due diligence, metal accounting and reconciliation audits, feasibility studies and independent competent person reviews.

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Adilbek is a processing engineer with the Kazakhstan office. He specializes in extractive metallurgy and mineral processing, geometallurgical modelling, processing plant flowsheet design, and laboratory and pilot-plant testwork. He has also worked as a mining engineer and plant metallurgist gaining research experience in froth flotation and gravity separation. Since joining SRK in 2021, he has worked from scoping to feasibility studies across iron, gold, copper, lithium, tungsten and limestone projects in Central Asia and the Middle East. His experience also includes metallurgical accounting, plant operations, cost estimation, process audits, and use of Cancha and AggFlow.

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