srk news
Caving

Addressing the challenges and future of cave mining

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SRK Consulting's
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Newsletter

Infrastructure development at Oyu Tolgoi

There are over 50 global cave mining projects in various stages of studies and development.

Despite the fact that the cave mining method is more than 100 years old, it is only within the past 20 years that this method has spread from initial cave mining centres to six continents. There are currently approximately 17 cave mining operations in 11 countries.

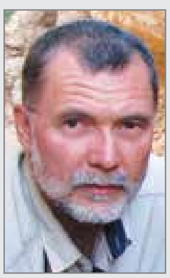
The interest in cave mining is being fuelled by the depletion of near surface orebodies suitable for open pit operations, relatively high production rates and low operating cost. Also, a number of open pits have a continuation of the orebody below their economic depth, and further exploitation of often large low-grade resources at depth would not support a more expensive mining method. In recent years, besides the economics of high strip ratio, the environmental concern also plays an important role when comparing open pit mass mining and caving. Cave mines can have a significantly smaller footprint than a comparable open pit, since waste mined is only limited to underground infrastructure development.

…continued

Addressing the challenges and future of cave mining *(continued)*

Shaft headgear at the Resolution Copper project, Arizona, USA

JAREK JAKUBEC



Jarek has over 35 years of worldwide operating and consulting experience in the mining industry, specialising in underground mass mining methods, diamond mining, rock mechanics and mining geology. He has worked around the globe on more than 80 mining projects in 30 countries on 5 continents. Jarek worked as geotechnical engineer at Cassiar cave mine and later, for De Beers Consolidated Mines in South Africa and Botswana. With SRK, he built and now manages a team of mining and geology experts who provide consulting services for the cave mining and diamond industries. Jarek has published over 25 papers on geology, rock mechanics, and mining, co-authored two mining guidelines books, and participated on several international research projects. Jarek is founder of the Cave Mining Forum and he is a qualified person in terms of National Instrument 43-101.

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Cave mining principles and economics

Traditionally, cave mining was a method based on the principle of undercutting rock and then naturally letting it cave. However, this mining method has been extended to very strong rocks which would not easily cave or would not be suitable for caving due to very coarse fragmentation. To mitigate this problem, pre-conditioning techniques have been developed to generate more fractures and reduce the fragments to a manageable size. This is achieved by hydraulic fracturing and, in some cases, in combination with confined blasting. Although some discussion is needed about the potential impact on in situ stress that is required for cave mining, several cave mines are in operation with preconditioned rock masses and several others are being developed. The most extensive work undertaken is at Cadia East mine and Northparkes Mines in Australia, and Andina and El Teniente in Chile.

Caving methods can be used with any type of commodity since it is the geological and geotechnical context that is important. There are many parameters to consider but typically the orebody needs to be at least 100 m thick for cave mining to be economical. In the past, typical caving heights were 150-250 m. Most of the designs which are on the drawing board today have caving lifts in excess of 350 m. Although higher lifts generally result in better NPV, they also have higher business risks of resource sterilisation, dilution, stability of the drawpoints, and extraction level in general.

By contrast, orebodies with relatively small horizontal footprints can also be mined economically if they have sufficient height and metal content to justify the capital expenditure. Good examples are Northparkes Mines in Australia, and the diamond mines in South Africa and Canada.

Mechanised cave mining includes several variations of the method, including block, panel, incline and front caving. Most of the current mines and projects utilise either block or panel caving but after several years, Ekati Diamond Mine, Canada successfully introduced an incline cave at their Koala Mine.

Cave mining differs significantly from other typically more selective underground mining methods in a number of areas. Because cave mining is a bottom up method that relies on first establishing a large fixed infrastructure underground that will provide a very long term production platform, the initial capital costs are typically very high.

To offset the impact of the large capital expenditure on project value, a consequent high rate of production and an increased tonnage per drawpoint is required. In this day and age, several cave operations are running at upwards of 50,000 tpd and newer operations are being constructed for nameplate capacities of 100,000 tpd and more.

Chuquicamata and New Mining Levels at the El Teniente project in Chile; Oyu Tolgoi projects, Mongolia; Grasberg caving complex, Indonesia; and the Resolution Copper project in Arizona all fall into the supercaves category. It has to be stressed that there are no examples where tonnage over 100,000 tpd was achieved on a sustained basis from single cave footprint, although El Teniente produced higher tonnage from concurrently mining several caves.

In terms of logistics, once a cave mine is in production, the execution is relatively straightforward. The production footprint remains fixed and mining consumables typically revolve around secondary breaking with campaign maintenance within the production drives. It is important that strict draw control is maintained and the extraction level is not experiencing excess damage requiring repairs.

Technical challenges of cave mining

As the number of cave mining projects increases, there are also heightened expectations for high production rates and caving lifts, and greater depths to be achieved. The analysis of the cave mine performance is far from satisfactory. In the past two decades, at least 12 cave footprints were put into production and all experienced some level of unforeseen difficulty related to ground conditions, fragmentation, mining induced seismicity, mudrushes, and underestimating ground support, or simply breaking basic cave mining rules, specifically in the area of undercutting and draw management.

On a positive note, in hindsight, most of the challenges could have been prevented with better upfront knowledge, correct design or draw disciplines. The other disadvantage of cave mining is the long lead time, it typically takes 7 to 10 years, or longer, from initial studies to production and the site may underestimate the logistics and skillset required for cave mining development and operation.

Because the cave mine has to be fully developed before all design parameters are known to a high degree of confidence, the design should be robust and technical success should have priority over economics, especially when greenfield projects are considered. Although the cave mine may not require the same level of resource definition in terms of drillhole density as selective underground mining method, the geotechnical and structural geology knowledge has to be typically higher than for other methods. Some of the information needed for the final feasibility design may not be possible to obtain from the drill core, and underground characterisation exposures may be necessary.

Future of cave mining

Cave mining is moving to new frontiers with high production rates, strong rock masses, very high caving lifts and greater depth. In forefront of such projects is Resolution in Arizona where their shaft was sunk to 2,100 m to develop deep copper porphyry.

Block and panel caves are very suitable for highly automated equipment like remote control loaders, trucks and crushers. A future supercave could potentially have less than 50-60 people underground.

Cave mining toolbox

The ever-increasing speed of computing and the sophistication of numerical modelling codes enable many mining companies to model complex mining problems. Better and more reliable instrumentation such as MPX cables, Smart Marker System (Elexon), and Cave Tracker (Mining3) also provide excellent data for calibration of such models. However, do not count on the high reliability of numerical models without calibration. Reliable and accurate input information for numerical models are typically available only after the cave is designed, developed and operating.

The track record of predictive models without comprehensive calibration, especially for greenfield projects, is not very good and does not necessarily increase confidence in the design in comparison to other empirical tools and benchmarking. Additionally, complex processes such as cave propagation, subsidence geometry, and material flow in a cave mine cannot be yet reliably modelled.

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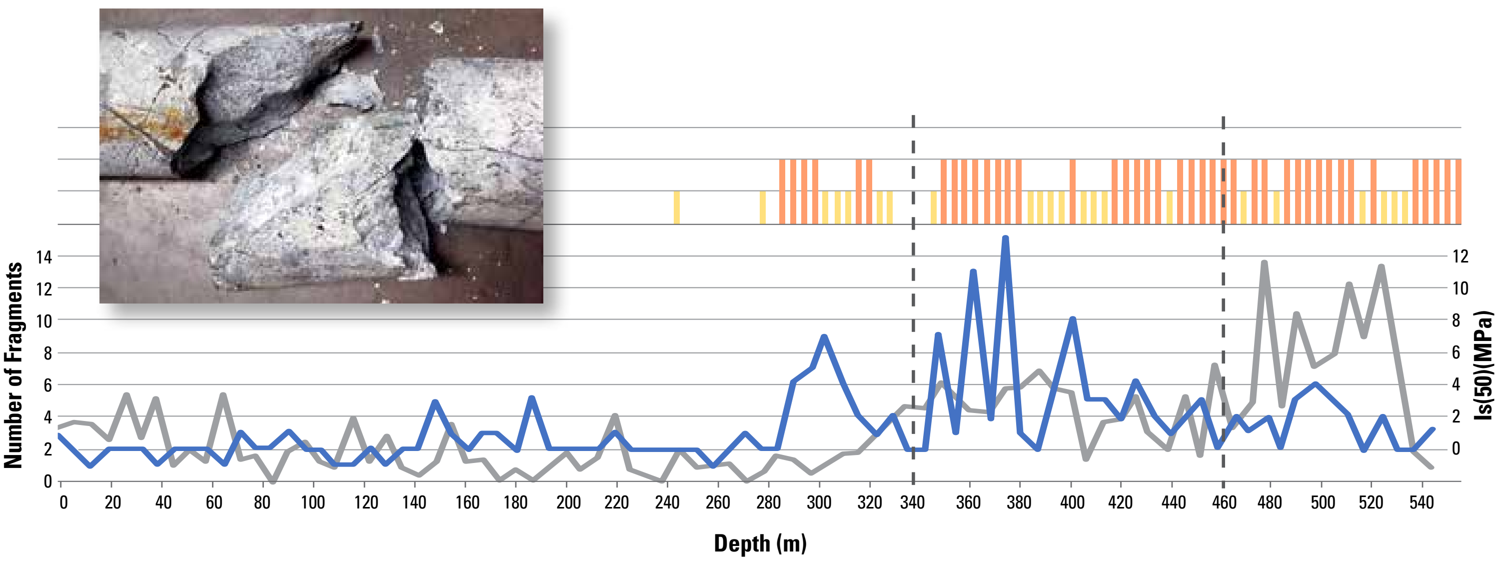
Accounting for micro-defects in rock mass rating



Plot showing micro-defect intensity, drop test results, and point load test strength for a drillhole in a copper porphyry deposit

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Andy, MEng, PEng, is a Geological Engineer with over 13 years of experience working as a professional in the field of ground engineering. He has extensive experience in designing, undertaking and managing geomorphological, geotechnical and hydrogeological investigations for projects in the mining and civil sectors. Andy has worked on a wide variety of projects in Australia, the Americas and Asia. He completed his specialist studies at the University of British Columbia where he focused on engineering rock mechanics. Andy's recent projects include designing, implementing and managing geotechnical and hydrogeological investigations and stress analyses for underground mining projects.

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In 2001, Laubscher's Mining Rock Mass Rating (MRMR) classification system (Laubscher and Jakubec, 2001) introduced the rock block strength concept to account for scale effects and the influence of closed defects on intact rock strength (IRS). Almost two decades later, rock mechanics practitioners are still challenged by how to appropriately incorporate defects, other than open breaks, into rock mass classification to arrive at in-situ rock mass rating (IRMR). A category of such defects is micro-defects, which are typically non-systematic with variable geometry and continuity. These fractures can sometimes be difficult to identify, let alone characterise, but they can have a significant impact on important mining considerations, such as the caving process and rock fragment block size (Jakubec et al., 2007).

Early stages of mining projects rely almost exclusively on rock core to define rock strength. Assessing the unconfined 'intact' strength of the rock core is mostly done by empirical methods, by observing how rock core breaks by hammer blow, and point load and UCS testing. However, in rock where defects are numerous and small, e.g. in porphyry-type rocks, it can be difficult to isolate sections of defect-free rock in which to obtain true intact strength. In such cases, the scale of micro-defects relative to the size of core means that core-scale strength tests reliably account for their influence on the rock strength.

The concept of the drop test was introduced and accompanied by the comment that when performed correctly, the drop test yields more consistent results than the hammer blow method. The drop test consists of dropping uniform length sections of the same-sized core horizontally-aligned onto a concrete floor and tabulating the breaks on fractures and through intact rock.

The major appeal of the drop test as a core testing tool is its efficiency, simplicity, and repeatability; gravity is a constant so only the drop height datum for the project, e.g. core rack level, need be defined. For rock with high micro-defect intensity, significant utility can be obtained from the drop test by simply counting the number of fragments that the core breaks into. In a recent study, the number of fragments correlated with the micro-defect intensity and point load strength (Figure left).

The plot shows that in the unaltered Post Mineral Volcanic unit, the point load test Is(50) values and number of fragments were equally low. In the Tonalite unit, the highly altered Sericite-Chlorite-Clay domain is characterised by zones where there were high numbers of drop test fragments, whereas testing the less altered but similar micro-defect intensity in the Sericite domain resulted in generally fewer fragments and far higher Is(50) values.

Although wetting the core helped, it was not always possible to see the fractures in the core. It was impractical to inspect each broken fragment (up to 15 fragments per test) to determine whether breakage was caused by defect or intact rock or a combination thereof. Counting the number of fragments proved to be a quick and practical method of addressing these limitations and assessing how the rock at that scale behaved mechanically.

It is important not to 'double dip' when selecting intact rock strength reduction to arrive at an IRMR. Although there is no current guidance on relating the drop test to quantitative strength values for rock mass classification schemes, it can be a useful tool to measure the prevalence and influence of micro-defects on the core-scale rock mass. This information can help decide whether, and how much, the intact rock strength needs be reduced or if the reduction is sufficiently captured in the point load and UCS tests.

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Microdefects: GSI for fragmentation assessment?

Recently, SRK Chile was involved in a caving project in Chile and in charge of numerical modelling to analyse pillars and overall mine stability and to define ground support. The review of the basic geotechnical information was the first task performed, pointing out an underestimation of the Geological Strength Index (GSI). The client justified the lower values of GSI by including microdefects, as they would be acting during the caving process, and argued that they should be included in the GSI estimation for fragmentation assessment by the software block cave fragmentation (BCF). SRK's position in this particular project was that GSI need only consider open joints since BCF already considered microdefects to calculate the rock block strength, and including microdefects in GSI would have a double lowering effect. Because of this debate, SRK verified the impact on fragmentation curves due to including microdefects in the GSI estimation.

GSI is not a direct input in BCF software, but it is used to scale the mi Hoek & Brown parameter to mb, which is an input parameter in BCF. To evaluate the impact of microdefects included in GSI, SRK estimates three fragmentation curves for two geotechnical units using mb input values scaled from a GSI value of 70, 50, and 30, resulting in three identical fragmentation curves.

It may be concluded that microdefects should not be considered for GSI estimation, since microdefects are already explicitly included in BCF.

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ANDREA RUSSO

Andrea has 25 years of experience in the mining industry. He has worked in porphyry copper deposits, acquiring valuable experience in geological, structural, and geotechnical mapping for underground mining, defining and characterising structural domains, geotechnical domains, and fragmentation assessments. Andrea specialises in rock mass geotechnical characterisation, analysing geomechanical laboratory tests, defining the caving sequence and front orientation, and defining ground support through empirical methods. He worked on various open-pit projects analysing slope stability in Canada and South Africa. On an environmental project, Andrea gained experience in rock mass grouting using the GIN method.

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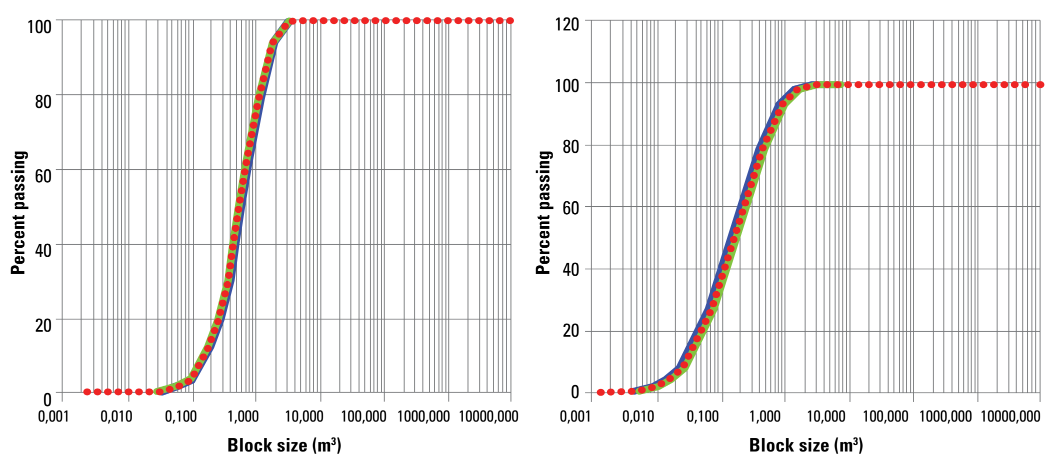
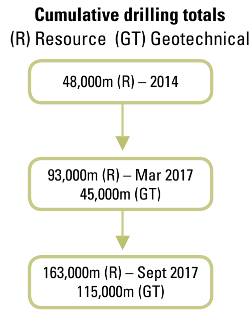
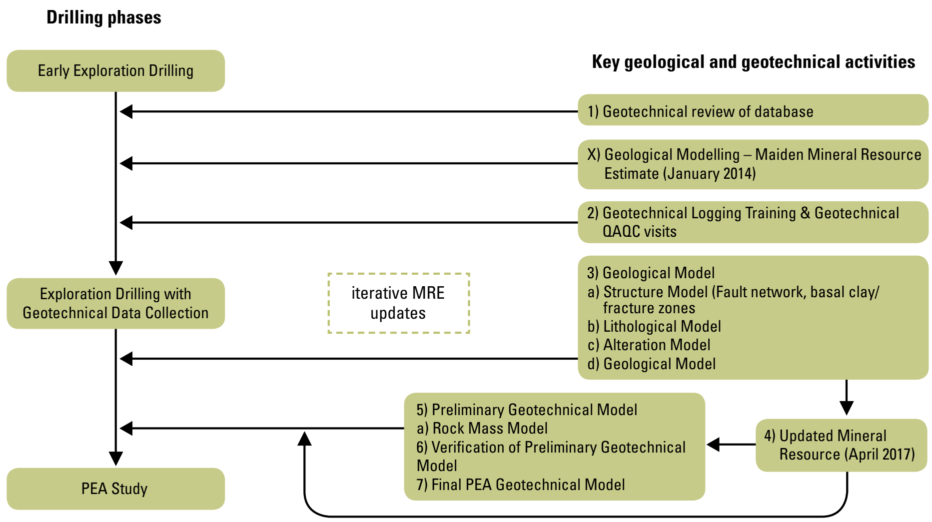


Figure 1: Fragmentation curves estimated for Geotechnical Units a) and b) considering a GSI = 70 (red dotted line), GSI = 50 (blue line) and GSI = 30 (green line)

Geotechnical data collection and approach to modelling for Cukaru Peki





NEIL MARSHALL

Neil Marshall (MSc, DIC, BSc [Hons], CEng, MIMMM) is a Corporate Consultant with more than 30 years' experience in geotechnical engineering for mining. While consulting, half of his time was spent working in underground and open pit mines in Zambia and Ghana where he held various technical positions. Neil specialises in the geotechnical characterisation of rock masses, open pit slope design, underground mining method design and evaluation, underground support and excavation design and numerical modelling.

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A geotechnical model is the fundamental basis for the design of an open-pit and underground mines. A fully understood and representative geotechnical model provides information on the engineering characteristics of the rock mass, defining how it will behave during excavation. The model's individual domains, each comprised of materials exhibiting internally similar geotechnical properties, reveal the critical characteristics and risks that the mine planners need to understand to design the optimal mine. The Cukaru Peki Upper and Lower Zones are part of the Timok copper-gold project.

Nevsun Resources Ltd. owns 100% of the Cukaru Peki Upper Zone; the Lower Zone is a joint venture with Freeport-McMoRan Exploration Corporation. The Timok project is located centrally within the Timok Magmatic Complex (TMC), which has one of the highest concentrations of copper enrichment in the Tethyan Belt.

The upper zone of the Cukaru Peki mineralisation occurs at depths between 400 and 800 m below ground level. The deposit does not outcrop at surface; it is buried beneath Miocene Clastic Sedimentary rocks that unconformably overlie the Upper Cretaceous Bor' Conglomerate and Bor' Marl. The Unaltered Andesite sits below the unconformity and the Lower Andesite below that.

The high sulphidation epithermal mineralisation found within the Late Andesite comprises massive and semi-massive sulphide. Pyrite is the dominant sulphide mineral, and the principal copper mineral is covellite with lesser enargite, bornite and chalcocite. Gold is associated primarily with the copper sulphides.

The top of the mineralisation is constrained by the unconformity and the lateral extents are constrained by faulting. Several alteration assemblages have been grouped into four types with mostly Phyllic and Propylitic alteration at its base.

Best practice: Geotechnical logging being carried out at the rig

The mineralisation is found within the Advanced Argillic with higher grades of copper and gold near the cap and then decreasing with depth.

SRK's early involvement in the exploration drilling was key to setting up the geotechnical data collection. A flow chart sets out the approach to geotechnical data collection and modelling for the preliminary economic assessment study.

A logical approach was used to develop the geotechnical model taking into consideration the geological, alteration, and structural conditions for the deposit. There is good correlation between the geological framework and geotechnical parameters.

The visual assessment and data modelling indicated that the spatial variability in the geotechnical parameters correlated well with the geology, alteration, and structure. A statistical analysis of the geotechnical parameters assessed each domain's representation of the geotechnical conditions.

A thorough assessment of the rock mass was based on the geology, structure, and alteration models. The geotechnical data was spatially and statistically analysed relative to these models to understand how the geology and structure affected the rock mass engineering properties. The structure and alteration were controlling the variability in rock mass characteristics and the models were used to generate the geotechnical model.

The data in each geotechnical domain was used for generating parameter inputs to the cave mining study. The real value added to mine planning came from knowing how the combined individual-models created a geotechnical model that was representative of the actual conditions.

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Downstream effects of cave fragmentation

Since the 1990s, 'mine-to-mill' studies have evaluated the impact of blast fragmentation on downstream plant throughput. This was because crushing and grinding circuits (in particular, SAG mills) are sensitive to feed size and the amount of fines generated from blasting. Significant gains in grinding circuit efficiency could be achieved by controlling and optimising blast fragmentation.

The advent of mass mining methods like block caving has introduced the term 'cave-to-mill', which considers the variability and uncertainty in fragmentation coming from each drawpoint. In the figure below, fragmentation estimates were made for each block in a potential caving zone underneath an existing open pit. To simulate the effect on SAG mill performance, these fragmentation curves were passed through a primary crusher model. As shown in the figure, the variation in mill feed (80% passing size, in mm) is evident as the cave propagates upward and the secondary fragmentation generates more fines and a smaller topsize.

Between the cave and the mill, there may be limited potential for controlling fragmentation, ore blending, and/or stockpiling, and the plant front-end needs to be designed for fluctuations in hardness and feed size. In addition, unless mixing within the cave is well predicted and understood, geometallurgical knowledge of the orebody can be destroyed.

While mass mining offers the potential to develop lower-grade underground deposits, the downstream effects on plant performance need to be carefully considered. Due to the potential for waste infiltration, pre-concentration or waste rejection opportunities ahead of grinding should also be included in any project study that considers mass mining methods.

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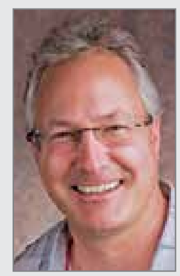
ADRIAN DANCE



Adrian is a Principal Metallurgist with over 25 years of industrial and consulting experience. He has established himself as an authority in the optimisation of crushing/grinding circuits and in adding value to operations through process improvements. Adrian is an advocate of grade engineering through pre-concentration methods including coarse beneficiation to address poor mill feed quality.

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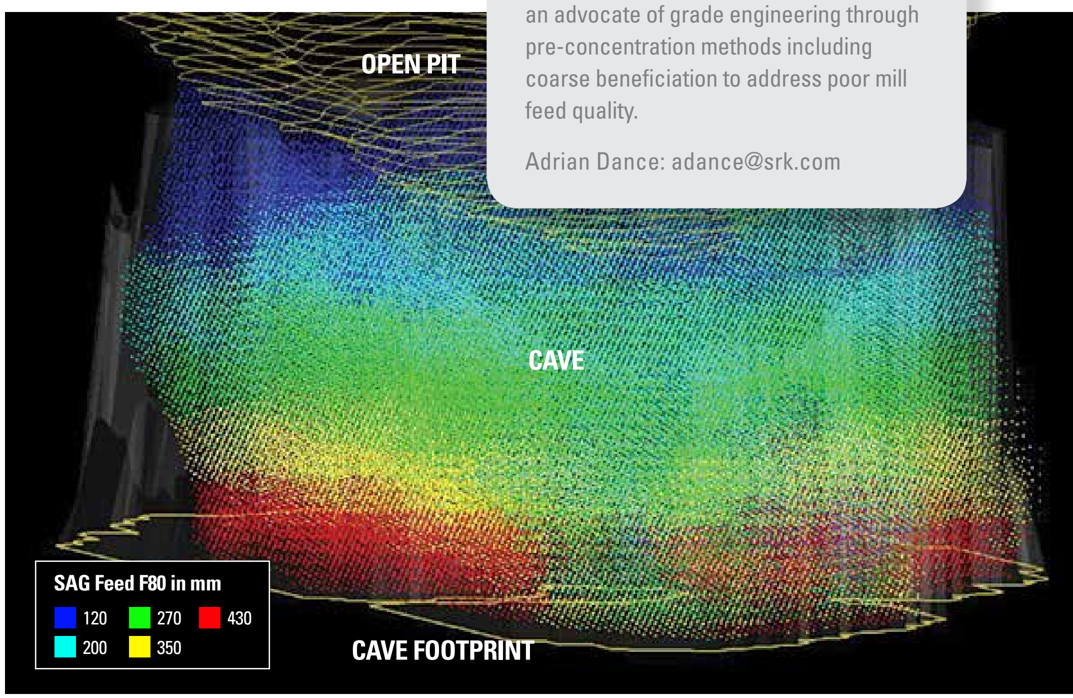
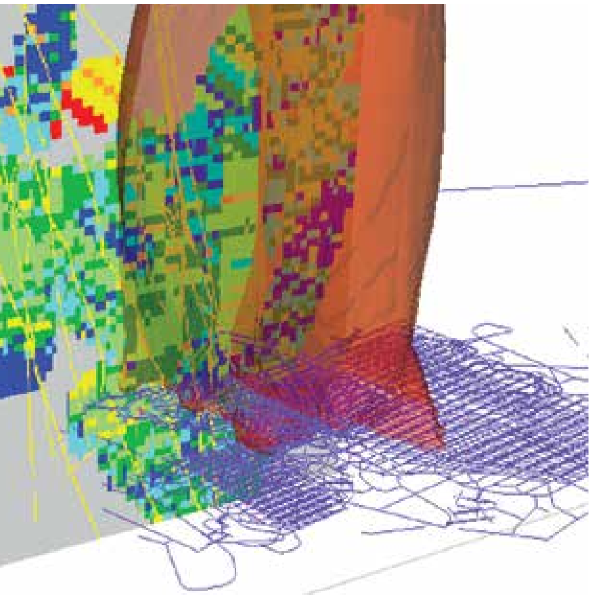


Geotechnical model development for caving design

SRK performed a comprehensive redevelopment of the geotechnical model for an existing large panel caving operation with the aim of assisting cave planning and design in five future cave blocks. Initially, separate models were created for the individual blocks to allow for smaller, more focused models; however, a large all-encompassing model was subsequently created.

The models incorporated more than 50 geotechnical domains based on major rock types and faults. They were constructed through review of the existing geotechnical drilling (485 drillholes totalling ~250,000 m of core) and underground mapping database as well as incorporating additional data from recent targeted drilling investigations. Careful characterisation and recalculation of key rock mass parameters ensured the final model inputs were appropriate, consistent, and thorough.

The products comprised detailed Datamine block models of maximum 25 m and minimum 5 m individual blocks sizes, providing data for lithology type, intact rock strength, rock block strength (as developed for the in situ rock mass rating calculation, weathering, fracture frequency per m, and fracture spacing. RQD; joint number rating; and calculated RMR, IRMR and Q’ classification values.



Predicted cave propagation relative to RMR model (warm colours indicate poor rock)

In addition, detailed statistical summaries of the characteristic rock-mass properties and their variability were provided for each domain for use in any geomechanical or numerical analyses. Supplementary in situ stress interpretations using core disking and drillhole breakout data were generally in agreement with past measurements and interpretations.

Key insights and uses for the modelling identified together with the client were as follows:

- The interaction of faults is important – each cave footprint requires the presence of one or many major faults to assist caving. Stress concentration in weaker rock mass within the fault intersections in the extraction and undercut levels pose an elevated possibility of instability. Sequencing the undercut through this region would be required to manage the possible outcomes associated with undercut angle and initiation point.
- The parameters controlling brittle behaviour of the rock mass (strain bursting of faces or local seismic responses during undercutting and cave establishment) include high strength rock and low joint number or fracture frequency.
- The presence of locally, very weak infill (decreasing rockmass strength) has controlled drive scale deformation. The deformation is managed with mine sequencing and ground support systems, and should abate once the undercut and cave have provided a suitable stress shadow.
- The seismic response to mining has recorded larger magnitude and more events in the south of the mine compared to the north, appearing to be a consequence of rock mass conditions and structural control. This has constrained the location of the planned infrastructure to reduce the potential for future damage. Preconditioning to reduce the occurrence of large damaging seismic events will become a necessity.

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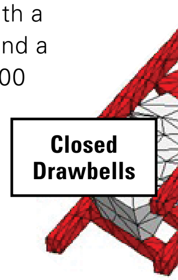
The Chuquicamata underground mine in the Atacama Desert in northern Chile is one of the largest planned mining projects in the world to use block caving with macro-blocks option to mine copper ore. CODELCO is currently finishing the detailed engineering stage and constructing the main infrastructure for the project. The underground mine is expected to begin operations in 2020, with a seven-year ramp-up period and a nominal production of 140,000 tonnes per day.

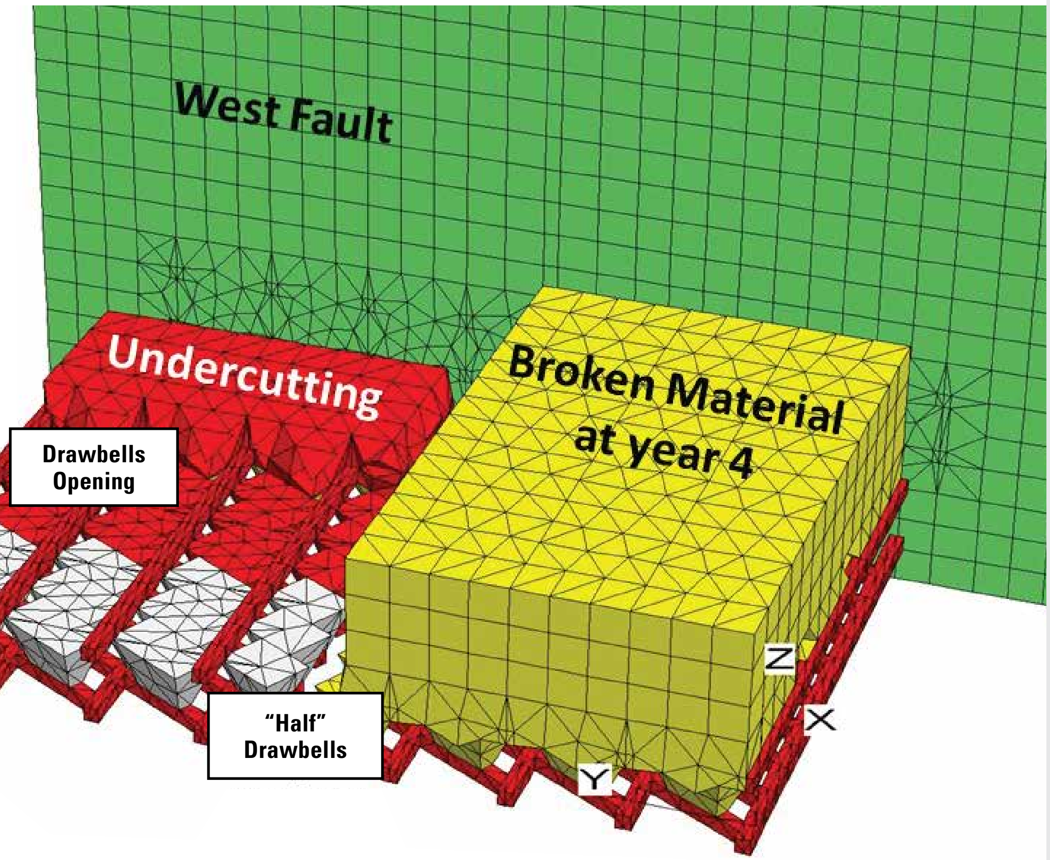


The rock mechanics team of SRK Chile has provided technical support to the Chuquicamata underground project for the last eight years, including the prefeasibility, value, feasibility, liaison, and detailed engineering stages.

One important aspect was to independently manage each macro-block in the geomechanical assessment to estimate magnitude and extension of the abutment stresses and tensile zones on the macro-block pillars during the different construction phases in macro-block preparation and during the ore column extraction involved in the macro-block operation. This phase depended on complex tridimensional geometry and the interaction of different cavities; so, a tridimensional analysis was required to consider the mining sequence (Figure right).

As part of this study, empirical methods, confinement-convergence analytical models, and 2D and 3D

Geomechanical design for the world's largest underground mine



Tridimensional numerical model for the Macro-block option; red-excavations, yellow-broken material, white-constructions (before excavations), green-West Fault zone (In situ rock mass has been purposely hidden) (i.e. Hormazabal et al., 2010).

continuum and discontinuum models were developed and applied to evaluate the influence of the stresses and existing geological features (e.g. the presence of two major shear zones, the West Fault, and different lithological units) on the mechanical response of the excavation.

SRK Chile has worked on a wide range of topics in the project, including the geomechanical design at the undercutting level, extraction level and haulage level, the macro-sequence definition, rib pillar and macro-block pillar stability, and the stability and support design of crusher chambers, transfer caverns and several large excavations. Tasks developed range from data collection and interpretation of geotechnical data to the design of underground excavations including more than 50 complex 3D continuum and discontinuum numerical models. To date, the work SRK carried out for the Chuquicamata underground project is summarised in more than 45 technical reports and 110 construction drawings.

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IAN DE BRUYN

Ian has 21 years of experience in geotechnical engineering over a wide range of mining and civil engineering projects. He specialises in geotechnical studies for open-pit mining operations, geotechnical characterisation, and modelling for underground excavations and open pit/underground mining interaction. He has worked on projects involving complex and challenging rockmass conditions where structure and groundwater play an important role in stability. His projects have involved site investigation, rockmass characterisation, stability analysis, design and risk assessment at all levels, from conceptual through feasibility studies and working design. Ian is team leader of the geotechnical group in Perth, Australia.

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ESTEBAN HORMAZABAL

Esteban is a Civil Mining Engineer with a Master in Geophysics, and specialises in applied hydrogeology. He has 23 years of experience in geotechnical engineering, rock mechanics, and geotechnical instrumentation, leading important open-pit and underground mining projects in Argentina, Chile, Colombia, Mexico, Peru, Russia, and Uruguay. In addition, Esteban is an expert in analysis and geomechanical design of underground mining and surface excavations using 2D and 3D numerical modelling, stability analysis, and slope design in open pits and waste dumps.

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Mass mining diamonds

DAN LAGACÉ

Dan has ten years experience working in underground and open pit mines, across multiple commodities (diamonds, base metals, coking coal and potash). He focuses on project evaluation and mining studies from scoping to feasibility, mine design, scheduling, and cost estimating. Prior to joining SRK, Dan worked at several mine sites across Canada gaining experience in mine engineering and project management roles. Most recently, he led underground and open pit mining projects from early stage to execution with Dominion Diamond Ekati Corporation. With Dominion, Dan managed the Sable Pit project from preliminary economic assessment to project execution, and the Fox Deep project from preliminary economic assessment to prefeasibility.

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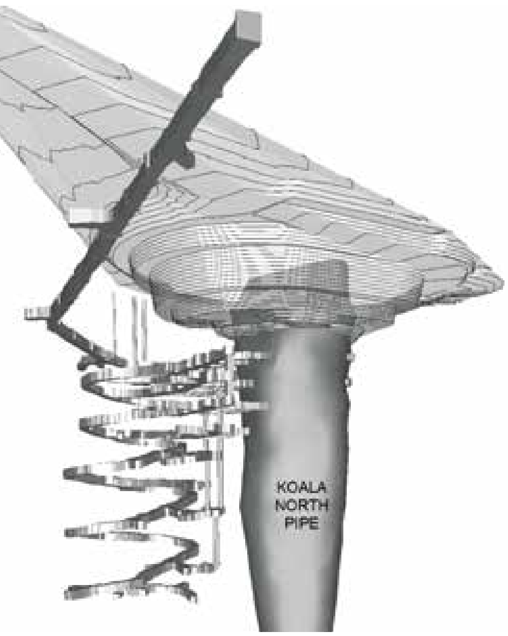
Mass mining including block caving, incline caving, front caving, sub-level caving and sub-level retreat are the principal mining methods for primary diamond deposits worldwide. Diamonds have only been mined on an industrial scale within the past 150 years, mainly as open pit mines. Underground mining of those deposits was first implemented within the second half of the 20th century in South Africa. A relatively large number of underground mining methods were tested, implemented, and evolved over the past 50 years, mainly in South African mines. In the mid-1990s, Alrosa, a Russian group of diamond mining companies, started developing the first underground diamond mine in Russia, Internationalnaya. Since then, Alrosa continued to implement underground mining on several of their mines, including Aikhal, Mir and Udachny. China also experimented with underground mining at Nhangma 701 Diamond Mine at the end of the 1990s, but the largest development of diamond underground mining took place in Canada. Today, out of some 40 diamond mines mining kimberlite, approximately half are underground and another 20 have underground plans or they are exploring its potential.

SRK has been involved in most of the underground diamond mining projects around the world. In Canada, the Ekati Diamond Mine was the first diamond mine to be developed near Lac de Gras in Canada's Northwest Territories. Koala North Pipe has been developed and mined as an open-benching, mechanised, and trackless operation to test the underground mining method and to provide access to the lower parts of the Panda and Koala pipes which were developed and mined underground once the open pit operations were completed. Koala North, North America's first underground diamond mine, formally opened in 2002. Since then, Panda and Koala Pipes were mined by three principal underground mining methods:



sub-level retreat, sub-level caving and Incline Caving.

Diavik Diamond Mine started open pit production in 2003. By 2005, underground development had commenced with plans to mine the A154 and A418 pipes using backfill methods. As geotechnical knowledge was gained, the mining methods were re-evaluated. The sub-level retreat method was chosen for the A154S and A418 pipes, and blasthole open stoping with cemented rockfill was chosen for the A154N pipe. In 2012, the open pits reached their ultimate depths and Diavik Diamond Mine became a fully underground operation. In 2018, open pit mining of A21 kimberlite was successfully commissioned, complementing underground mining at Diavik.

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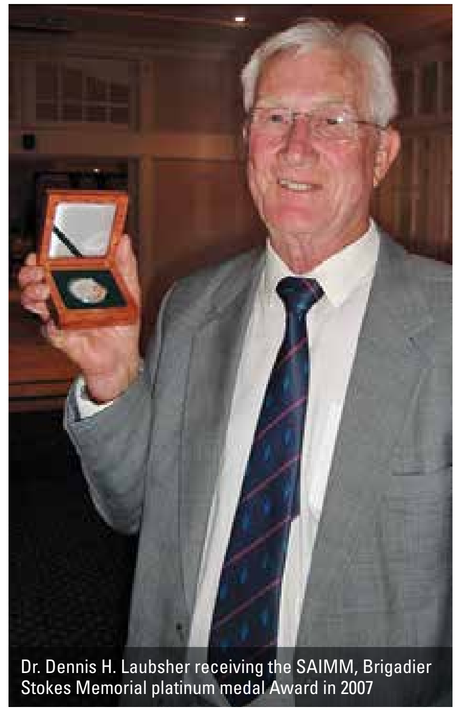
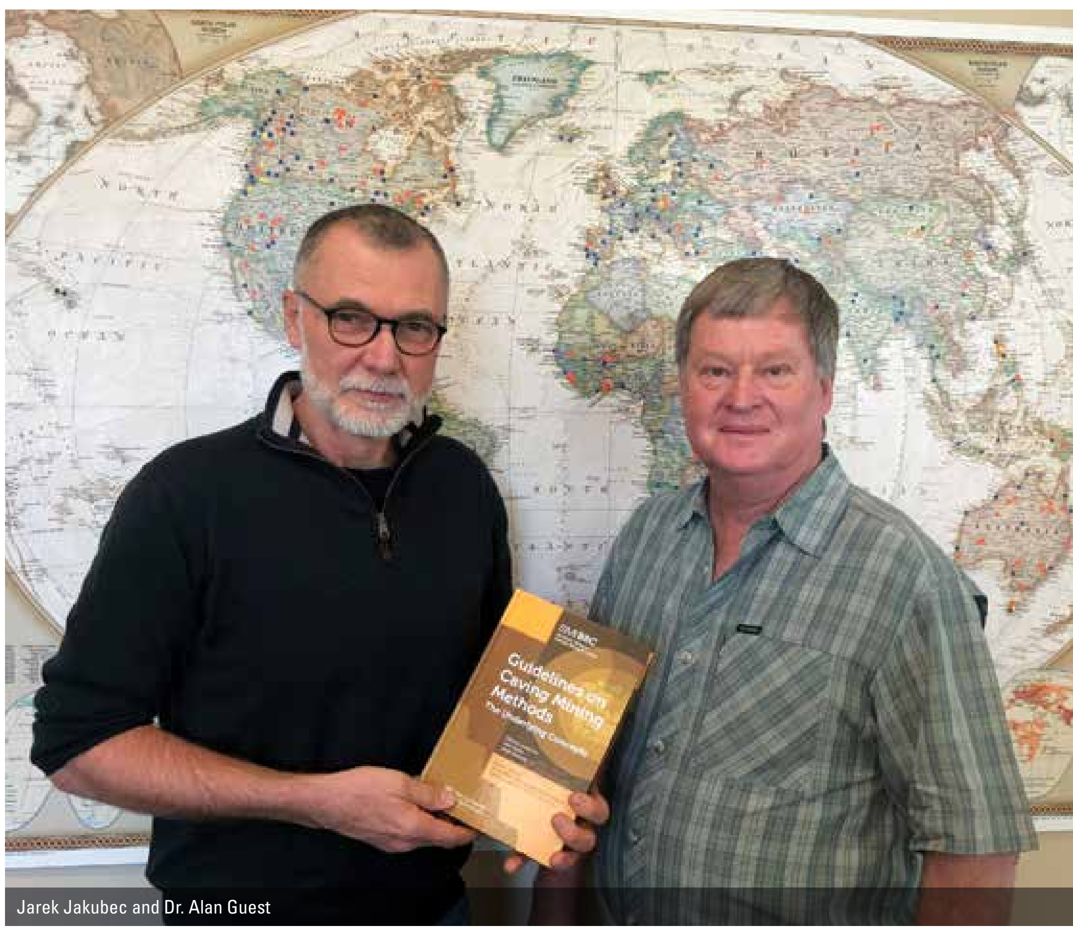
Guidelines on Caving Mining Methods: The Underlying Concepts

In 2000, International Caving Study (ICS) published a practical manual on block caving by Dr. Dennis Laubscher. This first comprehensive block caving publication was co-authored by several industry experts, including Dr. Alan Guest and Jarek Jakubec of SRK Consulting (Canada) Inc. Unfortunately, the distribution of this publication was not widely available. Meanwhile the demand for practical guidelines on cave mining was increasing as new projects developed. Mass Mining Technology (MMT) recommended that Dr. Laubscher, Dr. Guest and Jarek Jakubec undertake this task. In 2017, the design book 'Guidelines on Caving Mining Methods' was published as a practical tool for cave mining by The University of Queensland.



Dr. Dennis H. Laubsher receiving the SAIMM, Brigadier Stokes Memorial platinum medal Award in 2007



Jarek Jakubec and Dr. Alan Guest

Open pit to underground transition

SRK carried out a scoping study on an existing open pit operation (12 Mtpa) that is soon to be reaching a depth where the mine will need to transition to a large-scale underground mining method. The goal was to provide production continuity at a rate that will still be suitable to maximise use of the existing surface processing facilities. The ore body dips below the bottom of the planned open pit and is still open at depth. Around the periphery of the main ore body is a halo of disseminated lens-shaped types of mineralisation.

Due to this mineralisation, the ore halo requires smaller scale or selective mining methods, while the main orebody lends itself to mass mining where block caving or inclined caving are viable options.

SIMON HANRAHAN

Simon is a Mining Engineer with over 30 years of global experience as a team member and project leader across the whole resources value chain – option, pre-feasibility and feasibility studies, project development, and mine operations. He has significant experience in major projects involving the development of block-cave mines and operating open-pit mines above caving zones. Simon has carried out project management, project evaluations, and technical reviews for gold, base metal, platinum, industrial mineral, diamond, coal, and iron ore projects. He has demonstrated ability to work within and lead multi-disciplinary, multi-cultural teams across all resource types.

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SRK conducted a series of mining method evaluations to identify what the most suitable mining method options would be to maximise recovery, while also maintaining production continuity as the mine transitions from surface to underground. This resulted in a sub level open stoping (with backfill) mine design for the peripheral halo ore zone and two side-by-side block caves for the more massive ore area. Given the geometry of the ore body, an inclined cave could become more of a real option, but additional resource drilling is required and a firmer definition of the final open-pit bottom.

A critical aspect that is often underestimated is the transition time frame, particularly when additional ore body knowledge (including resource, geotechnical, hydrogeology, metallurgy and rock temperature) is still required to support detailed designs and approvals for a major underground mining complex. It is not uncommon for these transitions to take more than 10 years to complete the required sequences of work from orebody knowledge sourcing to feasibility studies, construction, development, and production ramp up. If the transition timeframe is underestimated, shortcuts could be required to achieve production continuity. However, there is significant risk that if these plans are not realistic, the successful operation of a cave mine for the longer term can be comprised.

The results of the scoping study provided the client with a solid understanding of a conceptual transition plan that is now being used to optimise production continuity while making plans to continue life beyond an existing open pit operation. A key outcome of the study was that the client now has a vastly improved understanding of what a transition will require, and plans are now progressing for a further open pit pushback to create adequate time to transition to an underground mine.

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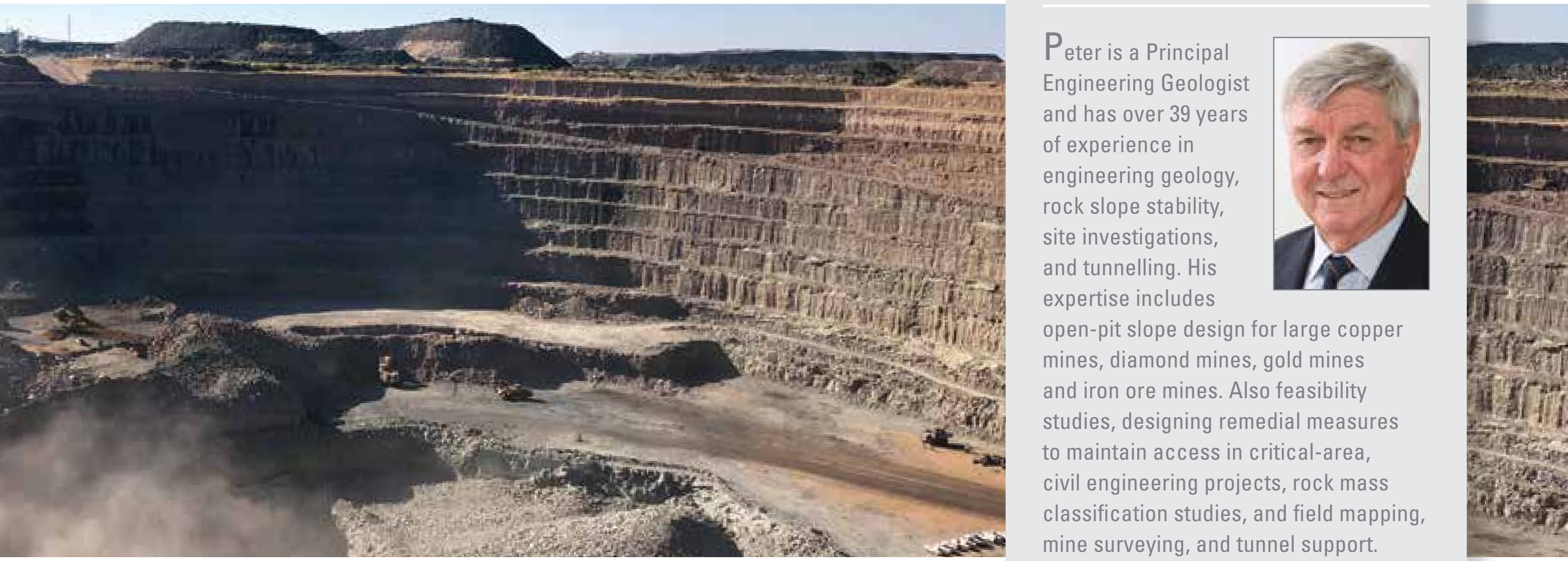
Many ore deposits extend vertically, a fact which is not always known at the start of mining. If initial mining is by opencast methods and ore reserves are proven to greater depths, the pits are often planned to go deeper than originally envisaged. In such cases, surface plants and critical underground facilities – conveyor tunnels, access ramps, ore passes, hoisting, and ventilation shafts – are often located much closer to the pit rim and the ore body than desirable. This raises the question of stability, which may be critical for operating the mine longer term. Key considerations to evaluate are: open pit stability, shaft stability, dilution, mud rushes and air blasts, and mining method selection.

Planning Considerations: The efficient transition from open pit mining to an underground operation requires extensive planning. For a large mining operation, planning could last as long as 20 years. The main factors and activities that need to be taken into account in the planning

Planning considerations for transition from open pit to underground



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Peter is a Principal Engineering Geologist and has over 39 years of experience in engineering geology, rock slope stability, site investigations, and tunnelling. His expertise includes open-pit slope design for large copper mines, diamond mines, gold mines and iron ore mines. Also feasibility studies, designing remedial measures to maintain access in critical-area, civil engineering projects, rock mass classification studies, and field mapping, mine surveying, and tunnel support.

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cycle are as follows:

- Definition of the ore body
- Rock mass characterisation
- Definition of the boundary conditions
- Investigation of suitable mining methods
- Underground infrastructure
- Surface infrastructure
- Ongoing open pit factors of influence
- Underground mining and layout considerations
- Underground and surface effects of the underground mining
- Surface and groundwater effects
- Risks
- Project timing

Conclusions: Aspects of particular significance include the following:

- An economically designed pit will have slopes close to their stability limits, with little scope for extending the open pit to greater depths.
- Planning and implementing transition from surface to underground mining can take 20 years. Planning must therefore commence at an early stage.
- Surface and underground infrastructure is often at risk as pits deepen beyond planned depths.
- Transition from open pit to underground mining often risks mud rushes (if mud forming minerals are present), and from sumps and surface dams. Air blasts can result from underground collapses or mud rushes.
- The presence of an abandoned pit above can lead to greater risks of dilution and mud rushes.
- The choice of underground mining method affects the surface; and stability requirements may dictate the choice of mining method.

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A schedule for an open pit to underground study

ACTIVITY	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	Y18
Exploration																		
Conceptual design																		
Stage 1: Prefeasibility																		
Board review																		
Stage 2: Feasibility																		
Board review																		
Stage 2A																		
Stage 2B Feasibility Study																		
Stage 2C																		
Stage 3: Final design																		
Stage 4: Implementation																		

Rapid cave design and production scheduling

For early stage caving projects, there is usually a high degree of uncertainty in the input parameters that impact the mine design and strategy. When dealing with such uncertainty, it is better to quickly generate multiple designs and schedules that cover the likely range of key parameters rather than evaluating only a few or even a single case based on precise but inaccurate parameter assumptions.

SRK has worked on many early stage projects and has developed processes and tools for rapidly generating an array of conceptual cave designs and schedules for use in our rapid economic evaluation and strategic planning process.

For block caving projects, the rapid generation of designs and schedules is done using GEOVIA's Footprint Finder> It is part of the PCBC caving simulation package, and complements a suite of proprietary software tools and templates used to automate and manage the process and collate the data. For sublevel cave projects, we use a similar mix of proprietary software and processes along with GEOVIA's PCSLC application. Using these tools, we can generate a suite of designs and schedules, each built to a specific scenario defined by a unique combination of parameter values.

Key parameters that most influence the cave design in terms of footprint boundary and elevation are the assumed commodity prices, metallurgical recoveries, discount rate and to a lesser extent operating costs. It is found that mixing and footprint development costs have little impact on the placement of the footprint or the overall mine strategy. Design details such as drawpoint layout, undercutting and infrastructure are not critical for this process and costs can be estimated based on area, perimeter, and depth of each footprint.

Each design or schedule can then be fed into our rapid economic evaluation model to see how it responds over a range of conditions. Designs can be evaluated using different assumptions on costs, prices, material handling systems, productions rates, and more. Instead of generating a single mine plan for an assumed set of conditions, this process enables the identification of robust strategies that perform well across a range of conditions.

SRK's strategic planning process has been used multiple times to assist our clients not only in assessing the economic viability of a caving project, but to select strategies for further study that balance risks with potential reward. The ability to rapidly generate designs and production schedules is a key component of this process.

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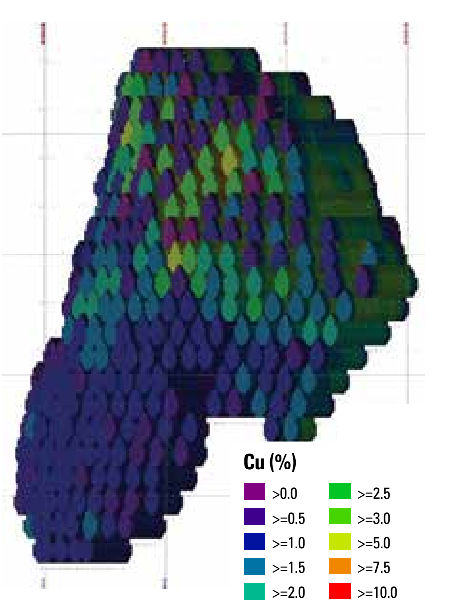

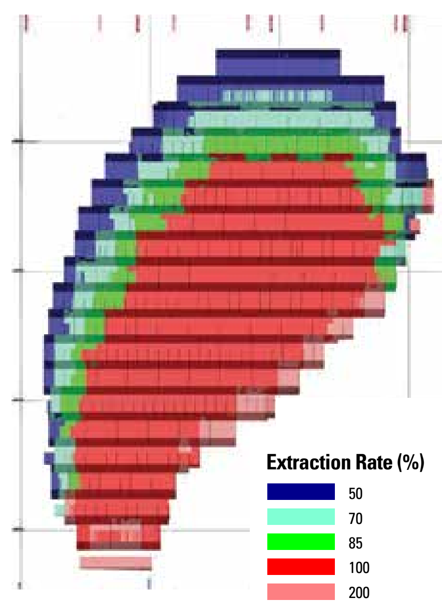

Cave Mining – Optionality in Operation

Option
Ultimate Size of Mine Plan
Mining and Milling Rates
Cut-off policy
Stockpiling
Ore Type Selection
Stop-start Mining

Cave mining, and in particular block-cave mining, stands at one end of the spectrum of mining method-related risks. It is not so much that the risks are greater, but rather that the ability of management to respond to variations in expected conditions is much less than with other mining methods. Compounding this in the case of extraction-level stability risk is that small issues can quickly become large issues as the cave operations are slowed and the geotechnical stresses build.

A conventional open-pit mine makes few irreversible decisions in the planning phase. The size of the mining fleet, the mining rate, the cut-off policy, and the stockpiling strategy can (and should) all be dynamically adjusted in response to economic and technical parameters to maximise cashflows and profits.

Cave mining risks - not necessarily greater, but definitely different

Open Pit Mine	Selective Underground Mine	Block Cave Underground Mine
Continuous Option	Step-wise Option	Limited Options
Few Constraints	Significant Constraints	Significant Constraints
Dynamic (truck-by-truck)	Dynamic (stope-by-stope)	Shut-off Only
Strategic	Surge	Surge
Easy	Possible	Impossible
Easy	Possible	Hard

The pit-slope angles, dewatering strategy and support strategy can all be adjusted as experience is gained and the geotechnical context and behavior is better understood throughout the mine life. The size and type of the processing facility (and its location) are really the only 'fixed' decisions at the time construction commences.

Contrast this to a block cave. Many major and effectively permanent decisions must be made before any operating experience at all is obtained. The orebody must effectively be delineated on five of the six sides before production starts. Only the shut-off policy remains available to optimise economics. The geotechnical context must be perfectly characterised, and designs developed to ensure stability of the extraction-level under the as-yet untested loading environment. No significant redesign on the fly is possible. Production rates are effectively set by infrastructure and layout. Cut-off grades have been 80% defined by the footprint configuration and a dynamic policy. Responding to economic drivers isn't possible.

Although sublevel caves (and other level-based variants) have a bit more flexibility, the implication of this is that there is great value in investing in a comprehensive strategic evaluation process for cave mines generally, quantitatively considering risk through sensitivity and scenario analysis, and assessing the degree to which design decisions stand up to inevitable variation. Getting it right up-front is essential. This is where the value is really created in cave mines. In contrast, the value in an open pit mine is created primarily through dynamic optimisation over the mine operations period, rather than at the initial design phase.

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SCOTT LOEWEN

Scott is an underground Mining Engineer with 15 years' industry experience. He has performed a variety of roles including mine planning, ventilation, and surveying, while working at several underground operations. Scott's most recent experience before joining SRK was working with mining software companies in the support and development of their products. He specialises in the design, planning, and scheduling of block cave and sublevel caving projects ranging from scoping to feasibility-level studies. Scott is an advanced user of multiple mine design packages, developer of custom software, and an expert user of PCBC and PCSLC.

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NEIL WINKELMANN

Neil has over 30 years of experience in the minerals industry. He has held senior management positions in operations, technical services, and business analysis. At SRK, Neil focusses on economic evaluation of mineral industry operations and projects. He has expertise in economic modelling, specifically in the creation of flexible models for scenario-based risk characterisation and strategic project evaluation and optimisation. Neil specialises in semi-stochastic analysis such as expected-value analysis, and full Monte Carlo simulations.

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Mudrush dynamics in underground mining

Examples of very stiff red clays from Northparkes Mine and a typical low-viscosity mudpush *(Photos courtesy of Rio Tinto and De Beers)*

Mudrush, mudflow, or mudpush are the most common terms describing uncontrolled ingress of assorted mixture of water and solids. Mudrush is the underground equivalent of surface debris flow. It can have different origins but produce the same results: injury, loss of life, damage to property, excess dilution, and production delays, or – in extreme cases – mine closure. Mudrush dynamics in underground mining are especially complex due to confinement and stress within the muckpile.

Block caving and sublevel caving operations are inherently susceptible to internal mudrushes because they have the potential to accumulate water, generate fines through comminution process, and through production activities, provide disturbances as well as a discharge point. Block caving operations are also susceptible to external mudrush flows because the broken muckpile connects the surface with the underground excavations.

Although mudrushes are more common in caves than in other mines, any mining activity that enables the accumulation of fine particles and water is susceptible to mudrushes. Cases exist of injuries and fatalities from sudden ore pass discharges, the collapse and subsequent flow of unconsolidated or poorly consolidated backfill, and the failure of tailings and slimes dams. In September 1970, 89 miners were killed at the Mufulira mine in Zambia due to an inrush of 450,000 m^3 of muck into the workings. The muck originated from tailings dams, which were located on subsiding ground above the workings. The water, impounded in the depressed crater of the tailings that had subsided, was seen as a major contributor to the inrush.

Over the past two decades, the mining industry developed a comprehensive risk assessment including risk rating and safe operating procedures. Although mudrushes are difficult to predict and impossible to prevent, if taken seriously, the impact on operation can be minimised with proper cave management and draw control.

A mudrush seldom occurs as the result of a single cause or fault; therefore,

any risk analysis has to take into account all contributing factors and combinations thereof. A system failure usually results when a combination of failures occurs in such a way that the disturbing forces exceed the capacity of the system to resist those forces.

Before assessing any risks to a mine, however, the following questions need to be answered:

- Is there potential to generate fines?
- Is there potential to accumulate water?
- Is there potential to form mud?
- What disturbance can mobilise and discharge the wet muck?

A number of caving mines operate safely with high rainfall and mud-forming potential using tele-remote equipment and strict mudrush risk mitigation procedures, such as:

- Interception of water flow into the cave (surface and underground)
- Pre-strip of mud-forming overburden waste from the subsidence zone
- Tailing ponds and other sources of water and/or mud located away from the expected subsidence zone
- Inspection of old workings for presence of water and/or mud
- Sealing off all possible access points to the cave other than operating drawpoints
- Strict draw control procedures
- Comprehensive monitoring program and reliable water balance

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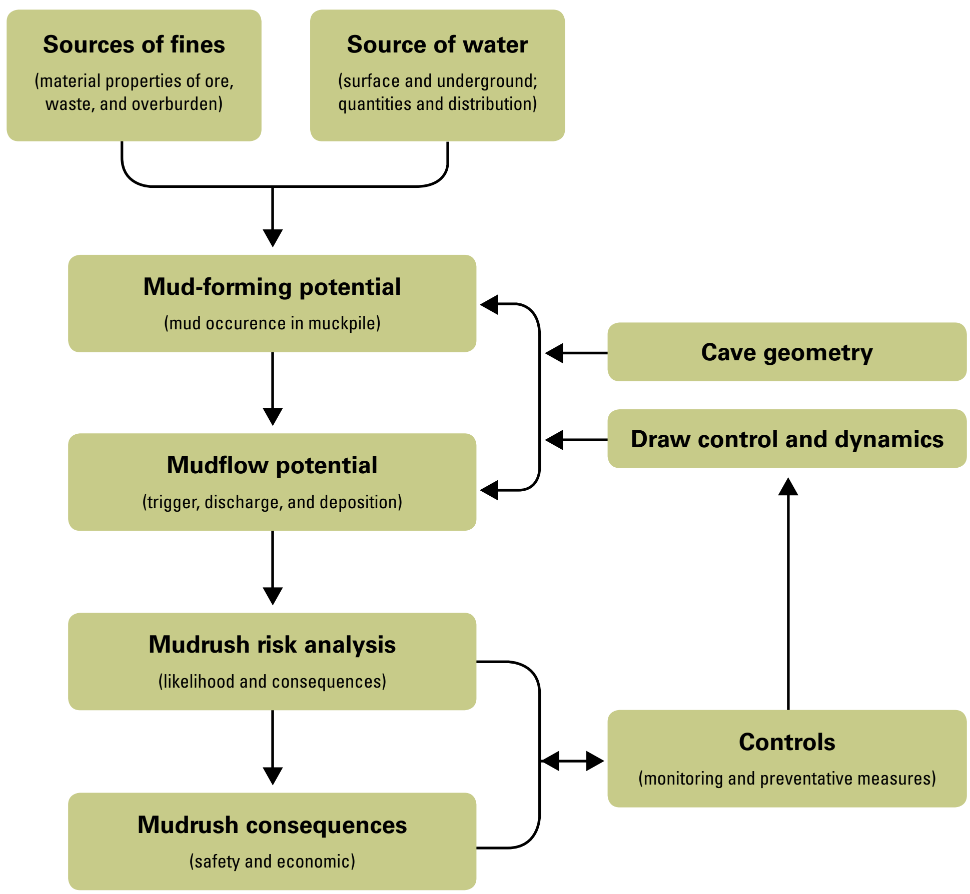
Figure illustrates the mudrush risk assessment process



The importance of post-drilling assessment

CARL KOTTMEIER

Carl, BASc, MBA, is a professional engineer with 30 years of experience in open-pit and underground mining environments in Canada and the United States. His operational experience includes mine design and construction, mine contracting, mine operations, blast design and optimisation, technical reviews and audits, mine permitting, project management, due diligence studies, cost estimation, and financial modelling. Carl's commodity experience includes projects involving coal, nickel, copper, molybdenum, lead, zinc, gold, and silver.

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Iouri's expertise is in engineering activities related to mine development and production, compliance with quality standards, safety objectives, schedules and costs. In addition to extensive underground coal production experience, Iouri's engineering consulting experience includes due diligence reviews, operational assistance, technical studies (scoping, pre- feasibility and feasibility) and detailed engineering for mining properties in Canada, USA, Mexico, South America, Africa, Europe and Asia.

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In sublevel caving operations, it is imperative that the production blastholes be drilled accurately so that there is no risk of unblasted ore remaining between adjacent drawpoints. Post-drilling assessment is the process of mitigating this risk by verifying that blastholes have been drilled accurately with the correct length and orientation, following the blast design.

Although the process can be time consuming, post-drilling assessment is an important process that is worth the time and the costs involved and blasting. Engineers should frequently assess how the blastholes have been drilled (length, orientation, and the spatial relationship between adjacent blastholes) and compare this information to the blast plan. In particular, special attention should be given to any blastholes that extend towards, and overlap with, blastholes from adjacent drawpoints.

Post-drilling assessment provides important feedback on blasthole drilling deviation; it allows a blasting engineer to make any required adjustments before the explosives charging process begins. Blastholes that have deviated excessively will have a considerably different burden than was planned and therefore the explosives loading – and in some instances the delay timing – will have to be adjusted.

Without corrective action, blasthole deviation can result in unblasted ore and/or poorly blasted ore remaining between adjacent drawpoints. Additionally, blastholes that have been inaccurately drilled may have excessive burdens that can lead to poor fragmentation, create excessive vibration, and in extreme cases lead to blasthole rifling. Blastholes that have been drilled with insufficient burden can generate excessive overbreak in the brow and pillars, cause blasthole cut-offs, and desensitise the explosives in adjacent blastholes.

Further, post-drilling assessments can help drillers determine what may need to be done to reduce drilling error.

Areas of focus may include the following:

- Improving survey controls
- Improving the orientation accuracy of each drill setup
- Reducing the number of drill setups per ring
- Properly fixing the drill in place with drill stingers and support jacks
- Using drill-string centralisers and stabilisers

For these reasons, post-drilling assessment was used with great success at the Cassiar Asbestos Mine, a sublevel block caving operation in northern British Columbia that operated until 1992. Approximately 50% of the blastholes in each ring were surveyed as part of the post-drilling assessment. Corrective action was taken prior to charging the ring blastholes to ensure the success of the blasting process. Corrective actions sometimes included redrilling the blastholes, using stronger explosives as a toe load, and adjusting blasthole delay timing.

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Automation in a cave mining environment

In general, automation is most effectively applied to repetitive tasks, such as production loading and trucking. The significant presence of these highly repetitive tasks in a cave mining environment make automation particularly attractive.

The increasing automation of mining equipment is the natural evolution of basic tele-remote operation. The primary benefit of tele-remote mining is in the safety and comfort for the equipment operator, having been removed from the seat. Historically, a tele-remote operator would be located at the mine site, near the machine being operated. However, recent improvements in communications bandwidth allow operators to be located wherever there is a good internet connection.

A remaining challenge for automation technology in the production process is automated bucket loading. Muck piles are not homogenous; subtle variations in rock size, compaction, and brow position mean that the optimum technique for filling the bucket will differ with every cycle. Although bucket filling algorithms are improving, in most applications, the highest productivity (and lowest cost per tonne) is currently thought to be achieved when the operator intervenes to load the bucket.

There is little actual saving in labour costs as a result of automation allowing one person to operate several machines. The reality is that the automated mine will require the same labour, more-or-less, albeit with different skills, and deployed in areas of technical support rather than in operations.

The true advantages provided by automation are more subtle.

Consistent, careful operation An automated machine will be operated far more carefully than a human operator. It will operate within the designed parameters – it won't hit the wall or ride the brakes or change into reverse while moving forwards.

Continued operation during shift and blasting breaks In an automated mine, the operator is located on the surface, and can keep the machines working during firing time. Hot seat changes happen steps from the mine parking lot and keep the machines working during shift change.

Data collection The automation infrastructure can also be used to capture operating data such as the ore source and destination. This is particularly useful as draw point management is a critical driver of an efficient production plan and effective control of the caving.

Implementing an automated system is most effective when it is considered before the mine is built, allowing a suitable design and the right equipment to be specified. Automation can also be implemented in an existing operating mine but some compromise is typically required. Pushback from personnel may be encountered making automation both more difficult and perhaps ultimately less effective.

It is valuable to consider automation at the PFS/FS level so mine infrastructure can be designed to accommodate automation. The layout of the extraction level and design of ore-handling system is critical with the overall strategy for effective and efficient isolation of automated zones an important factor.

The technology for autonomous underground production is available and appropriate for consideration. The opportunities and risk for autonomous haulage system are largely associated with the efficacy of its implementation rather than with the technology itself.

Successful implementation of automation requires effective planning and organisation. The distraction of the day-to-day can impact this process at operating mines. Enthusiastic leadership and effective change management are essential. It has been said that the journey to automation can be just as rewarding as the automation itself.

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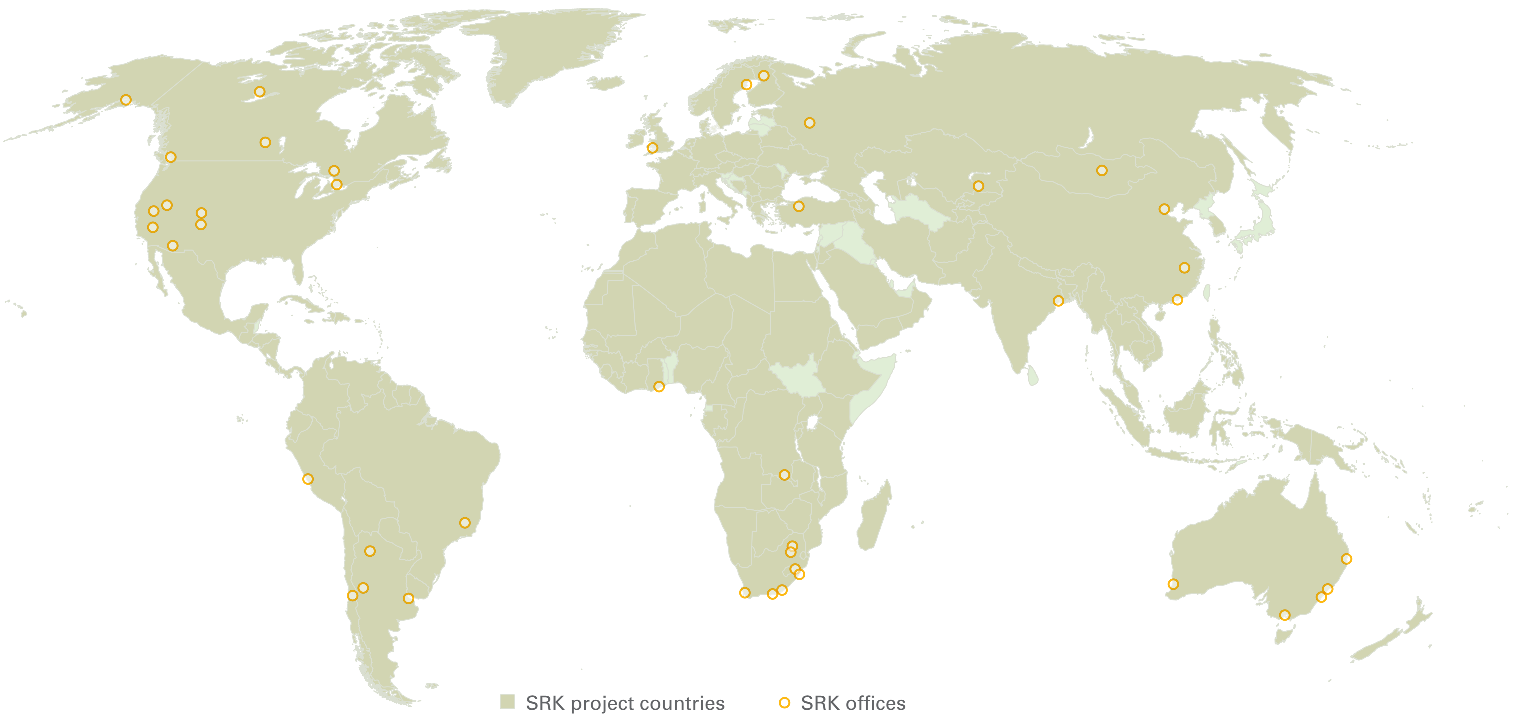

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