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A global review of recovery, dilution and draw control in sublevel caving mines

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Abstract

Sublevel caving (SLC) has previously been regarded as a high dilution and low recovery mining method requiring specific orebody geometry and rock mass conditions to be successful. Progress in the past 20 years at numerous operations has broken this misconception. A wide range of challenges have been encountered and mitigated at operations around the world, including high stress and seismicity, fines, inrush hazard, remnant mining and interaction with open pits and other caves. Significant improvements have also been made in ore recovery and productivity. Variants of SLC including sublevel shrinkage (SLS) and sublevel retreat (SLR) have also become more widely implemented in modern operations. Unfortunately, these advancements in knowledge and practice are not widely published and generally remain within individual companies. To overcome this shortcoming, a global review of current practices in SLC was undertaken as part of the Cave Mining 2040 research consortium.

The purpose of the global benchmark and mining review was to document and compare operational practices, technical aspects and hazard management techniques across SLC mines around the world. A total of 21 mines spread over four continents and 17 different mining companies participated in the study. This paper describes the main findings of the study related to ore recovery, dilution and draw control practices at the benchmarked mines.

Keywords: *sublevel caving, dilution, recovery, benchmarking*

1 Introduction

Sublevel caving (SLC) is a top-down mining method that relies on gravity flow of ore that is fragmented by blasting (Kvapil 1965). Blasted ore is extracted in accordance with a prescribed tonnage or grade shutoff. As the ore is extracted, the overlying waste material caves naturally as mining progresses. During loading from production drawpoints, the waste and ore mix together during the cave flow process which can cause dilution and ore loss. The mining method has previously been known for relatively high levels of dilution and ore loss (Bull & Page 2000), however progress in the past 20 years at numerous SLC operations has broken the misconception . Today, SLC is a safe, low capital and early production mining alternative to block caving, with greater geometric and sequence flexibility. It is a mining option when longhole open stoping is not financially viable and when block caving is not feasible due to orebody geometry, rock mass conditions or capital investment constraints. The method is amenable to a high degree of automation and has been successfully used in a wide range of geotechnical conditions, commodities and orebody geometries. Therefore, SLC mining will continue to be adopted as a technically and economically viable mining method for orebodies with lower grade and higher depth.

This paper uses the following definitions:

- Dilution is defined as any material drawn from an SLC drawpoint which has originated outside a blasted SLC ring (Power 2004). Dilution may or may not comprise of mineralised material. The dilution percentage is calculated as the tonnage of external material divided by the total tonnes drawn.

- Recovery in this paper refers to proportion of in situ material contained within a blasted ring/s that is extracted and is generally expressed as a percentage of total material blasted. Ore loss is the inverse of ore recovery, and is the amount of blasted ore that remains unrecovered in the cave.
- Draw is the amount of a blasted ring that is loaded as a percentage of the blasted ring tonnage. The draw strategy is the collective term for the various draw percentages applied throughout the mine, and the total draw is the amount of drawn tonnes as a percentage of the total blasted tonnes over the life-of-mine.

During mine production, waste mixes with economic ore during the cave flow process causing dilution and may result in abandoning ore extraction from a particular ring as highly diluted ore may not be economic to extract (Kvapil 1998). Increasing draw from a drawpoint will result in increased dilution, decreasing grade and a reduction in value per tonne as illustrated in Figure 1 (Jamieson 2012). Each SLC mine has an optimum draw strategy that maximises economic return which is also illustrated in Figure 1. This strategy is unique for every mine based on its mine plan and deposit characteristics. Dilution in SLC mines can range from 15–30% (Kvapil 2004) and the ore loss within the cave is between 10 and 20% of the total orebody (Bull & Page 2000). The amount of dilution and ore loss depends on a number of variables including the mine layout, overburden material, blast design, ore and waste fragmentation size and operating practices.

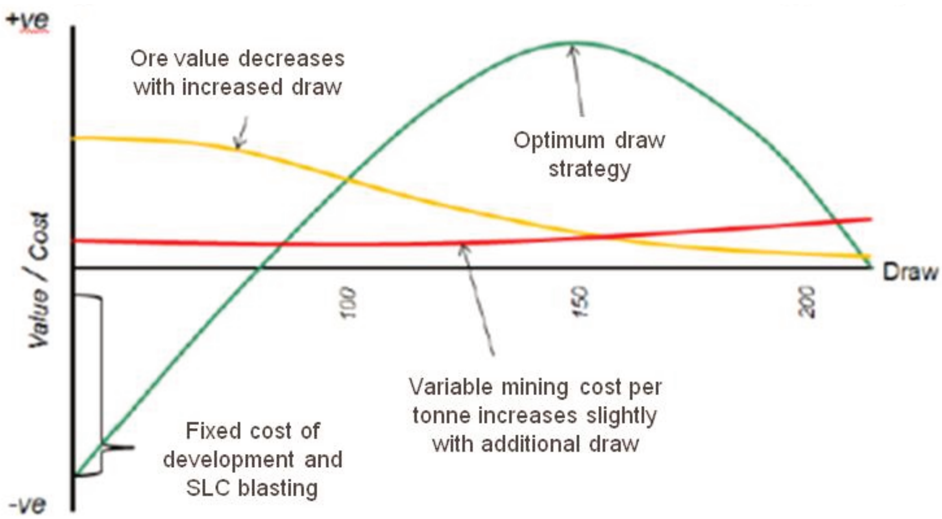
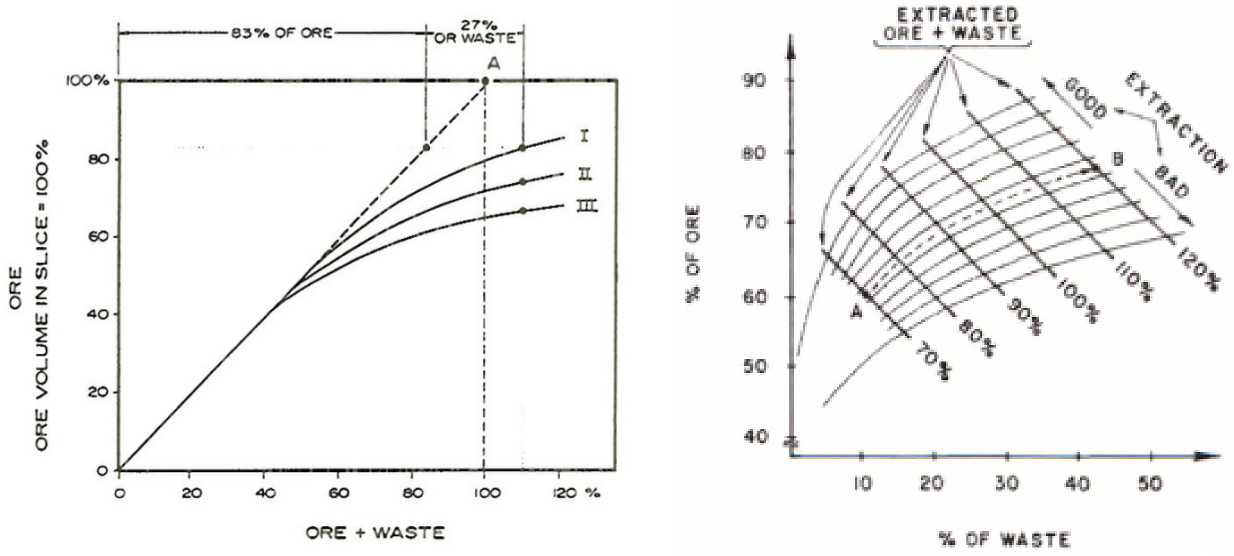


Figure 1 SLC optimisation concept (after Jamieson 2012)

Ore recovery and dilution are critical to the economic performance of any mine. Diluting waste material that is loaded from drawpoints with the ore is also hauled and processed, resulting in increased cost to the operation. Dilution has a double impact as it also displaces ore that would otherwise take its place in the mining and processing stream. Campbell & Power (2016) demonstrated significant improvements in net present value (NPV) of a mining operation by reducing dilution and improving head grade by reducing the amount of waste dilution extracted at the Ernest Henry SLC.

Typically, ore recovery of 80–90% is assumed for a total cave draw of 100–120% during conceptual studies. These numbers are somewhat experience based, but seldom justified by extensive benchmarking or back-analysis from operating mines. This paper provides statistics for recovery, dilution and draw control strategy benchmarked at different SLC mines around the world that have been in production for the past 20 years. The study found that an increasing number of mines use cave flow simulation software and numerical modelling to forecast recovery, ore grades and to optimise the draw strategy for maximum economic return. A decreasing trend in the number of mines undertaking drawpoint sampling was identified. Another key finding of the study in terms of dilution and recovery in SLC mines is that the mine design factors such as crosscut spacing or level spacing do not govern recovery as much as other factors such as orebody geometry and inclination, overburden thickness, grade of diluting material and draw control strategy.

Kvapil (1992) illustrated the relationship between ore and waste extraction in SLC mines as shown in Figure 2. Figure 2a is a lookup chart that expresses the proportion of ore and waste extraction that could be expected for an SLC mines based on a certain draw percentage (or total cave draw). The proportion of waste and ore varies in the chart based on extraction performance, which includes factors such as operational performance and compliance to plan, internal waste, grade of diluting material, external waste sources etc. The second chart shown in Figure 2b is essentially a series of recovery curves. A recovery curve is the relationship between ore recovery and waste egress in an SLC mine when the amount of draw continues to increase. The amount of ore recovery increases with continued cave draw, however the amount of ore recovery rapidly diminishes at high draw due to increasing amounts of dilution, and the curve flattens. In simple terms, increasing draw provides a diminishing return for ore recovery. Mines with favourable conditions and good operating practices recover more ore compared to those that do not, and this is illustrated by the three curves in the diagram. Although these charts are some 30 years old, they provide a useful reference for the concept of draw, recovery and dilution.



(a) (b)

Figure 2 Chart of recovery and waste egress (after Kvapil 1992) (a) and simplified recovery curves, where curve 1 represents good extraction, and curve 3 represents bad extraction (after Kvapil 1992) (b)

The SLC mining method was historically reserved for near vertical orebodies with strong ore and a weak hanging wall host rock (Bull & Page 2000). The global benchmark found that the SLC mining method is being increasingly adopted in a wide range of mineralisation, orebody geometries and mining conditions that are far more novel than text-book adaptations of the method. The flexibility of the SLC mining method is certainly an advantage, however there is limited information, benchmarking and operating guidelines available in the literature for the more recent and novel adaptations of SLC mining method. This benchmark includes a wide variety of SLC operations, including various commodities, mining scale and production rates, blind caves and those with open pits above, longitudinal and transverse SLCs, as well as modified SLC methods such as SLS and sublevel retreat (SLR).

2 Global benchmark of SLC mines

The global benchmark of SLC mines and operational review was carried out from 2019–2022 as part of the Cave Mining 2040 research consortium. The objective of the project was to:

- Document the current state of SLC mines around the world including technical and operational practices, hazard management, and current challenges at each mine.

- Benchmark and compare mines in a wide range of operating conditions, countries, commodities, mining depths and adaptations of the SLC mining method.
- Document advances in technology and operating practices over the past 10–20 years.
- Benchmark mines with unique conditions and challenges, for the benefit of future mines.
- Develop an extensive document to serve as a manual of operational practices around the world and identify the current state-of-the-art for each aspect of SLC mining.

The project included a site visit and underground tour for most of the mines. Each mine provided access to technical and operational information, mine plans, procedures, and management plans to enable a review of current practices. A total of 120 parameters were recorded for each mine ranging from production, development, equipment fleet, infrastructure, drill and blast and recovery. The information provided was used to write a report for each mine, including details of geology, mine design and planning, mine operations, drill and blast, geotechnical, infrastructure and materials handling, and hazard management practices. The reports provide context for the comparisons made in the benchmarking metrics and charts, as each of the mines has similarities and differences to the other mines. The reports also as reference source and guidelines for the reader.

A total of 21 mines spread over four continents participated in the review. Three mines which have ceased operations were also benchmarked from the literature. The majority of SLC mines are located in Australia and South Africa as shown in Figure 3. Four (known) large-scale SLC mines were not included in the benchmark due to access limitations and other constraints. The author acknowledges that there are other SLC mines around the world that were not included in the project.

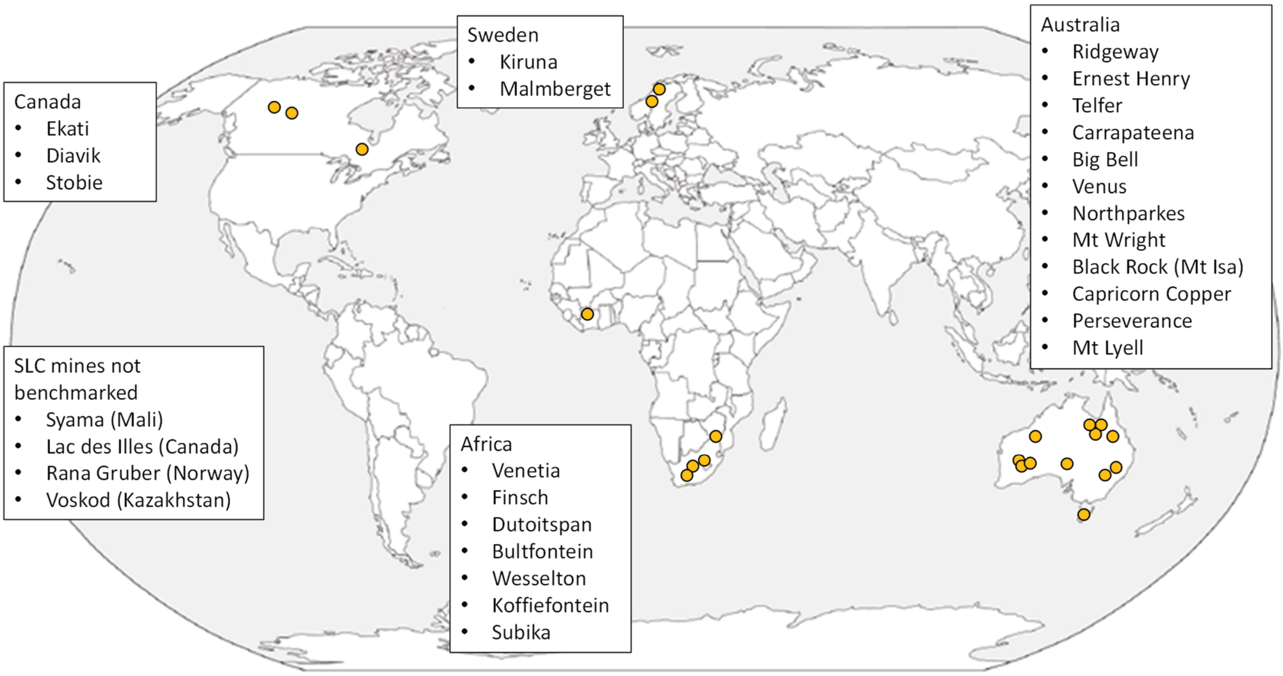


Figure 3 The location of sublevel caving mines included in the global review

The type of production ring design and cut-off methodology (i.e. grade-based or tonnage-based draw limits) differs from mine to mine. Kiruna and Malmberget implement a silo shaped blast design, while all of the other mines use a fan pattern for production blast rings. The two types of ring design are illustrated in Figure 4. The strong competent rock mass, orebody geometry and equipment used at Kiruna and Malmberget are the factors allowing the implementation of the large silo ring design which has long blastholes (up to 60 m) and widely spaced crosscuts. All other SLC operations in the world utilise a fan shaped drill pattern. The fan pattern is adopted where the maximum drilling and charging capability is in the order of 35–40 m, and sublevels spaced accordingly at 25–30 m. Adopting a fan pattern is generally governed by the equipment size that can fit into the drives, which is a function of the rock mass conditions and mine stability, as well as charging limitations and the ability for the mine to successfully fragment the entire ring.

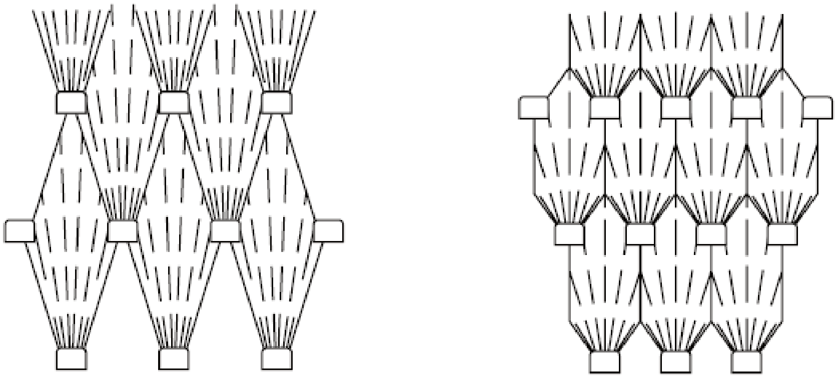


Figure 4 Cross-section showing types of sublevel caving ring layouts (after Dunstan & Power 2011). The silo design is shown on the left and fan pattern on the right

The presence, nature and volume of waste material above a caving mine influences the amount of dilution. Orebodies with large amounts of waste overburden (i.e. Ridgeway, Carrapateena and Telfer) have potential for high amounts of dilution due to the amount of waste above, particularly if this material is finely fragmentated once caved. Inclined SLC operations such as Ernest Henry and Kiruna have a new location for waste dilution on each level, as each sublevel steps out further into the hanging wall beyond the footprint of previously mined levels. Sublevel retreat mines such as Diavik and Koffiefontein have a direct transition from an open pit without a crown pillar or overburden, and much of the waste material above has been removed prior to the start of underground mining by the open pit. These mines can apply very high draw factors with relatively minor waste dilution compared to other mines. On the other hand, SLS mines (Mt Wright and Subika) introduce waste material into the cave to prevent airgap formation, and this waste material has the potential to cause additional dilution due to mixing with ore in the cave. The difference in each benchmarked mine is an important consideration when reviewing the recovery and dilution data provided. It is fair to compare similar mines directly, such as Carrapteena and Ridgeway, but unwise to expect similar recovery for mines with different conditions, such as Kiruna versus Mt Wright.

It is important to note that each mine has unique economics, ore value and cost drivers, and therefore a unique (optimal) draw strategy. This also means the trade-off for recovery and dilution varies from mine to mine on the basis of maximising economic value alone. Furthermore, there are many other geological, geotechnical and mining factors that impact recovery and dilution at each of the benchmarked mines which also needs to be considered when reviewing recovery and dilution records.

2.1 Recovery and dilution

Details of recovery, dilution and draw for each of the benchmarked mines are provided in Table 1. The table also includes details of design parameters which influence mine recovery, such as the level layout type, sublevel spacing, crosscut spacing and drive width. It should be noted that the chart shown in Figure 5 has been modified from the original developed by Kvapil (1992) with the x-axis being dilution rather than waste. The reader should also note that the recovery figures provided are those planned over the life-of-mine for each operation. This includes the mines such as Carrapateena and Venetia, which are in early production and development phases respectively.

The amount of ore recovery and waste dilution for each of the benchmarked mines is plotted in Figure 5, with the original chart developed by Kvapil (1992). This chart demonstrates:

- Improvements in modern SLC generally exceed the range of recovery performance compared to when the original chart was developed some 30 years ago.

- There is significant scatter in the data. This is to be expected given the wide range of mining conditions at each of the benchmarked mines.
- Most modern SLC operations achieve between 80 and 90% ore recovery, which is in line with typical assumptions and rules of thumb adopted for concept studies and early project evaluations. Only two mines.
- The amount of waste mining at each operation varies significantly from 4% to almost 43%.

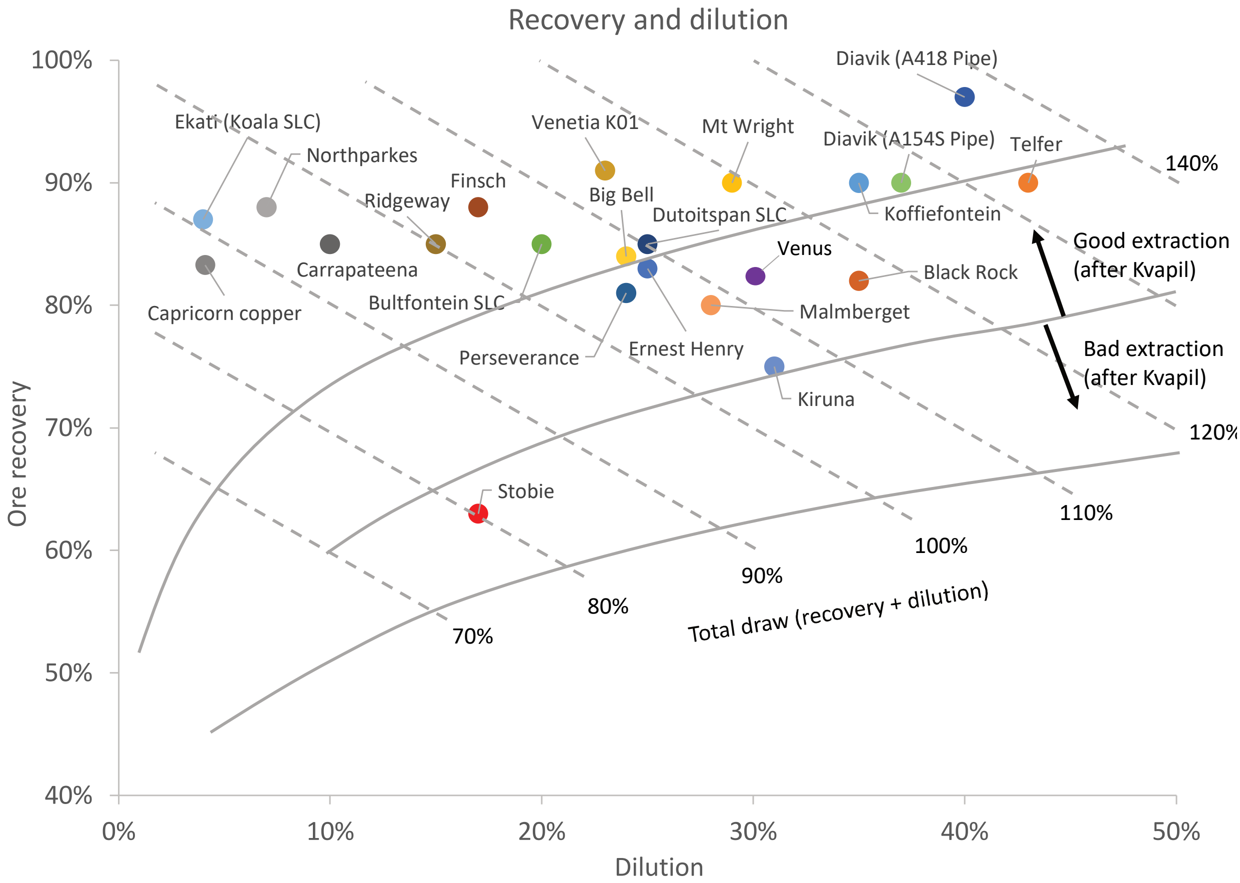


Figure 5 Ore recovery and waste for the benchmarked SLC mines (modified from Kvapil 1992)

There are some mines that are outliers in the dilution and recovery data. These include:

- Stobie, which suffered from very poor drill and blast performance due to the rock mass conditions. This resulted in high amounts of oversize and problematic brow stability which impacted production. The ore was also oxidising with poor flow properties. Hang-ups and poor flow of the oxidised ore often required the mine to blast the next production ring to continue production and this resulted in very high ore loss and dilution compared to the other benchmarked mines.
- Kiruna and Malmberget, which have unique cost drivers and economics due to low-cost magnetic separation of ore and waste. This encourages high production in favour of minimising dilution or maximising grade.
- Telfer, which adopted high draw percentages to recover high grade reefs above the cave footprint in the overburden region.

The relationship of ore recovery as a function of total cave draw is provided in Figure 6. Modern SLC mines are within the bounds of the three classes of SLC performance indicated by Kvapil. Many modern operations exceed the recovery classes first described by Kvapil (1992). It is noted that the study includes multiple kimberlite mines, which typically have high recovery and low dilution due to previous open pit mining which removed most potential waste and strong host rock which typically remains stable and does not cave or cause dilution. These types of mines were not believed to be included as part of the empirical charts developed by Kvapil. Some mines achieve very high recovery and low dilution due to favourable recovery conditions, such as diamond mines with open pits above, which have very low external dilution and low waste mixing, as shown in Figure 5. Some other mines apply high draw and accept high dilution to achieve similar levels of ore recovery. The points plotted in Figure 6 establish what is essentially a recovery curve for total cave draw versus recovery. This is not a true recovery curve as each of the mines vary significantly as previously described. However, Figure 6 does confirm that many SLC mines achieve 80–90% ore recovery at draw percentages between 100 and 120%. Another point to note is that although the charts by Kvapil are somewhat outdated, as to be expected after 30 years, the accuracy and foresight from his work is quite remarkable.

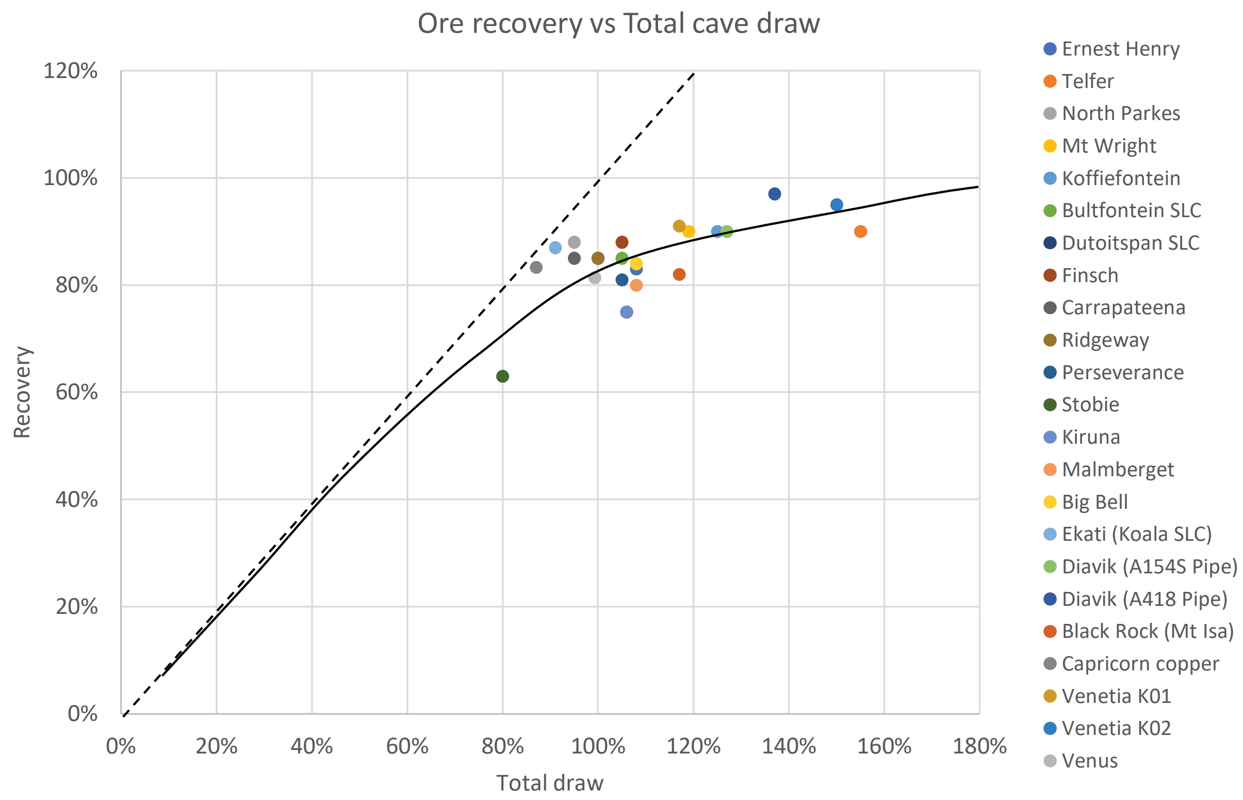


Figure 6 Ore recovery as a function of total cave draw for the benchmarked mines, similar to the original plot by Kvapil (1992) shown in Figure 2

Table 1 Recovery and dilution for various SLC mines

	Peak production rate (Mt/pa)	Commodity	Level layout	Sublevel spacing (m)	Crosscut spacing (m)	Drive width (m)	Total draw	Ore recovery estimate	Dilution estimate	Ore loss estimate
Ernest Henry	6.825	Copper gold	Transverse	25	15	6	108%	83%	25%	8%
Telfer	5.6	Gold	Transverse	25	14	5	155%	90%	43%	10%
Northparkes	1	Copper gold	Transverse	25	15	5	95%	88%	7%	12%
Mt Wright	1.4	Gold	Both	25	12	5.5	119%	90%	29%	10%
Koffiefontein	1.1	Diamond	Transverse	23	19	4	125%	90%	35%	10%
Bultfontein SLC	0.5	Diamond	Transverse	20	19	4	105%	85%	20%	15%
Dutoitspan NWC SLC	0.2	Diamond	Longitudinal	15	18	4	110%	85%	20%	15%
Finsch	3.2	Diamond	Both	25	21	4.5	105%	88%	17%	12%
Carrapateena*	4.25	Copper gold	Transverse	25	15	6	95%	85%	10%	12%
Ridgeway	6	Gold	Transverse	25 and 30	14	6	100%	85%	15%	15%
Perseverance	1.5	Nickel	Transverse	25	14.5	5	105%	81%	24%	19%
Stobie	1.825	Nickel	Transverse	21.5 and 30.5	12.2	6.1	80%	63%	17%	37%
Kiruna	27	Iron ore	Transverse	28.5	24.75	7	106%	75%	31%	25%
Malmberget	17	Iron ore	Both	25	22.5	6.5	108%	80%	28%	20%
Mt Lyell	2.5	Copper gold	Both	20 and 25	15	4.5	137%	–	–	–
Big Bell	1.55	Gold	Longitudinal	25	15	5	108%	84%	24%	16%
Ekati (Koala SLC)	1	Diamond	Transverse	20	14.5	5	91%	87%	4%	13%
Ekati (Panda SLR)	1.2	Diamond	Transverse	20	14.5	5	–	–	–	–
Diavik (A154S Pipe)	0.5	Diamond	Transverse	25	15	5	142%	90%	37%	10%
Diavik (A418 Pipe)	1.1	Diamond	Transverse	20 and 25	15	5	172%	97%	40%	10%
Black Rock (Mt Isa)	0.4	Copper	Longitudinal	20 and 25	15	5	117%	82%	35%	10%
Capricorn Copper	1	Copper	Both	25	15	5	87%	83%	4%	15%
Venetia K01*	4.5	Diamond	Transverse	25	17.5	5	117%	91%	23%	9%
Venetia K02*	1.5	Diamond	Transverse	25	17.5	5	150%	95%	15%	5%
Venus	0.7	Nickel	Transverse	25/30/35	20	4.5	99%	81%	31%	19%
Subika	2.5	Gold	Transverse	25	15	5	–	–	–	–

*Mines in early production and development. Draw, dilution and recovery figures listed here are for planned recovery over life-of-mine.

A significant finding from the global review and benchmarking project is that the recovery and dilution are mostly impacted by non-engineering parameters more than the design parameters such as drive width, level spacing or crosscut spacing. These non-engineering parameters include orebody geometry, host rock strength, overburden cover, grade of any diluting material, and geotechnical conditions. Operational discipline and compliance to plan was also identified as a significant factor for overall mine performance, including recovery and dilution. Intuitively, altering mine design parameters such as drive width or crosscut spacing at a specific mine would impact cave flow and therefore recovery and dilution. However, the mine scale conditions, such as orebody geometry and geology, at each mine was found to have the most significant influence on ore recovery and dilution. Altering design parameters such as drive width or crosscut spacing should be considered as potential optimisation opportunities, but not sufficient to overcome large-scale factors influencing recovery.

2.2 Recovery versus mine design parameters

Extensive marker recovery trials by Power (2004) and Campbell (2019) in operating SLC mines found the width of draw generally varies between 9 and 12 m, with an average of approximately 11 m. Dunstan and Power (2011) established a simple relationship for width of draw as a function of drive width as explained by the diagram and equation in Figure 7. The region between the draw zones illustrated in Figure 7 is targeted via secondary recovery on the level below, which is why the ore drives are offset between levels in SLC mines. Dilution enters drawpoints due to the high vertical extent of the draw zones which enables waste to flow down and be recovered when loading. Over lapping of the draw zones on primary and secondary levels (and additional levels below) also causes ore and waste mixing, and potential dilution, unless an ore blanket is left behind. The concept of an ore blanket to minimise waste dilution is discussed in Campbell and Power (2016). Other factors that influence draw width also include blast performance and ring breakage, as well as fragmentation size and flow properties of the blasted and cave rock.

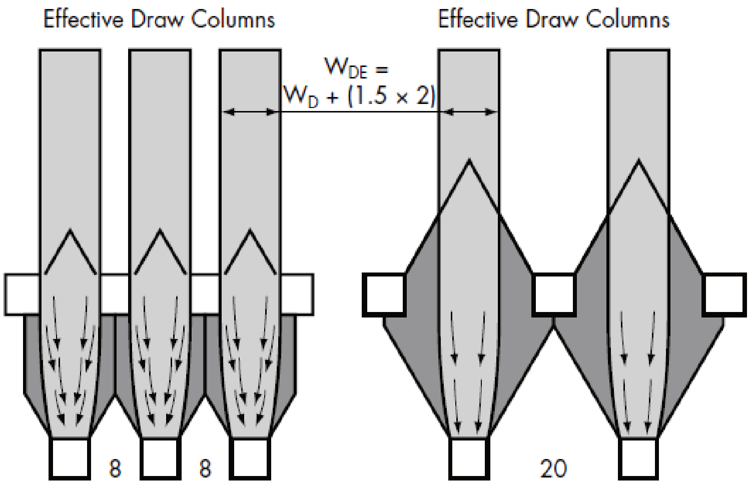


Figure 7 Effect of crosscut spacing on primary ore recovery (after Dunstan & Power 2011)

Rock mechanics demonstrates more closely spaced crosscuts (i.e. smaller pillars) may lead to instability as the pillars are too small to remain stable. The economics of some mines may drive a cost reduction approach which encourages the mine to adopt more widely spaced crosscuts to reduce mining costs. Recovery focused mines will generally aim to minimise crosscut spacing as far as possible to maximise primary (and secondary) recovery and to minimise dilution effects. This inevitably leads to a trade-off between recovery and stability, and most mines adopt the smallest pillar sizes that ensure the mine remains stable. The benchmarking data was interrogated to determine if parameters such as crosscut spacing or level spacing showed any correlation to dilution or recovery. The findings of this review were:

- Total ore recovery has no significant correlation with crosscut spacing as shown in Figure 8. The data illustrates the differences at each mine such as orebody geometry, overburden depth and the presence of an open pit at each of the various mines impact recovery more than crosscut spacing when comparing each mine. In theory, for a specific mine, altering the crosscut spacing would have some impact on recovery and dilution, based on Figure 7. It is also noted that mines with wider crosscut spacing generally have more challenging ground conditions and drill and blast challenges, which impacts recovery. For these mines, it is not the crosscut spacing alone that directly impacts recovery.

- The wide range of dilution figures from the benchmarked mines results in significant scatter and no obvious correlation for crosscut spacing versus recovery as shown in Figure 9. The range of dilution from 4–43% is particularly interesting and demonstrates the impact of variables such as overlying open pits compared to mines with thick waste overburden, for example.
- Figure 10 shows ore recovery as a function of sublevel spacing. Once again, there is no obvious correlation in the data from each mine. It is noted that for a specific mine, increasing the sublevel spacing would potentially increase dilution and ore loss as successfully fragmenting the entire blast ring would be increasingly difficult. Theoretically, the impact of increasing level spacing would not be as dramatic as increasing crosscut spacing, however marker trials or large-scale field experiments for such design changes have not been undertaken to date.
- The various drive widths at each mine are compared to ore recovery in Figure 11. Once again, there is no direct correlation, and this is attributed to other mine scale parameters that differ from mine to mine impacting recovery more than the drive width alone.

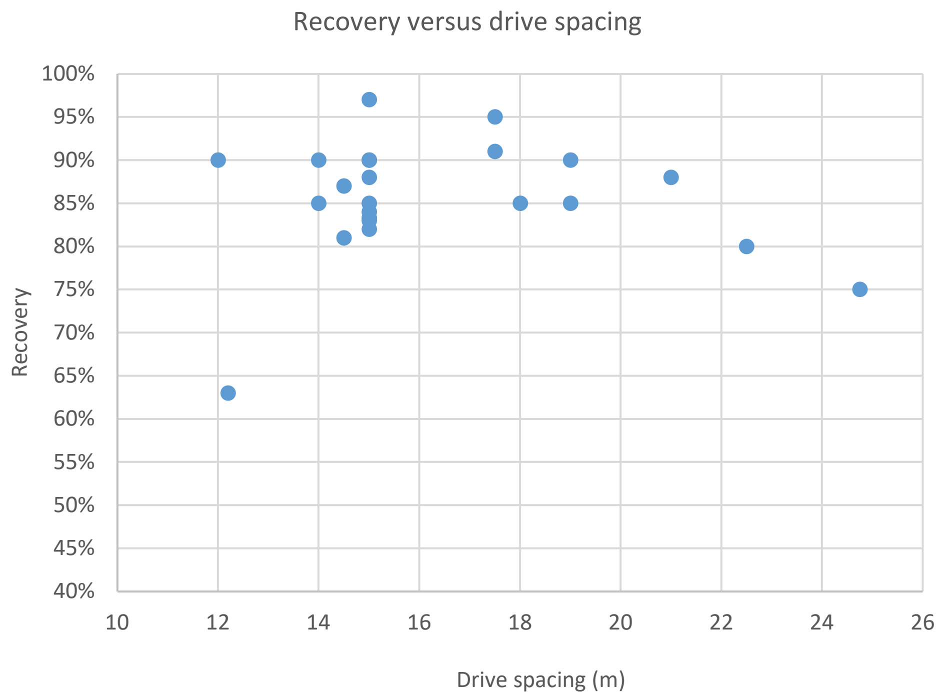


Figure 8 Total ore recovery at each benchmarked SLC versus crosscut spacing

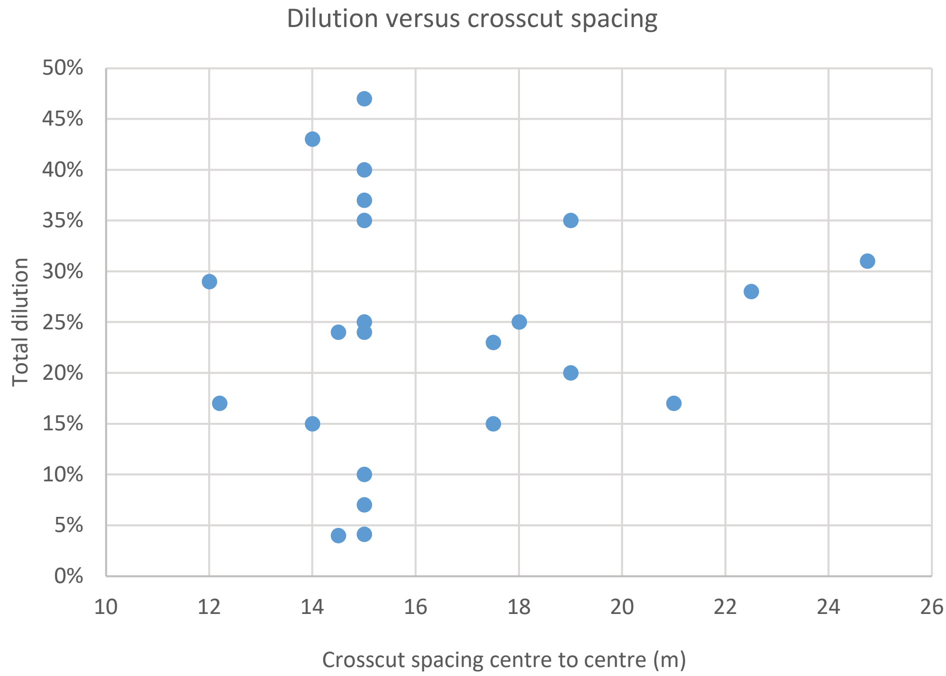


Figure 9 Total dilution at each benchmarked SLC versus crosscut spacing

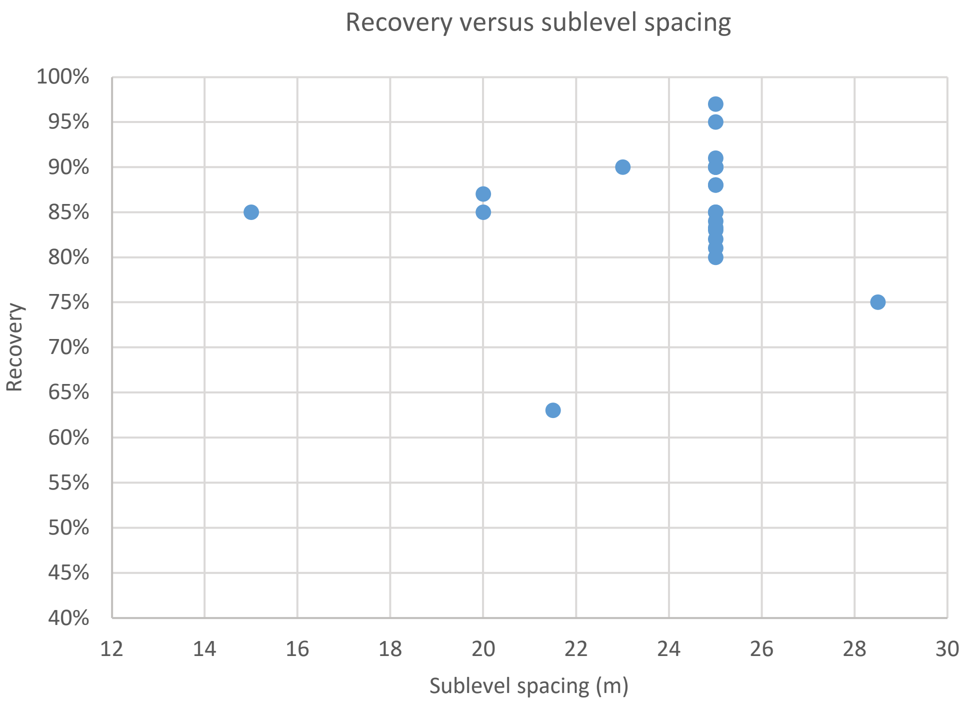


Figure 10 Total ore recovery at each benchmarked SLC versus sublevel spacing

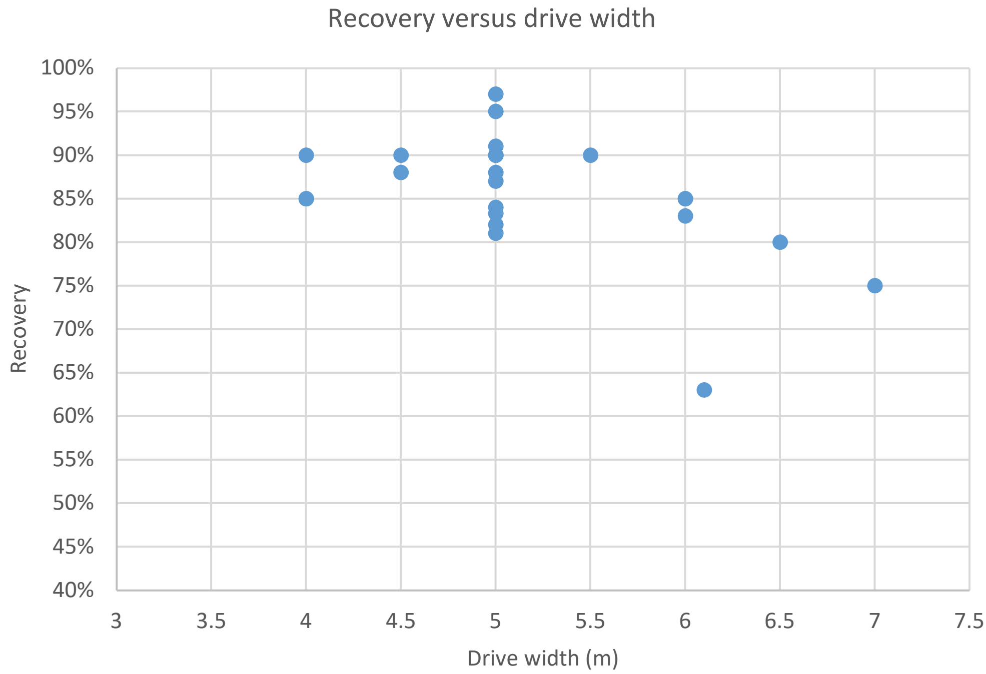


Figure 11 Total ore recovery at each benchmarked SLC versus drive width

3 Draw strategy and cave management

The goal of the draw strategy, from an economic perspective, is to determine the best possible production strategy that adheres to safety requirements, whilst also maximising the value of the resource. Generally, this is best achieved by delaying dilution entry as much as possible to maximise recovery and minimise waste mining. The draw strategy must also adhere to requirements for managing airgap potential, particularly during cave initiation and cave propagation stages. Restrictions for maximum draw are required as part of the mudrush hazard management plan for some mines due to the increasing risk of mudrush with increasing draw. The best draw strategy will also:

- Maximise economic return, which may be NPV or cash flow, depending on corporate strategy.
- Ensure the SLC production output can meet or exceed the target production rate.
- Exploit grade bearing dilution where possible.
- Avoid high draw percentages that cause high draw columns which can result in waste mixing.
- Maximise grade at the mill and minimise grade variability over time.

The draw methodology employed at each SLC varies significantly from mine to mine. Kiruna and Malmberget are both iron ore mines which produce high grade magnetite. It is a bulk commodity that benefits from very high production rates and has relatively low-cost magnetic separation of ore and waste during processing. The low-cost processing means that the dilution has significantly lower financial impacts compared to a gold or copper mine. The economics of these mines are biased towards high production with lower selectivity and less concern for dilution compared most other mines. The density of the ore is significantly higher than the unmineralised waste and the draw strategy involves material loading from the blasted rings until the weight of each loader bucket has reduced to a specified tonnage due to increasing amounts of dilution. Once the average bucket weight drops to a specific tonnage due to increasing dilution, loading ceases and the next ring is blasted.

The method for specifying how many tonnes to draw from a blasted ring varies from mine to mine and shutting off a drawpoint can be based on tonnage or grade. A 'tonnage-based' draw strategy is where a mine will draw a specific tonnage from each blast ring, mining area or specific level, rather than drawing to a sample grade in the drawpoint. Drawing to a specific grade is known as a 'grade-based' draw strategy. Tonnage-based draw is simply when a specific draw tonnage is issued to loader operators drawing from the cave. A grade-based draw strategy is where draw occurs in increments and the grade is sampled either by assaying or visual estimation, and loading is either continued or ceased based on the grade in the drawpoint.

A tonnage-based draw strategy may be applied when the amount of draw needs to be restricted during cave initiation and early cave propagation to manage airgap potential. Draw percentages less than 100% will often be adopted during the initial levels of an SLC to build up cave stocks to act as a physical barrier for hazards such as air blast or large-scale pit instability. Applying a maximum draw percentage to manage mudrush hazard is also an example of a tonnage-based draw strategy.

Many SLC mines use flow modelling software to calculate the amount of draw per blast ring to reach a specific shutoff grade. This tonnage is then used in mine scheduling software for planning purposes and the prescribed draw tonnage per ring is issued to supervisors and operators. This is a tonnage-based draw strategy that has been developed based on grade, and this can only be done using flow simulation software. Some mines will also verify forecast grade in the flow model via drawpoint sampling, and some mines use a combination of flow modelling to guide the draw strategy and cease ring draw based on grade sampling.

An observation from the benchmark is the significant opportunity for ore sorting technology to be adopted in SLC mines to remove waste without the cost of processing. This would enable mines to increase total recovery by drawing more tonnes as the economic impact of dilution is drastically reduced.

The benchmark identified a growing trend of mines using flow modelling software for grade forecasting which is verified by grade reconciliation from the mill. Flow modelling software of various types has progressively replaced empirical methods such as dilution entry or recovery curves, or grade factoring, although some mines still use these approaches. There is also an increasing trend of fewer mines undertaking drawpoint sampling. This is due to safety issues working near drawpoints, interaction with loaders in production areas, slow turnaround time of sample assays at laboratories, high production demand in active drawpoints, and difficulty visually estimating grade in drawpoints as mines target lower grade material. Mines that adopt grade sampling tended to be gold mines, smaller SLCs, and the mines that do not employ cave flow software for grade forecasting. Summary of grade estimation methods, drawpoint sampling and draw restrictions adopted at each mine is provided in Table 2.

Table 2 Summary of grade estimation methods, drawpoint sampling and draw restrictions adopted at each mine

Mine name	Grade estimation method/software	Routine drawpoint grade sampling	Draw restrictions applied
Ernest Henry	PGCA	No	40, 60, and 90% in the hanging wall step outs. Maximum ring draw of 250–300%
Telfer	NSO and PCSLC	Yes	40, 60, 80, and 100% over the first four levels, increasing to 12–200% in the main levels. Overdraw up to 350% on final levels
Northparkes	PGCA	Yes	40% draw prior to reaching critical hydraulic radius, then 60% draw on the remaining first level, 100% draw on the second sublevel
Mt Wright	Grade factor	Yes	50% draw in the 'bell' used to establish the SLS, 100% draw in the SLS with overdraw in the final levels
Koffiefontein	PCSLC	Visual only	120% draw on the first level (below the previous cave), up to 180 and 240% for the 2nd and 3rd levels (respectively)
Bultfontein SLC	Grade factor	Yes	Draw to dilution limit
Dutoitspan NWC SLC	Grade factor	Yes	Draw to dilution limit
Finsch	PCSLC	Yes	66–80% on top level (~2,500 t/ring), 90–130% on second level (~5,100 t/ring), 150%+ on subsequent levels
Carrapateena	PGCA	No	40, 60, and 80% draw limits for the first three sublevels (respectively)
Ridgeway	Grade factor	Yes	40% draw on the 1st level, 40–88% on the 2nd level, 90–110% on the 3rd level, 110% on the 4th level, 110–175% for the levels below
Perseverance	Grade factor	Visual only	50% draw on the 1st level, 70% on the 2nd level, 100% on the 3rd level and below
Stobie	Grade factor	Visual only	80% planned draw. No recorded information draw restrictions for initial mining levels was available
Kiruna	Grade factor	No (bucket weight only)	Draw determined by operators by tracking bucket weight, which is a proxy for the %ore and % dilution
Malmberget	Grade factor	No (bucket weight only)	Draw determined by operators by tracking bucket weight, which is a proxy for the %ore and % dilution

Mine name	Grade estimation method/software	Routine drawpoint grade sampling	Draw restrictions applied
Mt Lyell	Grade factor	Yes	Minimum draw of 50% for blasting purposes. Cave draw varied from 60–175% over life-of-mine
Big Bell	Grade factor	Yes	70% draw in slots, 100% draw (on average) in the SLC rings
Ekati (Koala SLC)	PGCA	No	No records available for the initial SLC levels
Ekati (Panda SLR)	PGCA	No	Effectively drawn to 100% in the open benching levels at the pit to underground transition levels
Diavik (A154S Pipe)	Grade factor	Sampling during development	Effectively drawn to 100% in the upper levels, restricted draw to maintain broken stocks above active levels currently applied
Diavik (A418 Pipe)	Grade factor	Sampling during development	Effectively drawn to 100% in the upper levels, restricted draw to maintain broken stocks above active levels currently applied
Black Rock (Mt Isa)	PGCA	Yes	60, 80, and 120% draw limits for the first three sublevels (respectively)
Capricorn Copper	PGCA	Yes	Low draw applied on the upper levels to manage airgap potential prior to surface breakthrough. Draw percentages not available
Venetia K01	PCSLC	Yes	50–80% draw restrictions for pit transition levels
Venetia K02	PCSLC	Yes	50, 70, and 100% draw limits for the first three levels in current mine plan
Venus	Unknown	Unknown	Not available
Subika	Pseudoflow	Yes	Draw to approximately 90%, with the SLS to remain full of tipped waste

4 Conclusion

This paper described ore recovery, dilution and draw control practices at a wide range of SLC mines around the world. The global review of SLC operations identified that modern mines achieve higher recovery at lower draw than in the literature and recovery charts published some 30 years ago. As expected, there is significant scatter in the recovery and dilution figures due to the wide range of mining conditions at each of the benchmarked mines. A general finding was that most modern SLCs achieve between 80 and 90% ore recovery at draw percentages of 100–120%, which is in line with typical assumptions and rules of thumb adopted for concept studies and early project evaluations. A somewhat surprising finding of the study was the range of dilution at each mine, which was as low as 4% and as high as 43%, and was outside the general range of 15–30% described in the literature.

A significant finding from the global review and benchmarking project is that the ore recovery and dilution are most impacted by large-scale effects rather than design parameters such as drive width, level spacing or crosscut spacing. Many of these large-scale parameters are outside of human control and include orebody geometry, host rock strength, overburden cover, grade of any diluting material and geotechnical conditions.

An increasing number of mines use cave flow software, with some mines forecasting ore grades with high accuracy and reliability. There is an increasing trend of mines shifting away from drawpoint sampling due to exposure of personnel to active mining areas, slow turnaround time for laboratory assaying, high grade variability and low reliability due to sampling bias.

The global review involved a wide range of mining practices, operating procedures, mine scale, depths, and technical challenges at the worlds SLC mines. The range of operating conditions and differences in the mines can only be described as remarkable, particularly those mines operating in conditions outside the 'text-book' specifications for the method. The implementation of variants of SLC such as SLS and SLR are also novel. It must be said that the flexibility of the SLC mining method is one of its true advantages and why the method will continue to be adopted as mineralised deposits being targeted increase in depth and companies attempt to mine at lower grades.

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