Sampling for resource evaluation and grade control in an underground gold operation: a case of compromise

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The foundation of any resource evaluation and/or grade control programme is the collection of high-quality samples within a geological context. The requirement for quality samples has long been recognised, where they must be representative and fit-for-purpose. Correct application of the Theory of Sampling reduces sampling errors across the collection to assay process. This contribution presents a case study where small-sample based assays understate grade in geometrically simple, coarse gold-dominated veins. Drilling with whole core sampling and assaying is applied to estimate Inferred Mineral Resources that are accepted to understate grade. Dominant gold particle clustering drives the application of bulk sampling. Development drives are sampled as bulk composites and processed via an on-site plant. Upper and lower development drive grades are assigned to stope blocks and reported in the Indicated Mineral Resource category. The case study illustrates the challenges and potential solutions to achieve representative sampling. Solutions ranging from individual bulk samples processed through a plant, to bulk composites and whole-core sampling and screen fire assaying are discussed. These approaches account for the nature of the mineralisation, where extreme gold particle-clustering effects render the analysis of small samples problematic.

Introduction

Sampling for Resource Evaluation and Grade Control

Underground mine evaluation and grade control aims to define tonnes and grade for project feasibility and production through the definition of ore and waste. The role of samples relates to informing resource/reserve block models; development ore/waste decisions; investigation of ore limits; identification of grade trends and/or continuity along development or stopes; and local/grade control estimation. Where samples feed into ore/waste decisions, the risks of potential misclassification and its economic impacts must be considered.[1–3] Many small- to medium-sized and some large mine operations rely on face samples and/or diamond core drilling for resource evaluation and/or grade control. These may be used to update a resource/reserve model that is publicly reported. This contribution presents a case study which emphasises ore characterisation, Theory of Sampling (TOS) application, component error analysis and an open mind.

Theory of Sampling

Sampling is a critical component throughout the mine value chain.[1–11] Without being able to analyse all material in advance, sampling of both in-situ and broken material serves to inform geological (resource and grade control), geoenvironmental and geometallurgical based mine planning and decision-making.[1,3–7] Sampling errors can generate both monetary and intangible losses.[3,5–11]

Representative samples are needed to effectively evaluate the style of mineralisation in question.[1–7] This can be particularly challenging in deposits with coarse gold (>100 µm particles dominate), where large field samples and special preparation-assay protocols may be needed.[1–16] Unrepresentative samples will not describe the true in-situ gold grade distribution and the overall result leads to a lower (undervalued) deposit mean grade. This is attributed to small samples having a high probability of missing influential coarse gold particles and reporting at the lower end of the grade distribution. As a result, there will be overestimation of block grades below the economic cut-off value,

doi: https://doi.org/10.1255/tosf.165

that is, blocks which report as waste. Any fine-gold (<100 µm) background population is likely to be represented relatively well by small samples.[12–14] At the other extreme, samples may report as "false" high grades when they occasionally contain coarse gold particles. For example, 1 m of half HQ core (c. 4 kg based on 63.5 mm diameter core) will yield a grade of 40 g/t Au and 295 g/t Au if it contains a single 2.5 mm or 5 mm gold particle respectively. The presence of rare coarse gold particles in small samples may positively bias the deposit mean grade.

Quality assurance/quality control (QAQC) is critical to maintain data integrity through documented procedures, sample security and monitoring of precision, accuracy and contamination.[17–20] The ultimate test of any grade control programme comes through reconciliation of actual mine performance versus that predicted by grade control samples.[20]

The TOS aims to provide answers to two questions: *how should a sample be selected* and *how much material should be taken*? It defines a series of sampling errors which, if not minimised, lead to error and uncertainty in the final assay value.[3,7–11] TOS attempts to break down this error into a series of contributions from sample collection through to assaying (e.g., the sampling value chain; Table 1).

Table 1. Sampling value chain from programme planning to assaying.

Stage	Planning	Collection	Transport	Laboratory Preparation	Assaying
	1	**2**	**3**	**4**	**5**
Activity	Scope Develop Execute	Observe Collect Bag and tag QAQC Integrity/security Chain of custody	Integrity/security Chain of custody	Equipment operation Equipment clean QAQC Integrity/security	Equipment operation Equipment clean QAQC Integrity/security
Sampling errors		GNE, FSE, GSE DE, EE, WE	PE	FSE, GSE DE, EE, WE, PE	PE AE
Dominant effect on results		Precision Bias	Bias	Precision (if splitting) Bias	Bias

GNE: geological nugget effect; FSE: fundamental sampling error; GSE: grouping and segregation error; DE: delimitation error; EE: extraction error; PE: preparation error; WE: weighting error; AE: analytical error.

The heterogeneity of a given variable (e.g. grade) can be quantified through the nugget effect and has a direct link to TOS.[3,10,14,21] The nugget effect is a quantitative geostatistical term describing the inherent variability between samples at very small separation distances. The nugget effect has a wider remit than just differences between contiguous samples and its magnitude relates to the small-scale geological variation and sample measurement error.[3,10,14,21]

The geological component of the nugget effect expresses short-range data variability, which is particularly significant when samples are small, and protocols not optimised. The sampling component of the nugget effect expresses errors induced by inadequate sample mass, poor sample collection and preparation methods and poor analytical procedures. Throughout the mine value chain, sampling protocols should be optimised to reduce the sampling nugget effect which, in turn, reduces the total nugget effect, data skewness and the number of extreme data values.[3,10,14–16,21] In many cases, coarse gold-bearing deposits display a nugget effect of >50%.[14,21]

Case Study: San Christina Mine

Introduction

The San Christina mine is in South America and is privately owned and operated. During the period 2005–2012, the mine underwent a period of evaluation and subsequent mining. The programme yielded 75,840 t of ore at a reconciled head grade of 23.2 g/t Au for 42,290 oz Au recovered. Reconciliation during this period displayed strong variability, with some estimates under-calling grade by 75% based on diamond drilling alone. It was known that the mineralisation was dominated by coarse gold and that a significant nugget effect existed. As part of the mine re-evaluation, commencing in February 2018, a series of characterisation tests were undertaken to investigate gold particle sizing and grade variability. An Inferred Mineral Resource of 55,000 t at 9.5 g/t Au and an Indicated Mineral Resource of 16,500 t at 25.7 g/t Au were declared in late 2018 in accordance with the 2012 JORC Code.[22] Mining recommenced in February 2019 and continues to the present time (June 2022). The operation targets c. 40,000 t per annum based on an Indicated Mineral Resource of 75,000 t at 25.8 g/t Au and Inferred Mineral Resource of

225,000 t at 12 g/t Au reported in accordance with the JORC Code 2012. Based on the Indicated Mineral Resource, a Probable Ore Reserve of 65,000 t at 22 g/t Au was declared in March 2022. The combined resource/reserve base indicates that the project is likely to have an on-going life of 5-6 years, subject to additional development to uprate Inferred to Indicated Mineral Resources. Exploration potential exists to extend production beyond 5-6 years.

Geology and Mineralisation

The sub-vertical vein system is hosted in a series of volcanic rocks. The veins comprise massive, brecciated to laminated quartz, with up to 5-20% pyrite, galena and sphalerite in the ore shoots. Individual vein widths vary from 0.5–1.5 m, with an average of 1.25 m. Outside of the ore shoots, the vein may reduce to a few cm or fault gouge. Locally the main Veta (vein) Christina (VC) splits, with splays emanating into short-lived (<25 m) to more continuous (up to 150 m) structures. The VC can be traced for 1,700 m along strike and for 400 m down-dip (confirmed by four deep drillholes).

The dominant fault movement associated with the veins is strike-slip, reflected by the sub-vertical to vertical orientation of the ore shoots. As well as the VC, four other vein systems have been identified where historical workings confirm gold mineralisation. The additional reefs contain an Exploration Target of 250,000–500,000 t with a grade range of 15–25 g/t Au. These reefs display similar characteristics to the VC, as observed in limited underground development, drill intersection and surface exposure.

Economic grades are located within the steeply plunging ore shoots that are traceable for 50–120 m along strike and >250 m down-plunge. All vein structures contain low-grades up to 2 g/t Au, with the ore shoots historically containing recoverable grades of between 15–30 g/t Au. The wallrocks contain minimal gold grades (<1 g/t Au, generally 0.25 g/t Au), except where stringer veins are present emanating from the main vein.

Two mineralisation stages are identified, an early sulphide-poor phase and a later sulphide-rich phase related to fault reactivation. Both phases contain coarse gold, though the earlier sulphide-poor phase generally contains more coarse and clustered gold. The two phases generally occur together, so the ROM feed bears both.

The veins that make up the ore shoots are generally continuous, through grades are variable and discontinuous low-grade zones can be present. Individual ore shoots globally represent between 45,000–150,000 t of mineralisation. Criteria for the recognition of an ore shoot, other than gold grade relate to: (1) well-developed laminated vein with thickness greater than 0.5 m; (2) the presence of pyrite-galena-sphalerite and locally visible gold as isolated particles or clusters; and (3) moderate to strong wallrock silicification. Low grade zones (<6 g/t Au) within the shoots generally lack laminations (or are poorly developed), sulphides and visible gold.

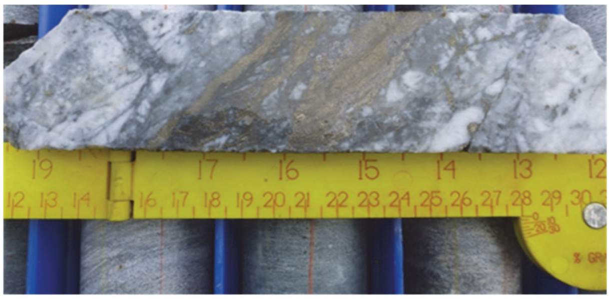

Figure 1. Length of strongly sulphide (late phase) mineralised core yielding a grade of 108 g/t Au over 0.2 m, typical of the VC. The other side of the core contained visible gold.

2018 Re-evaluation Programme

Heterogeneity Testwork

Two 50 (1.5 kg) single piece tests were undertaken on VC mineralisation.[23,24] The material sampled was medium to ROM grade ore (15–25 g/t Au). The individual fragments collected were quartz dominated to reflect the nature of the reef (>90% quartz). The two tests yielded K values of 250 and 990 g/cm$^{1.5}$ respectively. Back-calculated d_{95Au} values were 75 μm and 500 μm respectively.

The tests show the potential precision issues with heterogeneity tests. Field observation indicates discrete gold clusters and visible gold are present. Gravity processing of ore verified the presence of coarse gold in ROM mineralisation up to 1.5 mm. The company concluded that a bulk sampling programme was required to characterise the mineralisation properly.[1,4,5,14–16]

Gold Particle Size and Liberation Diameter: Characterisation via Bulk Sampling

A characterisation programme was undertaken based on a series of bulk samples collected on the accessible 2 level (VC2). Bulk samples were taken from the #2 shoot backs which extended for 65 m along strike. Samples were defined across a range of grades from low to high grade (Table 2). They were not collected consecutively but placed where required to achieve the desired grade. Bulk samples contained both early and late phases of mineralisation.

After detailed geological mapping and saw-cut channel sampling of the drive backs, seven locations were defined. At each location an approx. 1.5 m to 2 m long (strike) by 1.5 m deep (up-dip) by 1.5 m (target stope width) wide cut was mined into the level back to yield approx. 10 t to 13 t of sample. In the bulk sample area the vein width was between 1.1–1.5 m. Bulk samples were sent to an independent test facility in North America, where the material was stage processed through a pilot plant to liberate gold over a series of crush-grind concentration steps.[25] The gold liberated from each stage was sized and assayed to provide an indication of gold particle size distribution (Table 2 and Figure 2).

Table 2. Summary of gold particle size distribution by mass across different grades based on eight bulk samples from VC2 #2 shoot.

Grade (g/t Au)	+100 μm	+500 μm	+1000 μm	d_{95Au} (μm)	d_{maxAu} (μm)
0.5	3	0	0	95	200
2	53	0	0	300	400
[1] 6F	54	7	0	500	700
[2] 6C	66	21	5	1,000	1,500
9	65	16	6	1,200	1,600
13	67	22	8	1,900	2,100
24 (ROM)	70	26	9	2,000	2,500
39	69	26	10	2,250	2,500

[1] Fine-gold dominated; [2] Coarse-gold dominated.

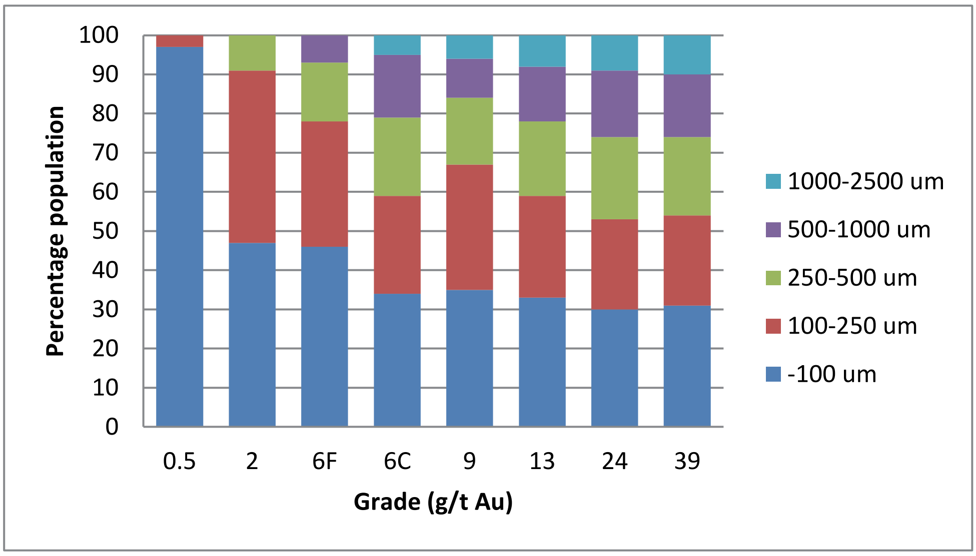

Figure 2. Gold particle size distribution by mass across different grades from the VC2 #2 shoot. Columns represent percent of gold particle size population within the given size range. Refer to Table 2 for summary input data. um = microns.

There is consistency of the sub-100 µm to 500 µm fractions with increasing grade and a relatively small increase in the >500 µm fractions. There is a distinct variation in population at 6–9 g/t Au, where in some cases a finer gold population dominates (Table 2 and Figure 2; refer 6F) but in others a coarser population exists (Table 2 and Figure 2; refer 6C). These indicate a potentially more disseminated finer gold background population that may be easier to sample.

Gold Particle Clustering

Core logging and face mapping (principally VC2 and 3, #2 and #3 shoots) reveal that gold particle clustering becomes locally material throughout the VC ore shoots. Clustering can have a marked effect on sampling requirements.[3,12,13] These grade hotspots relate to 1–3 cm^3 of clustered >200 µm gold particles, which provide gold-only composites of <0.25 to 1 cm^3 (Figure 3).[12] Individual cluster composites, assuming spheres, yield a mass of between 0.15 g to 9.5 g. These can be easily missed by small channel samples (13.5 kg/m) and core samples (4.9 kg/m).

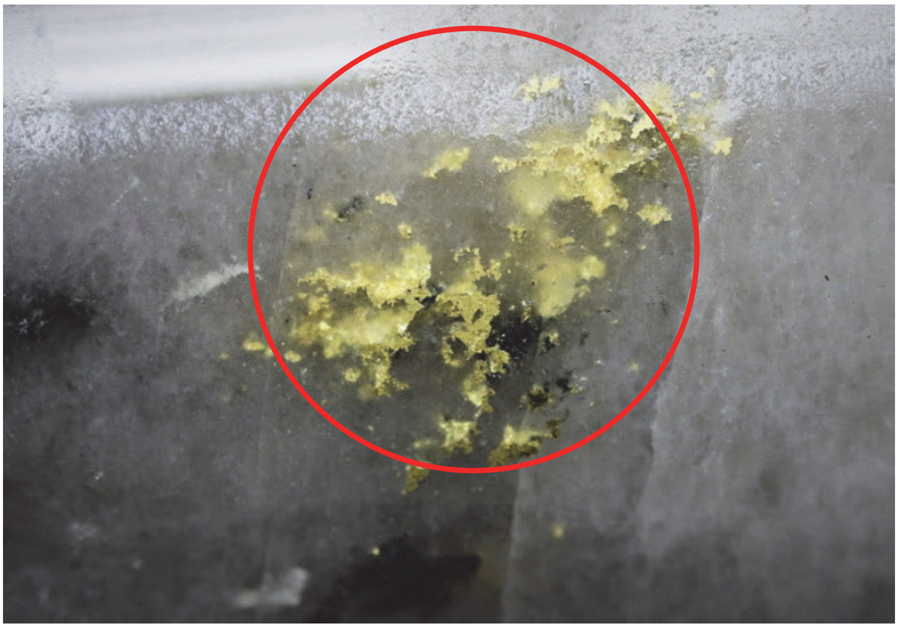

Figure 3. Coarse gold cluster in sulphide-poor (Early phase) mineralisation from VC drill core. Width of cluster on core surface c. 20 mm (red circle).

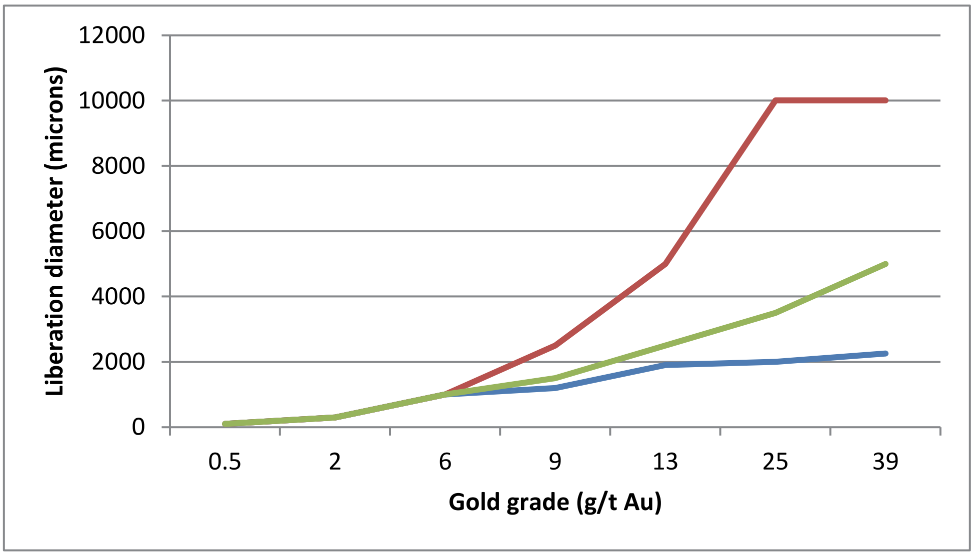

Figure 4. Inferred relationship between single particle d_{95Au} and effect of d_{Auclus} with grade in the VC. Red line maximum clustering effect; Green line minimum clustering effect; Blue line non-clustered (d_{95Au}).

Gold particle clustering becomes locally material particularly at grades above 6 g/t Au (Figure 4). It is difficult to assess the true number of clusters in any tonne of ore. During the initial and later bulk sampling and trial mining programmes, all possible vein exposures were reviewed to identify clusters. For 25 g/t Au ROM ore, it was concluded that between 40–80% of the gold was in 1–5 clusters with an individual cluster composite mass of 4.0–9.5 g. Lower grade ore of 8–12 g/t Au was likely to contain between 20–50% of the gold in 5–20 clusters with an individual cluster composite mass of 0.15–2.0 g.

Theoretical Sample Mass

A theoretical field sample mass can be estimated using Poisson statistics to achieve a given precision (±15% at 90% reliability).[25] The range of mass values for BCOG and run of mine mineralisation is given in Table 3. The major driver for large sample mass at San Christina is the gold particle clustering effect.

Table 3. Range of theoretical sample mass values for the VC across different grades.

Grade (g/t Au)	d_{95Au} (μm)/ [d_{Auclus} (μm)]	Clustering Effect	Optimum Mass
0.5	95	None	5 kg
2	300	None	10 kg
6 (BCOG)	500	None	30 kg
	1,000		165 kg
9	1,200	Potentially	175 kg
	[2,500]		1.5 t
13	1,900	High	5 t
	[5,000]		85 t
24 (ROM)	2,000	Very high	0.5 t
	[10,000]		35 t
39	2,250	Very high	270 kg
	[10,000]		24 t

Sampling Protocol Development

Channel samples were cut using a diamond saw to produce a near uniform 10 cm wide by 5 cm deep channel to yield around 13.5 kg/m.[2] Two 5 cm saw cuts, 10 cm apart were cut, and a hammer and chisel used to break the intervening block of rock out of the channel. Samples were collected across the vein as 0.4–0.5 m lengths (5.4–6.7 kg/m) from the reef hanging- to foot-wall.

Samples were weighed and compared to their expected mass, which was 6.75 kg for the dominant 0.5 m samples. Around 75% (N = 206) were within ±15% of the target mass (e.g. ±1 kg: 5.75–7.75 kg) based on 275 samples. Overall this was a good result, given the inherent challenges of collecting channel samples.[2] Mass variability related to the interrelationship between DE and EE, where the saw-cut depth could vary depending upon face profile. The extracted material depended on effort to remove the delimited sample and loss through fines and fly-rock.

Due to the presence of coarse gold, screen fire assay (SFA) was considered the most applicable technique. All channel samples were bagged and secured on-site and transported to an independent laboratory. Samples were dried and crushed to P_{90} –3 mm, one-third was split by rotary sample divider (RSD) and pulverised to P_{95} –75 μm and then split for two to three SFA1000.

Diamond Drilling Programme

During 2002−2003, a 49-hole surface diamond-drilling programme on the VC assessed the predicted ore shoot from surface to a depth of 250 m. The NQ (4.9 kg/m) holes were on an approx. 10−20 m by 10−20 m grid. Samples were collected across the vein as 0.4−0.5 m lengths (1.9−2.4 kg/m) from the reef hanging- to foot-wall. A 0.4 m sample was taken into both the hanging- and foot-walls for assay. After logging and photography, cores were cut in half and one half sent to an external laboratory. The samples were dried and crushed to P_{90} –3 mm and pulverised to P_{95} –75 μm and riffle split into two halves, and both sent for SFA.

Duplicate Pair Analysis—Channel and Core Samples

Duplicate pair analyses were undertaken for channel and core samples (Tables 4 and 5). The channel samples (79%) show a smaller sampling error component compared to the core (93%), probably relating to a larger mass (e.g. 4.9 kg/m versus 13.5 kg/m). Both values are relatively high and reflect a high geological nugget effect. The relatively high preparation error of the channel samples (32%) indicates the presence of coarse-gold at the split stage. The analytical error components for both channel and core samples are slightly higher than expected, reflecting the presence of residual coarse gold in the pulps. Overall the results show that channel samples are of better quality than core, though both error values are high.

Table 4. Face channel sample duplicate pair analysis.

Sample Type/Error (Preparation Route)	Sampling (%)	Preparation (%)	Analytical (%)	Total (%)
	Duplicate face	**−3 mm split**	**−75 um split**	**-**
Face channel	79	32	18	87
Number of pairs	75	150	150	-

Table 5. Core sample duplicate pair analysis.

Sample Type/Error (Preparation Route)	Sampling (%)	Preparation (%)	Analytical (%)	Total (%)
	Half drill core	**No split**	**−75 um split**	**-**
Diamond drill core	93	-	21	95
Number of pairs	100	-	200	-

Bulk Sample Trials

Bulk Sample Strategy

The high variability of channel and drill samples lead the project team to consider the use of bulk sampling to overcome the nugget effect.[14,16,26,27] During underground development, a programme of bulk sampling was undertaken. Bulk samples comprised three types: (1) drive round of 25−30 t; (2) raise development of 10−15 t; and (3) drive back cut of 15−20 t. All development faces were saw-cut channel sampled and mapped to guide the bulk sampling process. Individual rounds were transported to surface and isolated prior to processing.

Bulk Sample Processing

It was considered optimal that each bulk sample be processed in its entirety through an on-site plant. This was driven by the availability of a pilot plant, albeit requiring renovation and upgrading, and the wish to reduce sampling error (e.g. avoid splitting and complicated procedures on large samples). Each bulk sample lot was batch milled through a gravity pilot plant that was able to process up to 5 t per hour. The plant was used for both bulk samples and initial production batches. Ore was passed through jaw and gyratory crushers prior to being fed into a 20 t capacity fine (−1.5 cm) ore bin. This bin was attached to four strain gauges to provide a weight determination. The fine ore bin fed into a ball mill, yielding a P_{90} −125 µm. The ball mill was fitted with a large access panel to allow cleaning and a bunded wash area immediately below to allow access and containment for washings. Washings were collected, tabled and assayed.

A simple gold trap was located at the outflow of the ball mill, which typically collected 10−25% of the gold in a sample (usually particles >0.5 mm in size). This trap was cleaned out after every sample. The feed then passed through a 0.5 mm screen, with the undersize passing to a 250 mm Knelson concentrator. The oversize recirculated to the ball mill. The Knelson concentrate was passed over a shaking table.

The mill circuit was flushed out after every sample with 2 t of waste rock and stripped/cleaned after every 4th sample (e.g. 120 t). Gold recovered during stripping was proportionally re-combined with the previous bulk samples based on their percentage gold yield. This was found to be the best way in which to deal with recovered gold in-circuit, as the higher the grade of ore processed the greater the problem. Between 5–10% of the batch gold yield was usually recovered from the ball mill. Minimal gold was recovered from elsewhere.

All concentrates were weighed, combined and tabled, prior to size by assay to extinction. Tails from the Knelson unit were sampled (1 kg) every 10 minutes via an automated Vezin splitter. Every hour, the composite tails samples (6x 1 kg) were removed for drying and on-site pulverisation to P_{80} −100 µm and then RSD split down to 2 kg. The series of hourly splits were submitted to an external laboratory for SFA2000. A 30 t primary bulk sample yields 36 kg of tails sample, with 6x 2 kg (12 kg) samples assayed. Reconciliation of mill gold yield and tails assays showed a recovery of >60% for grades >5 g/t Au and up to 85% for grades >15 g/t Au.

Bulk Sampling of 2 Level Veta Christina Reef

Bulk sampling was undertaken along the VC2 #3 shoot drive. Sixty-five metres of 2.5 m by 2.8 m was driven along the reef, which varied in width from 1 m to 1.5 m. Based on bulk sample grade and geological features, the ore shoot zone was represented by 43 m of strike, comprising 24 bulk samples. Each round was blasted and mucked carefully to ensure collection of all broken material (reduction of DE and EE). All bulk samples were processed through the pilot plant. All faces were channel sampled and mapped. Table 6 shows a comparison of sample types along the VC2 drive.

The bulk and channel samples grades were back-calculated to a 1.5 m mining width. The lowest variability is displayed by the bulk samples, with an RSV of 73% and nugget effect of 48%. In contrast, the smaller channel samples show a high RSV of 306% and an extreme nugget effect. The grab samples were diluted with material outside of the minimum mining width, showing a high RSV and mean grade, despite the dilution. The challenges of fines bias during grab sample collection (e.g. high DE and EE together with GSE) are well-known.[2,3]

Table 6. Comparison of samples along the VC2 #3 shoot drive.

Sample Type	Bulk	Grab	Channel
Sample mass/Total mass	30 t 835 t	5× 5kg (25 kg) 1 t	13.5 kg/m 472 kg
No. of samples	24	120	24
[1] Mean grade (g/t Au)	27.3	38.4	14.7
Min. grade (g/t Au)	8.9	1.54	0.01
Max. grade (g/t Au)	69.6	452.3	225.5
RSV	73%	297%	306%
Nugget effect	48%	ND	90%
Difference with respect to bulk sample grade	-	+28%	−46%

[1] Grades back-calculated to minimum mining width. ND: not determined.

As bulk sampling progressed, it was possible to undertake duplicate pair analysis. The results display a total sampling error of 44%, comprising a sampling component of 40% and analytical component of 18% (Table 7). These values indicate the validity of the bulk sampling approach, where a sampling component of 44% can be considered acceptable given the strongly clustered nature of the gold.

Table 7. Bulk sample duplicate pair analysis.

Sample Type/Error (Preparation Route)	Sampling (%)	Preparation (%)	Analytical (%)	Total (%)
	Individual rounds	**-**	**−500 µm split**	**-**
Bulk samples	40	-	18	44
Number of pairs	128	-	65	-

Head Split Bulk Sample Grade Determination

Given the reliance on full bulk sample processing, an alternate way of determining bulk sample grade was sought. A sub-sampling option was devised which ran the 15–30 t bulk sample through the primary and secondary crushers to achieve a P_{90} −4 mm product. A linear splitter was installed after the secondary crusher to take a 2.25 kg sample every 2.5 min. Multiple increments were considered the best option to increase the probability of gold being encountered in the split. For a 30 t bulk sample, an approx. 200 kg sub-sample was collected. This was then processed via a laboratory-based process unit, where a preliminary recovered grade was declared in approx. 6 hours from arrival at the plant. A 10 kg tails sample was collected manually from the Knelson concentrator underflow.

For the first 30 bulk samples, two head-splits were taken, and the remainder of each bulk sample processed in its entirety. The head grade of the 30 bulk samples (approx. 900 t) was 20.6 g/t Au and the grades of the two sets of head-splits were 19.2 g/t Au and 22.3 g/t Au respectively. These lie within ±10% of the full bulk sample grade, which is an acceptable result.

Duplicate pair analysis of the head split bulk sample protocol yielded a total error of 57%, with relative components of 50%, 21% and 19% (Table 8). These values indicate that the protocol worked well, where clusters were broken down during crushing and multiple increments reduced periodic variability. The company opted not use this option routinely, as they wished to recover gold from the pilot plant for sale. The head split capability is available as required, including for batching material from other projects.

Table 8. Bulk sample head-split duplicate pair analysis.

Sample Type/Error (Preparation Route)	Sampling (%)	Preparation (%)	Analytical (%)	Total (%)
	Rounds	−4 mm split	−500 μm split	-
Bulk samples	50	21	19	57
Number of pairs	30	30	30	-

Pairs cover range of mineralisation grades from low to high.

Quality Assurance/Quality Control

QC for core and channel samples included the use of certified reference materials (CRM), blanks, pulp quality checks, umpire assays and duplicates.[20] CRMs were inserted at a rate of 1 in 20, and blanks inserted at a rate of 1 in 20 and after visible gold occurrences. Duplicates were collected at a rate of 1 in 20, though this varied depending upon the testwork being undertaken. Pulps were checked for quality at a rate of 1 in 20. Umpire pulp splits were taken at a rate of 1 in 30 and submitted to a second external laboratory. All samples (e.g. core, channel and grab) collected underground were removed to the on-site logging and sample preparation facility.

QC for the bulk sample circuit included blanks (2 t) at 1 in 15 and barren flushes (2 t) between all samples, which were assayed at a rate of 1 in 5. All concentrate and tails assays related to bulk sampling have the same QC as other samples. Samples going to the external laboratory were secured into boxes and transported by road in locked containers. QA documentation of activities included sample collection, security and transport, through to preparation and assaying. All QC results for the programme were in compliance.

FSE Analysis of Sample Protocols

An analysis for FSE was undertaken for each protocol applied at San Christina (Table 9). The highest error related to grab samples and the collection of 25 kg from a 30 t pile. The method was discontinued. The channel samples also displayed a high FSE relating to the splitting of the sample post-crushing.

Table 9. Protocols and FSE for resource evaluation and mine development stages at San Christina. FSE calculations based on the 2019 BCOG (6.5 g/t Au) and run of mine grade scenarios (Table 2). The current BCOG is 5.5 g/t Au, thus the FSE values that are not zero are likely to be slightly higher than noted below. All FSE calculations are based on f = 0.30; g = 0.25 and alpha = 1.5.

Stage	Type	Protocol	[1] FSE	Comment
Resource evaluation	Core (half core)	Half NQ core (1.9–2.4 kg) crush to P_{90} −3 mm Pulverise to P_{95} −75 µm and riffle split in half for 2x SFA1200	±0% ±0%	No FSE as entire sample prepared and assayed
Resource evaluation	Core (whole core)	Whole NQ core (2.8−4.8 kg) crush to P_{90} −3 mm Pulverise to P_{95} −75 µm and riffle split in half for 2x LW2500	±0% ±0%	No FSE as entire sample prepared and assayed
Mine development	Face channel	5.4−6.7 kg crush to P_{90} −3 mm, then RSD split off one third Pulverise to P_{95} −75 µm and RSD split into thirds for 2−3× SFA1000	±49% ±34%	Large FSE at post-crusher split
Mine development	Bulk (full sample pilot plant)	15−30 t crushed, pulverised and fed through gravity concentrator 36 kg of tails incrementally linear split at P_{90} −500 µm 6 kg RSD split and pulverised to P_{90} −100 µm for 6× SFA2000	±5% ±5%	Entire sample processed through plant FSE relates to tails sample splitting
Mine development	Bulk (head coarse split)	15–30 t primary and secondary crushed 200 kg incrementally linear split from the 30 t bulk sample at P_{85} −4 mm 200 kg crushed, pulverised and fed through gravity concentrator 10 kg of tails incrementally collected at P_{90} −500 µm 10 kg RSD split and pulverised to P_{95} −75 µm, 2× 1 kg sub-samples taken for SFA1000	±15% ±25%	Most FSE relates to the primary split Recoverable gold grade determined from gravity concentrate FSE relates to tails sample splitting
Mine development	Grab	5 kg crush to P_{90} −3 mm, then RSD split 2.5 kg Pulverise to P_{95} −75 µm and riffle split in half for 2x SFA1250	±305% ±205%	Sample collected at 5× 5 kg of sub-8 cm material Large FSE on collection of 25 kg from 30 t lot FSE given for entire process

Reconciliation between Grade Control Sampling and Production

As part of the original evaluation phase, a trial mine shrinkage stope was extracted on the VC between levels 1 and 2. This yielded 2,692 t at a head grade of 26.7 g/t Au compared to an estimated 23.6 g/t Au via bulk sampling (Table 10).

Table 10. Comparison between diamond drill, channel samples and bulk sample estimates for the VC trial (1-2 level) stope panel with the plant head grade. All estimated grades account for intentional and unintentional dilution.

Sample Type	No. Samples	Total Assayed/Processed	Estimated Stope Grade (g/t Au)	Difference with Reconciled Grade
Diamond drill	5	39 kg	6.1	−77%
Face channel samples	44	891 kg	10.0	−63%
Bulk sample (full)	44	792 t	23.6	−12%
Reconciled head	-	2692 t	26.7	-

The bulk sample grade understated the plant head grade by 12%. Other estimates based on diamond core and face channel samples understated the plant head grade by >49% (Table 11). Production (including development and trial mining) yielded 75,840 t at 23.2 g/t Au against a bulk sample predicted grade of 17 g/t Au (Table 11). During this period, the bulk samples were more limited in number and distribution, often restricted to 2−6 per level totalling 65−200 t. The bulk samples still provided a better estimate of grade than drilling, though they under-called mined grade by 27%.

Table 11. Reconciliation between reconciled plant head grade and diamond drill core and bulk sample estimates for the 2005–2012 period. All estimated grades account for intentional and unintentional dilution.

Year	Tonnes Processed (t)	Reconciled Head Grade (g/t Au)	Predicted grade (g/t Au)	
			Drilling	[1] Bulk
2005–2006	6,460	19.6	4.0	15.1
2007	9,510	24.5	6.8	16.5
2008	10,740	19.2	4.5	14.9
2009	12,630	26.7	14.3	17.9
2010	12,980	23.6	9.2	17.7
2011	11,950	28.1	-	21.6
2012	11,570	18.3	-	13.9
Total	75,840	23.2	8.4	17.0
Difference to reconciled grade	-	-	−64%	−27%

[1] From Q2 2011 all bulk sample grades as head split samples.

Sample Application and Resource Estimation

Sampling Strategy

The most effective sample type were the bulk samples, given that they provide an estimate that is closer to that mined. Allowing for development drive width (2.5 m), the effective mineralised bulk sample mass is 18 t based on a minimum mining width of 1.5 m, a drive height of 2.5 m and advance of 1.8 m. They are generally large enough to overcome the high geological nugget effect driven by the gold particle clustering. All small sample types (e.g. drill core and channel samples) have a low probability of intersecting clusters.

For the 2018 programme, resources defined by consecutive development bulk samples were reported as Indicated Mineral Resources (6 month ±15–25%) and those solely by diamond core drilling as Inferred Mineral Resources (globally expected to be ±50%).[28]

Resource Estimation based on Diamond Drilling

Diamond core drilling provides a method to evaluate reef location, geometry and internal characteristics. The 2018 resource estimate was based on 49 NQ holes, drilled on a 10–15 m by 10–15 m grid and whole core sampled (sampled separately as both halves). The programme yielded 106 reef whole-core composites with a total mass of 400 kg, where 14 holes contained visible gold and graded >15 g/t Au. An ordinary kriged block model yielded a global resource grade of 9.4 g/t Au, based on 5 m by 5 m estimation blocks. It is realised that global grade understates the mineable grade, which could be in the 22 g/t Au to 26 g/t Au range but provides confidence to commit to underground development.

The robust lower grade estimate likely reflects the presence of a finer more disseminated background gold population below 9 g/t Au (Tables 2, 3 and Figure 2). This mineralisation requires a lower sample mass (e.g. 30–35 kg; Table 13), where the number of samples informing a given block estimate will be >30 kg in total mass.

Trial Mining of 4 Level South Veta Christina South

Grade evaluation during 2019 has utilised development bulk sampling and full processing. An initial programme was undertaken on the VC between levels 3 and 4 (#2 shoot) in preparation for mining. A 70 m drive was developed along the reef, which varied in width from 1.25–1.50 m. Based on bulk sample grade and geological features, the ore shoot zone was represented by 55 m of strike, comprising 30 bulk samples. All bulk samples were processed through the pilot plant as a composite lot (e.g. all bulk samples, c. 982 t). All faces were channel sampled and mapped. Table 12 shows a comparison of sample types along the VC4 level drive.

Table 12. Comparison between diamond drill, channel samples and bulk sample estimates for the VC4 #2 shoot bulk samples with the plant head grade. All estimated grades account for intentional and unintentional dilution.

Sample Type	No. Faces/Samples	Total Assayed/Processed	Grade (g/t Au)	Difference with Bulk Sample Reconciled Grade
Face channel samples	31	633 kg	15.6	−36%
Bulk sample	30	982 t	24.5	-
Drill-only block model	-	-	9.4	−62%
Local block model (core and channel samples)	-	-	10.1	−59%

As observed previously (Tables 10 and 11), the block models based on drilling or drilling, and channel samples understate the bulk samples grades. The global bulk sample yielded 625 oz of gold bullion for sale. Between 2 and 4 levels (approx. 60 m vertically), bulk sampling defined an Indicated Mineral Resource of 16,500 t at 25.7 g/t Au to provide a base for mining over 6 months.

Activities Post-2019

Additional Characterisation Work

During 2020 two characterisation programmes were undertaken in 2020 along the VC6 #5 shoot drive. The first undertook a single selectively extracted bulk sample to collect by geological domain, across early (Figure 3; non-sulphide veining) and late (Figure 1; sulphide veining) veining, and barren wallrocks. To facilitate collection, the drive was stopped, and a side drive developed so that the target volume could be extracted across strike, from footwall to hanging wall. The domains were removed carefully with low explosives use to ensure minimal DE and EE. Some cross-contamination was inevitable but was considered less than a few percent based on visual inspection.

The two vein domains were sent to a commercial laboratory for pilot plant test work. The wallrock domain was processed via the mine plant, with head samples taken after the secondary crusher. The results of the study are presented in Table 13.

Table 13. Grade and gold sizing results from the vein domain bulk samples.

Domain	Width (m)	Tonnes (t)	Grade (g/t Au)	d_{maxAu} (μm)	d_{95Au} (μm)	d_{Auclus} (μm)	#Clusters
Early	0.9	12.9	50.4	2,500	2,300	7,500	5-10
Late	0.4	5.5	37.5	1,200	1,100	-	-
Wallrocks	1.2 (HW + FW)	17.7	0.15	-	-	-	-
Total	2.5 (Drive width)	36.1	23.7	2,800	2,100	7,500	-

The data show that the Early domain is of a higher grade and contains coarser gold with clustering, whereas the Late domain contains a lower gold particle sizing with no clusters (Figure 14). A theoretical field sample mass was estimated using Poisson statistics to achieve a given precision (e.g. ±15% at 90% reliability).[25] The results are presented in Table 14, with the highest masses related to the clustering. As with the previous estimate of representative sample mass (Table 3), the clustering is the key driver of a high mass requirement and further validates the bulk processing approach to evaluation.

Table 14. Range of theoretical sample mass values for the vein domains.

Domain	Grade (g/t Au)	d_{95Au} / [d_{Auclus}] (μm)	Sampling constant (K)	Optimum mass
Early phase	50.4	2,300	3,000	230 kg
		7,500	17,400	8 t
Late phase	37.5	1,200	1,500	45 kg
Combined (Diluted drive round)	23.7	2,100	5,500	365 kg
		7,500	37,000	16 t

The second test programme was undertaken to determine the gold grade by size fraction of a blasted development round. An expected high grade round was selected, screened on site to seven size fractions, which were shipped to a commercial laboratory for pilot plant test work. The results of the granulometric study are presented in Table 15. The bulk sample head grade was 36.3 g/t Au. The sub-15 mm fraction represents 31% of tonnes and contains 39% of the gold. The >15 mm fraction represents 69% of the tonnes and contains 61% of the gold (Table 15).

Table 15. Granulometric analysis of a bulk sample of blasted VC ore.

Size fraction	Fraction mass (t)	Fraction grade (g/t Au)	Mass fraction (%)	Contained gold (%)
−3 mm	3.3	55.6	9	14
3 to 6 mm	2.7	44.9	8	10
6 to 15 mm	5.3	38.7	15	16
15 to 25 mm	3.9	36.5	11	11
25 to 50 mm	6.6	46.9	18	24
50 to 100 mm	9.3	28.4	26	20
>100 mm	4.7	15.6	13	6
Total	35.8	36.3	-	-

The nominal fine fraction (−15 mm) shows high grades, but not substantively different from the coarser material, particularly >25 mm. In many cases the fines fractions are enriched relatively to the coarser material with the risk of gold loss on drive and stope floors.[27] In this case there is some risk of gold loss on drive floors. What is more interesting is that the higher grades in the >25 mm material may represent gold clusters. Clustering was verified by inspection of the larger (>50 mm) size fractions after screening.

Production

Since commencement of mining in May 2019, production has increased to 41,000 t per annum to produce over 27,000 oz Au recovered (Table 16). Over the next 12 months the operation will ramp up to 50,000 t per annum targeting 33,000 oz Au recovered. Mining continues via shrinkage stoping, with long hole stoping under trial.

Table 16. Production figures for the period 2019-2022.

Year	Tonnes mined (t)	Estimated grade (g/t Au)	Actual head grade (g/t Au)	Actual / estimated grade	Recovered ounces Au
2019 (8 months)	18,575	19.9	23.0	+16%	12,776
2020	34,254	20.2	23.7	+17%	24,328
2021	41,782	19.4	21.9	+13%	27,804
2022 (3 months)	10,257	22.2	24.6	+11%	7,650

The process plant was upgraded to 8 t per hour capacity (targeting 60,000 t per annum), and a floatation circuit added to improve recovery to 93–95%. The original gravity-only pilot plant has been retained and can be fed directly from the plant feed conveyor post-crushing circuit. A new laboratory was built 25 km from the mine and is shared with two other operations. The laboratory is capable of undertaking FA30–50 and SFA1000–5000, including all sample preparation.

Historical and current sampling methods are summarised in Table 17. The definition of Inferred Mineral Resources continues to be via diamond core drilling at a 10−20 m grid producing HQ core. All assays are whole core by single or multiple SFA. Indicated Mineral Resources are defined via development bulk sampling.

As the reef is developed, digital mapping indicates the present of the ore shoot. Saw-cut channel samples are collected from faces as and when deemed necessary to assist with orebody knowledge. The channel samples provide a good representation of grade trends within the ore shoot and assist in the location of low grade zones.

Development rounds are stockpiled at the plant until the shoot strike length has been developed. This is generally 50 m to 100 m, producing a mill parcel of between 1,800–3,500 t. The parcels are fed through the process plant and reconciled. Each 1.8 m of "on ore" development round delineates c. 185 t of stope ore and 35 t of development ore, based on a 25 m backs-to-floor separation. A dedicated team provides 24/7 cover for waste and vein development with an annual capability of 1,100 m. Some 55% will be on ore, 15% on low grade vein (waste), and 30% in wallrocks (waste). The "on ore" development yields approximately 12,000 t of ore (processed for evaluation purposes), and 62,000 t of stope ore per annum.

Based on a current (June 2022) BCOG of 5.5 g/t Au, selective mining is practised only to the extent of excluding low grade zones from stope design (e.g. use as pillars). In general <15% of the shoot is left behind because it is below the BCOG.

Table 17. Summary of sample types used at San Christina.

Type	Stage	Period	Comment
Core (half)	Evaluation	2005–2011	Discontinued
Core (whole)	Evaluation	2011–2012 2019	Targeting and preliminary resource estimate Continued in 2019 for Inferred Mineral resource estimation
Channel: hand cut) Saw cut	Evaluation	2005–2006 2019	Discontinued in 2006 Applied in 2019 for comparison. Used as required at present
Grab	Production	2005–2006	Discontinued
Bulk (full)	Evaluation	2005–2012 2019	Replaced by bulk (split) option in 2011 Continued in 2019, currently processed as full drive parcels along the ore shoot
Bulk (head split)	Evaluation	2010–2012 2019	Introduced to speed up development grade determination Can be used if required

The option to split off a plant-feed head sample is applied as and when required (Table 9). If geological observation and mapping during development indicates a likely lower grade zone, then this may be instigated. As the given development rounds are fed to the plant, cuts are taken for assay. This approach provides a local head grade but does not stop the plant operating.

The operation has also instigated a tactical geometallurgical programme to provide prediction of key ore properties to the plant. Beyond grade, the work aims to provide block models of metallurgical recovery (gravity and flotation), ore hardness, density, and various geochemical elements.[30] In addition, a programme of drive floor sampling is being undertaken to review gold loss in broken ore residues. The programme initially involves collecting thirty 250 kg samples from a recently stopped-out drive to achieve a composite mass of c. 7.5 t.[29] Individual 250 kg samples are being reduced to 20 kg and run through a laboratory Knelson concentrator for gold determination. Initial results of a few samples display residues grades of between 11.5–31.4 g/t Au.

Discussion

The San Christina reefs bears coarse gold-dominated mineralisation, where >65% of the gold is present in particles with a size greater than 100 μm for grades above 6 g/t Au. However, gold rarely occurs >2,000 μm in size, the maximum gold particle size observed being 2,500 μm. Traditional sampling methods such as face channel and diamond drill core samples understate the mean gold grade by 65% to 75%. This relates to gold particle clustering for grades nominally >6 g/t Au, where clusters of 0.5 cm to 2 cm of >200 μm gold increase the geological nugget effect. Given that at a run of mine grade tonne of ore may contain 1–5 gold clusters that contain up to 80% of the grade, the probability of intersecting zero clusters is >95% for core and channel samples. These small samples fail to intersect the sparse clusters but will yield extreme value grades if they do. Several sample types have been trialled at the project (Table 17).

Based on a Poisson-based probabilistic method, a representative sample mass up to 85 t (worst case scenario) may be required to achieve a precision of ±15% at 90% reliability.[25] The very large sample mass is driven 1–2 cm gold clusters within run of mine grade mineralisation. If these clusters did not exist, then a run of mine grade sample mass of 150−500 kg may be appropriate.

Given the challenges of small volume samples, a development drive bulk sampling programme was instigated where entire development blasts of approx. 35 t were taken and processed in their entirety through a surface plant. The composited bulk sample grades along the upper and lower drives of stopes provide a reliable estimate of stope grade. The current approach is to batch entire development parcels through the plant. Individual development round bulk samples are not processed individually, unless their grade is required (for example if it is believed to be low grade), then a head sample is collected after the secondary crusher. A risk review of the bulk sampling method used to support Indicated Mineral Resource estimation is provided in Table 18.

Table 18. Risk review of the San Christina bulk sampling programme used for Indicated Mineral Resource definition. During the original 2018 evaluation programme, individual development bulk samples were processed through the pilot plant.

Key Parameter		Comment	[1] Component Error	TOS Error	[2] Error Rating
1	Spatial distribution and number of samples	Samples collected along drives. Vertical drive separation approx. 30 m. Each stope block (~3,500–5,000 t) informed by between 20-55 bulk samples per level	40%	GNE	Low-mod.
2	Sample mass (representativity)	Each development round bulk sample 35 t; total sample mass collected around a stope block ranges between approx. 1,000–2,000 t per level Indicated optimum mass around 35 t to achieve 90% ±15% at ROM for clustered gold. Total lot currently processed through the plant			Low-mod.
3	Collection and handling	Sample extracted by blasting Sample collection by mechanised mucking unit. All samples transported to surface and kept separate prior to crushing and splitting		-	Low
4	Transport and security	Samples delivered directly from the mine to the plant stockpile area		-	Low
5	Preparation	Entire sample crushed and pulverised Plant cleaned and flushed between samples	18%	-	Low
6	Assay	Entire sample passed through gravity circuit Gold concentrates weighed and sent for fire assay to extinction Preparation and analytical error relate to tails sample split and assay		-	Low
7	QAQC	Duplicates and blanks within expectation CRMs within expectation Written protocols for the sampling-assaying process	-	-	Low
8	Validation/variability indicators	Individual bulk sample RSV 65% Individual bulk sample nugget effect 49% Stope grade reconciliation ±20% on a quarterly to annual base Indicated Mineral Resources defined	Total 44%	-	Low
Summary					
Sample representativity (1)–(3)					Mod.
Preparation and assay (4)–(7)					Low
Fit-for-purpose					Yes

Conclusions

This contribution demonstrates that effective sampling is critical for resource evaluation and grade control. Grade control is about adding value by delivering quality tonnes to the mill via the accurate definition of ore and waste. The magnitude of measurement error (e.g. the sum of the sampling, preparation and analytical relative errors) during grade control is a critical consideration, as it can undermine the quality of resource/reserve estimates and any decisions made thereon.

The case study presents an analysis which commences with evaluation of ore characteristics (e.g. d_{95Au}), duplicate sample pairs (e.g. relative error determination), sampling protocols in the context of TOS, and programme performance via reconciliation. A table-based method is presented to evaluate the fit-for-purpose nature of the programmes (Table 19).

Table 19. Stages in the design of a new grade control programme and for the review of an existing programme. Detail may differ depending upon circumstances (after Dominy et al.).[1]

Stage	New programme
1: Overview	Set programme goals and data quality objectives
2: Characterise	Review existing characterisation data and determine grade-liberation diameter relationships and critical optimisation grade Plan and undertake addition testwork if required
3: Design or review	Apply Stage (2) data to design protocols, including TOS-FSE analysis Undertake duplicate pair analysis (if possible)
4: Implement	Set-up systems and written codes of practice Training of mine geology and production staff
5: Monitor	On-going QAQC programme with timely review and action as required Annual internal and/or external peer review Review resource/reserve reconciliation Risk analysis
6: Update	On-going training Revision of protocols if required, return to Stage 2 or 3 as required

Case specific conclusions are:

- At San Christina, small-sample based assays understate grade in geometrically simple, coarse gold-dominated veins. Drilling with whole core sampling and assaying is applied to estimate Inferred Mineral Resources that are accepted to understate grade by 50−65% - a compromise. The under-called blocks are only reported above the BCOG with the knowledge, based on experience, that they will provide a higher grade during mining. Those blocks less than the BCOG, generally do reflect low grade mineralisation.
- Dominant gold particle clustering drives the application of bulk sampling. Development drives are batch sampled and processed via an on-site plant. Upper and lower development drive grades are assigned to stope blocks and reported in the Indicated Mineral Resource category.
- The mine operator is a privately owned entity. Given that the company is not required to publicly report its resources, the extensive sampling regime may appear to be excessive. However, the group has several international investors, and the owners may ultimately opt to list the company. Importantly, they understand that quality data underpins quality decisions and require all its technical activities to be carried out to optimum practice. Their investment has been validated by the success of the operation since 2019.
- The need for a strong and integrated technical team cannot be over-stated.

General conclusions include:

- A range of sampling methods are available for underground mine resource development and grade control, all of which require evaluation before routine application. The highest error is generally introduced during sample collection. A reduction in the need for chip or channel samples will only come from the use of more pre-development drilling at a spacing to allow local estimation.
- Application of TOS enables sampling programme design and practice to be optimised. All errors along the sampling value chain are additive and impart variability making local estimation less reliable. Estimation must consider the sampling strategy, with sample quality reflected in the resource classification.
- A truly representative sample probably does not exist, since extensive and often heterogeneous geological entities are being evaluated. Characterisation studies undertaken to support sampling programme design are unlikely to represent the mineralisation in question, though will generally provide better outputs that so-called heterogeneity studies. However, a best as practical characterisation programme is better than no characterisation. Samples must be collected within the framework of TOS. Technical teams should consider bulk sample and piloting programmes to evaluate grade and metallurgy as part of pre-feasibility or feasibility studies. This is particularly relevant where strong variability relates to mineralogical and/or textural complexities that impact on recovery.
- For high grade operations (nominally >15 g/t Au ROM), imposition of a BCOG may be unnecessary where ROM grades are >>BCOG.

- Characterisation samples should be undertaken early in the mine value chain to assess ore properties. Sampling, testwork and assaying programmes should be designed to support Mineral Resources and Ore Reserves that will be reported in accordance with the 2012 JORC Code (or other international reporting code). To ensure fit-for-purpose data, rigorous QAQC must be developed to support sampling and testwork. QAQC cannot be divorced from the TOS and is a mandatory step for fit-for-purpose assay results.
- There is a need for the quantification of sampling and analytical errors to better communicate uncertainty and risk. A first step is the application of the protocol pro forma and RSV metric presented in DS3077.[31] Resolution of component relative errors across sampling, preparation and analysis can be gained from duplicate sample pairs. A simple tabular tool is presented to communicate key sampling programme risks.

Acknowledgments

The authors acknowledge the mine owner/operator OCX Gold Group. This case study was compiled within a confidentiality agreement. Input of the San Christina operating company and technical team under the leadership of Peter Mendes is acknowledged. Dr Jon Davies is thanked for various iterations of the San Christina resource, reserve and grade control models. Professor Kim Esbensen is thanked for comments on the manuscript, and Dr Anne Cole for assistance with formatting.

Abbreviations

The following abbreviations are used in this manuscript:

AE	Analytical error
BCOG	Breakeven cut-off grade
CRM	Certified reference material
DE	Delimitation error
d_{95Au}/d_{Auclus}	Liberation diameter for sampling purposes, individual particle vs. clustered value
EE	Extraction error
FA	Fire assay (assay charge size 30 g; FA30)
FSE	Fundamental sampling error
LW	LeachWELL assay method
P_{90} or P_{95}	Percent passing (e.g., P_{90}; 90% passing a given screen size)
PE	Preparation error
ROM	Run of mine grade
RSD	Rotary sample divider
RSV	Relative sampling variability
SFA	Screen fire assay (assay charge size 500 g; SFA500)
TOS	Theory of Sampling
QAQC	Quality assurance/quality control

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