Underground grade control protocol design: case study from the Liphichi gold project, Larecaja, Bolivia

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Grade control programmes aim to deliver economic tonnes to the mill via accurate definition of ore and waste. The foundation of successful grade control is high quality sampling supported by geology and a suitable data management and modelling system. For underground operations sampling methods include chip, channel and panel samples, grab/muck pile samples, and drill-based samples. Grade control strategy is related to mining method and orebody type. Protocols must be designed to suit the style of mineralisation in question. Holistic studies focusing on ore mineralogy and gold particle deportment, size and distribution are required for sample collection and preparation protocol optimisation through 'Theory of Sampling' application. Where possible, characterisation programmes should be undertaken early in the life of a project. Appropriate assaying procedures are also required. Programme implementation will require suitably skilled individuals to train and mentor staff. On-going quality assurance/quality control monitoring and review will allow protocols and staff to be updated as required. A case study of protocol design from the Liphichi gold-antimony project in Bolivia is presented.

Keywords: Gold, Veins, Grade control, Sampling methods, Theory of Sampling, Ore characterisation, Bolivia

List of abbreviations

ACE	accelerated cyanide extraction
AE	analytical error
DE	delimitation error
DSA	duplicate series analysis
EE	extraction error
ESD	equivalent spherical diameter
FA	fire assay
FSE	fundamental sampling error
GRG	gravity recoverable gold
GSE	grouping and segregation error
HARD	half absolute relative difference
HT	heterogeneity test
PAL	pulverise and leach
PE	preparation error
P80/P90	80 or 90 per cent passing a given sieve size
QAQC	quality assurance/quality control
ROM	run of mine
SFA	screen fire assay
TOS	Theory of Sampling

Introduction

In any mining operation, ore and waste must be defined effectively to ensure an economic mill feed. Grade control is thus essential for efficient and economic mine operation, with key performance indicators including definition of ore and waste, minimal dilution and optimal recovery. The process of grade control comprises data collection, data integration and interpretation, local resource/reserve estimation, input into final stope design, supervision of development and mining, and stockpile management leading ultimately to reconciliation.

The requirement for quality samples and cost-effective sampling protocols during exploration and mine production has long been recognised (Sketchley, 1998; Vallée, 1992, 1998; Pitard, 2005; Dominy, 2007; Dominy, 2010a, 2010b; Minnitt, 2007, 2010). The consequences of poor sample quality include erroneous resource/reserve estimates, ore and waste misclassification, lost opportunities and lower profitability (Carrasco *et al.*, 2004; Minnitt, 2007).

This paper provides guidelines for the design of grade control protocols for new and developing underground gold operations, including the choice of appropriate sampling method with respect to mining method and orebody, and ore characterisation for sampling protocol

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Table 1 Underground grade control sampling types and methods

Sample type	Sampling method
Linear	Chip-channel Chip-panel Channel
Broken rock	Grab
Drill hole	Diamond core Blast hole/sludge

design. A case study from the Liphichi Project is presented.

Grade control considerations

Introduction

Underground grade control practices have evolved from the use of paper-based methods, through to three-dimensional (3D) modelling and geostatistical simulation. The foundation of all programmes is that of geological understanding led by sampling and geological mapping (Rickard, 1907; McKinstry, 1948; Peters, 1987; Dominy *et al.*, 2009).

Sampling for grade control

Grade control samples should be reproducible, unbiased, taken in a safe manner and operationally timely. A good grade control sampling strategy should provide quality information on gold grade and its relationship to geology. Common grade control sampling methods are discussed in Dominy (2010a, 2010b; see Tables 1 and 2).

Geological mapping

Geological mapping has a positive impact on grade control and supports mine development. It is particularly applicable where orebody geology and geometry are variable and mine openings need to be planned accordingly. The primary objective is to identify and locate the ore zone or at least the section likely to contain the ore with respect to the minimum stoping width. The secondary objective is to determine the attitude and position of relevant structures that control the 3D form of ore shoots or gold carriers (Dominy *et al.*, 2009, 2012).

Mining method and grade control

Grade control strategy is related to mining method, which can be either an entry or non-entry type (Tables 3 and 4). Stopes provide 3D exposure, with entry methods

Table 3 Application of different sampling methods to activity in the mine production chain. Refer also to Table 4 which integrates sampling method to different stoping methods

Activity in the mining chain	Sampling method
Development/pre-production	Linear Grab Diamond core Blast hole/sludge
In-stope	Linear Grab Blast hole/sludge
Post-stoping	Grab

such as shrinkage and cut-and-fill stopes offering opportunities for on-going mapping and sampling. These are well-suited to complex, narrow (<3 m) systems that require strong geological control, and some selectivity and flexibility. Non-entry methods such as longhole open stoping can only be reliably mapped and sampled in development drives, sub-levels and slot rises. These methods are suited to simple, planar but thicker (>3 m) structures where geological control is less critical and bulk extraction of the vein is appropriate. Longhole stoping has minimal in-stope flexibility if the structure proves more complex than expected.

Sample spacing and size

Grade control sample spacing is usually controlled by needs of the orebody and practicality. A small coarse-gold, high-nugget operation will usually require close spaced samples at 1 to 2 m to resolve small-scale variability, though in bigger, less variable systems face samples at a greater separation will likely suffice. Cross-cuts through a wide orebody will require a continuous sample in 1 to 2 m lengths. The separation distance between cross-cuts along strike will tend to be a mining decision, but should be responsive to geological requirements as well. Where enough sample data are available, the construction of semi-variograms will assist in determining optimum sample spacing.

It is important to understand that sample size (mass) is related to the frequency and size of gold particles (Dominy *et al.*, 2008b). When the frequency within a mineralised zone and within an individual sample is high, then sampling problems are not usually significant. When gold particles become rare, which could be

Table 2 Positives and negatives of sample types available for underground gold mine grade control (for error definitions refer to Table 5) after Dominy (2010a, 2010b)

Sample type	Positives	Negatives
Chip (chip-channel)	Moderately easy to collect and fast Reasonable number can be collected Relatively cheap	High EE and DE Generally poor quality
Chip (chip-panel)	Easy to collect and fast High number can be collected Relatively cheap	Very high EE and DE Generally very poor quality
Channel	Requires substantial effort Moderate number can be collected	Moderate EE and DE Moderate quality Time consuming
Channel (saw cut)	Moderate number can be collected High quality (low EE and DE)	Relatively costly Requires diamond saw
Grab	Easy to collect Moderate to high number can be collected Moderately cheap	Very high FSE, GSE, EE and DE Poor–very poor quality Manual handling issues

Table 4 Sample type for different stoping methods during the mine production chain

Stoping method	Stoping type	Development and pre-production stage	Production (stoping) stage	Post-production (bogging and transport) stage
Shrinkage	Entry	Linear Grab Drill hole	Linear Grab Drill hole	Grab
Cut and fill				
Room and pillar				
Drift and fill				
Longhole (open and sub-level variants)	Non-entry		Grab	
Block and Sub-level caving				

defined as less than 10 to 20 in any sample (based on Poisson statistics – Dominy *et al.*, 2010c), then sampling problems are likely and the primary sample size needs to be larger. Gold particle size and frequency within a deposit and its domains may vary.

Optimising sampling protocols

Overview

Sampling protocols inclusive of sample type, collection, preparation and assay methodologies should be designed to suit the style of mineralisation in question, designing the protocol to fit the mineralisation style is critical though is frequently ignored. As previously stated, the frequency and size of gold particles has a direct impact on the effectiveness of sampling, sample preparation and assay methods employed (Dominy *et al.*, 2008b). Within the coarse- to fine-gold spectrum, the ability to sample a deposit ranges from relatively simple for fine-grained disseminated particles, to more difficult for low-grade coarse gold-dominated ores. Ores with clustered gold particles may yield a pseudo-coarse gold effect with enhanced variability (Dominy and Platten, 2007).

Application of the TOS

The TOS deals with many issues related to sampling, but principally defines a number of errors and how to manage them (Gy, 1979, 1992, 1998, 2004; Pitard, 1993). The principal errors are FSE, GSE, DE, EE, PE and AE. A quality sample protocol is one where all sampling errors are minimised. FSE and GSE relate to sample precision and the others are bias generators. The errors and their implications for grade control sampling are summarised in Table 5.

A well-known part of TOS consists of the prediction, estimation and minimisation of the FSE. It provides a prediction for the value of the variance of FSE, based on the heterogeneity of the population from which the sample is taken using the well-known Gy Equation (Gy, 1979, 1992, 2004; Pitard, 1993). Recent work has questioned the validity of the equation (Geelhoed, 2011), but to date there is no practical alternative and most practitioners continue to have faith in the Gy Equation. It must be remembered that this equation is a theoretical application to estimate the variance of FSE, so should be used with care and in context.

The FSE is the smallest residual error that can be achieved even after homogenisation of a sample lot. Effectively it can never be removed. When FSE is not optimised for each sampling and sub-sampling stage, it often becomes a major component of the sampling nugget variance (e.g. nugget effect). FSE may represent up to 50% of the total sampling errors. The FSE is dependent upon sample weight, fragment size and shape, liberation stage of the gold, gold grade, and gold and gangue density. Experience shows that nugget effect is often artificially high because sample weights are not optimised. In addition, a high FSE may result from over-splitting before crushing and pulverising.

The FSE equation addresses key issues of ore sampling both in the mine and plant, key issues are:

Table 5 Sampling error definition and relevance to grade control sampling

Error	Error definition	Implication for grade control
FSE	The FSE results from the constitution (grade) heterogeneity of the whole. Of all sampling errors, the FSE does not cancel out and remains even after a sampling operation is perfect. Experience shows that the nugget effect can be artificially high because sample weights are not optimised (e.g. high FSE)	Relates to the sampling of broken rock. For example, muck piles, trucks or stockpiles. Grab sampling prone to high FSE. An *in situ* FSE exists when a channel sample is cut from a face
GSE	Is the error due to the combination of grouping and segregation of the fragments (distributional effect) in the lot to being sampled. Once a rock volume is broken, there will be segregation of particles	Refers to segregation within a broken rock pile, such as fines at the base of a coarse stockpile or muck pile
DE	The DE results from an incorrect shape of the volume delimiting a sample	A channel sample, for example needs to be properly delimited to provide a uniform volume
EE	The EE results from the incorrect extraction of a sample. Extraction is only correct when all fragments within the delimited volume are taken into the sample	The delineated volume of a channel sample, for example should be fully recovered
PE	Refers to issues during sample transport, preparation (contamination and losses) and unintentional human error	Emphasises the need for rigorous sample bagging, tagging and handling after collection (e.g. effective chain of custody)
AE	Relates to all errors during the assay and analytical process	Not directly related to the grade control process, but can have a profound effect on final assay grades. Includes laboratory human error, poor analytical machine calibration, machine drift

- what weight of sample should be taken from a larger mass of ore, so that the FSE will not exceed a specified variance
- what is the possible FSE when a sample of a given weight is obtained from a larger lot
- before a sample of given weight is drawn from a larger lot, what is the degree of crushing or grinding required to lower error to a specified FSE.

The FSE is a loss function during sampling (Pitard, 1993). The higher the FSE, the greater the likely financial loss. For any process where the FSE escalates, there is an associated loss due to uncertainty.

A number of difficulties have been encountered in the practical application of the FSE equation to gold deposits (François-Bongarçon, 1993, 1998; François-Bongarçon and Gy, 2002; Dominy, 2007; Minnitt and Assibey-Bonsu, 2009; Dominy *et al.*, 2010a). These include:

- ease with which inconsistency in equation parameter units can yield erroneous results
- difficulty in understanding the nature and meaning of the various parameters and how to adequately set/model their values
- difficulty in designing and performing the calibration and characterisation experiments required to customise the key parameters.

A key technical issue with the use of the FSE equation is the numerical value of the power in the liberation factor. Gy (1979) proposed the value of 0·5 as a *general case only* for all minerals. This value gives reasonable results for various types of ore and at different grades; however, it often gives unrealistic values when applied to low-grade ores such as gold. François-Bongarçon and Gy (2002) quote an example where an optimum sample mass of 13·9 t of blast-hole cuttings was required for a fine-grained gold ore, clearly an unrealistically large sample.

Appropriate application of the FSE equation lies in estimating the theoretical FSE made at successive mass reduction stages. They may not be correct in absolute terms, but are to some extent comparable and selection stages introducing large errors can be improved and redundant stages (i.e. those with minor errors) can be eliminated.

We assert that proper ore characterisation is critical to the application of the FSE equation and of the wider TOS to ensure reality and practicability come together (Dominy and Platten, 2007; Dominy *et al.*, 2010c; Dominy *et al.*, 2008a, 2008b; Dominy *et al.*, 2011b). There are instances where impractical protocols are required to achieve correct sampling particularly in the presence of coarse gold (Dominy *et al.*, 2000; Dominy and Petersen, 2005; Johansen and Dominy, 2005; Cintra *et al.*, 2007).

Further discourse of the TOS and FSE equation is given in Gy (1979, 1992, 1998), François-Bongarçon (1993), Pitard (1993, 2005), Frempong (1999), Minnitt (2007) and Dominy *et al.* (2010a).

Defining the liberation diameter

The part of the FSE equation that reflects the nature and heterogeneity of the ore type in question is the sampling constant (K). It is dependent on the microscopic geostatistical properties of the minerals, and varies with gold grade and liberation size. As liberation size reduces, so the value of K reduces; conversely, as grade reduces, K gets larger. Large K values are related to samples with a greater liberation size and low grade.

A key problem of defining K and applying the FSE equation is the determination of the liberation diameter (d_L: Gy, 1979; Pitard, 1993; François-Bongarçon and Gy, 2002; Dominy, 2007; Minnitt and Assibey-Bonsu, 2009; Dominy *et al.*, 2010a). Using the original definition of d_L (Gy, 1979), very low sampling constant values are generally defined for gold ores. Thus for gold deposits, the d_L value should be re-defined as d_{Lmax} to represent the coarse most influential fraction. This is effectively the screen size that retains 5% of gold given a theoretical amount of liberated gold.

Approaches to d_{Lmax} characterisation range from guesswork to the implementation of HT or DSA. The results of both HT and DSA can be used to calibrate the FSE equation, effectively defining d_L through estimating K (Gy, 1979; François-Bongarçon, 1993; Pitard, 1993; Minnitt *et al.*, 2007; Minnitt and Assibey-Bonsu, 2009).

The HT is most commonly applied calibration method in the mining industry. The DSA approach is both complex and time consuming to apply, so relatively

Table 6 Typical studies and outcomes from a 'sampling' characterisation programme (after Dominy *et al.*, 2010c). Outcomes from Stages 1 to 3 contribute to metallurgical characterisation. Multiple samples will provide a clearer understanding of all outcomes and potential grade and spatial variability

Stage	Study	Outcomes
1	Geology and mineralogy [*in situ* and sample studies – rock and core samples]	• Geological context of sample(s) • Gold deportment and mineralogy (free gold versus gold in sulphides) • *In situ* gold particle size range and distribution • Proportion of coarse versus fine gold • Clustering effects
2	Metallurgical testing [bulk samples of >50 kg each] [note does not include comminution studies]	• Sample head grade • GRG • Leach (gold in tailings/potential refractory gold) • Partitioning between free gold and refractory gold • Mineralogy of concentrate and tails
3	Coarse gold determination [same sample as Stage 2 and based on gold liberated during that stage]	• Coarse gold particle size and abundance
4	Data integration	• Gold particle size curve(s) • Liberation diameters and variability • Degree and impact of clustering

rare compared to the HT. The HT is prone to severe precision problems, particularly when coarse gold is present (Dominy, 2007; Dominy *et al.*, 2010a; Dominy and Minnitt, 2012). A further problem is that it provides values for K only at the fragment size at which the calibration exercise is carried out (often 10 mm). In such cases the values for d_L are far too low. In the presence of coarse gold, the HT approach may require samples of hundreds of kilograms in size. The method may not be a standard industry approach, since it is likely only to provide a correct value when mineralisation is disseminated.

As a result of these issues, the authors recommend a staged approach to characterisation (Dominy *et al.*, 2008a, 2008b, 2010c; Table 6). The key outputs will be:

- realisation of gold deportment, in particular the partitioning of gold as free gold, gold in sulphides and refractory gold
- gold particle size curve(s), including effects of clustering and relationship between gold particle size and grade
- definition of key FSE relationship inputs (e.g. liberation diameter versus clustered-liberation diameter) and the sampling constant K
- recommendations as to optimum *in situ* sample mass requirements.

As a result of undertaking a characterisation programme, optimisation of sample collection and preparation protocols within the context of TOS will be possible. Characterisation studies will allow the practitioner to set the sampling expectations of the ore. Where this requires specialist and potentially costly protocols, then it will be possible to determine the level of risk involved in using more practical methods. In essence a gap analysis between the theoretical need and practical reality of sampling can be undertaken. Finally, characterisation will allow benchmarking with other deposits and contributes to wider orebody knowledge (e.g. geometallurgical parameters).

Cost of developing and operating a grade control sampling programme

The investment required to design a sampling programme is variable and dependent upon the orebody type. A full characterisation study is likely to cost between AU$50k and AU$250k per domain, though much of the data can be gained and/or shared with metallurgical programmes. Programmes are required during project evaluation or during production when new orebodies and/or ore zones are encountered.

On-going grade control sampling costs will relate to orebody type and mining method. For a small operation ($\sim$100 kt per annum) an annual cost could be in the region of AU$350k, whereas for a much larger operation ($\sim$1 Mt per annum) more likely around AU$2M per annum. These figures include the cost of sample collection, sample preparation and assaying, staffing and consumables, but do not include diamond drilling cost.

The cost of good grade control sampling is easily justified against the potential loss generated through extra dilution sent to the mill and/or ore/waste misclassification.

Monitoring a grade control sampling programme

The ultimate monitor of grade control programme efficiency is reconciliation. Some practitioners believe that QAQC need not be applied to grade control programmes – this view is flawed, not least that grade control sample data often contribute to publicly reported resource and reserve estimates. The general issues of QAQC programmes are presented in Sketchley (1998), Vallée (1998), Simon and Gosson (2008) and Graindorge (2010).

Measuring and monitoring sampling quality is best achieved by regular duplicate sampling at each sub-sampling stage in the sampling regime. For more complex ores in the presence of coarse gold, duplicate sampling may be carried out as a batch each month or on a day to day basis at a sufficient rate to provide a suitable number of paired data to make a regular and statistically significant estimate of precision. The monitoring programme should test precision at each stage of the protocol, but in a low variability deposit measuring the total precision by duplicate field samples may be appropriate. A case study of the duplicate approach is given in Carswell *et al.* (2009).

Appropriate data analysis techniques should be used and could include HARD, mean absolute pair difference or Thompson–Howarth plots (Thompson and Howarth, 1976). A discussion of different precision metrics is given in Stanley and Lawrie (2007) and Abzalov (2008).

Poor sampling precision can be reduced to an acceptable level by maximising sample and sub-sample size and by minimising the number of sub-sampling steps. An acceptable precision will be dependent upon deposit type and sample protocol.

Consideration of all these factors then leads to a summary of QAQC needs and expectations (Table 7).

Implementation and operation of a grade control programme

The most important issue during the implementation and operation of a grade control programme will be people. Acceptance of the programme value by management will be critical and requires the business case and deliverables to be promoted early on. A programme manager or 'champion' is required to drive development and ensure that all parties are engaged. The overall team must include miners, managers, geologists, engineers and metallurgists.

Programme implementation will be via proper equipping and training of both geological and mining staff supported by documented procedures. Safety issues must pervade training. Suitable database and modelling systems will also need to be in place.

Experienced staff will need to mentor junior and new staff based on documented procedures including:

- sample collection, transport and security
- geological mapping and data recording
- laboratory submission, preparation, assaying and reporting
- mine-based QA and QC
- data handling, checking and validation
- timely use of data to control the mining operation
- feedback and continuous improvement.

Documentation is an important part of the development and implementation process and should include: protocol descriptions and roadmaps, QAQC procedures, face, side wall and back mapping sheets, underground development instruction sheets, sample tags and sample submission sheets.

An overall programme roadmap should be produced to ensure that all practical aspects are undertaken effectively, data integrity maintained and that all information is used and its implications communicated to stakeholders.

Grade control innovation

It might be argued that other than through improved computing capability (e.g. databases, 3D modelling, grade estimation and reconciliation software), there is minimal opportunity for innovation in grade control. To some extent this may be true, however whilst sampling methods are unlikely to be improved upon other than via some kind of mechanisation, opportunities do exist.

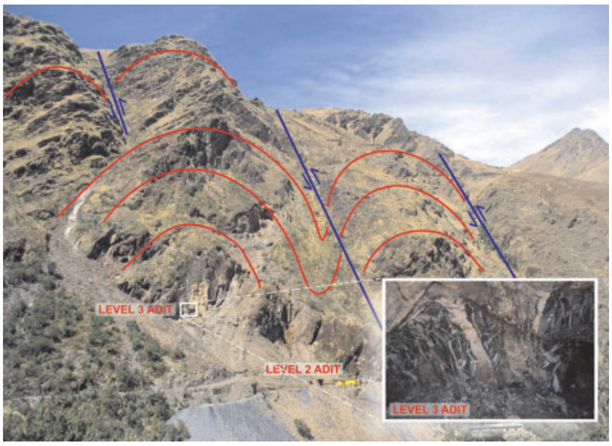
There is scope to be smarter through the better use of geology during the mining process. For example, at the Bendigo Kangaroo Flat mine (Australia) face samples were not taken with preference for a scorecard-based grade calling (proxy) system. This utilised various geological and mineralogical parameters in a fast and simple to use form (Dominy *et al.*, 2009). This approach was chosen as face chip sampling was biased due to the very coarse gold present (Johansen and Dominy, 2005). Other operations have also developed methods to support sampling based on the better use of geology (Dominy *et al.*, 2010b). In some operations, the efficient use of geology during grade control can be considered innovative.

Face or backs mapping can be made more efficient through the use of field tablet computers where mapping is directly onto the tablet. This results in an immediate digital format that can be easily ported to other software for editing and visualisation. Direct face mapping is possible via the Sirovision® stereo camera rig which uses two digital cameras to capture an image (Van Der Merwe, 2009). The geologist can draw lines on the image to represent geological features, which can then be ported to suitable mining software fully registered in 3D

Table 7 QAQC programme and expectations for an underground gold mine grade control programme. Note that this programme is generally applicable to all stages of gold project development

			Expectation	
QAQC action	Rate	Instigator	Fine-gold dominated deposit	Coarse gold-dominated deposit
Field duplicates*	1 in 20	Mine	90% ± 10–25% HARD	90% ± 25–50% HARD
Coarse reject duplicates†	1 in 20	Laboratory	90% ± 10–20% HARD	90% ± 15–50% HARD
Pulp duplicates‡	1 in 20	Laboratory	90% ± 10% HARD	90% ± 10–25% HARD
Standards§	1 in 20	Mine	2δ–3δ ('warning') re-assay 25% of batch $>3\delta$ ('action') re-assay 100% of batch	
Blanks¶	1 in 20	Mine	Less than three times detection limit (generally <0·15 g/t Au)	
Pulp quality**	1 in 20	Laboratory	Sample to P90 −75 μm	
Contamination††	1 in 20–50	Laboratory	0% gold loss	<1% gold loss
Umpire‡‡	1 in 20	Mine	90% ± 10% HARD	
Laboratory audit	Annually	Mine	Ensure that the laboratory is working to agreed practices and performance levels.	

*Applies to any sample type collected. For coarse gold/nuggety ores, very poor precisions are likely unless large samples are collected and appropriate sample preparation and assay routes taken. For diamond drill core, the duplicate is the other half of the core. In many cases, a quarter core will be taken as the 'duplicate'. Operators might consider cutting core into thirds so that 'duplicates' match. Some mine operators take the entire core as the sample, particularly where coarse gold is present.
†Laboratory crusher reject split.
‡Dependent upon nature of ore and assay method. For a coarse gold assayed via SFA, a good precision would be expected for undersize fraction. For ACE-LeachWELL, pulp duplicate may not be possible if all sample used. For PAL technique no pulp duplicate available, only duplicate available from coarse rejects.
§Recommendation to have around four to five standards at grades ranging from low-grade, through to cut-off, ROM and high-grades. Note that by their very need to be homogeneous, standards do not bear coarse gold but they can be matrix matched by being quartz-dominated and sulphide-bearing. Note that the laboratory will also insert standards. Standards used for SFA process will just be FA. Where ACE used, mass of standard used usually less than that of actual sample, due to cost unless a bulk standard has been properly defined for that mine. A 500g standard for ACE is generally fit for purpose.
¶Blanks provide a measure of contamination. They can be specifically inserted after expected high grade samples. Laboratory will also place blanks into the sample stream. In very high-grade coarse-gold dominated samples, contamination may be high and require specialised protocols.
**Test involves screening of the pulp to ensure 90% passing or better. All samples should pass or the entire batch should be reground. Maybe highly problematic in the presence of coarse gold, where loss and/or contamination are a risk.
††Assaying of the pulveriser cleaning agent (e.g. sand), and could also include crusher cleaner (e.g. barren rock). For fine gold ores, a rate of 1 in 50 is appropriate increasing to 1 in 20 for coarse gold ores. Careful management of coarse gold ores is required. It is suggested that laboratories include a 'wash' after visibly high-grade (e.g. visible gold-bearing) samples. However, if the ore bears notable coarse gold, then cleaning is best after *each* sample given that even low grade samples can bear coarse gold particles.
‡‡Monthly submission of samples (typically pulps), including standards and duplicates is sufficient to provide a check of primary laboratory results. This is especially important where an on-site laboratory is being used as it provides independent confirmation of the results. Where SFA, ACE or PAL used, there may be no pulp residues to submit. In this case, coarse rejects can be used. Umpire samples (e.g. pulps or coarse duplicates) should be returned to the mine and submitted by mine staff to the umpire laboratory. In some cases, the laboratory (mine or off-site) may submit umpire samples as part of their internal QAQC.



1 Folded stratigraphy and thrusts at the Liphichi site. The location of the two main mine levels are shown, and the inset shows sheeted veins on the 3 Level

mine space. Other innovations could include portable X-ray fluorescence spectroscopy units capable of *in situ* gold assay of mine faces and the application of down-hole radar to resolve mineralisation in wall rocks (Kemp and Morgan, 2012).

Operational safety issues

Working underground is an intrinsically dangerous activity. Grade control is no less onerous given that geologists will be in active headings, raises and stopes and around operating machinery. Mines will have local approved codes of practice which will include guidelines for where and how to undertake sampling. Geologists must ensure that they carry all required personal protective equipment, proper sampling equipment and they should not work alone. In addition, there are issues of manual handling of samples, working at height when sampling backs and raises, and working close to heavy machinery. Workplace hazard and risk assessments of specific activities are recommended.

One of the greatest risks for the geologist is working beneath unsupported ground. In many operations, access to the face is not permitted and leads to the application of grab sampling during development. This tends to occur in the larger mines. Awareness of the risk and proper training in barring-down is critical. High risk also faces the geologist when sampling within raises. Again awareness and proper training is required.

Liphichi gold–antimony–silver project, Bolivia

Overview

The Liphichi property is located in the Andes of Western Bolivia, 110 km to the northwest of La Paz.

Table 8 Mineral Resource for the Liphichi gold project reported in accordance with the JORC code at a cut-off of 1·5 g/t Au (Republic, 2006). The entire resource was classified in the Inferred Mineral Resource category

Commodity	Tonnage (Mt)	Grade
Gold	4·2	2·4 g/t Au
Antimony		1·2% Sb
Silver		17 g/t Ag

It comprises four concessions within the Larecaja Province, covering some 53 km^2 and includes the Liphichi, Progresiva and Maria Luisa deposits. Liphichi is located in a NW–SE trending, steeply-dipping deformation zone that is traceable for some 14 km along strike (the Liphichi-Luisa Belt). This zone locally hosts a 50 to 70 m thick zone of quartz veining. The country rocks comprise argillites and black shales crosscut by granitic intrusives. Mineralisation is characterised by quartz-sulphide veins forming individual narrow structures and multiple sets forming stockworks and sheeted vein systems.

From 2004 to 2007, the area was explored by the former Canadian listed entity, Luzon Minerals Limited who undertook surface mapping, diamond drilling, underground development and sampling. From 2004 to 2006, studies were undertaken to design a resource development programme which would include grade control sampling for trial mining (Snowden, 2004, 2005a, 2005b).

From 2006 to 2007, Luzon operated an alliance with Australian listed company, Republic Gold Limited. This resulted in the public release of a Mineral Resource estimate (Republic, 2006). At a 1·5 g/t Au cut-off, the resource contained 325 000 oz gold, 47 000 t antimony and 3 280 000 oz silver classified as an Inferred Mineral Resource in accordance with the 2004 JORC Code (Table 8).

This alliance terminated in mid-2007. At the current time (October 2011), the project is believed to be in private ownership and worked by artisanal miners.

Geology and mineralisation

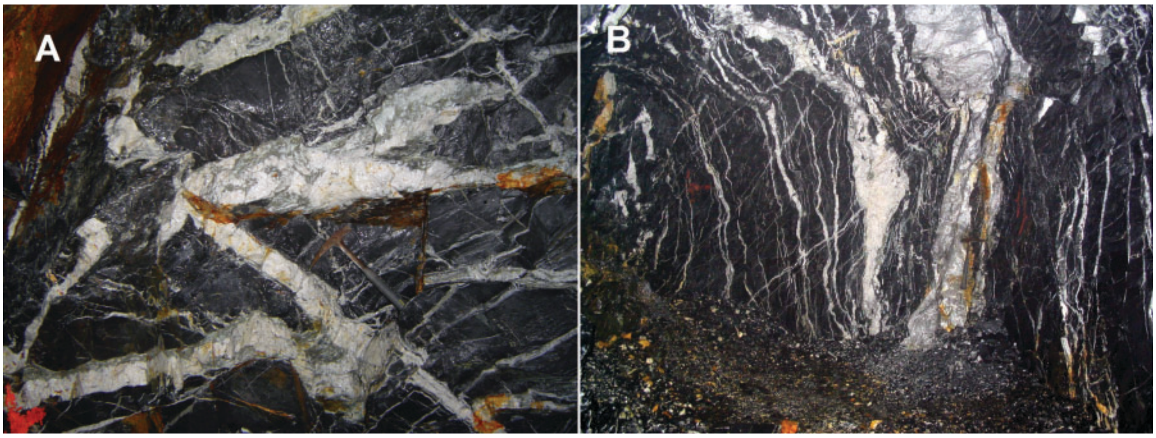
Regional and local geology

North-western Bolivia lies at the convergence of the South American and Nazca Plates, which were responsible for the formation of the Andes. The Central Andes consists of two sub-parallel mountain belts, the Palaeozoic Eastern Cordillera and Mesozoic-Cainozoic Western Cordillera. These belts are separated by the Altiplano, a Cretaceous–Cainozoic intermountain basin up to 200 km wide. Regional scale lineaments are prominent, and are related to thrust faults, normal faults and shear zones. The NW-trending, gently NE-dipping thrust structures verge to the southwest, and expose the folded Palaeozoic sequence. The attitude of the sedimentary rocks is strongly influenced by the thrusts and associated folding (Fig. 1).

Liphichi is located in the Eastern Cordillera, which is made up of over 7 km of shale and siltstone. Regionally distributed lithologies include Ordovician and younger quartzite, sandstone, siltstone and shale with overlying Permian carbonate. The Palaeozoic rocks have undergone intense folding, faulting and metamorphism related to the emplacement of Permo-Triassic granite.

The mapped units around Liphichi are the Liphichi Turbidite, North Liphichi Quartzite, North Liphichi Turbidite and the Pacuni Turbidite. The most important unit is the Liphichi Turbidite, which is characterised by Bouma sequences. These are a dark grey to blackish in colour and weather to a brown colour. The Bouma sequence consists of interbedded shale and fine-grained quartzite.

The sedimentary sequence is cut by fine- to medium-grained porphyritic intrusive rocks that form sills and dykes generally following the NW-regional tectonic control.



2 Stockwork (A) and sheeted vein style (B) mineralisation at Liphichi underground workings 2 Level

Mineralisation

Mineralisation at Liphichi is of the turbidite-hosted quartz-carbonate vein type. It is termed by local geologists as a '*Bolivian vein deposit*', a type that is apparently peculiar to the Bolivian Altiplano. It contains gold and antimony, but also significant values of silver, copper, lead, zinc and tungsten.

Four mineralisation styles are present:

- stratabound and stratiform mineralisation – this style is present throughout the sedimentary sequence and characterised by parallel to sub-parallel thin lamina of pyrite with rare arsenopyrite
- saddle reefs – these quartz structures are observed both on surface and underground. The saddles are hosted within axes of anticlinal structures
- stockwork vein systems – these comprise quartz veins in various orientations, ranging from a few millimetres to 30 cm in thickness (Fig. 2). The stockworks are hosted within axes of anticlinal structures
- sheeted vein systems – these comprise parallel to sub-parallel zones of individual quartz veins ranging in thickness from a few millimetres to over 30 cm (Fig. 2). The sheeted veins are hosted within axes of anticlinal structures.

All vein types are auriferous, though the majority of the inventory is hosted within the stockwork and sheeted vein types. Saddle reefs are relatively unimportant. There is an intimate relationship between stockwork and sheeted veins, in most cases they form a combined chaotic vein swarm.

Diamond drilling and underground sampling during 2004 to 2006 confirmed a broad zone of gold mineralisation ranging from 53 m at 5·3 g/t Au (surface channel samples) to 62 m at 1·8 g/t Au (1 Level channel samples). Core and channel samples also record short higher-grade zones within the wider zone, for example drill hole PG04 grading 125 g/t Au over 0·95 m and channel sample 917 grading 102 g/t Au over 1 m.

The Liphichi veins contain variable amounts of pyrite, arsenopyrite, pyrrhotite, chalcopyrite, sphalerite, stibnite, wolframite, scheelite and carbonate. These minerals give rise to high levels of silver, lead, arsenic and antimony recorded in geochemical analyses. Visible gold is recorded in oxidised near-surface material, drill core and underground exposures. Geological mapping around Liphichi indicated that mineralisation is related to a compressional setting and is best developed in the hinges of anticlines. The gross mineralised zone is 200 m thick by 2 km along strike. Mineralisation is multi-phase as evidenced by cross-cutting veins, differing vein mineralogy and textures, and overprinting of three alteration events.

Liphichi shows similarities to the Central Victorian goldfields of Australia, Dolgellau gold-belt of Wales, UK and Meguma Province of Nova Scotia, Canada. The stockwork/sheeted veins are broadly analogous to the 'spur' zones of the Bendigo Goldfield, Central Victoria, Australia.

3 Panel sample preparation at the Liphichi gold project. One-hundred kilogram samples taken for metallurgical testing and grade verification

Ore characterisation

Introduction

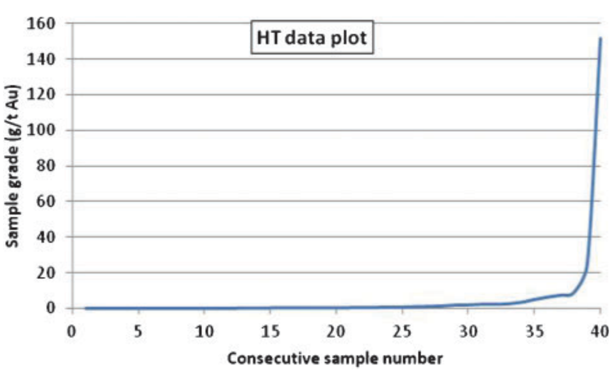
A characterisation study based on the approach outlined (Table 6) was undertaken (Dominy *et al.*, 2010c). Given the presence of coarse gold and its potential impact and dominance in terms of inventory value, characterisation and optimisation focused on gold rather than silver or antimony.

Three 120 kg panel samples were collected from three locations on 2 Level (Figs. 3 and 4). These represented one 1·5 m composite narrow vein and two 2 m sections of stockwork/sheeted veining. The samples were subjected to a test programme, including gold particle liberation and analysis, HT study and mineralogical determination.

HT

An HT study was undertaken on forty 0·2 kg fragments from sample #LMET02. The basis of the HT is given in

4 Collecting panel samples with hammer and moil at the Liphichi gold project (see Fig. 3). Samples were chipped from the drive side-walls onto a plastic floor sheet



5 Heterogeneity test results for 40 piece test on Liphichi ore

Pitard (1993), Minnitt and Assibey-Bonsu (2009) and Dominy *et al.* (2010a). This sample was chosen as the original face sample grades indicated close to the expected run-of-mine ROM grade. All samples were pulverised to P90 −75 μm and screen fire assayed (100 μm screens) in their entirety. Triplicate fire assays were taken on the undersize fraction. Coarse gold (>100 μm) was observed in two high grade samples (25·1 and 151·5 g/t Au), at 16 and 42% respectively. In one lower grade sample (2·39 g/t Au), 11% of the gold

6 Particles of visible gold within drill core from Liphichi. Grey streaks are mainly stibnite

was coarse gold. All other values were below 10% (mostly below 5%). Fragment grades ranged from 0·01 to 151·5 g/t Au with a mean of 5·7 g/t Au. A sampling constant (K) of 145 g/cm$^{1·5}$ and gold liberation diameter (d_L) of 50 μm was calculated for an equivalent nominal fragment size (d_N) of 8·3 cm.

The results of the HT where 40 sample grades are ranked from low to high grade (Fig. 5). The plot profile is typical of higher heterogeneity ores where there are a large number of relatively low grades compared to few high grades. Some 77% of contained gold is distributed in just two samples. In a low heterogeneity ore, gold distribution would be relatively even between samples. It should be noted that the HT is usually undertaken on a minimum of fifty fragments. A lesser number were used in this case due to limited availability.

Specialised test protocol

The test programme was designed to investigate coarse gold ores, principally from a perspective of gold particle size determination (Dominy *et al.*, 2010c). The protocol is based on three stages, comprising preliminary geological and mineralogical characterisation, followed by two processes addressing metallurgy and gold particle size determination after liberation.

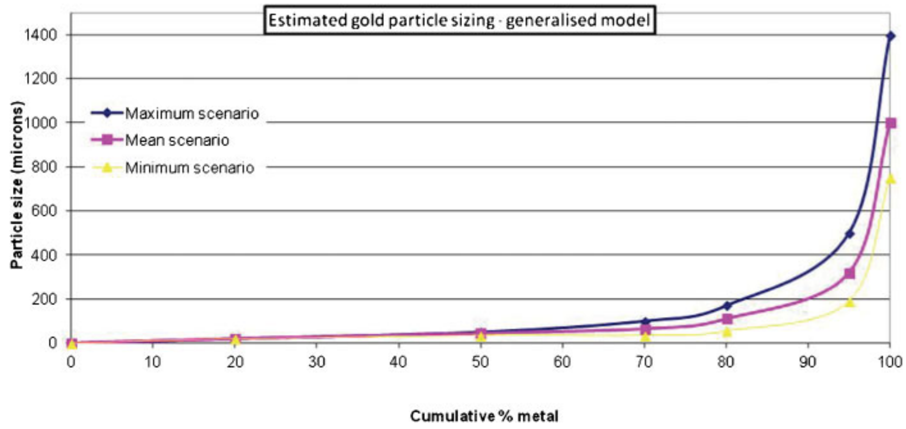
Based on a limited number of samples, the Liphichi ore contains some coarse gold (Table 9). After liberation, between 12 and 37% of gold recovered was coarse gold (>100 μm), though mainly below 500 μm and rarely to 1000 μm. GRG values varied between 31 and 57%, indicating the potential application of gravity concentration (Dominy *et al.*, 2011a).

Mineralogical study

Fifty polished thin sections were studied for each of the three samples (#LMET01 to 03). Gold particle mapping was undertaken using an automated electron microprobe supported by reflected light microscopy. The

Table 9 Summary results from the specialist metallurgical test programme

Sample	Face grade (g/t Au)	Laboratory split grade (g/t Au)	Test head grade (g/t Au)	GRG value (%)	Per cent of gold >100 μm	Au max size (μm)
#LMET01	23·1	8·2	14·8	57	37	1000
#LMET02	1·8	1·2	2·7	45	22	295
#LMET03	0·8	2·8	1·4	31	12	225



7 Generalised gold particle size model for Liphichi ore based on metallurgical and mineralogical studies

shortcomings of 2D-based thin section studies are well-known, but provided useful information. Gold particles were exclusively hosted in quartz and often closely associated with acicular stibnite or more rarely pyrite. Visible gold was observed in both drill core and underground exposure, but not commonly (Fig. 6). The largest particle seen was 1·1 mm in size. A summary of gold particle size distribution from the automated mineralogical study is shown in Table 10. In agreement with the metallurgical tests, the mineralogy indicates gold mostly below 1000 μm and around 25 to 50% coarse gold. Gold above 100 μm is generally up to 250 μm. The higher grade LMET01 sample bears more coarse gold (50%) and gold up to 1·1 mm in size.

Both the visual (e.g. core and hand specimen, and underground observations) and automated studies (thin sections) identified gold particle clusters. These range from groups of fifty 200 to 500 μm particles to one hundred 200 to 500 μm up to 8 mm across. Composite particle sizes range from around 1 to 3 mm in size.

Review of SFA data

Existing SFA data indicated that most samples contained less than 10% of +105 μm gold – nominally less than 10% coarse gold. This result differs from those obtained to the metallurgical and mineralogical studies, but such a divergence is not uncommon. Given that the other studies have indicated coarse gold mostly between 100 and 250 μm, the pulverising process is working relatively well. In addition, any gold clusters are fragmented during pulverisation.

Review of duplicate chip-channel and diamond core data

During 2004, Luzon undertook a small re-sampling programme underground and of diamond drill core. Out of eight chip-channel samples, only one was within ±20% of the original value. Variation included 0·5 g/t Au versus 5·4 g/t Au and 102 g/t Au versus 45 g/t Au for example. Three drill holes were re-sampled via quarter core yielding 30 m at 2·3 g/t Au versus 9·8 g/t Au (hole PG07), 44 m at 5·5 g/t Au versus 3·9 g/t Au (hole PG06) and 74 m at 4·3 g/t Au versus 2·2 g/t Au (hole PG04). These differences between field duplicates indicate a level of natural variability that may be explained by the presence of coarse gold. Some of the variability was related to the comparison being between original half-core versus duplicate quarter-core samples.

Gold particle size models

The studies enabled a generalised gold particle size model for Liphichi run-of-mine ore (assuming a grade of 2·5 g/t Au) to be constructed (Fig. 7). Defining d_{Lmax} as the 95th percentile (as noted previously, see Dominy *et al.*, 2010a), a mean value of 325 μm is given for Liphichi. A minimum of 180 μm was defined and a maxima of 1400 μm accounting for large particles and possible clustering (d_{Lclus}). The minimum value represents the likely distribution at the cut-off grade at 1·5 g/t Au and the maximum value for higher grade ore (>10 g/t Au). The mean K value for Liphichi was estimated to be 5700 g/cm$^{1·5}$, in a minimum–maximum range of 3000 g/cm$^{1·5}$ to 10 000 g/cm$^{1·5}$. K values below 200 g/cm$^{1·5}$ likely pose no sampling challenge and above 5000 g/cm$^{1·5}$ can lead to extreme issues. Liphichi ore sits just above the boundary of the major to extreme class and confirms that care is required.

The HT resulted in a d_L of 50 μm being defined. This understates the d_{Lmax} by over seven times and is a typical result using the heterogeneity approach in a coarse gold ore (Dominy and Minnitt, 2012). It is likely however to represent gold particles associated with a background grade. Preliminary evaluation of grade statistics indicates a background gold grade in the range 0·3 g/t Au to 0·5 g/t Au. This background is likely to represent more disseminated gold particles and yields a K value of 1400 g/cm$^{1·5}$.

Based on experience, Liphichi ore is classified as a 'medium' type coarse gold deposit (Table 11; Dominy, 1997). Like many orogenic vein systems it bears

Table 10 Summary of gold particle size data from the mineralogical study

	Per cent gold by size fractions					
Sample number	<50 μm	50–100 μm	100–250 μm	250–500 μm	500–1000 μm	Per cent gold >100 μm
#LMET01	32	18	33	17	<1	51
#LMET02	43	27	19	11	0	30
#LMET03	34	41	25	<1	0	26

Table 11 Key results from the characterisation study of Liphichi ore and comparison to Bendigo ore

Characteristic	Liphichi	Bendigo
Gold particle size	d_{Lmax}: 325 μm >100 μm: 40%; >1000 μm: <1%; >10 000 μm: 0%	d_{Lmax}: 10 000 μm >100 μm: 90%; >1000 μm: 60%; >10 000 μm: 5%
Distribution	As isolated particles and clusters. More coarse gold and clustering in higher grade ore Clustering observed, up to d_{Lclus}: 1400 μm	As isolated particles and clusters. More coarse gold and clustering in higher grade ore Clustering observed, up to d_{Lclus}: 10 000 μm
Deportment	Free gold in quartz and locally associated with stibnite	Free gold in quartz and locally associated with arsenopyrite and/or other sulphides
Grade	ROM grade of around 2–2·5 g/t Au	ROM grade of around 6–8 g/t Au
Sampling constant (K)	5700 g/cm$^{1·5}$ [d_{Lclus}: 40 000 g/cm$^{1·5}$]	200 000 g/cm$^{1·5}$ [d_{Lmax} and d_{Lclus}]
GRG	>30%	>65%
Indicative *in situ* sample size	ROM: 16 kg [Clustered: 1·2 t]	ROM: 22 t
Background grade	Around 0·3 g/t Au and dominated by <100 μm particles	Around 1·2 g/t Au and dominated by <100 μm particles
HT results	40 piece test ESD=8·3 cm; K=145 g/cm$^{1·5}$; d_L=50 μm	50 piece test ESD=19·4 cm; K=350 g/cm$^{1·5}$; d_L=500 μm
Visible gold	Observed up to 1 mm in size as individual particles and clusters up to 2 mm in (composite) size	Observed up to 10 mm in size as individual particles and clusters up to 10 mm in (composite) size
Comment	Moderate-nugget (around 50–60%) moderate-coarse gold system	Extreme-nugget (>90%) extreme-coarse gold system
Sampling difficulty	Low-moderate	High-extreme
Source	This study	Johansen and Dominy (2005)

moderate quantities (25 to 50%) of 100 to 300 μm gold. In addition, there is likely to be some pseudo-coarse gold effect where finer gold particles are in clusters. This is in contrast to the Bendigo system which classifies as an 'extreme' coarse gold ore. At Bendigo, diamond drilling, 120 t development bulk sampling and 100 kg mini-bulk samples were used during feasibility (Johansen and Dominy, 2005) to assess grade. A proxy-based system was developed for grade control (Dominy *et al.*, 2009; Dominy *et al.*, 2010b).

Sample mass requirements

Based on the identification of coarse gold in Liphichi ores, the Poisson approach was used to estimate likely sample mass requirements (Dominy *et al.*, 2010c). Sample mass expectations based on various grade-gold liberation diameter scenarios are in Table 12. The ROM grade mass to achieve ±20% precision is 16 kg. This is considered a maximum mass value.

Existing underground sampling programme

Overview

During 2005 to 2006, the sampling strategy at Liphichi involved collection of face (linear chip-channel), muck 'grab' pile (blasted development rounds) and NQ-sized core samples. Every development face was chip sampled and muck-pile sampled. Core samples were taken as 1 m composites in mineralised zones. A two to three man team using lump hammers and chisels cut an even channel for face samples. Chippings from each channel fall onto a tarpaulin and are bulked together to form a total sample. The total sample of around 30 kg was then reduced in size by so-called 'fractional shovelling' to produce a final sample of 15 kg for laboratory submission. Muck pile samples were taken as a series of cuts across the pile as the broken rock is bogged by hand. Approximately 15 kg was submitted to the laboratory. NQ drill core was logged and mineralised sections cut in half on approximately 1 m lengths and submitted to the laboratory (2 to 3 kg).

All samples were submitted to a commercial laboratory in Bolivia. On arrival, samples were dried, weighed and crushed in one pass to P70 1·7 mm using a Rhino crusher. After crushing, all samples were reduced to a mass of 1 kg by riffle splitting and then pulverised to P90 150 μm prior to screening and fire assay. The screen undersize was triplicate fire assayed. All items of equipment were compressed air-blast cleaned between samples and the pulveriser bowl cleaned using silica sand. All sub-samples were shipped to North America for fire assay.

Table 12 Indicative *in situ* sample size requirement for Liphichi ore based on different scenarios. Estimated using the Poisson method – mass calculated to precision of ±20% at 95% confidence limits

Grade (g/t Au)	Liberation diameter (d_{Lmax} or d_{Lclus}) (μm)	Indicated sample mass (kg)	Comment
2	1000	435	ROM ore assuming clustered particles with composite size to 1 mm
2	325	16	ROM grade ore
0·3–0·5	50	1	Background grade material with fine-gold liberation diameter

Review of protocols

Based on the defined d_{Lmax} of 325 μm, the total FSE variance was estimated for each existing protocol (Table 13) – FSE values where higher than acceptable. In particular, the channel sample protocol had an extremely high FSE due to the sample being split in half prior to crushing. In general, the precision required for a sample protocol should be less than $\pm 20\%$; above this value, estimates become non-Gaussian and Poisson distributed (Pitard, 1993, 2005).

Various issues needed addressing at site:

- the 'fractional shovelling' process applied was more of a series of grab samples from the rock pile method that was non-probabilistic and prone to bias (DE, EE and GSE errors). An 'alternate shovelling' method was deemed more appropriate based on twenty 1·5 kg shovel loads alternately placed onto two heaps

and at the laboratory:

- during riffling (after crushing), the sample container was moved from side to side on the splitter (thus the cutters did not receive an even flow of material) – this led to an EE error as the split was not a perfect 50/50
- a fixed device was used for screening which had the potential for contamination (and/or loss) as a result of gold particles lodging in the mesh (PE error)
- after screening, the coarse and fine fractions were bagged and shipped to a North American laboratory for assaying. For the coarse fraction in particular, there was a strong risk of gold loss due to particles lodging in the folds of the paper envelope (EE). During transport, strong GSE was likely and this may not have been removed depending upon how the sub-sample was treated at the laboratory.

Potential mining operation

The 2005 plan was to undertake an advanced resource development programme that would be supported by underground development, diamond drilling and trial stoping.

Small-scale narrow vein mining (~30 000 t to 60 000 t per year) could commence relatively quickly at Liphichi and likely achieve a head grade of 5 g/t Au or above. The deposit has greater potential as a bulk mining operation (>400 000 t per year) at a grade of between 1·5 and 2·5 g/t Au, with a cut-off grade of between 1 and 1·5 g/t Au.

For a bulk mine operation, the tonnage yield per linear metre of development and level interval (30 m) is ~4800 t. For a single narrow vein target, the same value is ~120 t per m. Assuming a gross strike extent of 600 m, the bulk tonnage per vertical metre is ~95 000 t. For a narrow vein target of 100 m strike extent, the tonnage per vertical metre is 400 t assuming a stoping width of 1·5 m. If the entire zone was to be stoped, then a bulk-mine sub-level open stoping method was deemed appropriate. If a selective operation was appropriate, then shrinkage stoping or possibly cut and fill stoping would be used. Both methods differ principally through being non-entry and entry respectively. For bulk stoping, the entire zone needs to be defined through both diamond drilling, foot-wall and hanging-wall development and regularly spaced linking cross-cuts. To some extent, a similar approach would be required if narrow vein targets were sought; however, once identified they would require development.

Proposed grade control programme

Overview

For all options, development faces would be mapped and chip-channel sampled. Cross-cuts would be 2 m chip-channel sampled over their length. Development drives (3 by 3 m) would be placed in a foot- and hanging-wall position based on geological control, but effectively where the stockwork veining began to reduce in density. At approximately 40 m intervals, cross-cuts would join the parallel drives. Where appropriate, an additional drive could be placed on a narrow vein within the ore zone. Vertical separation between main levels was initially planned at 30 m with 15 m sub-levels.

Diamond drilling from underground and surface locations was planned. Cross-cuts 15 to 25 m into the hanging- and foot-wall rocks aimed to define mineralisation around 75 m up- and down-dip from the drill bay. The intent was to stagger the drilling between levels to give an effective 20 m drill spacing enough to potentially define continuity for an Indicated Mineral Resource.

Geological mapping

Geological mapping of all drive faces and cross-cut walls via pro-forma face sheets and mapping sheets was planned. All faces were to be photographed. Horizontal plan maps would be produced from the face/wall maps and from specific mapping where appropriate. Geological maps would be digitised and photographs registered into 3D modelling software.

Sampling

Faces were chip-channel sampled using a two-man crew and hammer and moil. Broken material was collected by a tarpaulin on the floor. Cuts of 15 cm width and 2·5 cm depth were targeted, yielding ~10 kg per m. Face duplicate samples were initially planned at a rate of 1 in 10. It was recommended that a diamond saw was trialled.

Cross-cut walls were chip-channel sampled in 2 m lengths with the aim of collecting a 10 kg lot.

NQ diamond core was logged and sampled close to 1 m lengths, though matched to geology where appropriate.

In addition to the standard grade control sampling methods, a bulk sampling programme was also planned during resource development. The intent was to extract a series of cross-cuts from foot- to hanging-wall which would each total in the region of 1000 to 1200 t.

Table 13 FSE precision and absolute error for sampling protocols (field to assay) at Liphichi

Sample type	Precision (70% CL)	Grade error (g/t Au)
Channel samples	±155%	2±3·1
Grab/muck samples	±60%	2±1·2
Drill samples	±50%	2±1·0

Table 14 FSE precision for each stage of the revised Liphichi channel sample protocol

Stage	d_N (cm)	Mass reduction	Precision (70% CL)
1	0·17	10 to 5 kg	±19·5%
2	0·0075	5 to 2·5 kg	±1·9%
Total	–	10 to 2·5 kg	±20%

Table 15 FSE precision for each stage of the revised Liphichi bulk sample protocol

Stage	d_N (cm)	Mass reduction	Precision (70% CL)
1	2·0	200 to 10 t	±5%
2	1·0	10 to 0·5 t	±8%
3	0·5	0·5 t to 50 kg	±15%
Total			±18%

Laboratory protocols

Given the errors encountered in the original protocols, they were revised to minimise FSE.

For the face channel samples, the entire primary sample was crushed to P70 −1·7 mm, 2·5 kg riffle split off, pulverised to P90 −75 μm and screen fire assayed. Table 14 shows the calculated FSE for each stage.

For the drill core samples, the entire sample was crushed, pulverised and screen fire assayed. This effectively yields a zero per cent FSE as the sample is not split. This was deemed a sensible approach given that the data would represent a new drilling programme and be used to support a maiden resource estimate.

The bulk sampling programme required an on-site sampling tower to reduce a 100 t lot to a final sub-sample of 50 kg P80 −5 mm (Table 15). The sub-sample would be submitted to a laboratory for metallurgical processing.

Quality Assurance/Quality Control

Standard QAQC would include field duplicates, blanks and standards at a rate of about 1 in 20. Bulk sample cross-cuts were to be drilled with horizontal holes drive to drive, extracted and side-wall chip sampled to allow the different sample supports to be compared.

Selected faces and/or cross-cut will be channel sampled with both diamond cut and chipped channels. These methods would be part of the trial mining programme to investigate bias, and not part of any routine production grade control. Standard operating procedures were drafted for grade control activities and integrated into the health and safety programme. An annual independent review of grade control activities was planned.

Data management, integration and interpretation

A major need was for the introduction of a proper data management system beyond the use of spreadsheets. The integration of mapping, logging and grade data into a 3D model is important for resource and reserve estimation and to support final stope design. In addition, the system needs to be able to integrate external data such as stope survey, trucking and plant data to facilitate reconciliation studies.

Staffing and implementation

For the resource development and trial mining phase, a rostered-on two person underground geological team was planned, supported by two geo-technicians for seven day dayshift coverage. At production, the team would likely be double in size. The existing geological team had relevant expertise in underground grade control. Additional training was given in sampling and mapping, and data interpretation and integration into a standard mining package. Training for the geological team, in particular new starters was planned. In addition, the relative merits of grade control were to be included into the training programme of mining crews.

Summary

Liphichi is an advanced exploration project well-progressed into resource development. Its advantage is that a substantial amount of underground development exists. In early 2006, the resource estimate was supported by 1500 m of underground development (including 516 chip-channel samples) and 3100 m of surface and underground drilling (including 1725 core samples). The presence of underground works was

Table 16 Summary of Liphichi sampling approaches by project stage and comparison with methods used at Bendigo

Stage	Sample type	Liphichi	Bendigo
Resource development	Diamond core	NQ core. Half core taken for SFA	HQ core. Half core taken for SFA
	Face chip-channel	25–30 kg per face, split and half submitted to laboratory for SFA. Revised to 10 kg per m primary sample submitted for SFA	3 kg per 1 m sample, mainly assayed by FA but SFA used if visible gold observed
	Grab/muckpile	Initially 10–12 kg samples collected from development rounds. Discontinued	Minimal usage
	Mini-bulk	Not used	100 kg samples taken from individual development stockpiles and processed in small gravity plant
	Bulk samples	200 t (four 50 t development rounds). To be reduced to 50 kg for laboratory assay (planned, mainly to be taken along cross-cuts to enable comparison between drill hole and channel sample grades)	120–150 t development rounds collected with 15% split after crushing and processed in a purpose-built gravity plant
Production grade control	Diamond core	NQ core. Half core taken for SFA. After further testing, it is expected that SFA will be replaced by FA	HQ core. Entire sample taken for SFA. Developed a proxy-based system to determine intersection grade and support assay result
	Face chip-channel	10 kg per m primary sample, with 2·5 kg for SFA. After further testing, it is expected that SFA will be replaced by FA	Not used. Developed a proxy-based system to determine face grade
Source		This study	Johansen and Dominy (2005) Dominy *et al.* (2009)

Table 17 Key stages in the design and implementation of a new underground gold mine grade control sampling programme

Stage	Aim	Actions
1	Business case	Stakeholder engagement High-level programme review and business case
2	Characterise	Preliminary review and design of characterisation programme Undertake characterisation programme (see Table 6)
3	Design	Review and interpret from Stage 2 Consider orebody, mine size and mining method Design sampling protocols within framework of TOS
4	Implement	Set-up systems and written codes of practice Training of management, mine geology and production staff
5	Monitor	On-going QAQC programme (see Table 7) Annual internal and/or external peer review of systems Annual internal and/or external peer review of individuals
6	Update	On-going training/re-fresher Revision of protocols if deemed necessary in Stage 5 – return to Stage 2 or 3 as appropriate

supported by the low operating cost in Bolivia where a metre of development cost approximately 133% that of a metre of diamond drill core in 2005. Mineralisation is structurally controlled and requires moderate geological supervision during development and mining. The placement of the hanging- and foot-wall drives is crucial to define the limits of the likely mining zone and is based on both geological and grade criteria.

A characterisation study identified the presence of coarse gold at Liphichi. The coarse gold fraction present is not very coarse (e.g. over 1000 μm); however, clustering is likely to result in higher variability on a local scale. Liphichi classifies as a medium coarse gold type. This generally indicates that some specialised protocol may be required to achieve quality assay data. Continued SFA was deemed appropriate for resource delineation drilling, with its use for grade control to be evaluated as more data became available. The programme included a comparison programme between FA and SFA.

Unfortunately the planned resource development programme was not undertaken, so there is no verification of the protocols presented. The sampling methods at Liphichi are compared to those used at Bendigo (Table 16).

Conclusion

Grade control samples should be reproducible, unbiased, safely taken and operationally timely. These points have an impact on grade control and its ultimate effectiveness. Key recommendations for the design and implementation of a grade control sampling programme (Table 17). Mine geologists and geotechnicians must strive to collect samples within the framework of the TOS.

A critical issue during the implementation and operation of grade control will be people. Acceptance of the programme by all stakeholders will be important and requires the business case and deliverables to be promoted. A programme manager or 'champion' is required to drive development and ensure that all parties are engaged. The overall team must include miners, geologists, engineers and metallurgists. Programme implementation will be via proper equipping and training of staff, supported by documented procedures. Integration between grade control activities and stope planning and scheduling is required to achieve best practice. The grade control process allows grade (sampling), geological, geotechnical and metallurgical data to be collected. This information should be integrated into the final stope design process to ensure optimum design and risk profiling.

This paper addresses the design of underground gold mine grade-control sampling programmes. However, the general approach presented is also applicable to the design of open-pit grade-control programmes.

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