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A Discussion on Current Quality-Control Practices in Mineral Exploration

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1. Introduction

Vallée (1998) indicated that few exploration and mining companies have explicit and systematic quality-assurance policies, and identified three main approaches: laissez-fair, catch-as-catch-can, and systematic quality control, the latter being very uncommon. In the author's experience, this situation has not significantly improved in the intervening twelve years. Results of numerous recent audits and due-diligence jobs conducted on exploration and mining projects in South and North America, Asia, Africa, and Europe (many of them managed by North American and Australian companies) indicate that comprehensive geological quality-control programs are still relatively infrequent.

As a result of new regulations in place, junior and major companies are increasingly interested in implementing such programs, particularly when public financing is required. Unfortunately, the initial interest is often followed by shock and, sometimes, even by anger, when project management realizes that implementation of a quality-control program involves certain undesired modifications of the exploration budget.

Reluctance to implement comprehensive quality-control programs does not arise only from management or from budgetary constraints. Implementing such programs demands improved organization in the sampling process, database preparation, and data processing, and a dynamic and cooperative relationship with the laboratories. Due to the lack of appropriate training, project geologists do not always understand the need for such additional efforts, and often complain about these supposedly redundant control measures. In addition, laboratory personnel commonly identify geological quality control with lack of confidence in their results.

The purpose of this paper is to compare best quality-control practices with some current practices observed on international exploration and mining projects, and to discuss their direct implications on resource estimation and classification.

2. QA/QC definitions and principles

Quality assurance and quality control are the two major components of any quality management system. ISO (1994) defines quality assurance as "*the assembly of all planned and systematic actions necessary to provide adequate confidence that a product, process, or service will satisfy given quality requirements*", and quality control as "*the operational techniques and activities that are used to satisfy quality requirements*".

The quality-assurance program usually consists of written protocols that describe at least the sampling, sample preparation and assaying protocols, as well as the quality-control protocol (Shaw, 2009). Quality control includes the quality evaluation, or "*the system of activities to verify if the quality control activities are effective*" (Van Reeuwijk, 1998). While quality assurance aims at preventing problems, the purpose of quality control is detecting them, in the event that they occur, assessing their extent, and taking the appropriate actions to minimize their effects.
Rogers (1998) states that quality assurance policies and quality-control procedures in mineral exploration involve continuous monitoring of work processes and information flows, in order to ensure precise, accurate, representative, and reliable results, and to maximize data completeness (SMST, 2006). In the same line, quoting the Vancouver Stock Exchange Mining Standards Guidelines, Bloom (1999) writes that "*quality assurance programs should be routinely implemented as part of any exploration program that is generating analytical results. Such a program should verify the validity of sample collection, security, preparation, analytical method and accuracy*". Similarly, current international mining standards (JORC, 2004; CIM, 2003a, 2003b, 2005; CSA, 2005a) require that a program of data verification accompany any exploration program to confirm the validity of exploration data.

2.1 Precision

JCGM (2008) defines precision as the "*closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions*". Such definition can be in principle extended to repeatability (precision under repeatability conditions) and to reproducibility (precision under reproducibility conditions). Repeatability conditions imply the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time; reproducibility conditions include different locations, operators, measuring systems or procedures, and replicate measurements on the same or similar objects. However, precision is usually measured on repeatability conditions.
Precision refers to the random measurement error, the component of the measurement error that in replicate measurements varies in an unpredictable manner (JCGM, 2008). Precision is commonly assessed through a series of repeated measurements on the same sample material, or through successive measurements on different original-duplicate sample pairs. For assessing precision on repeatability conditions, the original and the repeated (or duplicate) measurements should consider similar sampling intervals and similar sampling and sample-preparation procedures, and should be assayed at the same laboratory, with the same analytical techniques, the same equipment, the same reagents and the same personnel. However, such ideal situation can only be attained if the original and the duplicate samples are included in the same submission batch.
Precision should be treated as a qualitative attribute (i.e. low or lower precision, high or higher precision), and is quantitatively measured through parameters expressing imprecision, such as standard deviation, variance, or coefficient of variation in case of a series of repeated measurements (JCGM, 2008). For assessing the random error of a series of original-duplicate pair measurements, the most commonly used parameter is the average of the absolute value of the difference between the original and duplicate values, which is known as ARD, for absolute relative difference, or simply relative difference (Long, 1998, 2000), or relative error (Simón, 2004), as well as a related parameter, the HARD, for half

absolute relative difference (Shaw, 1997). Most recently, Stanley and Lawie (2007) and Abzalov (2008) have suggested the use of the average coefficient of variation CV_{AVR}, which is described as an unbiased estimate of the random measurement error. Whatever the parameter used for assessing the random error, though, there is an inverse relationship between precision and the corresponding quantitative parameter: the higher the random error, the lower the precision, and vice versa.

2.2 Accuracy

Measurement accuracy, or simply accuracy, is defined as the "*closeness of agreement between a measured quantity value and a true quantity value of a measurand*" (JCGM, 2008). All measurements have an uncertainty attached to them. Furthermore, different samples of the lot will have different concentrations of the element being measured, and this contributes additional uncertainty to the hypothetical true quantity value of the material's grade, which makes it, in fact, unknowable.

Accuracy refers to the systematic measurement error, the component of the measurement error that in replicate measurements remains constant or varies in a predictable manner (JCGM, 2008). Accuracy is commonly assessed through standard reference materials (SRMs), which are usually prepared from natural materials, or metallurgical concentrates, or tailings. When establishing the grade of these materials, the true quantity value is never known; however, under very controlled conditions, an accepted grade or "best value" of a particular element in a SRM can be established with a sufficient level of assurance through a round-robin test, consisting of multiple measurements at a series of reputable laboratories. The best value represents, in fact, the consensus value resulting from a round-robin test.

By inserting SRMs in sample batches, it is possible to compare, indirectly, the performance of the particular laboratory where measurements are conducted to the performance of other reference laboratories and, therefore, to assess the possible existence of bias between that particular laboratory and the consensus of other laboratories.

Accuracy should be treated as a qualitative attribute (i.e. low or lower accuracy, high or higher accuracy), and should not be given a quantity value (JCGM, 2008). Accuracy is quantitatively measured through the bias, which is the estimate of a systematic measurement error, or the difference between the expectation of the test results and an accepted reference value (AMC, 2003). The bias is usually calculated as the difference between the average value of a series of measurements of the SRM grade over a certain period of time and its best value, divided to the best value. However, there is an inverse relationship between accuracy and bias: the higher the absolute value of the bias, the lower the accuracy, and vice versa.

Accuracy can also be assessed through check samples, pulp samples initially assayed at a primary laboratory and re-submitted to a secondary laboratory. This way, it is possible to quantify the systematic error existing between the two laboratories. Nevertheless, this method should be complementary to the use of SRMs. Whereas in a sampling campaign few SRMs only characterize some fixed-grade values, the check samples reassayed at a secondary laboratory usually cover a wider value range. The combination of both methods leads to a more representative quantitative appraisal of the accuracy.

It is essential that a highly reputed and reliable laboratory be always chosen as the secondary laboratory. However, in spite of the fact that the secondary laboratory is considered as a reference laboratory, its accuracy should also be established or confirmed through the insertion of SRMs in the check-sample batches.

2.3 Contamination

Contamination consists of the inadvertent transference of material from one sample or the environment to another sample, and may take place during sample preparation and/or assaying, or merely through sample manipulation.

Contamination is assessed through blank samples, which are barren samples on which the presence of the elements undergoing analysis has been confirmed to be below the corresponding detection limit. A significant level of contamination is identified when the blank sample yields values exceeding several times the detection limit of the analysed element.

In order to be effective, blank samples should always be inserted after mineralized samples. Whenever possible, the matrix of the blank samples should be similar to the matrix of the material being routinely analyzed.

3. A comprehensive quality-control program

A comprehensive quality-control program should monitor various essential elements of the sampling-preparation-assaying sequence, in an effort to control or minimize the total possible measurement error:

- Sample collection and splitting (sampling precision)
- Sample preparation and sub-sampling (sub-sampling precision; contamination during preparation)
- Analytical accuracy, analytical precision, and contamination during assaying.

Monitoring these aspects is achieved through the random insertion (or submittal) of various control samples, each of them having a particular purpose in the quality-control protocol. The control samples will also be useful to alert about possible mix-ups or mislabelling produced during manipulation. Whenever possible, the identity of the control samples must remain "blind" to the analytical laboratory. In addition to control sample insertions (or submittals), some control operations are often conducted to assess certain aspects of the preparation process.

A quality-control program also examines the reporting (clerical or data transfer) accuracy. Best practice for monitoring reporting accuracy is double data entry of the manually-entered data, which consists of using two independent teams to enter the most sensible data into two independent databases, and subsequently cross-checking both data sets. A simpler alternative is regular checking, with the same method, of a representative proportion (at least 5%) of the entered data.

3.1 Controlling sampling quality

Sampling precision, the main indicator of sampling quality, is monitored through coarse-grained, uncrushed control samples that are inserted in the submission batches during the sampling operation. Such samples usually include twin samples and field duplicates.

- Twin samples:
  In the case of half-core sampling, a twin sample would ideally be the second half of the core, usually kept as backup. However, companies and auditors are reluctant to leave portions of the hole with no material geological record. Alternatively, twin samples are collected as a quarter-core, resulting from the double-split of the original core sample. In this case, the sample is initially cut in two halves, and then each half is again cut in two quarters, one quarter representing the original sample, and the adjacent quarter

(preferably from the opposed half) representing the twin sample; the remaining two quarters are usually stored as backup.

An alternative solution, which can be applied if the core is sufficiently compact and wide (HQ or larger diameter), is cutting a fillet or slice, which is kept as backup, and cutting the remaining core piece in half, one portion representing the original sample, and the remaining portion representing the twin sample (Glacken, 2006).

In the case of channel samples, the twin sample should be taken as a channel adjacent to the original channel, using the same interval and the same sampling procedure. Blast-hole twin samples are taken using a spear or auger device, a sampling tray or a slotted hole on the blast-hole cone.

Twin samples are mainly indicated to assess sampling precision and, indirectly, mineralization homogeneity. In order to ensure repeatability conditions, both the original and the twin samples should be taken by the same crew, be submitted to the same laboratory (the primary laboratory), in the same sample batch and under a different sample number, so that preparation and assaying follow similar procedures. The term "duplicate" is herein avoided, since the original and the twin sample do not occupy, formally, the same spatial position (Long, 2000).

- Field Duplicates:

  These are samples taken from the first split of the original bulk reverse-circulation samples, without any previous crushing. The field duplicates are mainly used to assess the reverse-circulation sampling precision. In order to ensure repeatability conditions, both the original and the field duplicate samples should be taken from the same splitting step, be submitted to the same laboratory (the primary laboratory), in the same sample batch, and under a different sample number, so that preparation and assaying follow similar procedures.

3.2 Controlling preparation quality

Sub-sampling precision and contamination during preparation, reflecting preparation quality, are monitored through coarse-grained control samples that are inserted in the sample batch prior to or during preparation. Such samples usually include coarse blanks and coarse duplicates.

- Coarse Blanks:

  These are coarse samples of barren material, emulating the granulometry of the ordinary samples (with fragments over 1" diameter for diamond drilling or channel samples, or over ¼" diameter for samples from reverse-circulation drilling). These samples are used to assess contamination during preparation, and should be inserted into the submission batch prior to dispatching the samples for preparation. In order to be most effective, the coarse blanks should be prepared immediately after highly mineralized samples. Blanks sometimes inserted in the first position of the batch are not considered part of the quality-control program, but just a quality-assurance provision, since they are actually used to clean the preparation equipment.

- Coarse Duplicates:

  Coarse duplicates (also called preparation or coarse reject duplicates) are duplicate samples taken immediately after the first crushing and splitting step. The coarse duplicates will inform about the sub-sampling precision. In order to ensure repeatability conditions, both the original and the coarse duplicate samples should be submitted to the

same laboratory (the primary laboratory), in the same sample batch, and under a different sample number, so that pulverization and assaying follow similar procedures.

3.3 Controlling assaying quality

Assaying quality (analytical accuracy, analytical precision, and contamination during assaying) is assessed through fine-grained, previously pulverized control samples that are inserted in the sample batch after preparation and prior to assaying. Such samples usually include pulp duplicates, SRMs and fine blanks.

- Pulp Duplicates:
  These duplicates consist of second splits of finally prepared samples, analyzed by the same laboratory as the original samples under different sample numbers. The pulp duplicates are indicators of the analytical precision, which may be also affected by the quality of pulverization and homogenization. In order to ensure repeatability conditions, both the original and the pulp duplicate samples should be submitted to the same laboratory, in the same sample batch, and under a different sample number, so that assaying follows a similar procedure.
- Standard Reference Materials (SRMs)
  SRMs are samples with well established grades, prepared under specially controlled conditions. These samples should be included in regular submissions to the primary laboratory, as well as in check-sample submissions to the secondary laboratory, and will be used to assess the analytical accuracy.
  It is considered best practice to use at least three different SRMs for the most economically important elements and significant contaminants, covering the expected range of relevant concentrations. Minimum requirements are a low-grade SRM, with a grade close to the deposit cutoff; a medium-grade SRM, with a grade close to the average grade of the deposit; and a high-grade SRM, taking into consideration the grade level that for the particular deposit can be judged as high-grade (i.e., the grade corresponding to the 95^{th} percentile).
  When choosing the SRMs, it is always recommended to minimize the matrix-related analytical effect by using SRMs of a composition as similar as possible to the composition of the routine samples. The ideal situation would be to prepare the SRMs from the same type of material that will be evaluated. If possible, the SRMs should not be used to evaluate the accuracy of the same laboratory where they were prepared.
- Fine Blanks:
  The fine blanks are pulverized samples of barren material. These samples will assess the eventual contamination during assaying. In order to be most effective, the fine blanks should be assayed immediately after highly mineralized samples.
  When coarse and fine blanks are inserted, the following order is recommended: after a highly mineralized sample, the first one should be a fine blank, and the second one should be a coarse blank. Hence, the fine blank will be assayed immediately after the high-grade sample, whereas the coarse blank will be prepared immediately after the high-grade sample.

3.4 Check samples

Check samples consist of second splits of finally prepared samples, routinely analyzed by the primary laboratory, and resubmitted to a secondary laboratory, under a different sample

number. These samples are used to assess the assay accuracy of the primary laboratory relative to the secondary laboratory.

3.5 Control operations

In order to monitor the quality of the preparation process, it is highly recommended that particle-sizing tests be conducted at each stage of the comminution process (Shaw, 2009). In particular, regular sieve tests of the crushed and pulverized material are required, so that the proportions of material passing the stipulated sieve sizes are adequately known. Such tests are usually conducted by the primary laboratory after each crushing and grinding step. Other recommended control operations are weight checks before and after crushing, splitting and pulverization, to determine if significant losses of weight are produced.
When submitting check samples to a secondary laboratory, sieve checks should be requested to a certain proportion of the check samples, in order to obtain an independent assessment of the grinding quality achieved at the primary laboratory.

4. Control-sample insertion frequency

4.1 Current practice

During an examination of industry quality-control practices, the author reviewed current trends in control-sample insertion, using four main sources: well known international QA/QC consultants, SEDAR[1]-filed technical reports, documents from regulatory bodies, and information published in the Internet by exploration and mining companies in web sites and press releases (Simón, 2007).

- International QA/QC Consultants:
  A general agreement seems to exist between international QA/QC consultants about recommending an overall insertion rate of control samples close to 20% (Table 1).
- SEDAR-filed Technical Reports:
  The author reviewed a random selection of published NI 43-101 technical reports (16) resulting from placing Google® queries[2] for "technical report", "insertion rate", "qa/qc" and "43-101", with no preference for region, size of the company or type of mineral. Not all of the consulted reports had definite figures to describe the quality-control protocols, but those with detailed data are listed below:
  - Porcupine Project, Canada (GoldCorp): Coarse rejects: 5%; coarse blanks: 5%: pulp duplicates: 5%; SRMs, 5%; check samples: 5%. Total: 25%. Source: AMEC (2006)
  - Modder East Load Project, South Africa (sxr Uranium One Inc. and Aflease Gold Ltd.): Coarse blanks: 2%; SRMs, 9%; pulp duplicates: 11%; check samples: 2%. Total: 23%. Source: SRK (2007).
  - Perama Hill Project, Greece (Frontier Pacific Mining Corporation): Duplicates, 10%; other control samples: 9%. Total, approx. 19%. Source: RPA (2004).
  - Nuestra Señora, Mexico (Scorpio Mining Corporation): Coarse duplicates, 2.5%; SRMs+blanks, 2.5%; pulp duplicates, 5%; pulp check samples, 5%; coarse reject check samples, 2.5%. Total: 17.5%. Source: CAM (2006).

[1] SEDAR: System for Electronic Document Analysis and Retrieval, Canadian Securities Administration. www.sedar.com.
[2] Date of queries: 27 October, 2006.

Source	Details	Suggested Proportion of Control Samples
Rogers (1998)	Duplicates, SRMs, blanks: one in twenty; external checks: 5%	Approx. 20%
Vallée (1998)	10% duplicate plus SRMs, a 'somewhat lower figure' for rock sampling (?)	Approx. 15% (?)
Neuss (1998)	2%-5% field duplicates, 2%-5% coarse duplicates, 5%-10% internal pulp duplicates, 5%-10% external pulp duplicates, plus one SRM and one blank in every submission	Approx. 19% to 25%
Long (1998, 2000)	5% coarse reject duplicates, 5% pulp duplicates, 5% SRMs, one blank per batch (approx. 3%), check assays, a portion of the pulp duplicates (3%)	Approx. 21%
Sketchley (1999)	In a twenty-sample batch: one blank, one SRM, one duplicate; in addition, all pulp duplicates should be re-assayed at check lab	Approx. 20%
Bloom (1999)	In a twenty-sample batch: one blank, one SRM; in addition, sending one in ten sample pulps to an umpire lab	Approx. 20%
Lomas (2004)	In a twenty-sample batch: one blank, one SRM, one coarse duplicate and one pulp duplicate; in addition, 5% of the pulps should be re-assayed at check lab (including SRMs)	Approx. 25%

Table 1. Quality-Control Programs: Suggested Insertion Rates by Various Authors (After Simón, 2007)

- Twangiza Project, Congo (Banro Corporation): 2% coarse blanks, 8% SRMs; in addition, check assays (proportion not specified). Total: 15% (?). Source: Skead (2006).
- Mirador Project, Ecuador (Corriente Resources): Coarse duplicates: 5%; pulp duplicates: 5%; SRMs: 5%. Total: 15%. Source: MDA (2006).
- HC Property, Nevada (J-Pacific Gold): 5% twin samples, 5%; coarse duplicates, 5%; pulp duplicates, 5%. Total: 15%. Source: Durgin (2005).
- Pueblo Viejo, Dominican Republic (Placer Dome): 10% of SRMs and blanks. Source: AMEC (2005).

A general trend for using a 4% to 5% insertion rate for each type of control samples (duplicates, SRMs, blanks, check assays) could be observed, although in some cases particular sample subtypes are ignored. The insertion rate is less than 17% only when check assays are not included. An acceptable average is approximately 18%, with minor differences in some particular types of samples. The lack of duplicates in the Pueblo Viejo program invalidates it as an element for comparison.

In many of the studied examples, only one SRM was included in the quality-control program. When various SRMs were considered, sometimes there was no correlation between the grade levels of the SRMs and the actual sample grades. Not infrequently, the author has reviewed projects where SRMs have below cut-off values, or even close-to-detection-limit levels.

- Information from Exploration and Mining Companies:
  This information has been obtained mainly from press releases published in the Internet by a random selection of exploration and/or mining companies. The selection resulted from placing Google® queries[3] using "exploration", "mining", "qa/qc" and "insertion rate" as key words. Unfortunately, most companies do not offer details of their quality-control protocols in the press releases, but the author could find some examples:
  - Carpathian Gold (Colnic, Romania): Coarse blanks, 5%; CRMs, 4%; Check samples, 20% (before AMEC's Technical Report in 2006). Total: 29%. Source: www.carpathiangold.com/site06/images/CheckCode.pdf.
  - African Copper (Dukwe Project, Botswana): approx. 20% control samples. Source: www.mineweb.net/co_releases/302480.htm.
  - Aurelian Resources, FDN epithermal Au-Ag: CRMs, duplicates and blanks, 15%; in addition, samples from significant drill intercepts are sent to two reference laboratories. Total: 18% (?). Source: www.aurelian.ca/dynamic/press/pr-2006-08-21.pdf.
  - GlobeStar Mining. Regular practice: Duplicates: 4%; CRMs, 4%; blanks, 4%; check samples, 4%. Total: 16%. Source: www.globestarmining.com/content/standards.php.
  - Cambridge Mineral Resources: blanks, 5%; duplicates, 5%; CRMs; 5%. Total: 15%. Source: www.cambmin.co.uk/?page=press_releases&num=61.
  - Scorpio Mining Corporation (Nuestra Señora, Mexico): Coarse duplicates, 2.5%; CRMs, 2.5%; check assays: 5% pulps, 2.5% coarse rejects. Total: 12.5%. Source: www.scorpiomining.com/i/pdf/QAQC-NS.pdf.
  - Belvedere Resources: 12% control samples (only CRMs, blanks and duplicates). Source: www.belvedere-resources.com/rss/

  The same general trend for using a 4% to 5% insertion rate for each type of control samples (blanks, duplicates, SRMs, check assays) is observed. With the exception of the Nuestra Señora Project, the insertion rate is less than 16% only when check assays are not included. An acceptable average is approximately 20%, with minor differences in some particular types of samples.
- Regulatory Bodies:
  In 1999, the Toronto Stock Exchange and the Ontario Securities Commission prepared a document which later became the basis of NI 43-101 (CSA, 2005a). The document, named Setting New Standards (TSE-OSC, 1999), recommended that in a sample batch of 20 samples there should be a duplicate sample, a coarse blank, and an SRM. The document also recommended that previously assayed pulps be re-submitted to the same laboratory (rate not stated) and to another laboratory as check assays (rate not stated). The first three control samples would represent an overall 15% insertion rate, and the additional pulp re-assays (internal and external to the primary laboratory) would probably take the total to a figure close to 20%.

In conclusion, a general agreement appears to exist between the consulted sources: a 20% control-sample insertion rate has practically become an industry standard. However, most sources did not distinguish between duplicates or blank subtypes (twin samples, field duplicates, coarse and pulp duplicates, coarse and fine blanks), all of them with different functions in a comprehensive and properly conducted quality-control program.

[3] Date of the queries: 27 October, 2006.

In addition, the insertion of reference materials or the submission of samples for external control is often erratic and inconsistent. In many of the studied examples, only one SRM was included in the quality-control program. When various SRMs were considered, sometimes there was no correlation between the grade levels of the SRMs and the actual sample grades.

4.2 Recommended insertion rates

A comprehensive quality-control program should include all types and subtypes of control samples, so that precision, accuracy and possible contamination at the various points in the sampling-preparation-assaying sequence are properly assessed.

The quality-control programs should be tailored to the specific needs of each project and the average size of the analytical batches. Whereas an overall insertion rate of 20% is in principle recommended, the individual proportions of the various types of control samples should reflect those problems with higher probability of occurrence. With the advance of the project and the identification and correction of those problems, the absolute and relative proportions of control samples can be adjusted accordingly. A suggested, general-purpose insertion rate table is presented in Table 2.

It should be emphasized that the external check batches should also include pulp duplicates, SRMs and pulp blanks in appropriate proportions, so that precision, accuracy and possible contamination at the secondary laboratory could be independently assessed.

Sample Type	Sample Sub-Type	Suggested Insertion Rate	
Duplicates	Twin Samples	2%	6%
	Coarse Duplicates	2%	
	Pulp Duplicates	2%	
SRMs	SRMs	6%	6%
Blanks	Coarse Blanks	2%	4%
	Pulp Blanks	2%	
Check Samples	Check Samples	4%	4%

Table 2. Core-Drilling Quality-Control Program: Suggested Insertion Rates

5. Geological quality-control programs in the real world

As mentioned above, in spite of the fact that new regulations in place impose more strict requirements regarding the implementation of proper QA/QC programs (CSA, 2005a, 2005b; JORC, 2004), the author's experience on numerous audits and due-diligence jobs conducted in recent years on exploration and mining projects in South and North America, Asia, Africa, and Europe clearly indicates that exploration and mining companies should give additional attention to geological quality control.

The author evaluated the performance of the geological quality-control programs on 46 projects from South and North America, Africa, Asia and Europe audited or reviewed between 2007 and 2010. Each project received a qualitative score, based on how the author evaluated the actual degree of assessment of precision, accuracy and contamination by project geologists. The scores were assigned based on the following considerations:

- A (excellent): when precision, accuracy and contamination were fully monitored on real time, using a comprehensive control-sample selection and suitable procedures, and taking appropriate correction actions when required
- B (acceptable): when precision, accuracy and contamination were partially monitored on real time with an incomplete, but still reasonable control-sample selection, using appropriate procedures, and taking some corrective actions when required
- C (inadequate): when precision, accuracy and/or contamination were partially monitored with a very limited control-sample selection, unsuitable procedures, and not taking correction actions when required
- D (nonexistent): when a regular quality-control program was lacking.

In total, 14 projects (31%) were qualified as A or B, only three of them (7%) being ranked as A, versus 32 projects (69%) with qualifications of C or D, 13 of them (28%) being ranked as D (Table 3). This outcome represents an improvement when compared to a similar evaluation conducted three years ago on projects reviewed between 2003 and 2006 (Simón, 2008), when the proportions of projects ranked A-B and C-D were 16% and 84%, respectively (Table 3). Nevertheless, the current situation should still be considered unsatisfactory. Furthermore, a review of industry quality-control practices showed that, in spite of the fact that 43-101-compliant technical reports should describe in detail the QA/QC program and the nature and limitation of the verification, and should explain any problems encountered during data verification, no relevant details on the quality-control programs in place could be found in half of the consulted SEDAR-filed technical reports (Simón, 2007).

	2003-2006		2007-2010		Total	
Rank	**Number**	**Proportion**	**Number**	**Proportion**	**Number**	**Proportion**
D	11	42%	13	28%	24	33%
C	11	42%	19	41%	30	42%
B	3	12%	11	24%	14	19%
A	1	4%	3	7%	4	6%
Totals	26	100%	46	100%	72	100%

Table 3. Performance of Quality-Control Programs in Reviewed Projects (2003 to 2010)

6. Examples of poor quality-control practices

During the review of quality-control programs implemented in numerous exploration and mining projects elsewhere, the author has identified certain common practices that could lead to the inadequate assessment of precision, accuracy and contamination.

6.1 Practices leading to an inadequate assessment of precision

An inadequate assessment of precision commonly results from not respecting the repeatability conditions, but other factors are equally present in many reviewed quality-control programs. Examples of frequently observed poor practices are listed below.

- Making useless the assessment of precision by ignoring the results of the quality-control program:
  - Storing the duplicate data into the database and not processing them on a timely fashion, or not processing them at all.

- Providing an inadequate assessment of precision by putting in place an incomplete quality-control program:
  - Inserting only one or two duplicate types in the submission batches
  - Not maintaining a regular duplicate insertion frequency
  - Not conducting sieve tests to monitor the crushing and pulverization granulometry.
- Precluding the proper assessment of precision by not observing the repeatability conditions:
  - Using different crews to collect the original and the duplicate samples
  - Using different sampling methods to collect the original and the duplicate samples
  - Using different sampling intervals when collecting the original and the duplicate samples
  - Collecting the original and the duplicate samples at very different times
  - Collecting the field or the coarse duplicates from the last split of the bulk initial sample, instead of collecting them from the first split
  - Not inserting the duplicate samples in the same batches as the original samples
  - Using different analytical methods or conditions (aliquot size, detection limit) to assay the original and the duplicate samples
  - Using core, reverse-circulation material or coarse rejects to prepare new pulp samples and using them as pulp duplicates in order to monitor analytical precision, instead of using a split of the original pulp duplicate
  - Submitting the original samples to one laboratory and the duplicate samples to another laboratory.
- Affecting the assessment of precision due to poor handling practices that may produce sample mix-ups, wrong labelling and/or contamination.
- Preventing the assessment of precision by:
  - Not inserting duplicates in the regular submission batches
  - Not inserting duplicates in the check sample batches.

6.2 Practices leading to an inadequate assessment of accuracy

As explained above, accuracy can be assessed at the same laboratory, through the insertion SRMs in the batches, or by submitting check samples to a secondary laboratory. Examples of frequently observed poor practices are listed below.

- Making useless the assessment of accuracy by ignoring the results of the quality-control program:
  - Storing the SRM and check sample data into the database and not processing them on a timely fashion, or not processing them at all.
- Providing an inadequate assessment of accuracy by putting in place an incomplete quality-control program:
  - Inserting an insufficient number of SRMs in the submission batches
  - Not maintaining a regular SRM insertion frequency
  - Not submitting check samples to a secondary laboratory
  - Submitting twin samples or coarse or reject duplicates to a secondary laboratory instead of submitting pulverized check samples
  - Not inserting SRMs in the check-sample batches.

- Precluding the proper assessment of accuracy by not using suitable SRMs:
  - Inserting inadequately prepared or documented SRMs
  - Inserting SRMs not corresponding to the grades and/or composition of the mineralization of the regular samples.
- Jeopardizing the assessment of accuracy by not maintaining the anonymity of the SRMs:
  - Allowing the laboratory to identify the identity of the SRMs
  - Communicating the laboratory the best values of the SRMs.
- Affecting the assessment of accuracy due to poor handling practices that may produce sample mix-ups, wrong labelling and/or contamination.
- Preventing the assessment of accuracy by:
  - Not inserting SRMs in the regular submission batches
  - Not inserting SRMs in the check sample batches
  - Inserting supposedly valid SRMs, but not previously documented on a round-robin test.

A common problem in the assessment of accuracy is originated as a result of the construction and interpretation of the control charts used to process the SRM data. Control charts are helpful in assessing the stability of the analytical process. With that purpose, the center line of a control chart is defined as the average of a series of periodic measurements, around which the values vary at random, and process-dependant control limits are established on each side of the center line, usually at plus/minus three standard deviations (Mullins, 2003). The notion of control, therefore, has to do with precision, not with accuracy. For assessing the accuracy with SRMs, the first step should be identifying the in-control values, those values of the SRM that lie within the control limits, which implies that they are sufficiently precise to be used to estimate the bias during that particular period.

Many geologists prepare the control charts using the best value of the SRM as the center line, and define the control limits as a function of the standard deviation resulting from the round robin. However, the control limits for one process (the assays of a SRM at one laboratory) should not be established on the basis of another process (the assay of the SRM at various laboratories during the round-robin test). Furthermore, very often when supposedly out-of-control samples are identified, the laboratory is requested to repeat the entire batch.

Out-of-control values can be produced as a result of random errors, affecting only the SRM, or of systematic errors, affecting the entire batch. It is recommended that only the outliers (out-of-control samples) be repeated, together with some neighboring samples, to determine if the odd SRM value resulted from a random or a systematic error. Only in the latter case the repetition of the entire batch should be requested.

6.3 Practices leading to an inadequate assessment of contamination

As explained, above, contamination may be produced during preparation and during assaying. Examples of frequently observed poor practices in the assessment of contamination are listed below.

- Making useless the assessment of contamination by ignoring the results of the quality-control program:
  - Storing the blank sample data into the database and not processing them on a timely fashion, or not processing them at all.
- Providing an inadequate assessment of contamination by putting in place an incomplete quality-control program:

  - Only inserting one type of blanks in the submission batches
  - Not maintaining a regular blank insertion frequency.
- Precluding the proper assessment of contamination by not using suitable blanks:
  - Inserting blanks that were not previously analyzed to ensure that the grades of the studied elements are sufficiently low to allow the detection of contamination.
  - Inserting blank samples very different in composition from the regular samples
  - Using alluvial boulders and/or sand as the source of blank samples.
- Jeopardizing the assessment of contamination by not maintaining the anonymity of the blanks:
  - Allowing the laboratory to identify the identity of the blanks.
- Affecting the assessment of contamination due to poor handling practices that may produce sample mix-ups, wrong labelling and/or contamination.
- Preventing the assessment of contamination by:
  - Inserting blanks at the beginning of the batch, or following barren or poorly mineralized samples
  - Not inserting blanks in the regular submission batches
  - Not inserting blanks in the check sample batches.

7. Implication of poor quality-control programs for resource estimation

The importance of data quality for resource estimation can hardly be overemphasized. The use of the increasingly sophisticated mathematical processing methods on resource estimation can only be justified if the data on which they rely are sufficiently precise and accurate. On the other hand, resource classification is based on confidence of local and global estimations.
The first step in resource estimation is assessing the data reliability. Lacking proper quality-control data often results in having to exclude entire drilling campaigns from the estimation database, so affecting the resource tonnage, grade and classification. Poor precision due to the presence of coarse gold could lead to serious grade overestimation if this problem is not timely detected and addressed. Similarly, poor assay accuracy often require painful corrections, sometimes affecting the project feasibility. There is only one way to avoid unpleasant surprises when the critical moment arises: implementing from day one a comprehensive quality-control program, and following it strictly during the entire project life.

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The rich palette of topics set out in this book provides a sufficiently broad overview of the developments in the field of quality control. By providing detailed information on various aspects of quality control, this book can serve as a basis for starting interdisciplinary cooperation, which has increasingly become an integral part of scientific and applied research.

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