Sampling for proactive reconciliation practices

A. C. Chieregati*[1], H. Delboni Jr[1] and J. F. Coimbra Leite Costa[2]

Reconciliation is an activity carried out at most mines around the world which can be a useful tool to evaluate sampling accuracy throughout grade control processes. The historical practice of reconciliation is based on definition of the 'mine call factor' and its application to resource or grade control model estimates. However, the use of correcting factors will often disguise the causes of the discrepancies between results and estimates. Reconciliation should be done in a proactive way, i.e. analysing the information behind any discrepancy and, then, adjusting methodologies and processes so that results and estimates realign. A proper reconciliation system must be based on reliable data. Therefore, the optimisation of sampling techniques is indispensable for the development of a reliable reconciliation system. This paper analyses the reconciliation practices performed at a gold mine in Brazil and suggests a new sampling protocol, intended to eliminate significant sampling biases by taking preventive action.

Keywords: Reconciliation, Sampling, Resource estimation, Mine planning

Introduction

Reconciliation is the practice of comparing the ore tonnage and average grade predicted from resource and grade control models with the tonnage and grade generated by the processing plant. As discrepancies between these values are a common problem in both gold and base metals mines around the world, it is important to develop strategies to improve reconciliation results.

There are a number of different types of reconciliation available to every mining operation, which include:

(i) mine claimed versus treatment plant claimed
(ii) treatment plant claimed output against the amount of product sold to market
(iii) the premining ore reserve and mineral resource versus the mine, treatment plant and marketed product quantities
(iv) planned production performance against achieved performance.

These reconciliation points have both spatial and temporal components. That is, the measures of tonnage and grade taken as a part of the reconciliation system must allow the determination of the location of the tonnage in question and the time the measurement was taken. More robust, time based measures that are typically available in the latter stages of the production process can be compared to the location based estimates of the resource providing a feedback loop.[1]

Historically, reconciliation has been done in a reactive way, i.e. comparing the grades produced by the processing plant with the grades estimated by the resource and/or grade control models and, then, applying correcting factors such as the MCF ('mine call factor') to future estimates in an attempt to better predict how the operation may perform. After Morley,[2] however, the use of generic factors that are applied across differing time scales and material types is not industry best practice, since it will often disguise the causes of the error responsible for the discrepancy. The correct practice of reconciliation is to be proactive, i.e. analysing the information behind any variance and, then, making changes to methodologies and processes so that measurements and estimates realign. This approach turns estimates into forecasts and forms the basis for decision making to ensure that what happens in the future will match the present plan. Morley named it 'prognostication', or 'proactive reconciliation', an iterative process used to ensure that the variance between original estimates and actual results stay within acceptable ranges.

After Schofield,[3] mine reconciliation is often seen as the ultimate test of the quality of grade and tonnage estimates in resource or grade control models. However, without accurate sampling data, any statistical analysis is nonsense. In general, a sample is intended to represent a particular sampling unit, or volume of material. The sampling methodology is considered correct, i.e. unbiased, if all of the particles in the sampling unit have exactly the same probability of being selected for inclusion in a random sample.[4]

Correct sampling equipment, correct operating procedures and well designed processes are required to ensure successful sampling, i.e. guaranteeing the selection of representative samples. The sampling equipment should be designed to guarantee unbiased samples, and the sampling techniques should be based on theories that minimise sampling errors. Studies demonstrate that even small improvements in sampling processes can

[1]Mining and Petroleum Engineering Department, University of São Paulo, Av. Prof. Mello Moraes, 2373, 05508-900, São Paulo, SP, Brazil
[2]Mining Engineering Department, Federal University of Rio Grande do Sul, Av. Bento Gonçalves, 9500, Bloco IV, Prédio 75, 91501-970, Porto Alegre, RS, Brazil

*Corresponding author, email ana.chieregati@poli.usp.br

Published by Maney on behalf of the Institute
Received 31 March 2008; accepted 18 November 2008
DOI 10.1179/174328608X396526

result in significant benefits in an operation. Nevertheless, due to a lack of knowledge of the fundamentals of sampling theory, many companies lose millions every year with reconciliation problems.

This paper discusses and compares the reconciliation practices performed at a gold mine in Brazil and proposes new sampling equipment and a new sampling protocol, based on the concepts of proactive reconciliation. This new sampling protocol is intended to minimise sampling errors and eliminate significant sampling biases.

Reactive reconciliation versus proactive reconciliation

Reconciliation can be defined as a comparison between two estimates, which can be generated by the resource and grade control model or by the official production. Many companies calculate the MCF by dividing the produced grade by the estimated grade and apply it to resource or grade control estimates to predict what the operation may produce in the future. This practice is called here 'reactive reconciliation'.

However, the main objective of any reconciliation system should not be the generation of factors used to correct estimates, but the adjustment of sampling methodologies and techniques so that measurements and estimates align within acceptable tolerance ranges. This will result in significant benefits for the operation and provide a basis for ongoing improvements.

Proactive reconciliation is an alternative to reactive reconciliation that consists of constantly verifying estimates and measurements in an iterative process. When variations occur, their causes are analysed and corrective actions are taken to ensure that estimates and measurements realign. These actions include changes to sampling protocols and techniques, design of correct sampling equipment and procedures, etc., in order to improve data reliability and estimate quality. Proactive reconciliation, therefore, allows the correction of methodologies and not simply the correction of model estimates.

The usefulness of reconciliation data still remains dependent on the quality and reliability of the input data, i.e. estimates and measurements. Grade estimates are themselves dependent on the underlying sampling and the processes used to generate the estimates. The reliability of the sampling results depends on several factors – mineralisation characteristics, sampling quality, sample preparation and assaying – and can be evaluated by the variability of sample grades (precision) and the accuracy of the results (bias). The variability of sampling results can be broken down into three main sources:

(i) the inherent heterogeneity
(ii) the sampling errors, including sample preparation
(iii) the assaying errors.

According to Gy,[5] 'heterogeneity is seen as the sole source of all sampling errors' and is the only condition in which a set of units can be observed in practice. It is important to understand and quantify the sampling errors, so that the confidence of the final sample results can be reported and used in reconciliation investigations.[6]

Methodology

According to Crawford,[7] reconciliation should not simply examine the resource model against mining production estimates. In practice, each step of the operation must be examined sequentially from model to mine, mine to mill, mill to smelter or refiner or to final sales. This study is focused on the second step of reconciliation, also called 'mine to mill', which compares two estimates: the first based on grade control samples (mine) and the second based on head samples (mill).

Often grade control relies on blast hole sampling, which has two main advantages:

(i) the blast hole spacing is often close, providing a relatively high sampling density per ton of material
(ii) since the blast holes must be drilled anyway, there is no additional cost.

However, poor sampling precision is common with blast hole sampling, as well as the sample bias caused by particle size and density segregation. One of the main causes of this bias is the loss of fines, which can lead to an underestimate or overestimate of the ore grade.[8]

According to François-Bongarçon and Gy,[9] a sample is said to be correct when each fragment in the lot to be sampled has the same probability of being selected as any other. If a sample is correct and sufficiently reproducible, it is automatically qualified as representative. Therefore, a sample is said to be representative if the two following conditions are met:

(i) it is precise (i.e. has a sufficiently small error variance)
(ii) it is accurate or unbiased.

These conditions are illustrated in Fig. 1.

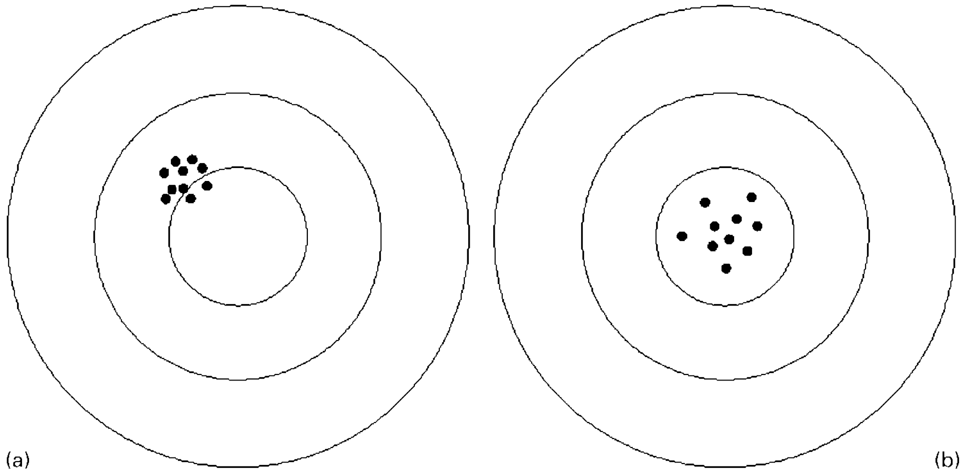
Unfortunately, representative sampling is much easier said than done. In practice, sampling often does not meet the above criteria, and because the risk of bias is never acceptable, we must reject any sampling procedure that fails these tests of representativeness. Not to do so will render the reconciliation process flawed from the outset.

Sampling is part of the grade control protocol and must be performed in order to minimise errors and assure the quality of the final estimate. Proper block estimation for short-term mine planning requires good sampling practices, and should improve result in terms of reconciliation.

For the gold mine considered in this paper, the previous sampling method for short-term planning (i.e. grade control) involved shovelling from the pile disposed around the blast hole after drilling. Four increments were taken from the pile to obtain an approximately 3 kg sample. This practice broke the main law of the sampling theory: any particle shall have equal probability to be extracted. The population of selected particles was thus assumed to have the same characteristics as those physically unreachable by the shovel. Since we cannot estimate the precision of manual sampling, it is an inherently unreliable and biased method.[10]

New sampling equipment

The experimental procedure was intended to minimise the errors previously described, by designing sampling equipment that could reduce the loss of fines and increase sample representativeness. The solution was the



a precision; *b* accuracy
1 Concepts of precision and accuracy

use of a stationary sectorial sampler, proposed by Pitard.[11] The sampling equipment is positioned around the blast hole before drilling. The sectorial cutter is a pie shaped bucket that shall be easily removed from the frame, and for the cutter to be correct it shall be radial with the centre of the blast hole. The bucket shall also be deep enough not to overflow before the end of the drilling. This sampling equipment minimises the risk of contamination and the errors introduced by manual sampling. Assuming an even distribution of particles around the pile during drilling, this approach should approximate correct sampling.

A modification to the sampling equipment proposed by Pitard was accomplished to reduce the loss of fines, which is a constant problem in blast hole sampling. A semispherical cupola, made of acrylic material, was added to the sampling equipment, respecting the conditions of extraction correctness. Figure 2 illustrates the proposed sampling equipment.

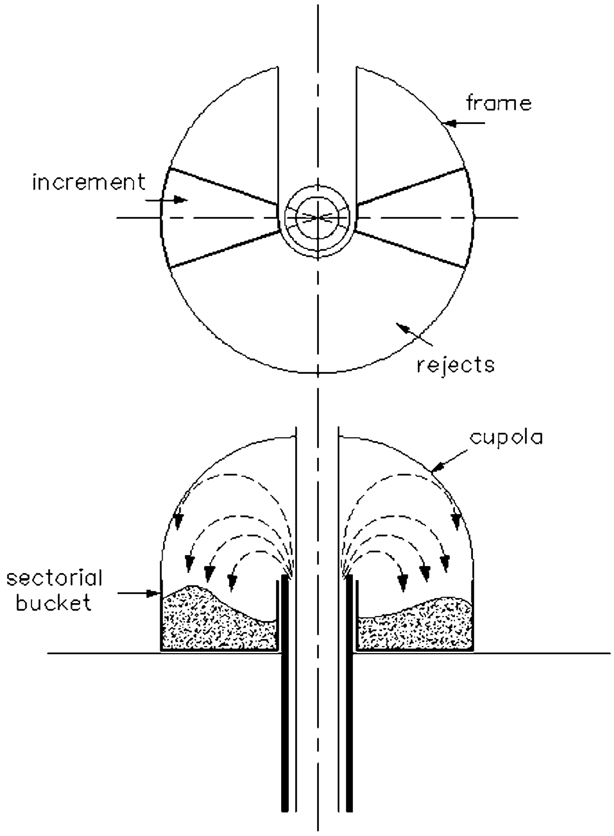
The sectorial sampler was attached to the drilling rig (*see* Fig. 3) and generated two samples, one per bucket, weighting approximately 3 kg each. The sectorial buckets were positioned in two quadrants of the sampling equipment, each one collecting an increment represented by a sector of the total sample.

New sampling methodology

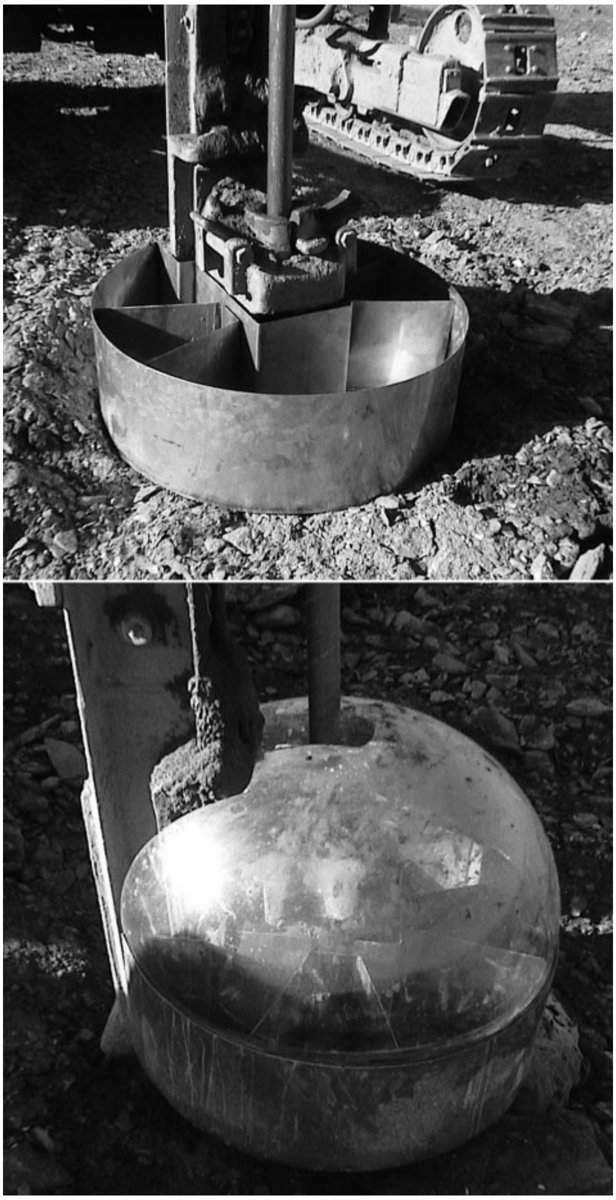
The proposed sampling methodology was based on Morley's proactive reconciliation concepts, where steps are taken sequentially, following an iterative process where changes to sampling protocols aim to reduce estimate errors as well as variances of sampling errors. Each step of this process aims to improve sample quality, consequently increasing its representativeness.

The new reconciliation method consisted of comparing the average grade of samples collected at the plant ('head samples') with the average grade of samples collected at the mine ('grade control samples'). The work reported in this paper included five sampling campaigns, referenced to five different mining blocks. The grade control samples consisted of material from the blast holes, using the sectorial sampler previously described, which provided two samples of approximately 3 kg each. The head samples, weighting approximately 50 kg each, consisted of 1 m belt material referred to its respective block, which, after mining and crushing stages, was sampled on the conveyor belts that fed the processing plant. The belt sampling procedure was simple: after stopping the conveyor belt at intervals from 30 to 60 min, 1 m belt material was collected using a shovel.

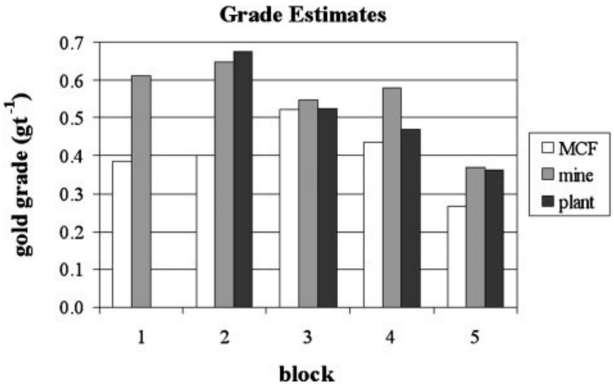
A total of 480 samples was sent to the laboratories for preparation and chemical analysis, including both grade control (382 samples of 3 kg each, from 191 blast holes) and head samples (98 samples of 50 kg each). All of them were prepared in the same laboratory and followed the same procedures of drying, splitting and crushing. Three aliquots of 50 g each were taken from each sample for gold analysis by fire assay. The results were submitted to a statistical analysis, based on Pierre Gy's sampling theory.



2 Stationary sectorial sampler with cupola



3 **Stationary sectorial sampler assembled on driller**



4 **Gold grade estimated by different methods**

Results

Table 1 shows, for each step, the changes to sampling protocol, the main objectives of proactive reconciliation and comments on the impact of various decisions made. For a better understanding of the entire process, the information is presented as a table, where the steps are chronologically shown.

Figure 4 shows, for each mining block, the average gold grades estimated by the application of the MCF to model estimates and the average gold grades estimated by different sampling methods at the mine and at the processing plant.

Statistical analysis

Information extracted from a dataset or any inference made about the population from which the data originate can only be as good as the original data. Therefore, before submitting any data for statistical analysis, it is especially important to verify data quality and authenticity. If inconsistencies exist, they should be checked and resolved before statistical analysis proceeds. Isaaks and Srivastava[12] suggest four steps to identify gross errors and assist in data cleaning:

(i) sort the data and examine the extreme values. If they appear excessive, investigate their origin and try to establish their authenticity

(ii) locate the extreme values on a map. Note their location with respect to anomalous areas. Are they located along trends of similar data values or are they isolated? Be suspicious of isolated extremes

(iii) check coordinate errors by sorting and examining coordinate extremes

Table 1 Proactive reconciliation steps performed at mine/plant

Step	Data source	Changes	Objectives	Observations/results
1	Mine	Replacement of the shovel by the sectorial sampler	Minimise the delimitation and the extraction errors	Correct sampling procedure
2	Mine	Insertion of a rubber seal above sampler's cupola	Minimise sample biases caused by the loss of fines	Reduction in bias (i.e. smaller mean of the sampling error)
	Plant	Sampling at the plant (crushing stage)	Calculate grade estimate errors	Not a representative value; based on 2 h sampling and 5% (mass) of block
3	Plant	Greater number of increments at crushing stage	Increase reliability of grade estimates	Representative but not ideal value; 70% (mass) of block sampled
4	Mine	Exclusion of rubber seal; increase in drilling water	Eliminate bias caused by the rubber and reduce the loss of fines	The worst estimate, due to the wash of fines; greater mean of the sampling error
	Plant	Greater number of increments at crushing stage	Increase reliability of grade estimates	More representative value; 90% (mass) of block sampled
5	Mine	Reinsertion of the rubber seal; drilling without water	Minimise biases caused by washing the fines	Smaller error variance and mean; better estimates of average grades
	Plant	Smaller time interval between increments collected at the plant	Increase reliability of grade estimates	The most representative value; 100% (mass) of block sampled

(iv) examine a posting of the data. Do the samples plot where they should?

The data were examined following the above guidelines. After checking sample diaries (driller records and belt sampling records), where information about eventual problems could be found, 40 unreliable sampling data were excluded from statistical analysis. Table 2 shows the results for each block and each sampling method. The 'MCF' grade represents the average gold grade provided by the application of the MCF to resource model estimates. This is still common practice at many mines around the world. The column 'grade estimate error – PROACTIVE' refers to the mine gold grade estimates using the new sectorial sampler. The column 'grade estimate error – REACTIVE' refers to the mine gold grade estimates applying the MCF to resource model estimates. Both errors were calculated based on the average gold grade estimated by the plant (the reference value).

The results show that reactive reconciliation practices cannot predict and/or control estimate errors and, therefore, they are unable properly to assist mine planning. On the other hand, proactive reconciliation practices allow personnel to understand these errors and to change sampling methodologies in order to minimise them. The chronological sequence also shows a continued decrease in sampling variances and grade estimate errors, which indicates improvement in sample representativeness.

The exception was block 4, which presented errors larger than the expected values, although exhaustive sampling was performed. We postulate that the cause of these errors was the increase in drilling water for this block. This was an attempt to minimise the generation and consequent loss of fines. What may have occurred is that washing the fines back to the blast hole increased the extraction error; consequently, the second condition of sample representativeness (unbiased sample) was not satisfied.

Discussion

The most obvious source of errors in reconciliation is sampling. Although sampling biases are very difficult errors to estimate, they certainly deserve special attention. After Grigorieff,[13] the variance of the overall estimation error is 80% due to sampling, 15% to preparation and 5% to chemical analysis. A sampling system must be designed to eliminate errors that can be eliminated and to minimise errors that cannot be eliminated. Thus, a proactive reconciliation practice will always improve sample representativeness.

The reconciliation practice presented in this work succeeded in minimising and/or eliminating sampling errors, by analysing their causes and, then, making changes to sampling methodologies and equipment. The results showed, over time, improvements in sample representativeness, which translated into increased accuracy and precision.

Conclusions

Even knowing the concepts of sampling theory, it is not always possible to do industrially what is theoretically correct. Gold has its peculiarities, especially regarding the segregation effect. Gold density is high, generating strong segregation phenomena as soon as gold is liberated. Furthermore, the gold content of an analytical subsample and the gold content of the sample from which it was selected can be very different. All these problems are amplified as the gold grade becomes lower, as gold deposits become marginal, and as the distribution of gold in rocks becomes erratic.

This study analysed a very low grade gold deposit, using blast hole samples, which in general present poor sampling precision and biased samples, due to size and density segregation. Starting from the worst situation, this study aimed to develop a practical sampling methodology that, at least, could reveal (i.e. make transparent) the errors involved, so that the final results were acceptable for use in reconciliation systems. Special attention was given to the generation of reliable data, or representative samples, respecting the fundamentals of sampling theory.

The concept of proactive reconciliation was introduced as an alternative to reactive reconciliation, and the results show that:

(i) as the variance of the sampling error s^2(SE) decreases, the sampling precision increases
(ii) as the mean of the sampling error m(SE) decreases, the sampling accuracy increases
(iii) as precision and accuracy increase, both sample representativeness and input data reliability increase.

Table 2 Comparison between reactive and proactive reconciliation practices

Block	Data source	Average gold grade, g t^{-1}	Error mean *m*(SE)	Error variance s^2(SE)	Grade estimate error – PROACTIVE	Grade estimate error – REACTIVE
1	MCF	0·385	*	*	*	*
	Mine	0·612				
2	MCF	0·400			3·5%	40·6%
	Mine	0·649	−0·024	0·054		
	Plant	0·673				
3	MCF	0·522			4·6%	0·38%
	Mine	0·548	0·029	0·053		
	Plant	0·524				
4	MCF	0·436			22·7%	7·4%
	Mine	0·578	0·103	0·040		
	Plant	0·471				
5	MCF	0·265			1·7%	26·9%
	Mine	0·369	−0·011	0·028		
	Plant	0·363				

*No sampling performed at crushing stage and, therefore, no reference value to calculate estimate errors.

As shown, proactive reconciliation can bring significant benefits to the mining industry. It is evident that sampling errors are far from being completely eliminated, but a first step was taken and improvements were demonstrated. When reconciliation is done in a proactive way, model estimates become forecasts, or prognostics. Aiming to determine the underlying cause of errors rather than factor them away is an important philosophic change.

References

1. S. Jackson, S. Dunham and J. Vann: 'Components of reconciliation', Quantitative Group, 2008, available at: http://www.qgeoscience.com/services_reconciliation.asp
2. C. Morley: Proc. 5th Large Open Pit Mining Conf., Kalgoorlie, Australia, 2003, The Australasian Institute of Mining and Metallurgy, 185–192.
3. N. A. Schofield: in 'Mineral resource and ore reserve estimation: the AusIMM guide to good practice', (ed. A. C. Edwards), 601–610; 2001, Melbourne, The Australasian Institute of Mining and Metallurgy.
4. P. M. Gy: 'Data handling in science and technology', Vol. 10, 206–208; 1992, Amsterdam, Elsevier.
5. P. M. Gy: 'Sampling for analytical purposes', 1st edn, 24; 1998, West Sussex, John Wiley & Sons.
6. M. Noppé: Proc. Mining and Resource Geology Symp., Queensland, Australia, 2004, EGRU Contribution No. 62, James Cook University, available at: http://www.snowdengroup.com/Files/GradeControl-1.pdf
7. G. D. Crawford: *Pincock Perspect.*, January 2004, **50**, 1–4, available at: http://www.pincock.com/perspectives/Issue50-Reconciliation-2.pdf
8. V. Snowden: Proc. Applications of Computers in the Mineral Industry, New South Wales, Australia, 1993, University of Wollongong, 42–45.
9. D. François-Bongarçon and P. M. Gy: *J. South Afr. IMM*, 2002, **102**, (8), 481–484.
10. A. Grigorieff, J. F. C. L. Costa and J. Koppe: *Revista Escola de Minas*, 2002, **55**, (3), 229–233.
11. F. F. Pitard: 'Pierre Gy's sampling theory and sampling practice: heterogeneity, sampling correctness, and statistical process control', 2nd edn, 488; 1993, Boca Raton, FL, CRC Press.
12. E. H. Isaaks and R. M. Srivastava: 'An introduction to applied geostatistics', 1st edn, 107–139; 1989, New York, NY, Oxford University Press.
13. A. Grigorieff: 'Desenvolvimento de um novo protocolo de amostragem de carvão mineral', Master's dissertation, UFRGS, Porto Alegre, Brazil, 2002.