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A comprehensive literature review reflecting fifteen years of debate regarding the representativity of reverse circulation vs blast hole drill sampling

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Blast hole sampling is widely used for grade control by the mining industry all over the world, both in precious and base metal open pit mining. Blast hole (BH) samples are often regarded as inferior in comparison to "proper drill sampling" like reverse circulation (RC) and diamond (core) drilling (DD), and are accused of lacking representativity by the sampling community. The present paper aims at collecting all peer reviewed publications from 2000 onwards that concern open pit mine sampling performance of BH, RC and/or DD drill sampling. This will form a comprehensive literature review reflecting on the debate between the representativity of the different sampling methods. The literature review collected a total of 31 publications (two were more or less duplicates and one consisted of an abstract only). The main source for publications on RC and BH drill sampling were dedicated sampling conferences, other mining conferences and some publications were found in peer-reviewed journals. From the gathered publications, it is not possible to draw a general overall conclusion as to the superiority of one drill sampling method over another. Both RC and BH have advantages and disadvantages and the choice of system needs to be related to the ore type and to the mining conditions. The overall conclusion is that it is always necessary to evaluate the specific sampling system to be used in light of the Theory of Sampling (TOS) (and with respect to the characteristics of the ore to be mined). It is always necessary to ascertain that the specific drilling sampling system contemplated does not lead to hidden losses that could have been avoided or missed profits that could be gained with a more relevant and representative sampling system. It would appear that the mining industry is doomed to continue to follow local, often economy-driven objectives and sampling solutions even if these can be documented as inferior when seen in the light of the representativity imperative. A call is made for universal adherence to the principles laid down by TOS for representativity in the primary sampling stage, before economic, logistical or other (local) factors are allowed to intervene. What is the objective to analyse and to make decisions in the mining industry, based on samples that can be documented not to be representative?

Introduction

In the mining industry, misclassifications of ore types due to poor sampling practices can easily generate large value losses and contribute to economic inefficiency in the crushing stages, as has been vividly demonstrated by Carrasco *et al.*[1] Internal calculations at LKAB indicate that misclassification of ore can lead to unnecessary costs of up to US$200,000 if one blast of waste is classified as ore, or loss in revenue of up to US$700,000 if one blast of ore is classified as waste. These estimates only represent pure costs or losses, and do not include losses due to decreased quality of final products, loss of customer trust, increased product handling or increased strain on waste dumps and dams. These examples clearly show the need for correct and representative sampling methods in open pit mining, for high quality and cost effective mining operations.

Blast hole (BH) sampling is widely used for grade control by the mining industry all over the world, both in precious and base metal open pit mining. BH samples are often regarded as inferior in comparison to "proper drill sampling" like reverse circulation (RC) and diamond (core) drilling (DD) and are accused of lacking representativity by the sampling community.[2,3] Figure 1 presents some of the well-known BH sampling problems and issues. Nevertheless, many mining operations continue to rely on manual BH sampling methods which are claimed to lead to "good results". However, Abzalov *et al.*[4] concluded in a study of (mainly) existing BH and RC samples in

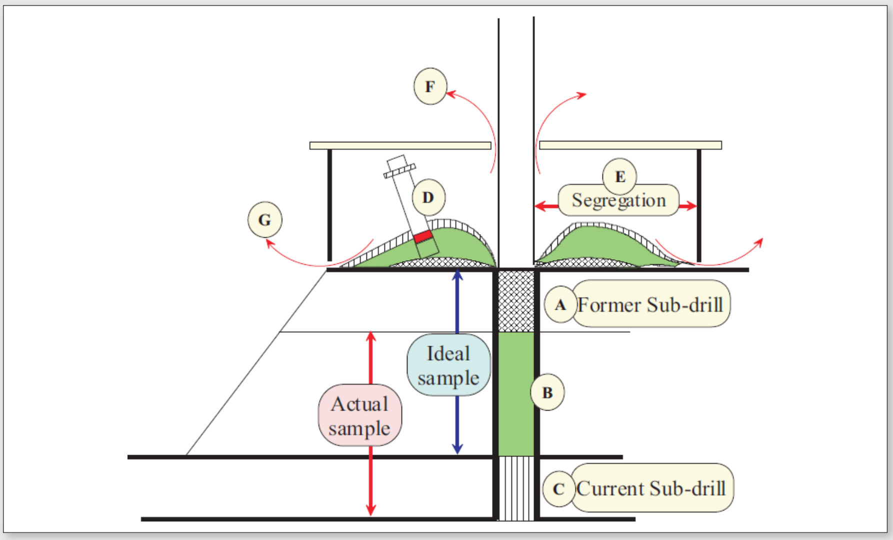

Figure 1. Summary of blast hole sampling problems and errors (from Reference 2 with permission).

Figure 2. Manual BH sampling at a LKAB open pit mine. a: Cutting a sectorial part of the BH cone. b: Collecting a vertical slice of uniform thickness from the bottom to the top in the centre of the blast hole cone.

an iron ore deposit, that both methods can be equally biased compared to full cone BH sampling. See Figure 2 for a contemporary example of manual sampling in iron ore open pit mining.

The present paper aims at collecting all peer reviewed publications from 2000 onwards that concern open pit mine sampling performance of BH, RC and/or DD drill sampling. This will form a comprehensive literature review reflecting on the debate between the representativity of the different sampling methods. With a summary of published conclusions the authors will attempt to see if it is possible to find an overall consensus regarding the superiority of any of the sampling methods.

Method

This literature review is conducted with both a quantitative and qualitative focus. First, all identified papers covering the topic of open pit mine drill sampling performance were compiled in a complete reference list. The search for publications was done through the web-based databases SCOPUS and ScienceDirect with keywords: "blast hole (BH) sampling", "open pit mine sampling", "drill sampling" and "reverse circulation (RC) sampling". The search also covered review of proceedings from the specific sampling conferences Sampling and World Conference in Sampling and Blending, as well as proceedings from various mining conferences and congresses. Last, all references in the hitherto gathered publications were reviewed for any further publications on the topic. Apart from internet based searches, some physical digging was also conducted, Figure 3.

The abstracts of all primary identified publications were reviewed to collect articles that specifically discuss the representativity or performance of at least one of the three drill sampling methods. Publications that concern a drill sampling method, but do not further discuss its representativity or precision of collected samples were excluded from the literature review during review of abstracts. The focus of the literature review is to assess performance, i.e. representativity and/or precision of open mine drill sampling methods; all publications that discussed this issue were included in the review. As the performance of actual drilling, *in situ* or bulk sampling or assay methods is not the main focus, publications that only discuss these matters were excluded from the review. Publications regarding underground drill sampling have also been excluded from the review as the present focus is on open pit mine sampling.

The ambition from the authors was to identify all publications from 2000 and onwards addressing the representativity of drill sampling methods. There might, however, still be some publications that could not be identified with the search methods used here. Any additional literature items that may surface in this context will be included in an updated survey which will be the base for discussions in the PhD thesis which includes the present feature. Defence is planned for 2019.

Results

The main sources for peer reviewed publications in the subject of open pit mine sampling and its representativity were specific sampling conferences, i.e. *Sampling* in Australia and the international *World Conference in Sampling and Blending* biannual series. A second source is other mining conferences and a few publications could be found in peer-reviewed journals. See Table 1 for the sources of all publications in the literature review. Comprehensive references for all publications can be found in the list of references. A brief summary of the most important conclusions from all collected publications can be found in Table 2.

The collected publications include seven theoretical discussions based on the Theory of Sampling (TOS) as well as previous publications and personal experience. In 22 of the publications, one or more case studies were conducted to evaluate the performance of one or both drill sampling methods. See Table 2 for a summary of all publications. Two publications were more or less identical with the same case study, results and conclusion; consequently, only one has been added to this summary.

Figure 3. A selection of some physical sources collected for the literature review.

Table 1. Sources for the collected publications.

Publication	Sampling specific conference	Other mining conference	Peer reviewed journal
Total: 31 publications	16	10	5
Abzalov *et al.*[4]		✓	
Abzalov *et al.*[5]			✓
Alfaro[6]	✓		
Caccioppoli *et al.*[7]		✓	
Carrasco *et al.*[1]			✓
Chieregati *et al.*[8]	✓		
Chieregati *et al.*[9]	✓		
Chieregati *et al.*[10]	✓		
Crawford *et al.*[11]		✓	
El Hajj *et al.*[12]	✓		
François-Bongarçon[13]	✓		
Goers *et al.*[14]	✓		
Gomes *et al.*[15]	✓		
Hapugoda *et al.*[16]	✓		
Hapugoda *et al.*[17]		✓	
Holmes[18]			✓
Holmes[19]			✓
Hoogvliet[20]		✓	
Kirk *et al.*[21]		✓	
Magri *et al.*[3]	✓		
Magri *et al.*[22]		✓	
McArthur[23]	✓		
Minkkinen *et al.*[24]	✓		
Niemeläinen *et al.*[25]	✓		
Ortiz *et al.*[26]		✓	
Pitard[27]		✓	
Pitard[2]	✓		
Séguret[28]	✓		
Spangenberg *et al.*[29]			✓
Young[30]		✓	
Ziegelaar *et al.*[31]	✓		

Last, one publication consisted only of an abstract, the study was presented orally at a conference in full but no article was prepared for the proceedings. In 12 of the case studies, existing grade control data was used while in 16 publications experiments were performed to generate new data, Table 3.

Table 4 shows a summary of the drill methods evaluated, the reference method and the most important conclusion of each publication. Table 4 also show which ore type is mined in the case studies presented. About half of the publications evaluate BH sampling and the other half compare BH to RC sampling. Four of the publications only evaluate RC sampling. The most common reference method used is DD sampling (nine publications), while full cone BH sampling, RC sampling and plant feed or reconciliation are used as reference in three to six publications. In as many as seven publications, RC drill sampling is assumed to be representative by the author(s), either from previous publications or "by experience". At the same time five (other) publications conclude that RC sampling can be non-representative as evaluations show several sampling problems and biases. Eleven publications conclude that RC sampling is more representative then BH sampling, while thirteen publications indicate that BH sampling can be representative or fit-for-purpose.

In summary, the results and conclusions show a very diverse picture of the debate between RC and BH sampling. One weak indication *could be* that base metal mining (iron ore) might show a slight tendency to accept BH sampling as representative. In contrast, the literature review shows that for sampling in gold mining, RC is generally concluded to be more representative than BH sampling. One exception is Chieregati[8,9] which both conclude that BH sampling can be fit for purpose if using correct equipment and sampling procedures, Figure 4.

Discussion

The different aspects of RC vs BH sampling are complex and in all cases clearly relate to the specific ore type and the prevailing mining conditions. The wide range of conclusions from all publications show that there is no universal answer to one sampling method always being superior. BH sampling is indeed accompanied by many problems like loss of fines, upward/downward contamination, influx of sub-drill material, pile segregation, pile shape irregularities, operator-dependent sampling, too small sample size, frozen BH cones and non-equiprobabilistic sampling equipment, see Figures 5 and 6 and References 2 and 6 among others.

Solutions do exist that handle some of the problems related to manual BH sampling and are able to reach a representative or fit-for-purpose status, however. Examples that counteract the most glaring sampling bias problems are channel sampling and sectorial sampling, Figures 4 and 7. Another solution that has proved to provide representative BH samples (in two publications) is automated BH sampling systems, Figure 8. Even though these can produce good quality samples, they have not made a breakthrough on the market for BH sampling, mainly due to the increase in drilling time when applying the automated sampling approach.

Figure 4. New modified sectorial sampler fitted to the PWH drill (right) and detail of the buckets/frame (left) (reproduced from Reference 9 with permission).

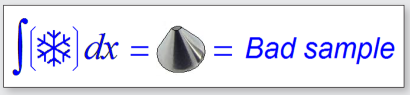

Figure 5. Frozen BH piles are a big problem in some open pit mines, from Reference 6.

The scale of resolution of sampling grids is in many publications concluded to be more important than sampling performance. Typical RC sampling grids are *ca* 25 × 25 m compared to BH sampling grids that are in most cases around 5 × 5 m. This large difference in grid size often leads to a larger increase in the number of misclassified mining blocks than BH sampling imperfections. If great care is taken when developing sampling methods, adapted to the drill rig at hand and accommodating the need of each mining situation, BH sampling can come satisfactorily close to being fit-for-purpose in some mining situations. In other case studies, RC sampling is proved to be more representative and is proved

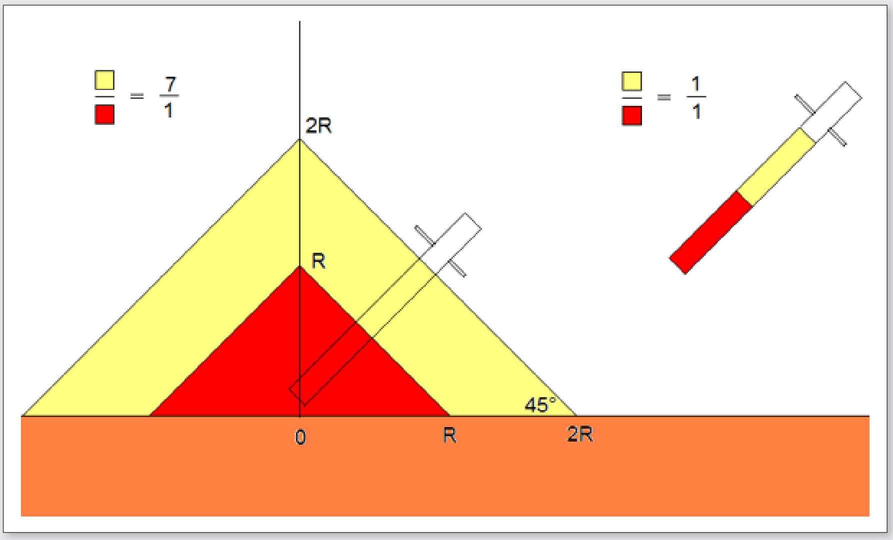

Figure 6. Non-equiprobabilistic sampling tube (reproduced from Reference 6 with permission).

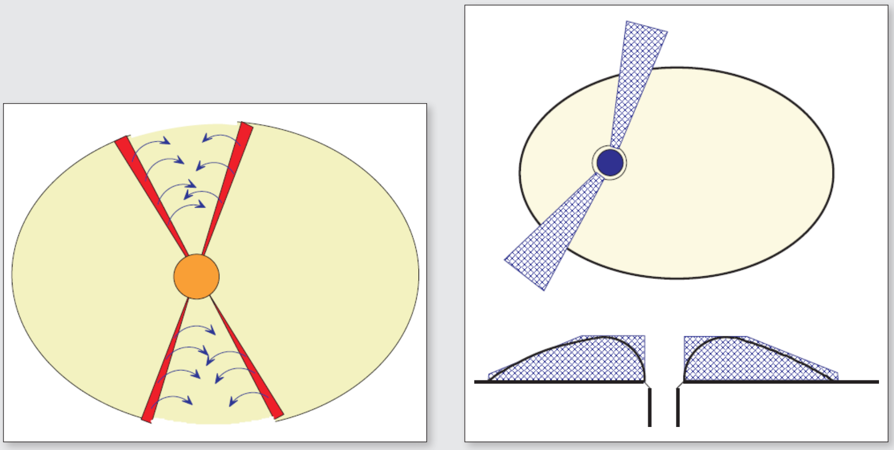

Figure 7. Left: digging two radial channels, from which to extricate four thin, radial increments to make a composite sample. Right: correct design and positioning of radial bucket/sectorial sampler. Reproduced from Reference 2 with permission.

Figure 8. Top: Drillsampler™ from Harrison Cooper for automatic blast hole sampling installed underneath the drill deck (reproduced from Reference 2 with permission). Bottom: the Finnish "Autosampler" system with Softcore™ sample socks attached (reproduced from Reference 24 with permission).

Table 2. Main conclusion of collected publications.

Publication	Main conclusion from publication
Abzalov *et al.*[4]	Manual BH sampling with shovel from BH cone on 6×6m grid, compared to RC drill sampling on 25×25m grid. BH and RC sampling proved equally biased in comparison to full BH cone assays. BH and RC or DD results are consistent at distances of 1m, but the variations in grade between twin holes increase when the distance increase and holes 10m apart show excessively poor repeatability. Indicating that a sampling grid of 25×25m will be sub-optimal at this mine. The quality of grade control procedures depends on both quality and quantity of grade control samples. In this case study, the amount of misclassified selective mining units would increase from approximately 5.8% to 12.3% when increasing sampling grid from 5×5m to 25×25m.
Abzalov *et al.*[5]	Comparison between BH and RC sampling in iron ore open pit mine. The study incorporates both sampling error and sampling grid to optimise sampling procedures. Currently, BH sampling is used for grade control, but RC sampling was considered as an alternative approach for grade control. Sample duplicates and twin holes with RC and BH sampling revealed that RC sampling does not guarantee improved sample quality. RC and BH exhibit similar precision errors and RC were biased, underestimating Al_2O_3 and SiO_2 grades, and overestimating Fe grades. Simulation showed that change to RC grade control with 25×25m grid would not reduce grade control errors, but rather increase the number of misclassified ore and waste blocks.
Alfaro[6]	A case study of the Rio Blanco ore deposit is porphyry copper, located in the central zone of Chile. Many problems with manual BH sampling in winter due to moist and frozen material. Comparisons between BH and DD assay results is done by identifying holes with maximum inter distance of 5m. The comparison indicates problems with the BH samples, especially for As and Mo.
Caccioppoli *et al.*[7]	Comparison between RC and manual BH sampling is done for flitch mining. The authors are using RC drilling as reference for the manual BH samples that are taken separately for top and bottom flitch. The result show differences between full cone BH and RC assay results in 20% of the blast holes. Improvement of the material recovery in the remaining blast holes could improve the accuracy of the BH assays.
Carrasco *et al.*[1]	A case study of BH sampling in a porphyry copper operation shows a nugget effect of 70% of the total variability. The sampling did not take the equiprobable rules into account and collected 250g of material from a 2ton lot with 2cm top size. The variability was much greater than for diamond drilling even though DD had a much smaller support. By the use of statistical and geostatistical calculations, the authors calculate losses due to poor BH sampling to approximately 22 MUSD.
Chieregati *et al.*[8]	Summary of several aspects that make sampling gold challenging based, on two case studies. Even though RC drill sampling is regarded as a more appropriate sample method, a significant (up to 20%) loos of fines can occur through overflow of the cyclone. BH sampling also have problems with loss of fines due to wind, and manual sampling with a shovel is common and does not conform to TOS equiprobabilistic principles. The authors suggest that the use of a correctly designed sampler could eliminate problems with delimitation, extraction and weighting errors in BH sampling. RC sampling can also be improved, for example by adding a secondary cyclone to collect the fines.
Chieregati *et al.*[9]	Validation of a newly designed cupola stationary sectorial sampler for BH sampling. The sectorial sampler has a significantly higher recovery of fine material which minimised sampling error due to loss of fines. The sampler did not lower production compared to previous manual BH sampling. The two opposite sectorial sample collectors were unbiased to each other. The sampler did not show any bias to the reference used, which in this case was TOS correct sampling of the plant feed. The authors note that double-discharge drills are a completely different scenario and cannot be directly compared to this case study with single-discharge, narrow diameter drill.
Chieregati *et al.*[10]	Case study of RC drill sampling compared with manual BH sampling. Complete BH cone as well as complete RC material was used as reference. Result show that the BH drilling loses coarse material in the hole and the manual BH method oversamples the coarse particles. The RC sampling system is unbiased compared to the complete RC material. The new RC rig shows both representative sampling results as well as increased reconciliation reliability.
Crawford *et al.*[11]	Investigation of manual BH sampling proved it to inaccurate and have poor repeatability. Trials showed that RC sampling was able to produce better sample representativity and depth flexibility, but the cost of RC was too high for the operation. The solution for improved BH sampling was to implement an automatic sampling system for the BH rig. This sampler could collect four samples over the 8m drill hole depth. Even though some loss of ultrafines resulted in a sampling bias, the flexibility and improvement of sampling representativity compared to manual sampling outweighed the concerns about ultrafines.

Publication	Main conclusion from publication
El Hajj *et al.*[12]	Manual sampling from a BH drill rig and RC sampling was compared to each other as well as to a DD reference. Both BH and RC sampling overestimate Au and Cu grades, but the bias for BH is about double to RC. The manual BH sampling is in turn underestimating the Au and Cu grade leading to satisfactory, but illusory, reconciliation results. Conclusion show that the manual BH sampling method was not suitable for reconciliation. There was also concluded that the estimate errors from the sampling method was not as significant as the errors from the type of drill rig used. Recommendations are to work with automated RC drill sampling in spite of extra cost and more traffic in the mine.
François-Bongarçon[13]	A comprehensive discussion of advantages and disadvantages of both BH and RC drill sampling without prerequisite assumption on one or the other's superiority. Conclusion states that the advantages and disadvantages are not clear-cut between the two methods, and certainly not as much as previously presented. Resolution is concluded to be a more critical factor than the performance of each sampling method as long as greatest of care is given to obtaining unbiased samples.
Goers *et al.*[14]	Three different RC drill sampling systems on two different drill rigs have been tested. The systems tested were: conventional cyclone and three tiered splitter sampling system, the Rotaport cone splitting system and the Progradex PGX1350R sampling system. Field duplicates and fines samples were collected to assess the sampling performance during the testing. Results show that the fines have a different grade then the rest of the material, meaning it is essential for the sampling system to sample the fines as well, which the PGX1350R managed. Field duplicates cannot alone be used to assess sample quality as loss of material from the drill hole or sampling systems is not detected. "With sample analysis costs of US$25–30 per sample and annual total drilling assay costs of US$1–1.5 M confidence that sample quality is high is critical. The efforts and costs to produce these high quality samples are justified with the knowledge that the downstream effects of poor samples and the decisions made from them can result in the loss of profits and increase in production costs."
Gomes *et al.*[15]	Case study of the mine to mill reconciliation including analysis of possible BH sampling biases. Comparison was made between manual BH sampling using a canvas and using a drum fitted to the drill, with small opening for the drill rod. Results show that the normal method resulted in a loss of fines as the mass of the drum sample was 8.7% greater and the relative mass of the two finest fractions were much larger than for the canvas method. The study led to development of a BH sampler with cupola that further improved sample representativity.
Hapugoda *et al.*[16]	Comparison of DD, RC and RAB drill sampling methods. Conclusion is that DD is able to produce the best samples but is expensive and slow. RC has a better sample recovery and provide reasonably uncontaminated samples compared to the RAB sampling. Some identified problems with RC include damaged pipes, excessive dust generation. Advantages of RAB drilling include lowest cost, greater speed and large sample volume.
Hapugoda *et al.*[17]	More or less the same article as above, published in a different forum. Identical evaluation, results and conclusion.
Holmes[18]	Theoretical discussion about problems and solution with lack of representativity for BH sampling. Recommendation include taking sectorial or radial cuts from the BH cone, either using some sort of sectorial cutters placed prior to drilling, or using a shovel after the drilling is finalised. Using an automatic sample divider on a cyclone that collects the drill cuttings is also recommended but has many problems like loss of material around the blast hole as well as loss of fines in the dust filter. RC sampling is mentioned as a recent advance for drill sampling but not evaluated for representativity.
Holmes[19]	Theoretical discussion about problems with BH sampling similar to above publication. RC drill sampling is presented as being considered best solution for open pit mine sampling even due to the much higher cost. Presented solutions for accepted BH sampling is extracting radial sectors, vertical slices or channel cuts from the BH cone. Another suggestion is automated collection of drill cutting using compressed air and a cyclone. Best approaches for BH are, however, considered to be channel sampling or sectorial cutters.
Hoogvliet[20]	A case study of a gold and silver mine in Borneo where the grade control system was changed from BH sampling to RC sampling. The original sampling method was to collect samples over 2.5 m using a wedged pie sampler at the collar of the blast hole, any existing sub-drill is not sampled. After viability studies showing improved profits, the grade control was changed to RC drilling. Reconciliation studies show that the annual profit increased by approximately US$2.87 M after implementation of RC. Even after deducting the extra cost for drilling, over US$2 M remained. The authors conclude that desktop studies comparing different drill sampling methods are not sufficient and often overestimate possible profits. The best method to evaluate a new method is by reconciliation and actual produced ounces, i.e. profitability. Another conclusion is that even if RC in some cases has a large impact on profitability, the benefits over BH sampling may be minimal in some other situations.

Publication	Main conclusion from publication
Kirk *et al.*[21]	Evaluation of BH sampling in regards to RC sampling and evaluation of implementation of RC drill sampling systems as a substitute for the BH sampling. BH samples were collected every 2.5 m intervals using a wedge-shaped sampling tray placed radial to the drill string. Two previous studies had indicated that the BH sampling performed reasonably well for high-grade or and waste samples. For low- to medium-grade samples the BH sample was biased as the low grade mineralisation occurs predominantly in the fines that was lost in the BH drilling process and therefore not sampled. Some other BH sampling problems were high top size compared to sample size, as well as frequent collar collapses contaminating the samples. The main result of the biased BH sampling was that approximately 30% of low grade ore was misclassified as waste due to the loss of fines. The BH sampling was also showed to be less accurate than RC and DD sampling.
Magri *et al.*[3]	Theoretical simulation of the economic losses due to poor BH sampling as well as using kriging or polygonal estimation as estimation method. 10%, 20% and 30% fundamental sampling error for BH sampling was used in the simulation to approximate the losses. These numbers are derived from sample systems commonly used in the mining industry (not explained how). The study shows that both estimation methodology and sampling errors lead to losses of millions of dollars per annum.
Magri *et al.*[22]	Case study with comparison between BH and RC drill sampling as well as collection of complete BH cones. Duplicate samples from the BH manual sampling was also collected for analysis of precision. Results show that radial bucket BH sampling is biased compared to both complete BH cone and RC samples for $CaCO_3$. The study also compared previous results from DD, RC and BH which showed good correspondence between all methods and biases between BH and DD were lower then between BH and RC. Variograms were used to estimate nugget effect and these were very low for both RC and DD, but BH nugget effect was considerably larger in spite the larger support for BH. Conclusion is that "Higher quality samples and better short term planning could be achieved by replacing BH sampling with RC sampling, if an economic analysis which includes the hidden costs of misclassified blasted material supports the change."
McArthur[23]	Case study of manual BH sampling in flitch mining. Experiments were carried out to evaluate if the manual method to divide the BH cone in upper and lower flitch and sub-drill is representative. Result show large variability in the ratio between flitches and sub-drill causing problems when sampling. The sub-drill is over represented by an average of 10%. The conclusion is that despite the misallocation of some material between flitches and sub-drill, comparative assay result show that the manual sampling method produce and overall unbiased result.
Minkkinen *et al.*[24]	Case study of a new automatic sampler for BH drill rig. A sampling belt collects a sectorial sample from the drill cutting ejection and transfer the material to a rotating cone splitter. Full BH cone samples were used as reference and in general the new sampling method showed good agreement with this reference.
Niemeläinen *et al.*[25]	Test of an on-line XRF analyser for percussion surface drill rig. The conclusions are that the system is equally representative as DD and RC drill sampling, but much faster. Some deviations between results could be seen but is expected to come from calibration problems. The on line analyser does not collect the dust (similar to RC) as this is deviated by the dust collector.
Ortiz *et al.*[26]	The authors conclude in the introduction that BH samples have poor quality due to time and space constraints, that most BH sampling methods suffer from delimitation, extraction and segregation-related errors. The authors use a simulation methodology applied to three case studies to evaluate the performance of different sampling methods on different drilling grids. The relative error for BH sampling is evaluated by duplicate sampling to a range between 14% and 20% while the error for RC sampling is set from zero to 8%. The conclusion is that moving from BH to RC sampling provides significant economic benefits reaching millions of dollars per annum. "The case studies show that when operating conditions allow for a dedicated drilling rig, it is worth considering investing in a sophisticated sampling system mounted on an RC drilling rig to operate well in advance, thus providing timely data for building short-term models that can include several additional relevant variables."
Pitard[27]	Theoretical discussion regarding sampling, including RC and BH sampling methods. Problems with RC sampling is said to be down the hole contamination, preparation error, selective separation of coarse and fine particles and poor or excessive recoveries leading to extraction biases. BH sampling is presented as a monumental problem for the mining industry due to delimitation, extraction and preparation biases. The author also discusses three new automated BH sampling methods that are stated to be able to produce correct and representative samples. As the systems are not yet in production it is not clear which will be most reliable, but they do represent a major breakthrough in ore grade control for the mining industry according to the author.

Publication	Main conclusion from publication
Pitard[2]	Theoretical discussions about problems associated with BH sampling and advantages with RC drilling. Examples of BH sampling problems presenter are: upward/downward contamination, upward material losses, refluxing, sub-drill material, pile segregation, pile shape irregularities, loss of fines, operator dependent sampling, sampling interfering with mining productivity, too small sample size, vertical drill holes and so on. A few presented advantages with BH sampling are: the same drilling technique for blasting and grade control, small visible cost, good lateral interpolation, less traffic in the pit. Presented advantages with RC sampling are: absence of sub-drill, possibility to drill several benches at once and to drill at an appropriate angle, limited contamination and losses, no interference with productivity, can drill months ahead of mining, possibility to drill less but better holes, smaller sample mass, information from lower benches, better vertical definition of ore and waste, automation is easy, and so on. The disadvantages with RC presented are: additional visible cost, increase in traffic in the pit. The conclusions are that BH sampling cannot provide representative samples and that RC sampling provide many advantages that may far outweigh the additional cost.
Séguret[28]	Case study of a copper mine in Chile. Comparison between BH sampler and DD using 3000 DD samples and 13,000 BH samples for the study. The authors use vertical and horizontal variograms, migration and cross variograms to evaluate the sampling methods. Conclusion show that DD sampling has errors and that both DD and BH variograms show approximately 50% nugget effect. Analysis of the BH error leads to conclusion that it is not the primary sampling step that generates the error, but it can rather be found later in the process. The authors suggest that DD and BH are used together for short term mine planning and that linear systems can be used to remove nugget effect from the data.
Spangenberg *et al.*[29]	The authors state RC drilling as preferred open pit mine sampling with no discussion regarding BH sampling. The authors discuss a few aspects of RC splitters that are biased and should be avoided. A specific sample mass reduction solution is mentioned as being representative and therefore correct.
Young[30]	Case study of a Zn/Pb/Ag mine where traditional BH sampling was replaced by RC sampling. BH sampling was conducted by using a PVC pipe, collecting eight increments from the BH cone. Problems with this method include: cone destruction by rigs, hole vs sample number mismatch, incorrect sampling technique, vertical drill holes in 75° ore body and time constraints. The BH sampling is, however, stated to have been relatively reliable when blasting benches of consistent height. Implementing RC sampling instead of BH did not increase cost for samples handling as the drill grid increased but the samples per hole increased. However, the cost of drilling increased due to the dedicated sampling drill holes that are not drilled when sampling blast holes. Comparison between the sampling methods (using RC as reference) show that BH sampling misclassified 18% of waste as ore and 13% of ore as waste. The cost of processing this waste without cost of lost opportunity (ore going to waste) more than covers the cost of RC drilling.
Ziegelaar *et al.*[31]	This publication only has an abstract and no prepared article for the conference presentation. The study is a comparison of different drilling techniques with DD used as reference. No conclusions are given by the abstract.

Figure 9. Left: drilling operations using a conventional cyclone and three-tiered splitter system. Right: drilling operations using the PGX1350R sampling system. Reproduced from Reference 14 with permission.

Table 3. Context and data collection methods in publications.

Publication	Theoretical discussion	Case study	Use of existing grade control data	Experiment generating new data
Total: 31 publications	10	22	12	16
Abzalov *et al.*[4]		✓	✓	✓
Abzalov *et al.*[5]		✓		✓
Alfaro[6]		✓	✓	
Caccioppoli *et al.*[7]		✓		✓
Carrasco *et al.*[1]	✓	✓	✓	
Chieregati *et al.*[8]	✓	✓	✓	
Chieregati *et al.*[9]		✓		✓
Chieregati *et al.*[10]		✓		✓
Crawford *et al.*[11]		✓		✓
El Hajj *et al.*[12]		✓	✓	✓
François-Bongarçon[13]	✓			
Goers *et al.*[14]		✓	✓	✓
Gomes *et al.*[15]		✓		✓
Hapugoda *et al.*[16]		✓		✓
Hapugoda *et al.*[17]	More or less the same article as above, published in a different forum.			
Holmes[18]	✓			
Holmes[19]	✓			
Hoogvliet[20]		✓	✓	
Kirk *et al.*[21]		✓	✓	✓
Magri *et al.*[3]	✓		✓	
Magri *et al.*[22]		✓	✓	✓
McArthur[23]		✓		✓
Minkkinen *et al.*[24]		✓		✓
Niemeläinen *et al.*[25]		✓		✓
Ortiz *et al.*[26]	✓	✓	✓	
Pitard[27]	✓			
Pitard[2]	✓			
Séguret[28]		✓	✓	
Spangenberg *et al.*[29]	✓			
Young[30]		✓		✓
Ziegelaar *et al.*[31]	Abstract only, no paper was prepared for this presentation			

to generate a large increase in profit when substituting BH sampling.

One major concern that is widely addressed is that the cost of RC drill sampling is "too high". Even when improved sampling performance can be proved, the increased cost for RC sampling is typically not accepted by the mining operation. This is most often due to the fact that it is more or less impossible to exactly quantify the possible value gain or economic losses due to inaccurate BH sampling.

There are several mining operations using RC drill sampling for short-term grade control despite the higher costs. Especially in precious metals mining, the improvements with RC drill sampling have proven to result in larger profit increase than the cost of drilling.[20]

However, the conclusion regarding representativity of RC drilling is not uniform in all publications. Some publications state as a prerequisite that RC is representative, while others conclude that RC, just as BH sampling, can be proven to be biased. Goers[14] evaluates different RC drill sampling systems and concludes that the choice of sampling system for the RC rig as well as the complete system for RC sampling and handling determines if sampling can be representative. Loss of fines, leading to sample bias, is for example a major problem with some RC sampling systems, see Figure 9.

Conclusions

The literature review collected a total of 31 publications (two were more or less duplicates and one consisted of an abstract only). The main source for publications on RC and BH drill sampling were dedicated sampling conferences, other mining conferences and some publications were found in peer-reviewed journals.

From the gathered publications, it is not possible to draw a general overall conclusion as to the superiority of one drill sampling method over another. Both RC and BH have advantages and disadvantages, and the choice of system needs to be related to the ore type and to the mining conditions. The overall conclusion is that it is always necessary to evaluate the specific sampling system to be used in the light of TOS (and with respect to the characteristics of the ore to be mined). It is always necessary to ascertain that the specific drilling sampling system contemplated does not lead to hidden losses that could have been avoided, or missed profits that could be gained with a more relevant and representative sampling system.

It would appear that the mining industry is doomed to continue to follow local, often economy-driven objectives and sampling solutions even if these can be documented as inferior when seen in the light of the representativity imperative. A call is made for universal adherence to the principles laid down by TOS for representativity in the

Table 4. Scope and reference methods used in publications.

Publication	Evaluation of BH sampling	Evaluation of RC sampling	Comparison between RC and BH sampling	Full BH cone used as reference	RC drilling used as reference	DD used as reference	Plant feed or reconciliation used as reference	Prerequisite assumption of RC as being representative	Conclusion show RC to be more representative than BH drill sampling	Conclusion show that RC drill sampling methods can be non-representative	Conclusion show RC and BH drill sampling to be equally (non) representative	Conclusion show that BH sampling can be representative / fit-for-purpose	Conclusion show that BH sampling is not representative	Sampled ore used to draw conclusion
Total: 31 publications	12	4	15	6	5	9	3	7	11	5	5	13	6	
Abzalov *et al.*[4]			✓	✓		✓				✓	✓	✓		Fe
Abzalov *et al.*[5]			✓							✓	✓			Fe
Alfaro[6]	✓					✓							✓	Cu, Mo
Caccioppoli *et al.*[7]			✓		✓			✓	✓					Fe
Carrasco *et al.*[1]	✓					✓							✓	Cu
Chieregati *et al.*[8]	✓	✓									✓	✓		Au
Chieregati *et al.*[9]	✓						✓					✓		Au
Chieregati *et al.*[10]			✓	✓	✓			✓						Au, Cu
Crawford *et al.*[11]			✓	✓					✓			✓		Fe
El Hajj *et al.*[12]			✓	✓		✓		✓						Au, Cu
François-Bongarçon[13]			✓							✓	✓	✓		—
Goers *et al.*[14]		✓			✓					✓				Au
Gomes *et al.*[15]	✓						✓					✓		Au
Hapugoda *et al.*[16]			✓			✓			✓					Au, Cu
Hapugoda *et al.*[17]	More or less the same article as above, published in a different forum.													
Holmes[18]	✓											✓		—
Holmes[19]	✓								✓			✓		—
Hoogvliet[20]			✓				✓		✓					Au, Ag
Kirk *et al.*[21]			✓			✓			✓					Pt
Magri *et al.*[3]	✓						✓						✓	Au, Cu
Magri *et al.*[22]			✓	✓		✓			✓					Cu
McArthur[23]	✓											✓		Fe
Minkkinen *et al.*[24]	✓			✓								✓		Fe
Niemeläinen *et al.*[25]			✓		✓	✓					✓			Cu, Ni
Ortiz *et al.*[26]			✓					✓	✓				✓	Au, Cu
Pitard[27]	✓	✓								✓		✓	✓	—
Pitard[2]			✓					✓	✓				✓	—
Séguret[28]	✓					✓						✓		Cu
Spangenberg *et al.*[29]		✓						✓	✓					Au
Young[30]			✓		✓			✓	✓			✓		Zn, Pb, Ag
Ziegelaar *et al.*[31]	Abstract only, no paper was prepared for this presentation													

primary sampling stage, before economic, logistical or other (local) factors are allowed to intervene. What is the objective to analyse and to make decisions in the mining industry, based on samples that can be documented not to be representative?

References

1. P. Carrasco, P. Carrasco and E. Jara, "The economic impact of correct sampling and analysis practices in the copper mining industry", *Chemometr. Intell. Lab. Syst.* **74,** 209–213 (2004). doi: https://doi.org/10.1016/j.chemolab.2004.04.013
2. F.F. Pitard, "Blasthole sampling for grade control—the many problems and solutions", in *Proceedings Sampling 2008*. The Australasian Institute of Mining and Metallurgy and CSIRO, Perth (2008).
3. A. Magri, E. Magri and C. Neira, "Blasthole sampling validation at Mantoverde", in *Proceedings 5th World Conference on Sampling and Blending*, Santiago (2011).
4. M. Abzalov, B. Menzel, M. Wlasenko and J. Phillips, "Grade control at the Yandi iron ore mine, Pilbara Region, Western Australia—comparative study of the blastholes and reverse circulation holes sampling", in *Proceedings Iron Ore*. The Australasian Institute of Mining and Metallurgy and CSIRO, Perth (2007).
5. M.Z. Abzalov, B.B. Menzel, M.B. Wlasenko and J.B. Phillips, "Optimisation of the grade control procedures at the Yandi iron-ore mine, Western Australia: Geostatistical approach", *Trans. Inst. Min. Metallurg. B* **119(3),** 132–142 (2010). doi: https://doi.org/10.1179/1743275811y.0000000007
6. M. Alfaro, "Blast hole sampling in two areas of the same deposit", in *7th World Conference on Sampling and Blending*, Bordeaux (2015).
7. A.D. Caccioppoli and M.J. Candy, "Iron ore grade control for flitch mining – an alternative method for the Hope Downs Operation, Hamersley Province, Western Australia", in *Proceedings Eighth International Mining Geology Conference*, Queenstown (2011).
8. A.C. Chieregati and F.F. Pitard, "The challenge of sampling gold", in *Proceedings 4th World Conference on Sampling and Blending*, Cape Town (2009).
9. A.C. Chieregati, B.B. Frontini, D.B. Carvalho, F.F. Pitard and K.H. Esbensen, "Experimental validation of new blasthole sampler for short-term planning", in *Proceedings 5th World Conference on Sampling and Blending*, Santiago (2011).
10. A.C. Chieregati, T. El Hajj, C.F. Imoto and L.E. Pignatar, "Validation of reverse circulation drilling rig for reconciliation purposes", *TOS forum* **Issue 5,** 105–110 (2015). doi: https://doi.org/10.1255/tosf.58
11. D. Crawford, P. Leevers, S. Parsons, G. Solly and S. Nielsen, "Grade control in the Southern Middleback Ranges—a case study", in *Proceedings Iron Ore 2005*, Fremantle (2005).
12. T. El Hajj and A.C. Chieregati, "Illusory reconciliation: compensation of errors by manual sampling", *Proceedings 5th World Conference on Sampling and Blending*, Lima (2013).
13. D. François-Bongarçon, "Are blasthole samples that bad and reverse circulation samples that good for open pit grade control story of a trade-off", in *Proceedings Sampling 2010.* The Australasian Institute of Mining and Metallurgy and CSIRO, Perth (2010).
14. M. Goers and M. Almond, "Bit to bag—the importance of a total coordinated system in reverse circulation drilling", in *Proceedings Sampling 2012*. The Australasian Institute of Mining and Metallurgy and CSIRO, Perth (2012).
15. W.L. Gomes, A.C. Chieregati, H. Delboni and D.B. Carvalho, "Mine-to-mill reconciliation variability study of blast hole sampling in Serra Grande gold mine", in *Proceedings 5th World Conference on Sampling and Blending*, Santiago (2011).
16. S. Hapugoda and J.R. Manuel, "A comparison of drilling and sampling techniques as they relate to base and precious metal exploration in the Mt Isa inlier of North West Queensland and the Southern Lachlan Fold Belt in New South Wales", in *Proceedings Sampling 2010*. The Australasian Institute of Mining and Metallurgy and CSIRO, Perth (2010).
17. S. Hapugoda and J.R. Manuel, "Techniques used and problems encountered in normal and reverse circulation drilling at the Mt Roseby Project, Cloncurry, North West Queensland", in *Proceedings XXV International Mineral Processing Congress*, Brisbane (2010).
18. R.J. Holmes, "Correct sampling and measurement—the foundation of accurate metallurgical accounting", *Chemometr. Intell. Lab. Syst.* **74,** 71–83 (2004). doi: https://doi.org/10.1016/j.chemolab.2004.03.019
19. R.J. Holmes, "Sampling mineral commodities—the good, the bad and the ugly", *J. S. Afr. Inst. Min. Metall.* **110,** 269–276 (2010).
20. H. Hoogvliet, "Drill blast versus reverse circulation grade control sampling—a case study from the Mt Muro gold silver mine, central Kalimantan, Indonesia", in *Proceedings Fifth International Mining Geology Conference*, Bendigo (2003).
21. G. Kirk, T. Muzondo and D. Harney, "Improved grade control using reverse circulation drilling at Mogalakwena Platinum Mine, South Africa", in *Proceedings Eighth International Mining Geology Conference*, Queenstown (2011).
22. E. Magri and J.M. Ortiz, "Estimation of economic losses due to poor blast hole sampling in open pit mines", in *Proceedings of 6th International Geostatistics Congress*, Cape Town, Vol. 2, pp. 732–741 (2000).
23. G. McArthur, C. Jones and M. Murphy, "Blasthole cone sampling experiments for iron ore flitch mining", in *Proceedings Sampling 2010*. The Australasian Institute of Mining and Metallurgy and CSIRO, Perth (2010).
24. P. Minkkinen, I. Auranen, L. Ruosalainen and J. Auranen, "Comparison of sampling methods by using size distribution analysis", *TOS forum* **Issue 5,** 175–185 (2015). doi: https://doi.org/10.1255/tosf.63
25. E. Niemeläinen, J. Raatikainen, J. Siikaluoma and I. Auranen, "Comparison of traditional and novel on-line blast hole sampling in ore grade control", in *Proceedings 5th World Conference on Sampling and Blending*, Santiago (2011).
26. J.M. Ortiz and E.J. Magri, "Designing an advanced RC drilling grid for short-term planning in open pit mines: three case studies", *J. S. Afr. Inst. Min. Metall.* **114,** 631–637 (2014).
27. F.F. Pitard, "New sampling technologies for ore grade control, metallurgical accounting, and laboratory preparation", in *Proceedings MetPlant 2004*, Perth (2004).
28. S.A. Séguret, "Geostatistical comparison between blast and drill holes in a porphyry copper deposit", *TOS forum* **Issue 5,** 187–192 (2015). doi: https://doi.org/10.1255/tosf.51
29. I.C. Spangenberg and R.C.A. Minnitt, "An overview of sampling best practice in African mining", *J. S. Afr. Inst. Min. Metall.* **114,** 91–102 (2014).
30. B. Young, "From blasthole to RC sampling—changing grade control methods at Black Star open cut zinc-led mine, Mount Isa, Queensland", in *Proceedings Eighth International Mining Geology Conference*, Queenstown (2011).
31. B. Ziegelaar, P. Bleakley, G. Lee and R. Millington, "Grade variations from various drilling methods in Darling Range bauxite", in *Proceedings Sampling 2010*. The Australasian Institute of Mining and Metallurgy and CSIRO, Perth (2010).