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Quantifying error and bias in sampling thin carboniferous reef types

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QUANTIFYING ERROR AND BIAS IN SAMPLING THIN CARBONIFEROUS REEF TYPES

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Masters in Engineering.

13st October 2015

DECLARATION

I Andries Fourie Student no 343784 declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

_____

Dries Fourie

_____day of_____ 2015 in _____

ABSTRACT

This study examines the history of underground face sampling since the earliest writers documented their findings regarding the method. An historical review of the errors associated with sampling is followed by a discussion of findings from a number of underground investigations. The thesis examines how errors introduced during and after sample extraction are responsible for error and bias. A Simulated Chip Sample Model was created and used to evaluate the nature of sampling errors and bias. Learning's from this model include an understanding of the effects of sample extraction on variations in grade and precision. The effects of sample shape on error were considered and the aspect ratio of the sample was found to be a critical factor in minimising error It was found that if the homogeneity of the ore material decrease the error increase proportionally, despite the extraction error remaining constant. During extraction the material will be biased and the effect of using accumulation values will amplify the error and bias in samples; the error and bias in this case is secondary and has nothing to do with the extraction error. The historical ideas about error being a consequence of the nugget effect have been shown to be false; variability between samples in this case is a direct result of poor sample extraction rather than the occurrence of large gold grains in the ore.

The thesis also identified sources of sampling bias and two distinct types, namely the soft-reef bias and waste-discard bias were identified. The perception that soft-reef bias is the main contributor to the deterioration of the MCF was found not to be the case. This finding is based on a comparison between chip sampling and perfect sampling, in the form of so-called "coffin samples", that indicated there is no bias between these sample types. Other possibilities for sample error and bias were investigated and found to be related to human preference for selecting material that had to be discarded during or immediately after the sample had been taken. This was confirmed by a survey of 70 samplers with different experience levels and from different mines, who indicated the same preferences when selecting material they chose to discard from the sample material collected. The waste-discard bias is a better contender for introducing bias serious enough to affect the MCF because it occurs at each and every sample site, unlike the soft-reef bias. This type of bias was shown to mimic the soft-reef bias using the Simulated Chip Sample Model.

Chip sampling has been the simplest and at the same time most misunderstood sampling method there has ever been, but it has stood the test of time and is shown to be without a meaningful replacement. Despite the appearance of poor extraction compared to other methods, chip sampling is an acceptable technique when one understands and eliminates biases during and after extraction.

DEDICATION

This project is dedicated to my family with special mention to my wife, Michele, who has been very supportive during my preparation of this document. My family's understanding and patience over this period is truly appreciated.

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LIST OF ACRONYMS

Analytical error	*AE*
Broken ore sample preparation	*BOSP*
Code of practice	*COP*
Certified reference material	*CRM*
Centimeter gram per tonne	*Cmg/t*
Council for Scientific and Industrial Research	*CSIR*
Fundamental sampling error	*FSE*
Group and segregation error	*GSE*
Half Absolute Relative Difference	*HARD*
Historical Data Weighting Error	*HDWE*
Increment delimitation error	*IDE*
Increment extraction error	*IEE*
Increment preparation error	*IPE*
Increment weighting error	*IWE*
In-situ nugget effect	*INE*
Mine call factor	*MCF*
Quality assurance and quality control	*QAQC*
First world conference on sampling and blending	*WCSB1*
South African Code for Reporting of Exploration Results,	
Mineral Resources and Mineral Reserves	*SAMREC Code*
Standard operating procedure	*COP*
Theory of sampling	*TOS*
Total sampling error	*SE*

GLOSSARY

The descriptive terms used in this thesis are those which have been widely accepted and used in the same sense by other authors. Many of the definitions have been extracted with little or no modification from the descriptive glossaries of De Jager (1997).

Apparent Gold Loss:

Occurs in the gold called for side of the equation and is in all probability gold that was not there in the first instance.

Gold Accounted For:

Is the gold produced in the plant, as well as the gold accounted for as lost in the plant's residues.

Gold Called For:

Includes the gold called for from all sources expressed in grams. It could include that from stopes, development and old areas in certain instances.

Real Gold Loss:

occurs within the mining and recovery cycle and can be prevented to a certain extent.

Unaccounted Gold:

Is the difference between the gold called for and the gold accounted for. is a theoretical gold loss that can be split into apparent gold loss and real gold loss.

CHAPTER 1 – INTRODUCTION

1.1 Purpose of the study

The purpose of this study is to examine and understand the magnitude of the random and systematic errors that are introduced during the practical implementation of the chip sampling protocol in the underground gold mines of South Africa. Many millions of chip samples have been collected by the unsung band of heroes known as “samplers” from the stope and reef exposures in deep level Witwatersrand type mines since the beginning of the exploitation of these reefs in 1886. Over the years since the start of gold mining the tools of choice for extracting chip samples was the hammer and chisel because the tools are reasonably manageable, relatively light and can be directed to a specific point on the reef. Numerous studies have been undertaken to try and quantify the error associated with chip sample extraction, especially when extractions are performed in-situ with the current tools of choice “the hammer and chisel” on a narrow carboniferous reef type. Previous research by Beringer, (1938); Cawood (2003); De Jager (1997); Fourie and Minnitt (2013); Freeze (2013); Harrison (1952); Hallbauer and Joughin (1972); Jackson (1946); Lerm (1994); Magri and Mckenna (1986); Muller (1950); Sichel (1961) and Storrar (1987) have indicated that the current tools generally extract samples of poor quality.

One of the principle reasons for poor sample extraction is due to the hardness of the material being sampled, which prevents the sampler from extracting a sample of the exact shape, volume, mass and position as demarcated on the reef face before the chipping takes place. In cases where the reef type to be sampled is not homogenous and consists of material of varying hardness such as the carboniferous reef, it was observed that the application of the hammer and chisel tends to oversample the softer high grade portions and under sample the harder surrounding host rock (De Jager, 1997; Lerm, 1994; Sichel, 1947; Storrar, 1981). It is believed that consistent oversampling of the softer high grade material could introduce serious bias that may overestimate the overall grade by as much as 16 per cent (Cawood, 2003).

The study by De Jager (1997) created a perception among the mining personnel that most of the unaccounted gold calculated by the Mine Call Factor (MCF) is a direct

result of poor sampling practice. The MCF is a ratio that calculates the gold unaccounted for by comparing the 'gold called for' with the 'gold accounted for' (Storrar, 1987). Gold called for is what the expected gold content is for an area of flat lying placer reef, whereas gold accounted for is gold metal actually poured after the processing and recovered by the carbon and leach process. According to De Jager (1997) the unaccounted for gold is a theoretical gold loss which is a combination of 'real gold loss' and 'apparent gold loss'.

Poor extraction is not limited to carboniferous reefs only, but occurs on other more homogenous reefs as well. The true impact of poor sampling practices and its linkages to a deterioration of the MCF is not well understood. Over the years many studies on the MCF have been undertaken, but none of them has provided a definitive solution to the unfavourable position that the mining industry currently finds itself in where the actual origin and source of errors and bias from mining and sampling is left unchallenged. A comprehensive study is therefore essential to identify exactly how the limitations of the tools, in application to sampling specific reef-types, is responsible for introducing error and bias.

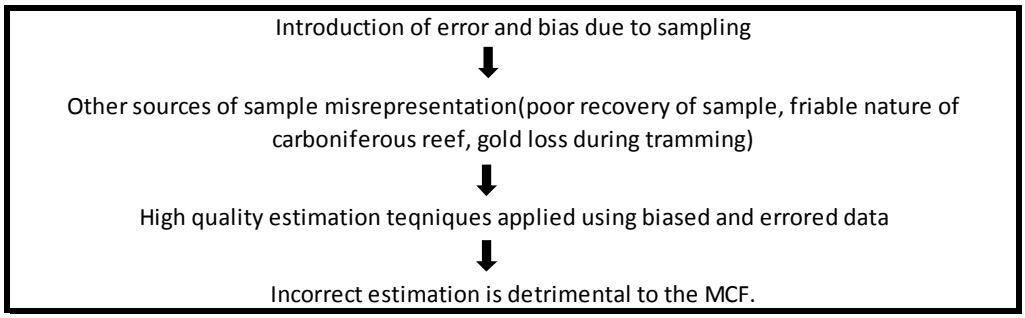


Figure 1.1: The impact that incorrect chip sampling has on the estimation and ultimately the MCF.

1.2 Expected benefits from the Research

Understanding the cause of the errors and the effect thereof may help to improve the current sampling protocol with mitigation or intervention. It is not the intention of this research to improve the MCF for any particular mine or shaft, but rather to understand and manage the risk associated with this specific method of sample extraction. If the error or bias introduced with chip sampling is found to be significant and could be reduced with intervention, then by implication the MCF should automatically improve.

The detailed research by Cawood (2003) has indicated that for every percentage decrease in the sampling value, there is the same percentage increase in the MCF. If management is made aware of the limitations of the current sampling method they may invest more resources in terms of development and training to improve the quality of sample extraction than is currently the case. Management may also find that despite its poor reputation, the gold values obtained with chip sampling are within acceptable limits. The deterioration of the MCF could come from other processes in the mining chain that have not been previously considered.

"*It is easier to perceive error than to find truth, for the former lies on the surface and is easily seen, while the latter lies in the depth, where few are willing to search for it*." (Johann Wolfgang von Goethe (1749-1832) German poet, novelist and dramatist.).

1.3 Importance of this Research

Despite all previous investigations done to understand exactly how chip sampling introduces errors during and after extraction, there is still little known about its actual contribution to the deterioration of the MCF. The aim of this research is to develop a deeper understanding of how errors are introduced at each stage of the sampling process. It is just as important to quantify the extent of uncertainty on the accuracy and precision of the results. There is also a perception in the sampling profession that the sampling errors generated from chip sampling are greatly reduced because of the large number of samples collected. Errors obtained on individual samples taken at the face could be significant and provide misinformation leading to bad decisions and ultimately result in financial losses.

Largely depleted ore bodies from which most of the high grade resources have been extracted together with ever increasing costs, are enforcing higher cut-off grades. To remain economical and profitable the remaining ore body must be mined more selectively than ever before (Minnitt, 2007). To do so successfully the precision and accuracy of the samples extracted will have to improve. This will only be possible with improved understanding of how the errors are introduced during extraction.

1.4 Research Questions

The typical carboniferous reef in the Witwatersrand basin is viewed as a single entity in terms of its economic extraction because the gold mineralisation is distributed across the full extent of the reef face. On a more detailed scale the reef actually consists of two components, the thin (1 mm - 20 mm) softer, more brittle carboniferous reef, which is usually overlain by a quartzite conglomerate that may be matrix or pebble supported. Research by others indicates that sample extraction with the current sampling equipment is not suited to use on the thin carboniferous reefs because oversampling on the softer carboniferous reefs, which may contain as much as 80 per cent of the gold introduces significant bias (Cawood, 2003; De Jager, 1997; Lerm, 1994; Sichel, 1961; Storrar, 1987). The independent variables contributing to the error or bias are not well understood and this thesis is designed to bring the much needed clarity to the problem No workable solution was found to eliminate the bias introduced when sampling thin carboniferous reefs, despite all the investigations and recommendations done to date. The following considerations and questions are points that have arisen over the years in the writers experience and will guide the research:

1. Is it possible that a 22mm flat cold chisel and a 4 pound hammer in the hands of an experienced sampler are capable of extracting a sample with the exactly delimited shape, size and volume required by the protocol, from a very hard in situ reef? Although other methods have been tried, the millions of chip samples have classically been extracted with the hammer and chisel.

2. If it is not possible, how does this affect the accuracy and precision of the sample assay values?

3. How is it possible to quantify the error associated with this sampling method if there is no benchmark with which to compare it?

4. What is the main cause of sampling error: is it the limitations of the tools or the heterogeneity of the material that varies in hardness and grade, or is it a combination of the two?

5. If sample extraction is totally random then the error should cancel itself with large amounts of data, why then in most cases is the gold called for always

higher than the belt grade for carboniferous reefs? If the error associated with extraction is totally random then over a large number of samples the error should be self-compensating. If this is the case why then is the gold called for always higher than the belt grade for carboniferous reefs?

6. Does the experience of a seasoned chip sampler have any influence on the quality of the sample extracted?

7. How much variance is poor extraction contributing to the overall nugget effect?

8. Does an increase the mass of the sample, especially when sampling thin carbon reef types really reduce the extraction error or does it only cause a reduction in sampling variance?

9. Will perfect chip sample extraction minimise error and eliminate bias?

10. Why do some shafts have better MCF's than others, even though they employ the same sampling method?

11. Is oversampling of the softer portions and under sampling of the harder portions the only source of bias? How much carbon is required to introduce bias? In the event that the carbon contact is only 1mm thick, would oversampling still be possible?

1.5 Hypotheses

i. Poor extraction achieved with chip sampling introduces error and bias- The bias could be quite significant when sampling the thin carboniferous reef types. This is based on the observation that the softer gold bearing material is over extracted in relation with the harder surrounding material. The result is a sample that is bias towards the gold bearing material thus overstating the true in situ grade. Constant oversampling will introduce a bias whereby the gold called from underground sampling will always overestimate the grade. This will cause a shortfall of gold when calculating the MCF that was not really there in the first place.

ii. The magnitude of the error or bias as a result of poor extraction is directly dependent on the heterogeneity and composition of the type of reef sampled. It is believed that the bias and error increases proportionally with the amount of waste included in a sample. Thin carboniferous reefs with a high ratio of waste to reef are especially vulnerable to this bias.

CHAPTER 2 – LITERATURE REVIEW

2.1 Introduction

The sampling of tabular ore bodies in South Africa has a long history and became highly developed when mining started on the Main Reef conglomerates in the Transvaal (Storrar, 1987). The frequency with which the reefs were sampled increased rapidly to maintain a steady supply of reliable information necessary for grade estimation and grade control (Cawood, 2003). Initially the sampling protocol was developed for very homogeneous tabular reefs with thicknesses of about 100 cm or more and managed to deliver acceptable results. The discovery and mining of the thin Carbon Leader Reef brought with it new challenges in regard to sampling that was not addressed by the status quo (Cawood, 2003). Most of the mines that were extracting the thin, high-grade carbon-rich reefs experienced much lower MCF compared to mines that were mining the thicker reefs at lower grades. The gold “called for” from the stopes was significantly higher compared than the gold actually accounted for. Identifying a single cause for the MCF problem is compounded by the contributing factors which include aspects related to sampling, survey, evaluation and mining. The interaction between these factors also means that quantifying the MCF and laying the cause at the foot of a single variable is not possible (Cawood, 2003).

Initial investigations done on the MCF identified sampling as a possible culprit because of the poor sample extraction achieved with this method. It was observed that oversampling of the soft carbon-rich portions was common and could result in overestimation the face grade and inclusion or exclusion of waste from a sample could affect the accuracy of the reported grade (Sichel, 1947). Applications of alternative sampling methods managed to improve the extraction of the sample, but were never successfully implemented due to the difficult underground environment. Despite its dubious reputation, chip sampling remained relatively unchanged, and is still the preferred method employed in most South African underground mines.

2.2 Historical Background of Underground Sampling

2.2.1 The Definition of Sampling

Harmony Gold Mining Company Limited (Harmony) is the third largest gold mining company in South Africa and their Sampling Code of Practice (COP) defines sampling as *"the process whereby the average value of a number of small portions or samples of an ore deposit taken uniformly over its full width and at predetermined intervals, is used to estimate the average value of a much larger part of the whole. The greater the number of samples taken, the more accurate is the subsequent valuation"*. (COP, 2006: p4)

2.2.2 Purpose of Sampling

The purpose of sampling on a typical gold mine is to establish whether an ore body contains enough metal to be mined economically in the future. This information is obtained by extracting small representative samples from the in situ ore by means of core drilling, pitting, trenching, or mining (Storrar, 1986). If a mine opens up, all new on-reef exposures are sampled and the data are used to estimate the payable and un-payable reserves. Minnitt (2007) says that development and stope sampling is one of the most important activities in a mining operation and that it provides information about the analytical results which are used to make decision about a course of action. The information is also used to direct the development for future mining. When production commences, regular sampling of the panels is maintained for the purpose of grade control. Sampling is also done to monitor the grade of the ore in transit from the face to the plant. This sampling process is usually mechanised and may occur at various locations during hoisting, transport to and treatment at the plant.

2.2.3 Underground Sample method

Groove or channel sampling is the most widely applied sample method used on South African mines and remained almost unchanged in the last 100 years. Samples are extracted from a solid face by cutting a groove (or channel) 10cm wide and 2cm deep at varying widths across the ore body with a hammer and chisel. A sample is considered to be good if it is cut to an even depth, rectangular in shape with square corners (Storrar, 1987). With the current tools and time allocated to do the job it is

impossible to achieve the physical dimensions called for by such a method of extraction. Anything other than a 'good sample' is considered a waste of time and money (Figure 2.1) and should not be accepted (COP, 2006). If this criterion for accepting or rejecting a sample was strictly enforced then the current data bases would have significant less data, if not empty. On South African mines the term "*Chipping*" and or "*to chip*", generally refer to the physical act of chiselling or chipping out a groove or channel sample with a hammer and chisel (Storrar, 1987). Chip sampling referred to in this research has the same connotation as channel or groove sampling mentioned above.

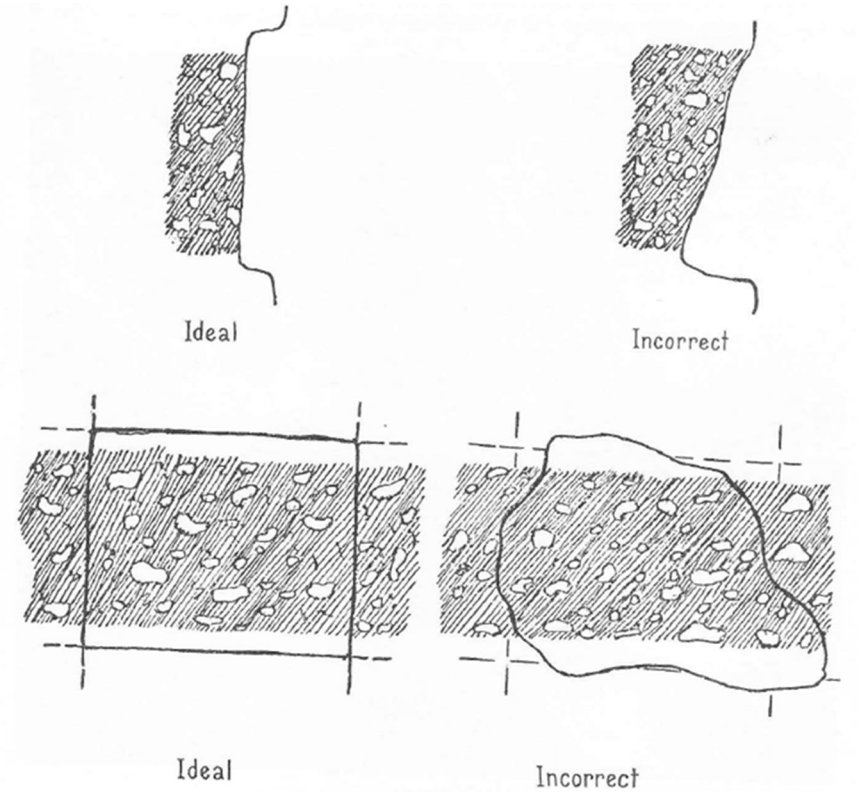


Figure 2.1: Diagram indicating what a good sample should look like (Storrar, 1986:44)

2.2.4 Sampling Tools.

Since the start of mining in South Africa, before the advent of power tools the preferred tool for underground face sampling consisted of a 1.8 kg hammer and 22 mm chisel. These are the ideal tools for sample extraction in the very physically demanding underground environment because they do not require services in the form of air or electricity to operate. It is considered fast and economical, but has some serious limitations in its ability to extract a demarcated sample from the very hard quartzite

host rocks. During the early years of sampling Hoover (1933) observed that it was very difficult to achieve proper extraction with the tools provided and said that people responsible for the extraction must be diligent when extracting samples. Sichel and Rowland (1961) also mention it was almost impossible to chip a perfectly uniform sample after observing the method underground. In a more recent study where chip sampling was compared to a gold analyser, Lerm (1994) also said that it was virtually impossible to chip a sample uniformly and to an even depth. This is due to the contrast of the hardness present in the reef band. In a study based on the observation of samples extracted from five different AngloGold Ashanti mines, Spangenberg (2012) commented that perfect delimited sample extraction is almost never achieved. Freeze (2013) also reported that observations based on moulds of chip samples found that the samples were unbalanced and irregular. The observations also found that the depth of the samples were not consistent and wedging towards the bottom. It was also found that the demarcated sample area was not always chipped. Despite its poor extraction no consistent bias could be identified. The author has almost 22 years experience in the mining industry specifically in sampling and in all the years of observing underground sampling perfect extraction of a sample has never been observed.

It is generally accepted that underground chip sampling introduces error and bias because of poor sample extraction. The available literature does not provide any indication of how to quantify the percentage error or bias introduced during sampling extraction. Some theories have been developed during the history of sampling, but insufficient statistical analysis has been done to convince practitioners of the types and the size of errors introduced by the chip sampling method. Sichel (1947) identified that quantification of sampling error is difficult because of the nature of sampling and the nature of the lot being sampled. Today more than a century on and despite the many technical advances in powertools and their applications, mining companies are still using the hammer and chisel as the preferred method for sample extraction. This is not because alternative methods and tools were not investigated but it is due to the very difficult conditions presented at a stope face and the very hard nature of the material to be sampled.

2.2.5 Characteristics of the reef

In South Africa most of the underground sampling is done on exposed gold bearing tabular ore bodies situated in the Witwatersrand Goldfields. The Witwatersrand Goldfield is a 350 km arcuate basin (Figure 2.2) that stretches east and west of Johannesburg and southwards into the Free State (Viljoen, 2009).

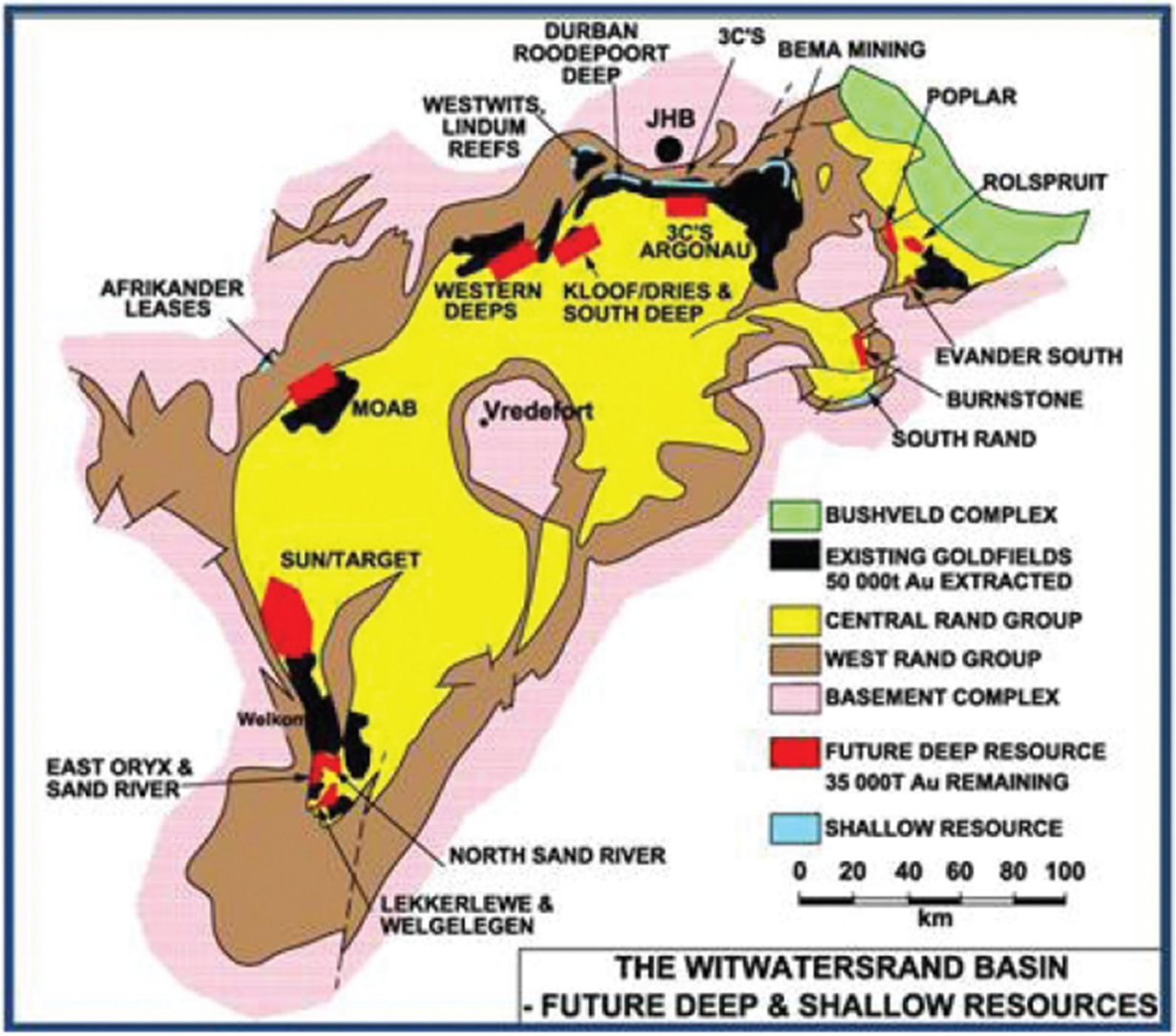


Figure 2.2: Major geological features of the Witwatersrand basin showing major goldfields (Viljoen, 2009:131)

The reefs of the Witwatersrand conglomerates are a heterogeneous blend of mineralised and un-mineralised material. Often, the mineralised portion of the rock is preferentially softer due to the presence of seam carbon. This blend of mineralised and un-mineralised material influences the error or bias of the sample extracted.

Early chip sampling methods were developed on the Main Reef, Main Reef Leader Reef and Kimberley Reefs which had a high degree of grade continuity and relatively thick channel widths (Cawood, 2003). Sampling of these reefs was considered accurate and no warnings or special recommendations when sampling these thicker reefs are recorded in the literature. Inclusion or exclusion of waste in the sample did not make a difference to the accuracy of the grade (Beringer, 1938). Magri and McKenna (1986), in a comparison between chip sampling and diamond cutting, do not mention any oversampling of softer material.

Problems associated with sampling of the thin high grade carboniferous reef types using the current sampling tools is related to the observation that samplers tend to oversample the soft reef portions and under sample the harder waste portions. Cawood (2003) stated that “The literature survey revealed that, given the nature of narrow carboniferous-type reefs, traditional gold mine sampling techniques are likely to over-estimate the gold content in the reef by as much as thirty per cent”.

Sichel (1947) noted that over representation of the softer conglomerate in a sample may result in overvaluation of higher than 100%. Harrison (1952) stated that samplers overvalue up to 99% on narrow reefs and Lerm (1994) stated that due to the contrast of hardness between the brittle basal lag and the overlying conglomerate oversampling may exist of up to 20%. De Jager (1997) also observed that samplers tend to oversample the softer carbon portions. Johnson (2012) in a personal communication said they used moulds to measure the actual material removed during sampling and from observing them they found that most of them indicated some sort of oversampling occurring at the contact area.

2.3 Problems associated with chip sampling

The gold mining industry relies on channel sampling of the underground stope faces to provide an indication of gold grades that can be anticipated in the reef that lies ahead of the production crew. This is essential for evaluation processes, and where selective mining is practiced, it also provides the necessary information about whether the reef should be extracted or left in situ (Minnitt, 2007). The act of chip sampling is described by Parks (1949) and Storrar (1987) as being a representative sample that is cut accurately and conscientiously to an even depth throughout the demarcated sample.

In effect a series of continuous channel samples collected from a raise or stope face may be thought of as a highly heterogeneous, one dimensional stream that is cut at regular intervals, rather than a static, two-dimensional face. This is seldom if ever achieved due to the limitation of the tool and the hardness of the material being sampled.

Proper sample extraction determines the success or failure of the sampling protocol Pitard (2009). According to Storrar (1987) a chip sample is only deemed correct when it is chipped to an even depth throughout the area marked. Smith (2001) says that the principles of correct sampling require that each and every part of a lot must have an equal chance of being selected in the sample and that the integrity of the sample should be preserved throughout the process. She also said that correct sampling could only be achieved by correctly defining the sample we will take, and then physically obtaining the sample we have defined. She also warns that if any part of the lot becomes inaccessible or if the sampling tool fails to collect a sample correctly defined, the rules of random sampling have been compromised and this can introduce a bias. If you consider the conditions a sampler encounters underground on a daily basis then the limitations of the sampling tool and the hard material to be sampled makes it very difficult to achieve “correct sampling”

2.3.1 The Operator

The role of the sampler in introducing error during and after sample extraction has been long debated. Beringer (1938) and Jackson (1946) believed that the sampler or operator has a direct impact on the quality of a sample extracted. They insisted that every person employed as a sampler must be trained and technically skilled. Harrison (1952) was convinced that almost all samplers tend to oversample but are doing so unintentionally, especially when they are sampling the narrow reefs. There are many stories and examples of sampler’s committing fraud claiming that a sample was properly extracted when indeed it was actually picked up from the footwall. Samplers would only resort to such tactics when the act of sampling becomes to tiring or difficult. The limitation of the tool to extract a proper sample from the face, places the sampler in a position where he may consider alternative areas which allows for easier extraction. The sampler now becomes a role player in adding error that could have

been avoided if the tool was capable of extracting a perfect sample initially. The only way to remove the sampler from introducing additional error or bias would be to develop alternative sampling tools or methods that would be able to extract representative samples effortlessly (See Chapter 2.5).

2.3.2 Poor Sample Extraction

Incorrect measuring of the sample width was recognised as an additional source of error or bias. The width is used as a multiplying factor to calculate the centimetre gram per tonne value and is especially significant when the sample is not taken correctly and the width not measured accurately (Cawood, 2003).Table 2.1 illustrates the introduction of a 10 per cent error as a result of incorrect sample width measurement. One centimetre over measuring of the true width by one centimetre results in 10 per cent over estimation of the value when calculating the cm.g/t value.

Table 2.1: Impact of 1cm overestimation of reef channel on value (Cawood, 2003: 22).

Category	ChW (cm)	Grade (g/t)	Value (cm.g/t)
True width	10	150	1500
1cm over -measurement			165
Result			10% Error

In Table 2.2 the same example indicates the expected grade from a perfect extraction and illustrates how the incorrect shape of a sample could result in a 17 per cent overestimation of the cm.g/t grade. In Table 2.3 it was assumed that the external waste above and below the reef has been marked, but not sampled, resulting in an over estimation of the grade by 27 per cent.

Table 2.2: Grade expected from perfect extraction (Cawood, 2003; 23).

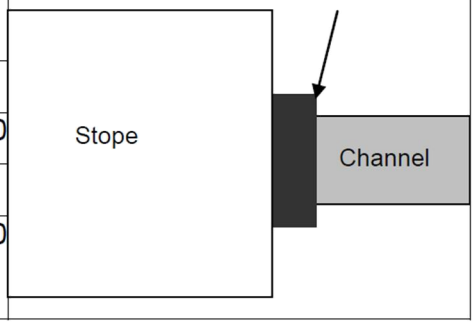
Category	ChW (cm)	Grade (g/t)	Value (cm.g/t)	Sample shape (section)
Waste above reef	2	0	0	
Reef	10	150	1500	
Waste below reef	2	0	0	
Recorded Channel	14	107	1500	

Table 2.3: Incorrect extraction, affecting the grade (Cawood, 2003:23).

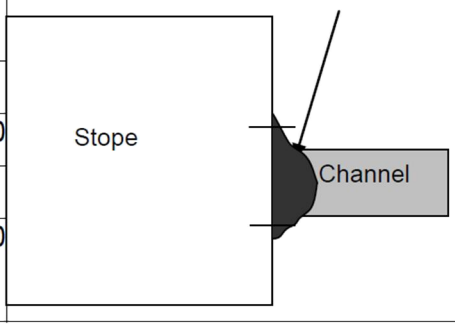
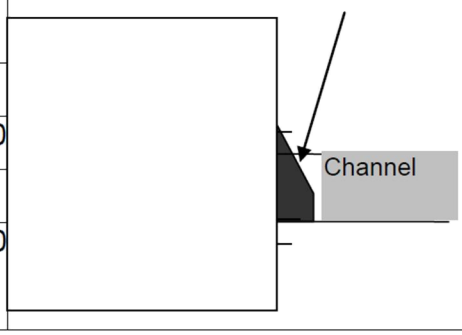
Category	ChW (cm)	Grade (g/t)	Value (cm.g/t)	Sample shape (section)
Waste above reef	1	0	0	
Reef	10	150	1500	
Waste below reef	1	0	0	
Recorded Channel	12	125	1500	

Table 2.4: Oversampling of the contact affecting the grade (Cawood, 2003:24)

Category	ChW (cm)	Grade (g/t)	Value (cm.g/t)	Sample shape (section)
Waste above reef	1	0	0	
Reef	10	150	1500	
Waste below reef	0	0	0	
Recorded Channel	11	136	1500	

Sichel (1947) did not find significant errors associated with sample width measuring and concluded that if errors were introduced then they must be small in comparison to poor sample extraction and can therefore be neglected. Cawood's diagrams capture how incorrect sample shape extracted and inaccurate measuring of the sample width, can lead to over-estimation, especially if the proportion of reef to waste is relatively large.

2.3.3 Over Sampling of the Reef

In a study to investigate the gold losses at Rand Leases an experiment was conducted to test the idea that when sampling narrow reefs the samplers tend to include a much lower percentage of waste resulting in an overestimation (Muller, 1948). The sampling was conducted in a reef drive on the South reef where the reef width was constant at a width of 4cm. Twenty-two diamond drill holes were drilled and sampled along strike at 30cm intervals (Figure 2.3). The holes were then charged with explosives and blasted, which resulted in a continuous face. Sections opposite to each hole were chip sampled in duplicate, one at a vertical width of 10cm and another at vertical width of 15cm.

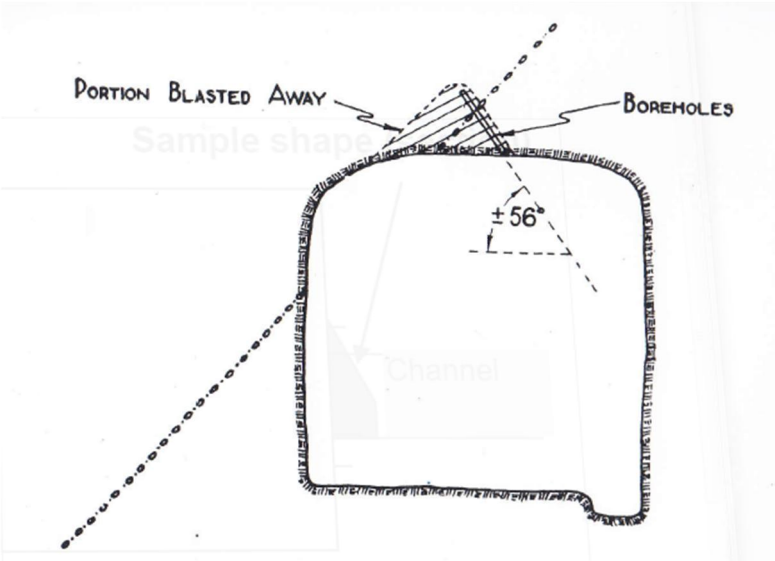


Figure 2.3: Section explaining sample methodology used to test sampling theory (Muller, 1948:575).

A total of 110 samples were chipped at a sample width of 10cm and 15cm and the results indicated that the 10cm samples compare well with the core samples, but that the 15cm samples resulted in a higher cm.g/t (Table2.5).

Table 2.5: The percentage error for chip samples increased as the sample width increases.

	Borehole Cores	Width of Sample	
		10cm	15cm
Average cm.g/t	758	753	958
Percentage Error, assuming boreholes cores to represent true value	0	-0.60%	26.40%

The results from the core sampled at 10cm widths compared well with the results of the chip samples extracted at 10cm. The 15cm chip samples with the additional 5cm of waste were expected to return a lower g/t value and almost similar cm.g/t value as the 10cm samples. However the outcome was counter-intuitive and it was found that the opposite was true. The 15 cm wide samples returned higher grades and Muller concluded that "*Under normal system of sampling, all reefs are probably being overvalued*" (Muller, 1948:576). Muller does not state if the mass of the samples extracted at the 15cm width also increased proportionally. De Jager (1997) conducted a similar experiment which he claims had the same outcome.

Figure 2.4 is a representation of all the possible causes resulting in an apparent gold loss, and sampling is one of them (Freeze 2013).

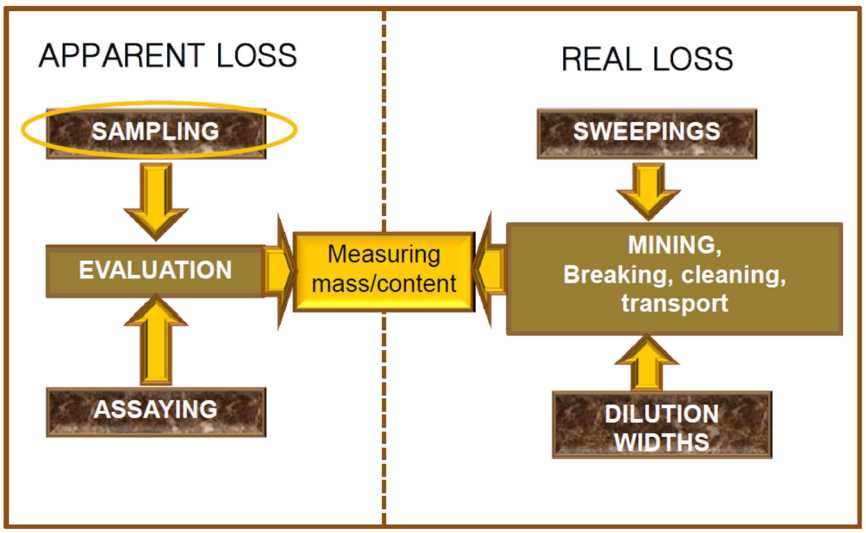


Figure 2.4: Table explaining the differences between factors responsible for real loss and apparent loss. (Freeze, 2013)

Apparent gold loss was first described by (De Jager, 1997) when he found that the correlation between face grade and the MCF for a specific shaft under investigation was statistically insignificant, although he questioned the accuracy of grade estimations. De Jager concluded that most of the apparent gold loss was due to the rudimentary sampling methods and the incorrect relative density applied in the ore reserves (De Jager, 1997). De Jager conducted a "7cm vs. 4cm sampling experiment" to test the theory that inclusion of waste increases the error and tent to overestimate the grade. De Jager compared the grades of two check samples taken next to each

other but with different dimensions. The initial sample included only the reef portion of 4cm and 2cm footwall waste over a horizontal width of 15cm. A second check sample was taken immediately adjacent to the first at 7cm and now included 3cm of internal waste over a horizontal width of 10cm. Although De Jager expected that the g/t value of the 7cm sample to be lower than that of the 4cm sample because of the inclusion of waste, he found that the results between the two datasets were almost identical.

Results indicated that 52 per cent of the time the 7cm samples returned a higher g/t value than its neighbouring 4cm sample (Figure 2.5). The high grades reflected in the 7cm samples could indicate that the extra waste that is included when the samples are demarcated is not extracted. De Jager said that it could also indicate that the portion considered waste in the 7cm sample actually contains some gold.

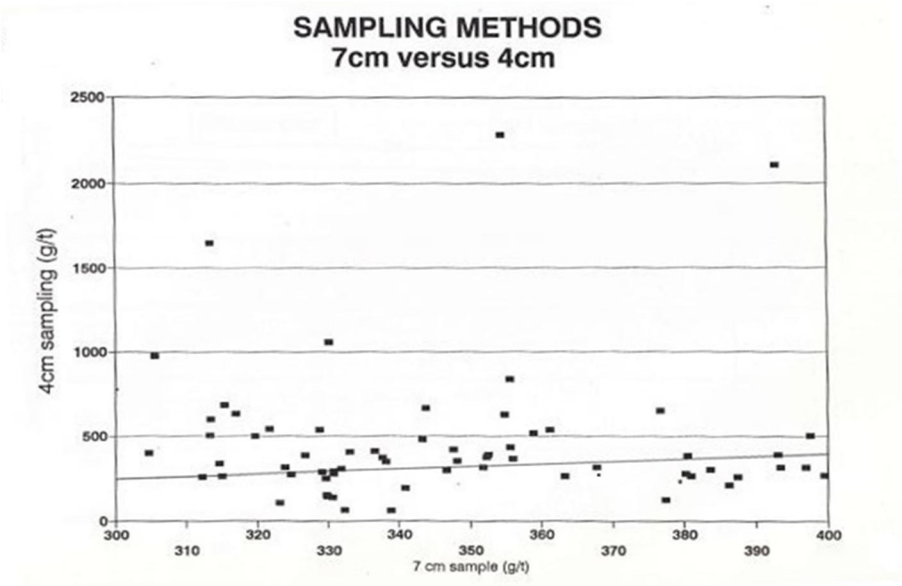


Figure 2.5: Grade comparison done between samples taken at different sample dimensions (De Jager, 1997: 92)

To test if the waste portion carried grade, the experiment was repeated and the waste portion was sampled separately. A diamond saw was used to extract the waste portion of the sample and the results of 0g/t confirmed that there was no gold present in the waste. De Jager (1997) said that it did not explain why the 7cm samples had a higher value and the only explanation remaining was that it could be contributed to the variability of the reef.

The scale used by De Jager to construct the graph (Figure 2.5) is not really representative and a constant scale for the X and Y axis could indicate a different outcome. The actual values for the individual samples depicted in (Figure 2.5) were obtained by scaling of their respected values. Some of the values were rounded due to the large scale and a new graph was constructed (Figure 2.6).

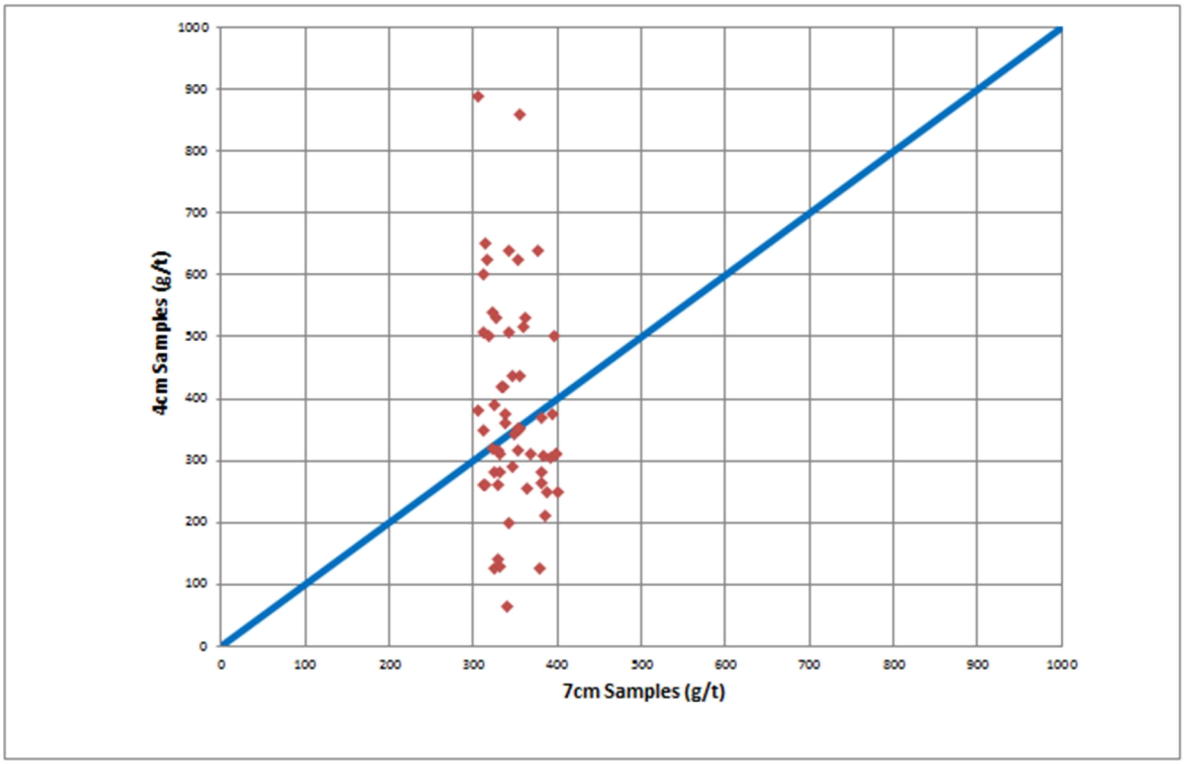


Figure 2.6: New comparisons between samples of different dimensions indicate something artificial happening in the 7cm data.

Table 2.6: Results indicate that 4cm data is more variable than the 7cm data.

	4cm (Samples)	7cm (Samples)
Average (g/t)	472.16	347.71
No Samples	62	62
Std Dev	402.428	27.374

De Jager was correct when he said that 52 per cent of the observations the 7cm samples returned higher values than its adjacent check sample of 4cm. However he failed to mention that on average the 7cm samples returned a lower value of 347.71 g/t compared to the 472.16 g/t of the 4cm samples. The extra waste of 3cm included in

the 7cm sample represents a dilution of 33 per cent ((4cm + 2cm) =6cm and (4cm +2cm +3cm) =9cm Difference = (9cm-6cm)/9cm = 33.3 %)

The grade of the 7cm samples with the extra waste is expected to be about 33.3% lower in grade than that of the 4cm samples. From Table 2.6 it is calculated that the difference is 26 per cent ((472.16 -347.71)/472.16=26%) suggesting that the extra waste diluted the grade of the 7cm samples. There also seem to be a problem with data used by De Jager especially the data obtained with the 4cm sample width. The standard deviation of 402.428 g/t for the 4cm data is much higher than the 27.374 g/t calculated for the 7cm samples. This difference in variability between the two data sets is clearly visible in Table 2.6.

The quality of the 7cm data seems to be much better than that of the 4cm samples.

De Jager's conclusion that the 7cm samples were over estimating the grade is not entirely true. Table 2.6 indicates that inclusion of waste did reduce the g/t value of the 7cm grades by 26 per cent. It would be interesting to know how the two weights of the two datasets compared with each other.

Samples extracted with a hammer and chisel tends to have highly irregular shapes in all three dimensions and to accurately measure their true width is not possible. Storrar, (1987) suggested that the true chipped width should be measured with callipers. While it may be possible to measure the length of the sample extracted it is very difficult if not impossible to measure the true extracted sample shape or width, simply because the extracted materials consist of rock chips. Again it is not humanly possible to extract a perfect geometric shape with the tools that are made available for the task. Poor extraction is the main limitation associated with chip sampling especially if the sampling materials vary in hardness. It is therefore not surprising that almost all the investigators suggested, in one way or another, that an alternative method or tool must be developed that would eliminate the most of the errors due to poor extraction.

Both experiments by De Jager (1997) and Muller (1948) conclude that the inclusion of waste in the demarcation of a sample, effectively dilution, did not significantly decrease the gold grade as expected. In fact the grade in some cases even increased

indicated over estimation of the actual grade. Neither of these investigators provides a plausible explanation for why this may be happening.

2.4 Alternative Tools

The following section covers the contribution and suggestions presented by some of the authors in the historical literature to either;

- Improve extraction by investigating alternative sampling tools like the Diamond saw and gold analyser.
- Mitigate current limitation of the sampling tool by investigating alternative sample methods. Methods include reduction of waste from the demarcated sample, increasing sample mass and applying factors.

There was a strong believe that chip sampling is responsible for introducing errors and bias as a result of its poor extraction capabilities the next logical step was to find alternative sampling methods that would improve the quality of the sample extracted (Freeze, 2013; Hoover, 1952; Sichel, 1947).

2.4.1 The Gold Analyser

2.4.1.1 Chamber of Mines of South Africa Research Organisation (COMRO)-1974

In 1974 the Chamber of Mines of South Africa Research Organisation (COMRO) investigated alternative methods for determination of gold in situ and the radioisotope-excited X-Ray fluorescence (XRF) method showed the most promise (Rolle et al, 1974). The first fluorescence scanner used underground was the actual laboratory equipment enclosed to protect it from the underground environment. The equipment weighed approximately 100 kg and the probe which needed to be mounted on a tripod weighed 11kg when filled with liquid nitrogen. The main aim of this research was to test in situ measurement of the gold content of the reef.

Comparisons were made between chip sampling and the fluorescence method and the tests were done on a stope at the Leslie Gold Mines Limited. The results reported between the two methods were very similar but the variation between the grades done

with the fluorescence method was much lower. The only challenge at that stage was to develop a tool that would allow us to use this technology on a daily basis.

- **Methodology**

The test panel was located in the western area of the mine and on the B-reef. The thickness of the reef band scanned varied from a few centimetres to zero with an average stoping width of 100cm (Rolle et al, 1974).

The sampler marked a continuous row of rectangles 15cm wide and 3cm high along the face. Measurements were made by positioning the probe about 4 cm central in front of each half rectangle. It was calculated that at that position from the solid rock more than 90% of the intensity was received. The scan area was equivalent to a bowl shaped mass 10cm in diameter and 2.5cm deep. The sample viewed by the probe is very constant in its mass and depth and is within 3% irrespective of the condition of the surface or the composition of the reef. This is a big improvement over chip sampling because the sample support remains constant and Increment Delimitation Error (IDE) and Increment Extraction Error (IEE) are minimised. The measurement took about 100 seconds and the content is expressed in g/t or cm.g/t. The demarcated rectangles were then chipped afterwards.

- **Results**

Statistical analysis of the results showed that the mean of the two methods agreed with each other and that in-situ determination of gold by means of a Gamma Ray fluorescence analyser was feasible (Table 2.7). However for it to become practical they would need to develop equipment that is lighter and more robust. They concluded that with the right instrument scanning would be at least ten times faster than chip sampling.

They also found that scanning the reef with the X-ray fluorescence technology, i.e. taking samples over short distances or every few meters may not give a true reflection of the value of a stope. Continuous samples along the face give a better estimate of the true average value. Another advantage of the gamma-ray fluorescence method is that the grades are immediately available and could be used as a tool for ore valuation.

Table 2.7: Comparison of means of fluorescence and chip sampling

Sample group	Fluorescence values:	Chip values:	N
	Mean	Mean	
A	9.7	10.4	11
B	56	56	19
C	77	93	10
D	38	38	23
E	57	69	27
F	120	103	19
G	45	17.7	29
H	38	32	16
A-H	62.9 (σ =60)*	57.7 (σ =72.7)	136
A to F and H	67.9 (σ=64.9)	68.5 (σ =77.6)	107

*σ= standard deviation of mean.

**Group G eliminated because the results were suspect.

2.4.1.2 (COMRO)-1979

In 1979 COMRO tested a portable prototype gold analyser on the Loraine Gold Mine Limited (Davies et al, 1979) and Blyvooruitzicht (Roberts and Lloyd, 1980). Earlier work indicated that the scanner was well suited for the thin high grade reefs with large variation in gold distributions. The effective scan or measuring width of the instrument was about 8cm. With the capability of the instrument in mind they chose two sites on the Carbon Leader at Blyvooruitzicht and one site on the Basal Reef at Loraine.

- **Methodology:**

The experiments on both mines were the same and were designed to allow various methods of valuating the reef. Twenty five stretches of about 30m in length were evaluated for the Loraine Mine and two adjacent panels about 40m long were chosen for the Blyvooruitzicht Mine. The sample pattern shown in (Figure 2.7) was used for this experiment and the sampling procedure was as follows.

- Scan the first meter twice with the instrument
- Mark two 8cm x 10cm wide samples at the centre of each 3m long stretch and measure with the scanner.
- Chip the two 8cm x 10cm samples.

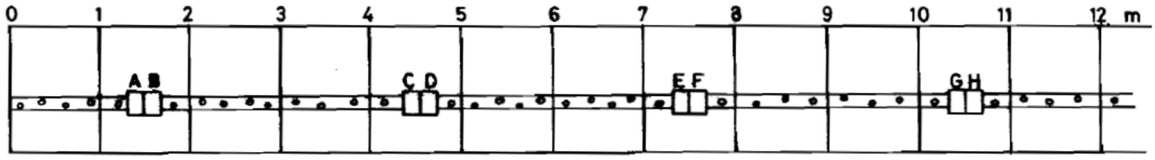


Figure 2.7: Illustration of the sampling procedure (Davies et al, 1979:18)

Over 800m of face length was sampled during a period of 32 shifts.

- **Results**

The experiment was designed to compare the accuracy of the chip sampling method with that of the scanner. Standard statistical techniques were used to determine the accuracy of each method. Statistics calculated indicated that the distribution of the results were very similar for the scanner and the chip method for Loraine (**Table 2.8**)

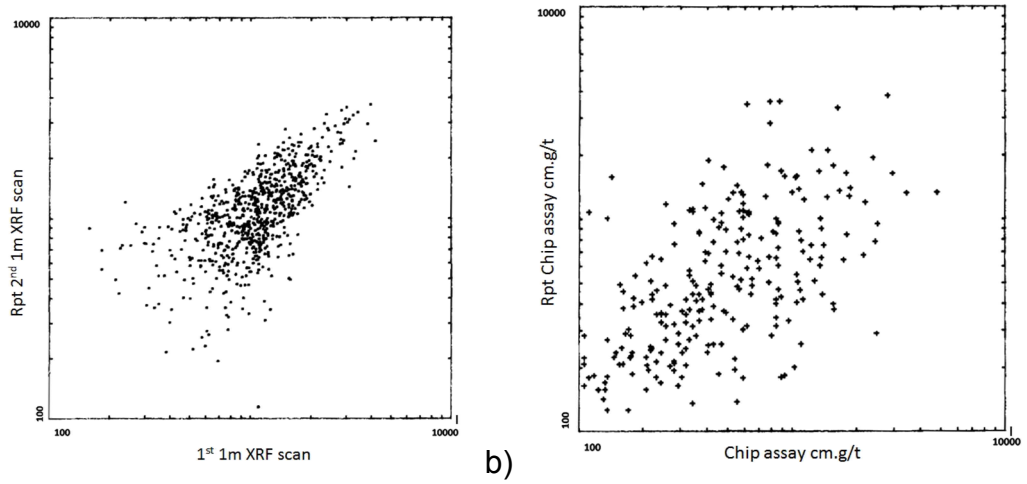
Table 2.8: Reproducibility of each method compared very with each other at Loraine.

Item	Relevant distribution or distributions	Number of samples	Mean	Standard deviation	Null hypothes	Testing statistics	Mean		Conclusion
							Lower	Upper	
1st 1m scan vs 2nd 1m scan	$\log_e$(scan 1+560)-$\log_e$(scan 2+560) (normal)	75	-0.013	0.42	Population mean =0	-0.84			unbiased
Original chip sample vs repeat chip sample	$\log_e$(scan 1+100)-$\log_e$(scan 2+100) (normal)	250	-0.14	0.739	Population mean =0	-0.3			unbiased
All chip samples vs all 1m scans	Chip samples (log n) Pooled log-normal distribution of scan1 and scan2	500 75	555.3 614.3	617.04 566			511.1 577.3	601.9 652.6	probably biased
Chip samples vs spot reading	(Chip 1+ chip 2)/2 (log N with β=100, log var. =0.55) Mean 4 spot samples on equivalent 2 chips. (log N with β=240, log var=0.55)	158 158	576.9 620.7	552.3 692.2			507.6 534.4	651.8 715.2	probably biased

Table 2.9: Reproducibility of each method compared very with each other at Blyvooruitzicht.

Variable	Mean Value	Logarithmic error variance	No. of Measurements	No. of measurements	95% Central confidence limits	
					Lower	Upper
Mean scan	2500	900	0.63	1899	2620	2380
Mean spot	2900	900	0.69	943	3110	2710
Chip	3000	500	1.08	941	3260	2770
Scan 1	2500	900	0.64	1903	2620	2380
Scan 2	2500	900	0.62	1900	2670	2430

The average grade on Blyvooruitzicht is substantially higher than the average grade measured at the Loraine Mine. Comparison of the duplicate chip samples and the 1m scan measurements against each other in Figure 2.8;a;b clearly shows the superiority of the instrument which also indicates increases precision with increase grade.



a) b)

Figure 2.8: A comparison of the results between; a) duplicate 1m scans and b) duplicate chip samples. (Davies et al, 1979:24-25)

The scanner is statistically not biased when compared to chip samples indicating little advantage. The analysers precision increases proportionally with the distance scanned compared to chip sampling. And if the analyser is used to scan 1 m length there would be a major improvement in the estimate compared to spot measurements or chip sampling. Because the time incurred to do the extra scanning is not difficult to achieve this could improve accuracy on identifying payable and un-payable blocks. The analyser was suited for reefs less than 8cm and not yet developed for wider reefs.

2.4.1.3 Lerm 1994

Lerm (1994) conducted a study to investigate the credibility of chip sampling and to test a gold analyser as a possible replacement method. The study was conducted on one of the Vaal Reef shafts that were at that time mining the Stilfontein facies of the Vaal Reef. The reef contained carbon bands ranging in thickness from 1cm to 10cm (Lerm, 1994). A consistent low shaft call factor experienced on the shaft initiated the investigation and underground investigation of the chipping process revealed that the representation of a well-balanced sample was very low. The reef width also varied between 7 cm and 15cm and the basal carbon-rich lag tended to be brittle compared to the overlying conglomerate zone. The difference in hardness present in the reef band made it almost impossible to extract a uniform sample. Oversampling of the softer higher grade contact portion of the reef was observed and Lerm found this to overestimate the face grade by up to 20 per cent. (Lerm, 1994)

Lerm initially tested the Rock Saw as an alternative sampling tool but found it not to be a solution for the problem. Lerm then focused on the CSIR Mining Technology (COMRO) scanner to compare results obtained with regular sampling.

The investigation consisted of three parts of which the first part the scanning was done in –situ on the underground face. Out of a total of 37 panels analysed 12 panels returned values higher than the chip sampling and 24 panels lower than the chip sampling. The panels were also divided into panels with carbon < 1mm and panels with carbon > 1mm. According to Lerm the results indicated undervaluation by the analyser with most of the variance found in the > 1mm panels.

Table 2.10: Comparisons between the mean chip value and the mean analyser value

	Low Carbon Facies < 1mm Carbon	**High Carbon Facies > 1mm Carbon**
Panels sampled	21	16
Sections sampled	180	110
Mean chip value	534 cm.g/t	1943 cm.g/t
Mean analyser value	522 cm.g/t	1147 cm.g/t
Analyser as a % of chip	-2%	-41%

The second part of the scanning was done on surface on four samples extracted from the face. The samples were scanned on one side only before it was send to the lab for assaying. The results of the single scan now indicated overvaluation by the scanner of almost 19 % (Table 2.11).

Table 2.11: Results of scanning four samples on one side only.

Sample	Analyser (g/t)	Assay (g/t)
1	34.8	19.9
2	115	146.1
3	146.5	134.1
4	595	446.4
MEAN	222.8	186.6

The third portion of the investigation scanned 12 samples were brought to surface and scanned on both sides before being sent to the laboratory for assaying. The variance decreased, but Sample 7 and Sample 8 indicated values much higher than any of the other assaying methods. If the two samples were included in the average calculation then it would overstate the grade by 318%. Excluding the two samples would indicate undervaluation of 1.5 % (Table 2.12).

Table 2.12: Results of scanning 12 samples on both sides.

	Fire assay	Aztec	Scan1	Scan2	Scan3
1	89.1	90.1	67.3	70.8	69.05
2	57	57.3	23.8	137.2	80.5
3	12.8	10.6	3.5	30.7	17.1
4	17.9	17	26.2	16.6	21.4
5	18.7	19.7	24.1	15.1	19.6
6	21.3	22.7	27.6	29.8	28.7
7	157.3	163	118.1	2355	1236.7
8	124.4	125.4	389.8	487.8	438.6
9	9.8	9.7	16.9	0	8.45
10	29.7	30.8	0	45.1	22.55
11	66.9	69.9	88.9	34.7	61.8
12	26.1	23.3	31.3	0	15.65
Mean 12	52.58	53.29	68.13	268.37	168.33
Mean 10	34.93	35.11	30.96	38	34.48

Correlation between the scan values and that of the assay was not good. This could be attributed to the fact that the scanner was more sensitive to the distribution and nature of gold situated close to the surface of the sample scanned. A final test was conducted whereby 50 samples extracted from underground were scanned on both sides and the results populated under column headings scan1 and scan 2 in Table 2.12. The samples were then pulverised and quartered into +- 1, 0 kg portions for scanning (scan3) and assaying. Results still indicated a variance between results of the sample surface scan and that of the pulverised scan. Lerm (1994) finally concluded that the nugget effect found on the surface of the extracted sample still existed in the pulverised sample.

The mean values of the pulverised scans were similar to the mean values of the assay results and only differed by 4%. The difference between the grades of the solid scan and that of the pulverised scans differed by -13.9%. Initial results still indicated that in-situ scanning could be overestimating the value by as much as 15.1%. The initial results of the scanner was promising even though it still required more development and testing before it could be used as a replacement for the chip sampling method. Benefits from such a tool would be enormous, in situ scanning would eliminate the need to extract the samples and assaying costs.

The gold analyser never made it past the experimental stage despite initial tests comparing well with the results and reproducibility of chip sampling (Davies et al, 1979; Roberts and Lloyd, 1980; Rolle et al, 1974). Again it could be argued that chip sampling done during the experiment was of a higher standard than was normally performed. The question remains why did development of the analyser was halted when initial experimentation had such a promising outlook.

2.4.2 The Rock Saw

2.4.2.1 Sichel -1961

The “Rock Saw” was one of the first mechanical tools tested as a possible replacement tool for chip sampling, and initial trails were promising (De Jager, 1997; Magri and McKenna, 1986; Sichel, 1961). When conditions on the face where favourable for extraction with this method it managed to extract a sample that was very

representative once the outlines of the sample had been delimited using the rotary diamond saw.

The first model was called a 'C Sampler' (Figure 2.9) and had a 20cm diameter disc with a cutting depth of 5cm and if the grooves were cut to a depth of about 2cm then 4 samples could be chipped per hour (Sichel, 1961). The tool was introduced to be used in the sampling of important reef intersections and also to be used as a benchmark to compare the work of the senior samplers.

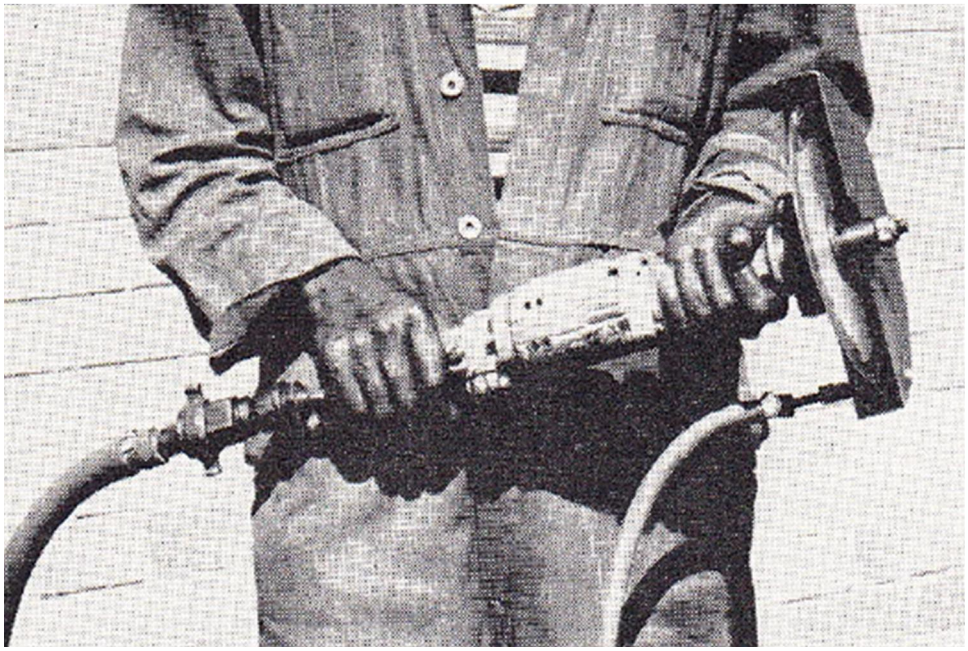


Figure 2.9: The then modern version of the St. Clair sample cutter used to compare with conventional chip sampling. (Sichel, 1961:567)

- **Methodology:**

For the investigation a total of 100 sections were sampled on the Vaal Reef and Western Reef mines. Four samples were demarcated side by side at a particular section. The samples extended over the narrow reef width and included some of the footwall waste. The most experienced sampler was used to chip two samples with unlimited time to ensure a good quality. The remaining two samples were extracted with the diamond cutter.

- **Findings:**

Statistical analysis of the 400 parted assay results indicated that chip sampling was almost as good as machine sampling (Sichel, 1961). Machine sampling was on average only 3% higher than the values obtained with chip sampling. Statistical comparisons did not indicate any bias present in the chip sampling results. Sichel (1961) contributed this to the possibility that the experiment was done under controlled conditions and that normal sampling conditions could yield different results.

Data was also used to test the reproducibility of values from check-sampling. The duplicate check samples were taken either in the same groove or immediately adjacent to the first position.

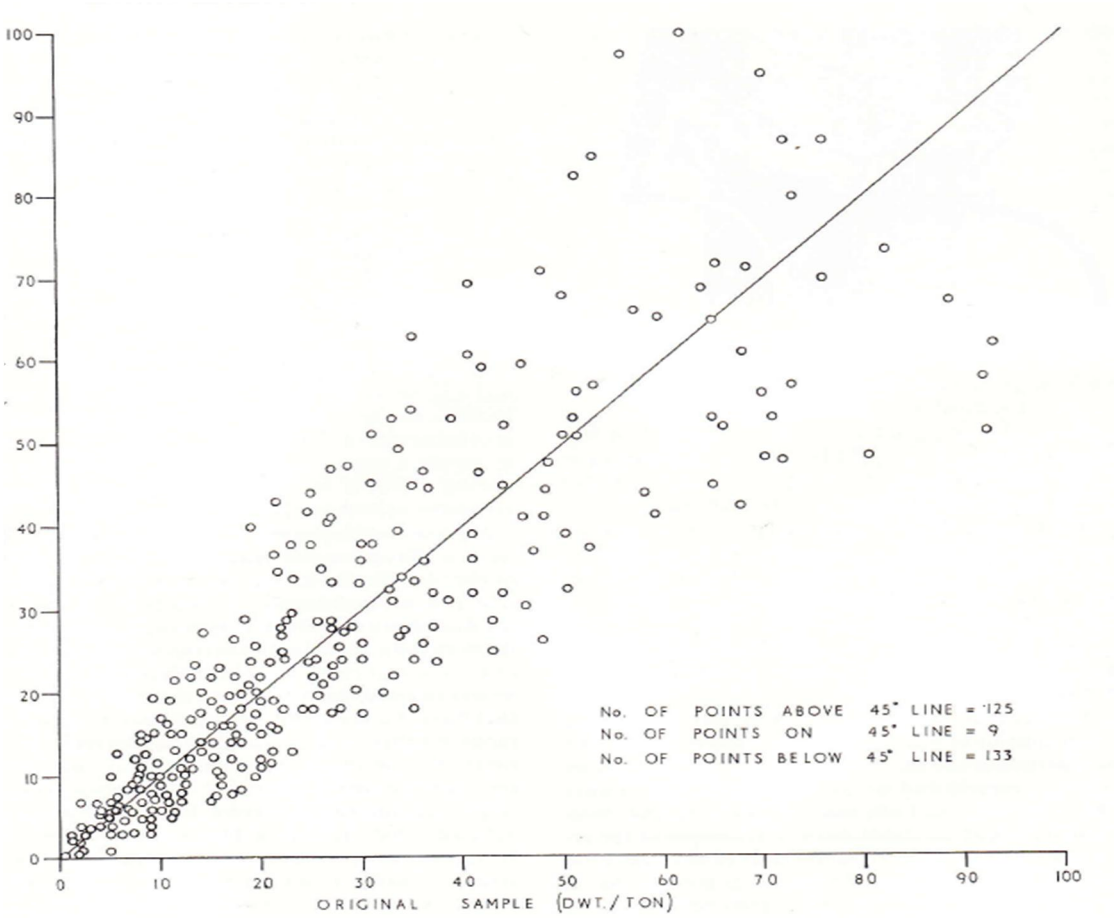


Figure 2.10: Scattergram of original and check values at the Witwatersrand mine (Sichel, 1961:568).

Figure 2.10 represents a plot of 267 pairs of samples and shows no significance difference between the mean value of the original values and that of the corresponding check samples. This plot indicates good reproducibility of chip sampling and saw sampling making saw sampling a good option as a replacement for chip sampling.

2.4.2.2 Magri and Mckenna – 1986

Magri and McKenna (1986) conducted a similar geostatistical study based on the results between diamond saw and chip sampling. The study was carried out on the then Rand Estates Gold Mine (REGM) and the Western Areas Gold Mine (WAGM). This study was different from previous studies undertaken (De Jager, 1997; Lerm, 1994; Sichel, 1961; Freeze et al, 2013) in the fact that it was not intended to investigate a low MCF and it was done on a reef type that was more homogenous in composition and grade than the typical thin carboniferous reefs previously tested on. This was done to statistically compare the data of chip sampling against the data obtained with a rock saw.

- **Methodology:**

Two sampling raises (one at each mine) of approximately 100m in length were sampled at 1m intervals with conventional chip sampling and the diamond saw. Comparisons between the two datasets were then used to quantify the differences between the two methods and to establish the optimum sampling spacing. For the thesis, the focus will remain on the comparison of the two sampling methods only. A single bladed type of saw was used for the project similar to the one that Sichel (1961) used.

Randfontein Estates Gold Mine

A raise developed on the Middle Elsburg Reef on the Cooke 2 shaft was selected for the experiment. The methodology for sample collection (Figure 2.12) was used for this exercise. The face was marked as per normal procedure and chipped then a smaller diamond saw sample was extracted at the exact same position. Chipping of samples

was done under strict supervision and the sample mass averaged between 500g and 1kg (Magri and McKenna, 1986).

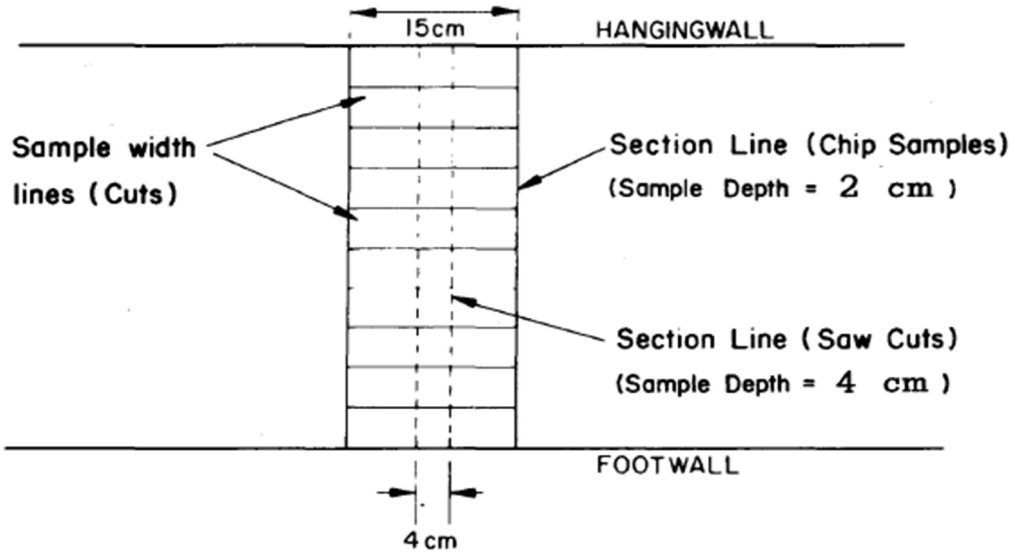
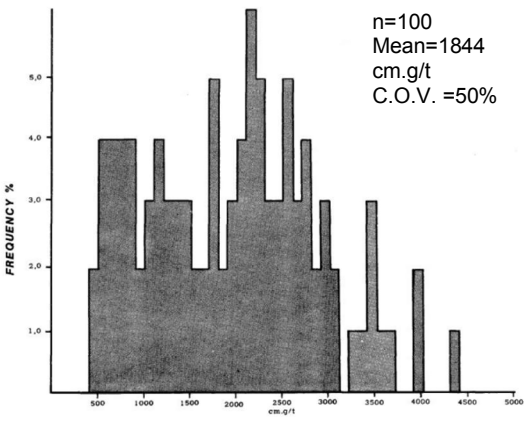


Figure 2.11: Sampling method applied at the Randfontein Estate Gold Mine for chip sampling and diamond –saw (Magri and McKenna, 1986:338).

- **Results:**

The results for the two data sets were similar and the mean value for chip sampling of 1844 cm.g/t was almost the same as the value of 1862 cm.g/t for the saw sampling (Figure 2.12, a, b). The nugget effect calculated for each dataset was also very similar. Magri and McKenna concluded from this research that the chip sampling was just as good because it was done under strict supervision.

a)



b)

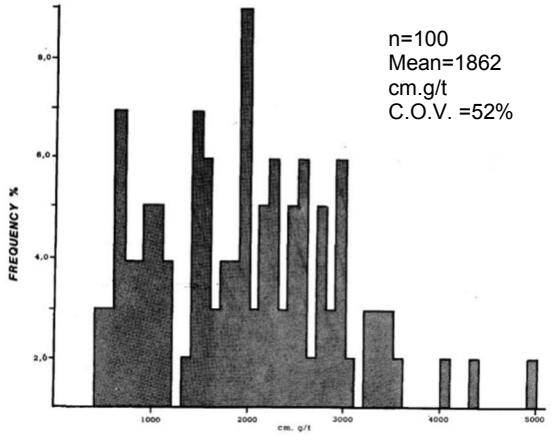


Figure 2.12 Histograms of a) chip sampling values and, b) diamond saw values at the Randfontein Estates Gold Mine.

Western Areas Gold Mine

The experiment on Western Areas Gold Mine was also done on a Middle Elsburg Reef raise. The sampling method employed changed from that method employed in the first experiment. Now the chip sampling was done in the normal production manner and the diamond-saw sections were not made between the existing channel lines but were off-set by 50 cm (Figure 2.13)

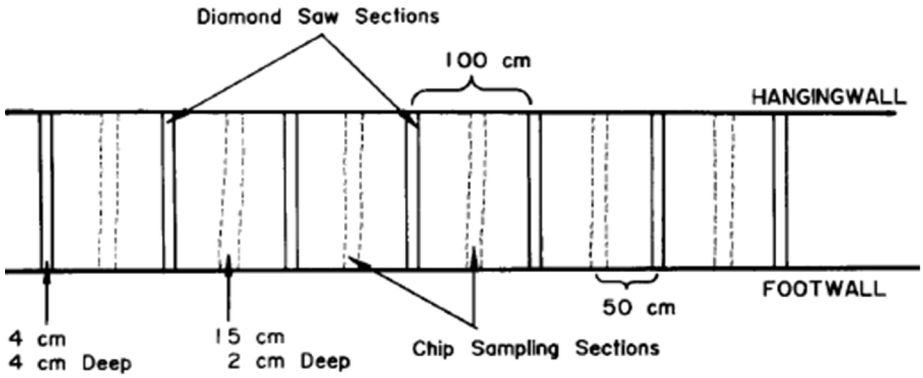


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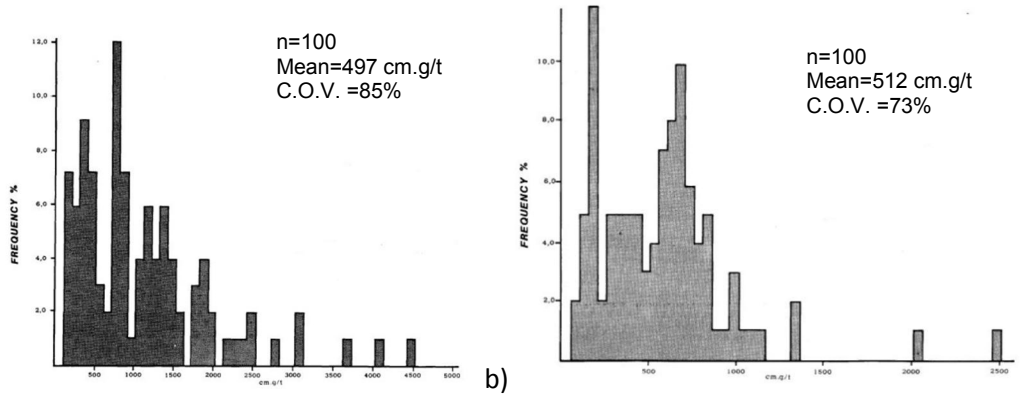
Figure 2.13: Sampling method at the Western Areas Gold Mine. (Magri and McKenna, 1986:344)

The new method was considered a more realistic basis for comparing the two sampling methods (Magri and McKenna, 1986). The variability of the gold and channel widths over short distances even as close as 10cm would make comparative studies very difficult.



a) b)

Figure 2.14 Histograms of a) Chip sampling values and, b) diamond saw values at the Western Areas Gold Mine

Statistics revealed that the confidence limits where much narrower for the diamond saw samples than for the chip samples (Figure 2.14). The values obtained with two different methods at the same point should be relatively equal and could be the base for comparison. If the position of the check sample changes in relation from the initial sample then grade and channel width variation could result in results very may be different from the initial sample results but may not necessarily wrong or poor in terms of quality.

The sample support is also not equal which could have affected the results. Because the Middle Elsburg reefs are relative homogenous in its inherent variability and gold distribution the change of support had little effect on the grade and the outcome. But a similar exercise done on a more heterogeneous reef types like the Carbon Basal could have had very different results and conclusion. The results of the gold values now indicate a log-normal distribution for both methods and the nugget effect for the diamond-saw sampling is now less than half that for the chip sampling (Table2.13).

Table 2.13: Lognormal confidence limits for the mean grade of a mining panel at Western Areas Gold Mine.

	σ^2_E	Low 95% (g/t)	Mean (g/t)	Upper 95% (g/t)
Diamond saw	0.0201	3.7	5	6.8
Chip sampling	0.0419	3.2	5	7.8

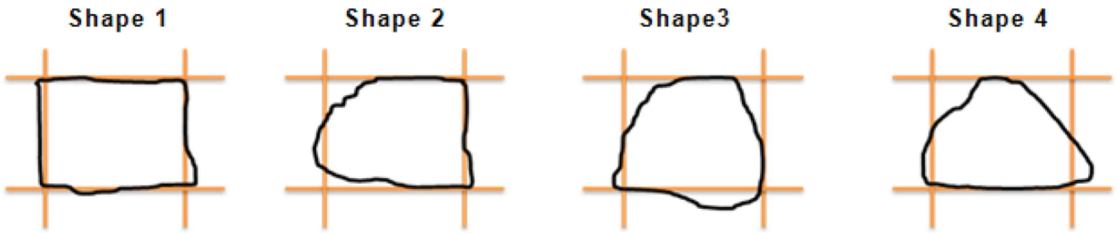
According to Magri and McKenna (1986) this geostatistical study supports the view that the proposed new diamond-saw tool is an improvement over normal production chip sampling. It could be argued that even with the less than perfect extraction of the chip samples the effect on the quality of the results was minimal, and there was no indication of any bias so why change the method? It is suggested that the use of the diamond saw for face sampling on gold mines could reduce the error as a result of over extraction of certain portions which may lead to a situation of overestimation. This

tool may improve some of the issues found with chip sampling, but it brings with it its own set of issues which could affect the quality of the material extracted.

2.4.3 Drill Core

2.4.3.1 Anglo Gold Ashanti - 2011

In 2011 Anglo Gold Ashanti conducted an investigation into their sampling methodology and practices at Kopanang Mine, in an effort to improve their poor Mine Call Factor (Freeze et al, 2013). Underground chip sampling was identified as a possible area of concern when underground observation found that 90% of the samples extracted were not done to the required standard. This was based on a project where they made use of silicon moulds to determine the shape and the size of the material removed during chipping (Figure 2.15). It is not explained if the demarcated area in Figure 2.15 already includes the 2cm waste below the contact. If it does then according to Figure 2.15 most of the contact was extracted. If however the 2cm waste was not included in the diagram then most of the contact was not extracted.



Mould	Shape 1	Shape 2	Shape 3	Shape 4
Total Picture	19	19	17	10
%	29%	29%	26%	16%

Figure 2.15: Results indicated that between 28 - 77 per cent of the samples extracted failed to include the basal reef contact and the footwall. (Freeze, 2013)

According to (Freeze, 2013) up to 77 per cent of samples extracted failed to include the contact is quite the opposite from the expected occurrence of oversampling of the carbon contact. If the samplers are constantly failing to extract the contact and

footwall, then on a first principle basis this practice will under estimate the true in-situ grade. The contact portion contains most of the gold in this reef, and if this portion is excluded from the sample, the actual grade would be significantly under represented. In an effort to try and quantify the issues with poor extraction they undertook one of the most comprehensive studies done to date. They compared the grades obtained with the current “incorrect” chip sampling method and grades obtained with “perfect “sampling collected via core drilling (Flitton, 2011). The project was initially planned to be completed over a three month period. But due to the difficult process involved to extract and cut core into perfect dimension samples the project extended more than a year.

The perfect sample or “Cut- coffin “as they refer to it is a text book sample obtained by cutting the exact dimensions from a drill core. The drill cores were extracted from panels situated in three different estimation domains, and each domain is an area where the grades have similar trends. Core was drilled horizontally to the face to a depth of 30-70cm with a diameter of 20cm and for every core drilled a standard chip sample section was chipped within 1m of the core position. Not all the cut- coffin samples had matching project chip samples. The core was taken to surface where it was cut into “perfect samples” depending on how intact the core was (Flitton, 2011).

Statistical studies between the grades of cut coffin and chip samples were inconclusive to prove that any bias is introduced with chip sampling (Table 2.14). Analysis of the 440 Estimation Domain’s chip sample data revealed under sampling but still within the inherent variability of the reef. Analysis of the 460 Estimation Domain’s chip sample data revealed over sampling also within the inherent variability of the reef. Data comparison between the two data sets indicated similar inherent variability (Flitton, 2011). This finding is very interesting because it was expected that perfect sampling comparison would finally confirm that chip sampling is indeed responsible for overestimating the data due to poor extraction.

Table 2.14: No consistent bias was observed in value and grade across the ED's between chips and cut-coffins (Flitton, 2011: 11).

Mean (cm.g/t)	Cut Coffin All	ROI Data (trend, structure, all data)	Cut Coffin Paired A	Chip Paired	Cut Coffin Paired B	Chip Paired	Cut Coffin Paired C	Chip Paired
430ED - Mean	897	1003	869	1192	1322	1033	754	929
No of pairs / samples	78	480	35	35	18	18	12	12
440ED - Mean	3302	3375	2961	1527	2741	1252	1666	1012
No of pairs / samples	210	867	69	69	46	46	23	23
460ED (460W ED)* - Mean	1012	1277	750	1682	1334	2366	1473	3188
No of pairs / samples	210	398	68	68	27	27	18	18

* Representivity Coffins only used

% Diff in Mean (cm.g/t)	Cut Coffin All - ROI (trend, structure, all data)	Cut Coffin Pair AB	Cut Coffin Pair BC	Cut Coffin Pair CD	Cut Coffin A - Project Chip Pair	Cut Coffin B - Project Chip Pair	Cut Coffin C - Project Chip Pair	Nugget to sill ratio (cut coffins)	Nugget to sill ratio (check chip)
430ED - % Diff in Mean	12%	22%	-44%	-56%	37%	-22%	23%	103%	37%
No of pairs		18	12	4	35	18	12	18	1968
440ED - % Diff in Mean	2%	-2%	-5%	-10%	-48%	-54%	-39%	23%	22%
No of pairs		58	31	17	69	46	23	58	636
460ED (460W ED)* - % Diff in Mean	26%	-1%	-8%	-61%	124%	77%	116%	42%	40%
No of pairs		32	21	10	68	27	18	54	648

* Representivity Coffins only used

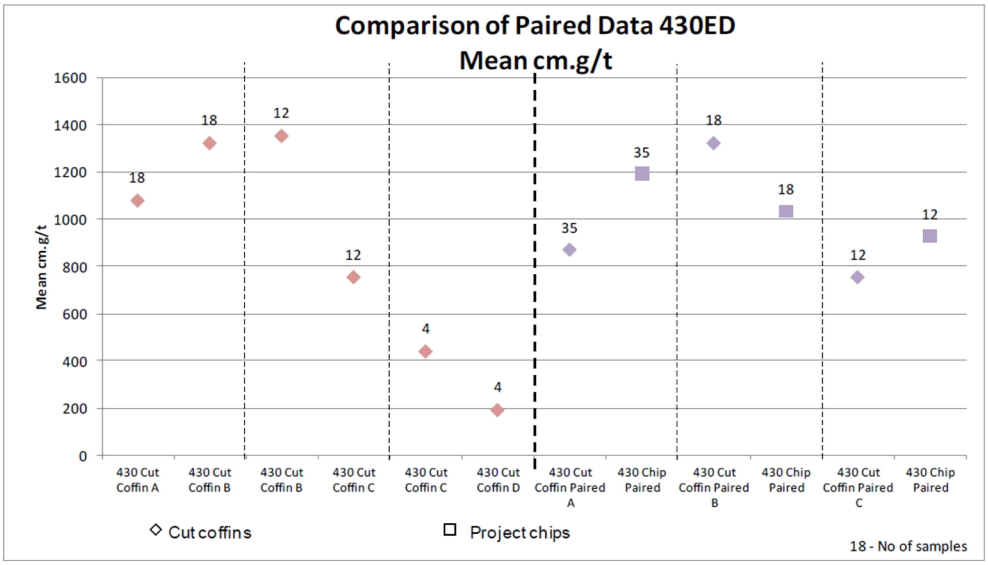


Figure 2.16: Comparison of mean cm.g/t paired data for the 430 estimation domains (Flitton, 2011:11).

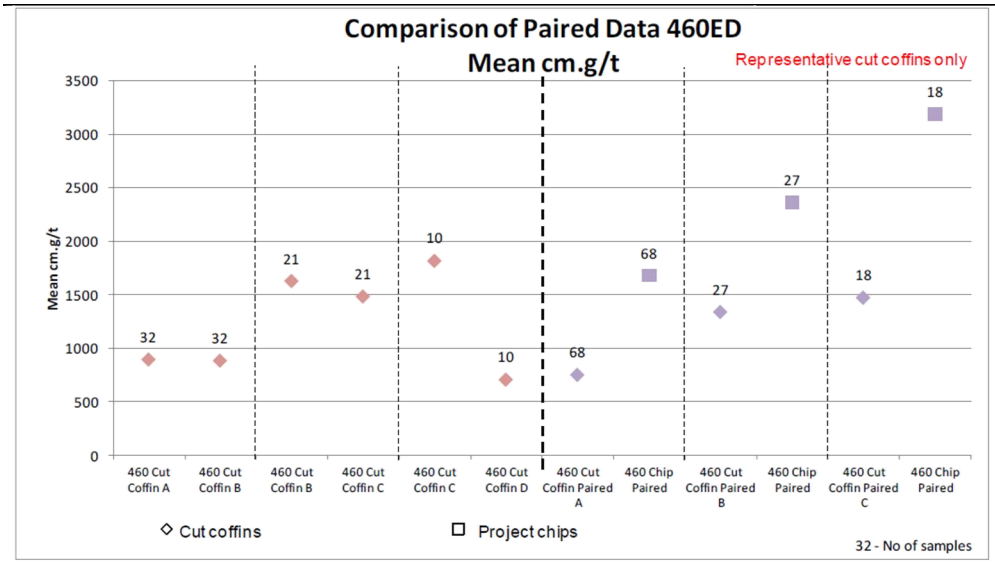


Figure 2.17: Comparison of mean cm.g/t paired data for the 460 estimation domains (Flitton, 2011:13).

Comparisons on the channel width and sample masses of the paired data revealed that the width of chip samples can vary as much as 11cm when compared to a neighbouring cut-coffin sample. They also found that the reef channel width of the project chip samples were, on average, less when compared to neighbouring cut-coffin samples. In the 630 Estimation Domain the difference was almost 6cm. It is not certain if the channel width was under-measured, or if the difference is due to the natural variability of the channel width.

The results also indicate that the mass of the chip samples does not follow a positive relationship with the channel width. It was evident that on average the mass of the chip samples remained 400g even when various channel widths were being sampled (Figure 2.18). Flitton, (2011) suggests that the Mineral Resource Officers (MRO's) are only chipping enough material until 400g is reached(It may also indicate that enough material are discarded) and she made a valuable comment when she concluded that "*This implies that the sample support size is not channel width but actually mass and urgent attention should be placed on rectifying this."* (Flitton, 2011:2)

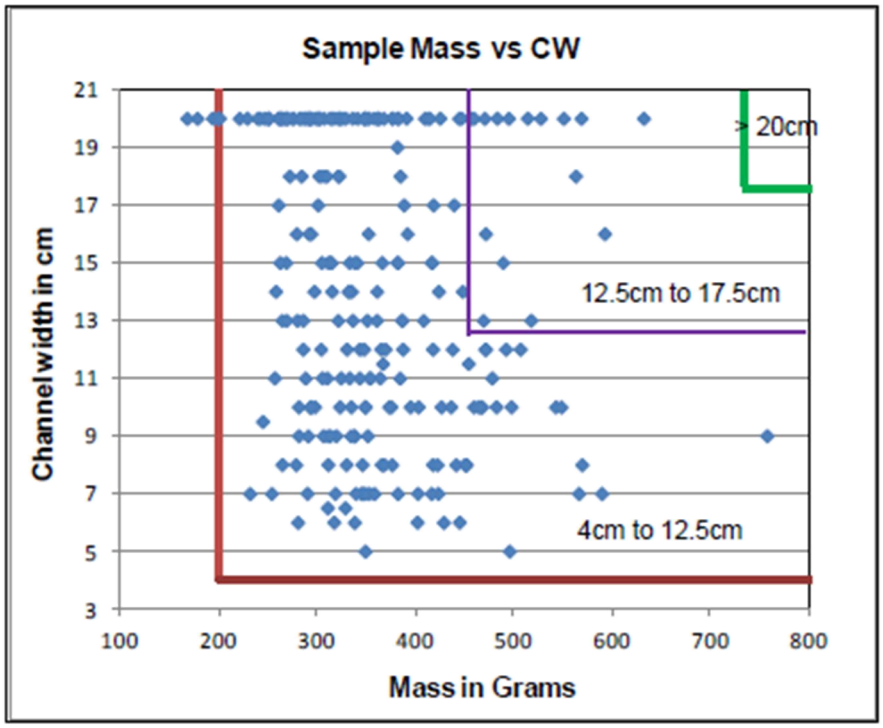


Figure 2.18: Chip data not indicating any relationship between the width extracted and the sample mass. Source: Freeze, 2013:16

The research failed to find any evidence that chip sampling is responsible for introducing bias. On the contrary, it found that chip sampling produces acceptable results despite the fact that extraction is poor. No statistical evidence of bias was observed across the three Estimation Domains. They recommended therefore that no factors should be applied to their in situ Resource estimates and noted that applying factors is pretty risky in any case. Results of precision tests done on their check samples were the same as the results of precision tests of the cut – coffin (perfect dimension) samples. The chip samples are under-measured when compared to paired cut coffin samples. This is the opposite of what is normally assumed, i.e. that samplers are on average over measuring the sample widths. According to Flitton (2011) this could be due to the observation that the channel width varies drastically over short distances and the fact that not all cut- coffin samples were matched by corresponding chip samples for comparison. Flitton (2011) suggested that the proposed Quadrant Cw-Mass plot depicted in (Figure 2.19) should be used as a control to guide the decision to accept or reject samples when deciding to implement the Quality Index. This will depend on the actual mass of the sample material collected, compared to their expected minimum mass calculated on the sample width.

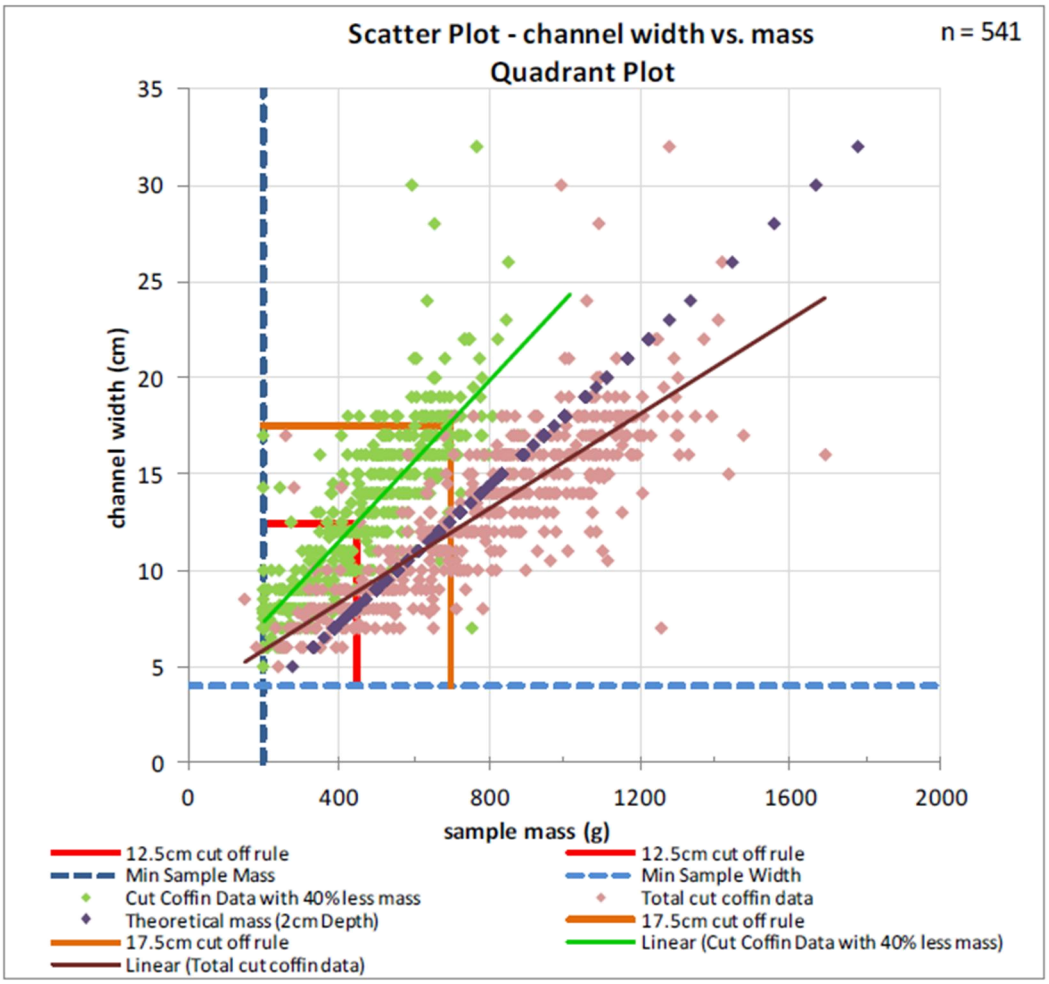
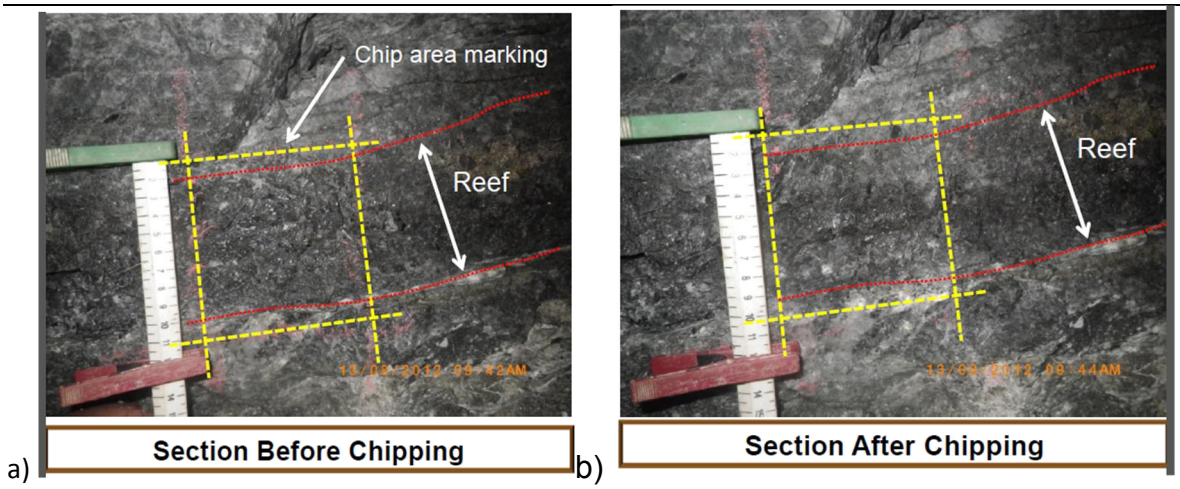


Figure 2.19: Quadrant Cw-Mass plot used for quality control (Flitton, 2011:15)

The recommendations made by Flitton (2011) were introduced in 2011. At the recent SIAMM "Best-practise in African Mining" Conference, Freeze (2013) stated how this quality control initiative improved the overall quality of their underground chip sampling. Maintaining this quality drive has in fact improved the MCF for the 2012 period.

- **The Quality Index**

The "Quality Index" initiative was implemented in 2011. Digital photography as well as mass measurements is used as controls to measure the quality of each sample extracted underground (Figure 2.20). The evaluator uses the Quality Index to rate each sample and allocate points accordingly which will be used to accept or fail a sample.



a) b)

Figure 2.20: Photos used to rate the quality of a sample a) "Before" and b) "After extraction (Freeze, 2013:)

They also keep a record of the time it takes a MRO to collect a sample and the total time spent at the panel (Table 2.15). It is interesting to note that the time it takes to extract a sample is still quick even with the increase in sample mass. According to the time when the pictures were taken in Figure 2.20 extraction only took about 2 min.

Table 2.15: Average time spent per panel and per section (Freeze, 2013)

Time control						Checked by	Evaluator
Time Started with panel	Time Ended with panel	Total Time in Panel	Average Time per section	Number of sections			Sections Failed
			minutes	sect	photo		
9:54	10:34	0:40	00:05:43	7	7	CP	
9:29	10:05	0:36	00:05:09	7	7	CP	2
9:22	9:49	0:27	00:03:51	7	7	CP	
9:30	10:10	0:40	00:05:00	8	8	CP	
9:49	10:49	1:00	00:07:30	8	8	CP	

The Evaluator then assigns points based on the index and fails or accepts a sample to the database depending on the outcome.

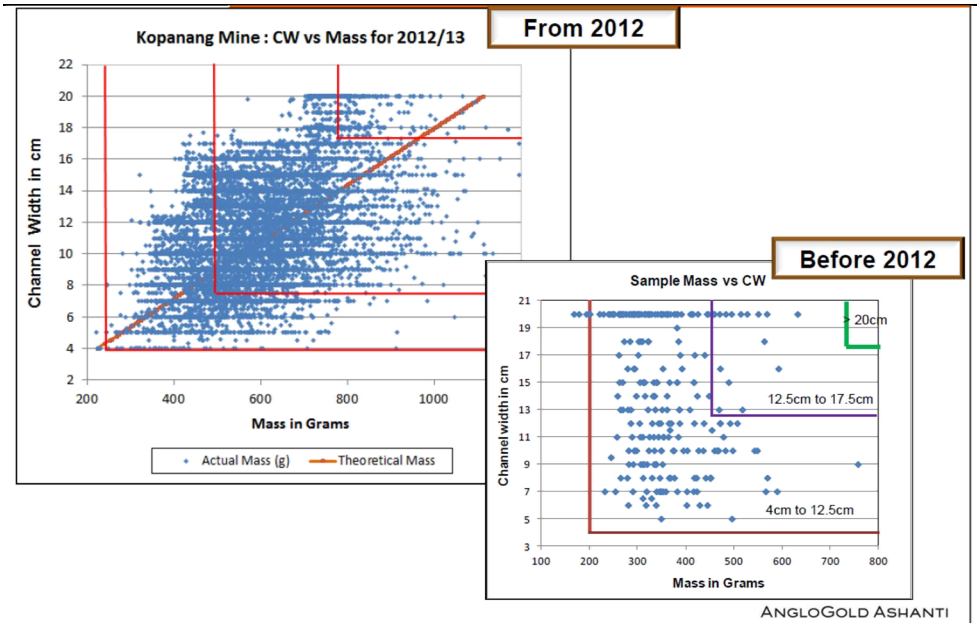


Figure 2.21: Comparison of the improved correlation observed between the actual mass and the theoretical mass before and after implementing the quality index (Freeze, 2013)

According to Freeze (2013) improved focus and quality with extraction resulted in an increase in the individual sample mass which eventually led to an improvement in the MCF.

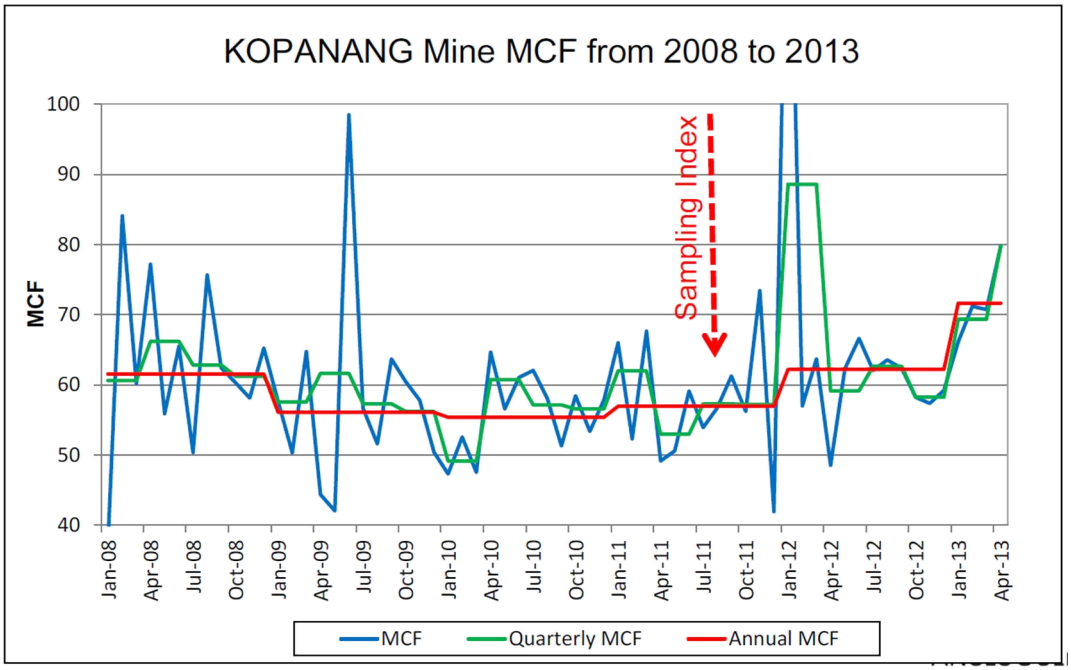


Figure 2.22: Progressive MCF indicating when the sampling index was introduced and the significant improvement that follows (Freeze, 2013)

The following positive changes were reported after only 20 months after implementing the “Quality Index “

- The overall quality of the samples improved.
- The overall chipped mass of the samples has increased and is now in line with the expected mass (Figure 2.20).
- There has been a noticeable improvement in MCF.

A decrease in Mineral Resource Officers (MRO’s) efficiencies and sample coverage was the only negative spinoff from the quality index initiative.

Even though initial investigation identified chip sampling as a possible source of bias because of the poor extraction, observed comparison of the datasets did not indicate any bias. The “cut-coffin” samples represent a perfect sample cut to the exact required dimensions. It is possible that chip sample extraction, when supervised, is of a higher standard and because this effort was maintained over an extended period the improvement in quality improved the MCF. Johnson (2014) said they noticed that the face grade steadily dropped while the belt grade remained constant when they started implementing the “Quality Index “.

Maintaining this initiative for an extended period indicated that in some way or another chip sampling is introducing bias that is responsible for the deterioration of the MCF, even if the comparison between chip sampling and coffin samples could not find statistical evidence to validate this conclusion.

2.4.4 Lessons from the past

Poor extraction due to the limitation of the tool is still considered a major source of introducing error (Cawood, 2003; Sichel, 1947). Most of the historical research was not very successful in quantifying the errors introduced with poor extraction. The severity of the errors increased drastically when reefs which are highly heterogeneous in composition are sampled. Poor extraction in combination with sample heterogeneity is probably the main source of introducing error, and affects the precision and accuracy of the data. The error usually increases as the percentage waste included in the sample width increases (Sichel, 1947; Muller, 1950).

So for thin carboniferous reefs the error introduced with poor extraction will be higher compared to other reefs, without varying areas waste or of hardness present in the demarcated sample. This was confirmed by the observations that found that the tool tends to extract more from the soft high grade material, and less from the surrounding hard material, when sampling thin carboniferous reefs (De Jager, 1997; Lerm, 1994; Sichel, 1947; Storrar, 1986). This oversampling of the softer gold bearing material is introducing major bias and is responsible for overestimation of the face grade. (Cawood, 2003; Lerm, 1994; Sichel, 1947)

The only solution agreed on by most of the previous researchers to solve this issue was to find an alternative tool or method that would improve extraction (Sichel, 1947; Storrar, 1983). Improved sample extraction would reduce some of the errors currently introduced with the chip sampling method and eliminate the bias of oversampling the softer carbon material. Comparisons between chip sampling and mechanized sampling tools were conducted and under certain conditions it managed to extract samples of improved quality (De Jager, 1997; Lerm, 1994; Magri and McKenna, 1986; Sichel, 1961). The “Rock Saw” managed to extract a better delimitated sample but comparisons of the data when compared to that of chip sampling were inconclusive to determine if chip sampling was introducing a bias (De Jager, 1997; Magri and McKenna, 1986; Sichel, 1961). One could argue that the data collected was inadequate to draw any statistical conclusions.

In 2011 AngloGold Ashanti conducted probably one of the most comprehensive studies ever attempted to determine if chip sampling was indeed responsible for over estimating the face grades (Spangenberg, 2012; Johnson, 2013; Freeze et al, 2013). Core sampling was used to compare results obtained with chip sampling. The core extracted from the face was taken to surface where it was cut to the exact sample dimensions demarcated in the neighbouring chip sample. This is as close as one can get to compare the results of a perfectly extracted sample with that of a chip sample. With much difficulty and at a great cost they managed to extract enough data to enable statistical comparisons between the coffin samples and chip samples. Comparisons of the data also did not find any systematic bias between core samples and its corresponding chip samples (Flitton, 2011). Despite all the effort and costs and frustration to produce the perfect extracted sample statistically it was no better or

worse than the poor extracted neighbouring chip sample. Enough data were collected to do comparisons that are statistically sound.

The results were consistent with previous studies which found that chip sampling if done under supervision will give acceptable results (Lerm, 1994; Magri and McKenna, 1986). Constant oversampling of certain units will certainly introduce significant bias; the question is just why did the comparative studies not confirm this? Perhaps the bias responsible for over estimating the face grade is more complex than initially thought. From the literature review it is obvious that the tendency of samplers to extract more material from the softer high grade portions of the demarcated sample is not significant enough to cause a bias. The following tables compare the advantages and shortcomings of chip sampling versus the diamond rock saw. According to tables (Table 2.16; Table 2.17; Table 2.18) the variability of the grades remained similar between chip sampling and rock saw despite the fact that better extraction was obtained with the rock saw. Statistically no benefit was observed with improved extraction.

Table 2.16: Operational and safety capabilities of Chip sampling compared to mechanised diamond saw.

	Hammer + Chisel	Mechanised diamond saw
Ease of use	**Easy:** Tools are lightweight and fit into a haversack. Can operate tool in confined spaces. Don't require any services to operate the tools.	**Cumbersome:** Difficult to handle because of the size, weight and bulk of the tool. Require services (air, water) to operate. Difficult to operate in small confined spaces and footing must be secure. Difficult to use when face width is in access of 1.5m.
Safety Risk	**Low:** Regular inspection of the tools to ensure chisel is still sharp and handle of hammer is still secure.	**High:** Electrocution possible because of water required to cool the blades. Serious injury possible from cutting.

Table 2.17: Extraction capabilities of Chip sampling compared to mechanised diamond saw.

	Hammer + Chisel	Mechanised diamond saw
Sample shape	**Irregular:** Sample shape highly irregular. Types of error introduced are IDE, IEE, IWE and IPE.	**Regular:** Sample shapes are regular. IDE, IEE, IWE and IPE are negligible.
Sample width measured	**Difficult:** Measurement of the actual width is difficult because of the irregular shapes extracted. Error types introduced IWE and IPE	**Easy:** Sample width measurement very easy because of the highly regular shape of the sample extracted. IDE, IEE, IWE and IPE negligible.
Operator dependant error	**Highly likely:** Oversampling of reef or carbon very common, discarding of reef or waste after sample has been extracted. Types of error includes IPE and IWE	**Less likely:** Operator is almost completely eliminated as a source of bias due to improved extraction capabilities

Table 2.18: Effect of Reef characteristics on sample extraction for Chip sampling and mechanised tools.

	Hammer + Chisel	Mechanised diamond saw
Reef types	**Highly recommended:** Best suited for the thicker, homogenous, average grade reefs types. Not Recommended: Not suited for thin carboniferous reef types, tool tend to extract more from the softer higher grade material. Types of error include IDE, IEE, and IWE.	**Highly recommended:** Suited for thicker reefs. Not Recommended: Thin carboniferous reefs. Water used to cool the blades may wash away carbon material. Types of error include IDE, IEE.
Heterogeneity of the reef	**Highly affected by reef heterogeneity:** Tool less suited for reefs with high waste to reef ratios, error will be proportionally higher because of poor extraction capabilities. Types of error IDE, IWE.	**Not affected by reef heterogeneity:** Tool is not affected by reef to waste ratio because of its good extraction capabilities. IDE, IEE, IWE and IPE negligible.
Variability of sampled grades	**Highly Variable:** Grades highly variable due to poor extraction capabilities.	**Highly Variable:** Despite its improvement in extraction and minimising errors IDE, and IEE, comparisons with chip sampling could not find statistical evidence that it improved the overall variability of the results.

CHAPTER 3 – EVALUATE EXISTING THEORIES VERSUS THE AUTHOR'S UNDERGROUND OBSERVATIONS

3.1 Underground Sampling

It was established from the literature review that chip sampling was not the best method to use to extract samples, especially when sampling thin carboniferous reef types. Observation of this sampling method underground confirmed that the tool tends to collect more material from the softer, higher grade portions and according to some authors (Cawood, 2003; Lerm, 1994; Sichel, 1961) this could lead to a situation where the actual grade is overstated, in some cases up to 30%. All of the previous researchers agreed that the tool also failed to extract the required sample dimension required by the sampling protocol. It is not clear from the literature review if the tendency to oversample the softer material is happening occasionally(once every 10 samples) or frequently(almost every sample). It was therefore considered important to conduct an underground investigation and test existing theories with current practises. A development raise situated in the northern Leeuwbosch area of Harmony's Tshepong mine was selected for this project because it had all the characteristics of the reefs mentioned in the literature review. It had a thin channel width and contained carbon.

The Basal Reef member or Basal Reef Zone (BRZ) is the sequence of quartzite's and subordinates conglomerates that lie on an unconformity surface marking the top of the UF1 Zone 1 footwall quartzite's of the Welkom Formation. The top of the BRZ is represented by the overlying Harmony Formation, either known as the Khaki Shale member, or locally known as the Waxy-brown Leader Quartzite (WBLQ) member. The BRZ across the Tshepong Mine area is strata bound unit with widths varying from 40 cm to over 200 cm in thickness. The BRZ typically consists of a basal conglomeratic unit which sits on the UF1 footwall unconformity. This is overlain by clean coarse grained gritty quartzite's. Above these quartzite's, a second unit, frequently less well developed, is present. This second upper unit appears to be better developed in the south of the Mine area.

Two facies types have been recognised in the area. The first is known as the Black Chert Reef (BCR) facies and the second is known as the Lorraine Reef facies type. The BCR is universally present in the extreme north of the Mine Area and it is typically a thin oligomictic quartz pebble lag which also contains carbon, pyrite and gold mineralisation.

3.2 Methodology

A total raise length of 20 meters was sampled at 20 cm intervals with an additional section every 50 cm. The channel width ranged from 0.5 to 1.5 cm and a total of 120 samples where chipped with a sample width of 7 cm. Figure 4.1 is a diagram depicting the heterogeneous composition of the material found in a sample at a specific dimension. Most of the gold is contained in the soft carboniferous portion which is found just above the hard footwall quartzite.

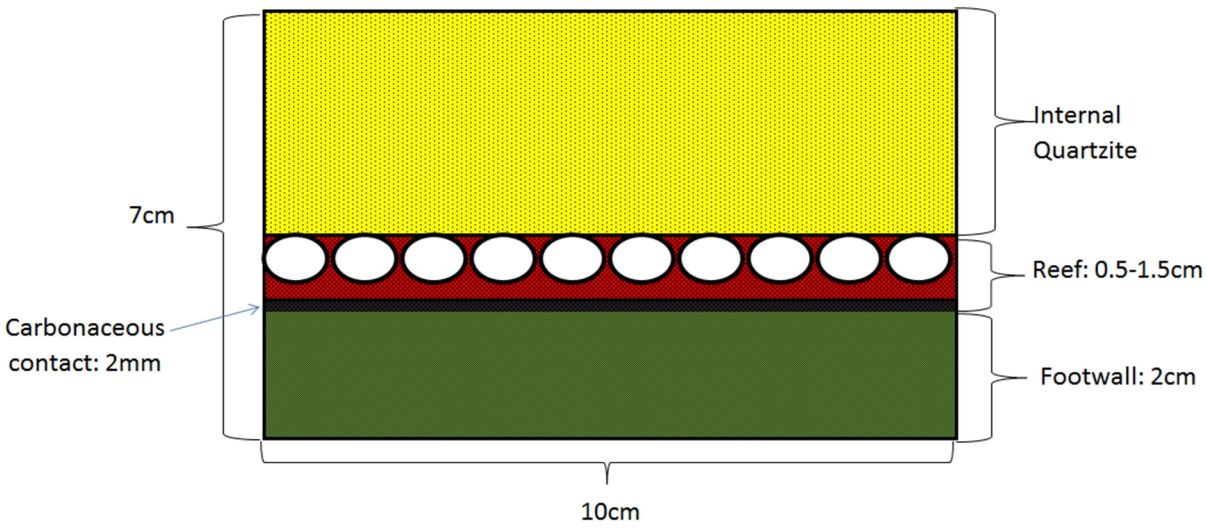


Figure 3.1: Diagram depicting the sample composition.

The standard tools for chip sampling have always been the hammer and chisel (Figure 3.2a). Harmony's sampling protocol (COP, 2006), requires that the sample extracted must be rectangular in shape with solid square corners and should be chipped to an even depth. This is very difficult to achieve with the current tools. The hammer and chisel was incapable to extract a proper sample due to the hardness of the reef and its surrounding rocks. The sampler and his team could only manage to remove material

that was already fractured or loose. Any attempt to remove material from a solid area on the face only resulted in a white spot remaining where the chisel had bruised the surface of the rock. Such a chipped white spot is shown inside the yellow marked sample (Figure 3.2b)

a) 

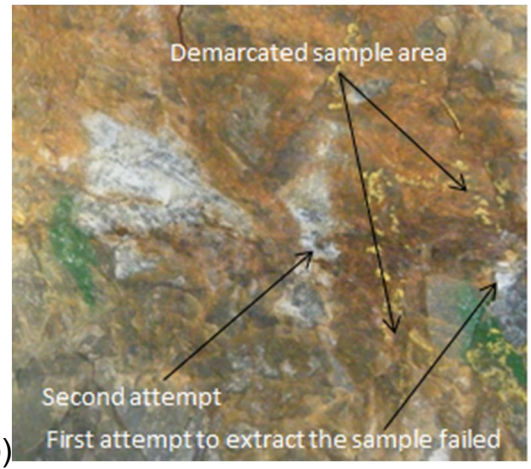
b) 

Figure 3.2: a) A hammer, chisel, and dish, the preferred tools for sampling on the gold mine, and b) a white spot on the right side of the picture and inside the demarcated sample area where the first attempt to chip reef material was made.

The very hard and solid state of this particular position on the face made extraction as per COP impossible, and the sampler decided to chip a little to the left of the initial position demarcated. Here the sampler managed to chip out some material but insufficient for a sample, they left the material in the dish and moved and chipped from another position even further along the face. The material in the dish represents material from three different positions, yet the sampler when entering the data into the software will do as if all the material was removed from a single demarcated area.

The COP also requires that a section demarcated for sampling must first be trimmed solid before attempting to extract a sample. One of the major problems arising from this is expressed by a sampler "*We do not trim the section to be sampled otherwise it's too difficult to collect sample material*" Anonymous Sampler. A total of 120 samples were extracted and not even a single sample met the prescribed standard. To be exact not one sample chipped matched any of the other samples chipped in terms of shape, composition, volume, or mass (Figure 3.3a; b).

a)  b) 

Figure 3.3: a) and b) Irregular shapes of the sample material removed during the chipping process clearly visible.

The sampler or operator had absolutely no control over the shape or volume of the material removed during the chipping process. Sometimes the material removed during the chipping process included more footwall waste or internal waste than was demarcated. It may also happen that a slab much bigger than the demarcated area was removed from the face by the sampler. They would then trim most of the excess material with the hammer and then further reduce the bigger fragments left in the dish into smaller sizes by hitting it with chisel. When they had collected sufficient material in the sample dish they would select some of the bigger pieces mostly waste, to be discarded until they believe that they had sufficient sample mass. This was observed with most of the samples chipped.

The development end sampled presented other environmental factors that hampered the team's ability to extract samples effectively. In some areas the services obstructed access to the exposed reef contact and made it difficult to freely swing the hammer. In some places the reef contact was very close to the hanging wall which meant that the crew had to build a temporary scaffold in order to take a sample (Figure 3.4)

a)  b) 

Figure 3.4: Pipes hindering the sampling process. b) Temporary scaffolding helping the sampler to reach the channel width for sampling.

Blast induced fracturing on the face regularly hindered the sampling process (Figure 3.5). When the samplers extracted material from within the demarcated sample area, some of the fractured pieces outside the delimited sample area dislodged during the hammering and chipping process and fell into the collection pan, so becoming part of the sample. The ambient temperature in excess of 30 degrees Celsius with very high humidity means that the sampling team has to function for protracted periods of time in difficult physical circumstances.

This led to a significant decline in the team's ability to perform good quality sampling activities continuously at a high standard. Some members of the sampling team began chipping single samples from a variety of positions and members began to quarrel amongst themselves as fatigue and heat exhaustion took its toll.

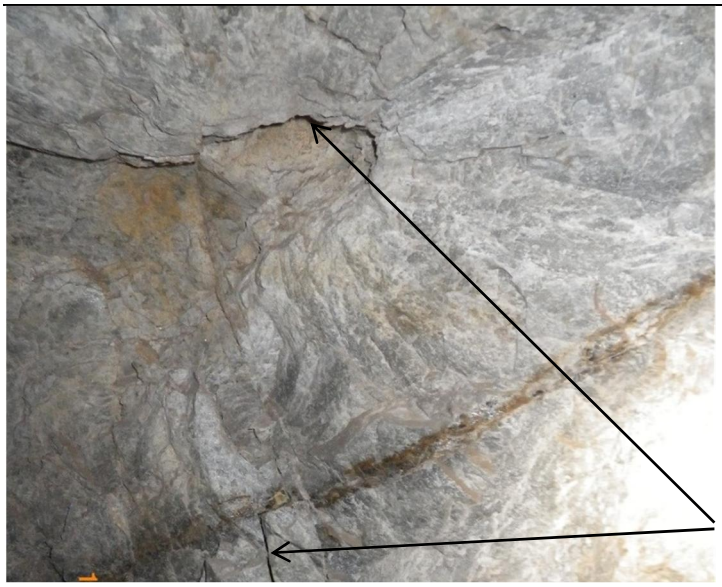


Figure 3.5: Blast induced fracturing may increase the risk of contamination.

The error of oversampling the softer carbon-rich portion of the reef was only observed at one sampling section (Figure 3.6).The reef contact for this particular section was mainly carbon and exposed just below the hanging wall contact. The material was so soft and brittle that the sampler only needed to use the chisel to collect material. The material was all collected from a vertical sample width of about 1.5 cm. The grade of 266.2 g/t returned for this section was the highest of all the 120 samples extracted Even though the material was only representative of the 1.5 cm carbon portion the grade was now wrongfully allocated to the 7cm demarcated width.

The centimetre gram per tonne (cmg/t) value was now overstated by almost 467 %. This confirms that oversampling of the carbon portion only will definitely overestimate the grade of that particular sample.

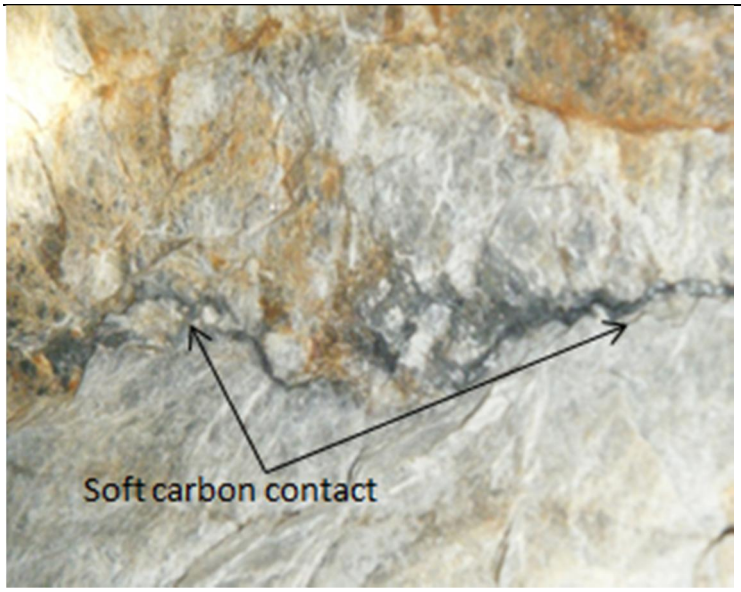


Figure 3.6: A narrow carbon rich zone exposed just below the hanging wall.

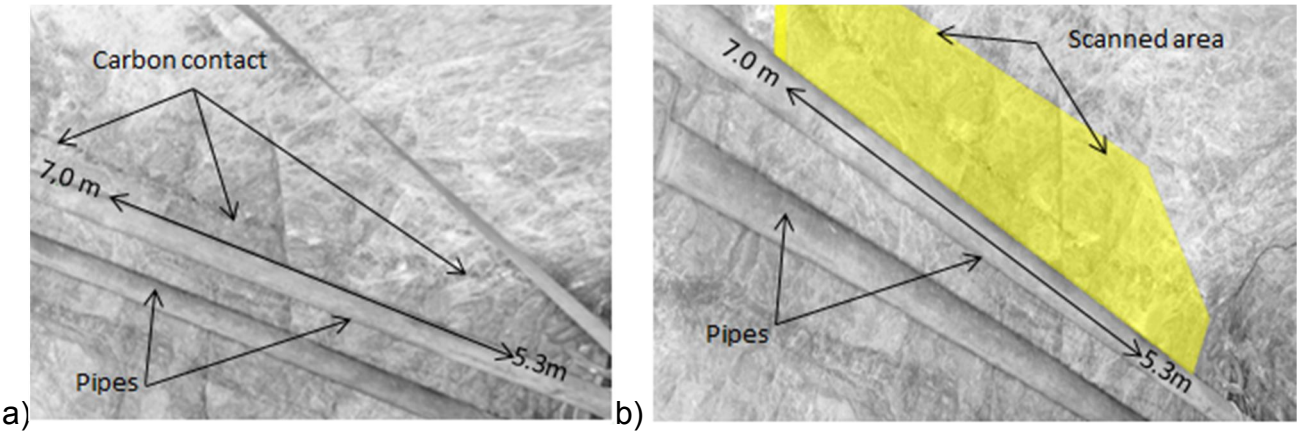
The underground visit confirmed that the sampling tool is failing to extract a well-balanced sample as per standard because the reef is just too hard. Even though the samplers did their best to extract the samples as per standard they constantly failed because of the tools limitations. Not a single sample extracted met the requirements set out in the COP. Marking of the sample area was just a formality, because the actual volume and shape of the material extracted, was determined by the fractured material in and around the sample area. Even though oversampling of the carbon material was only observed at one section it was not happening constant enough to be considered a bias. No difference in the quality of extraction was noted between the older more experienced sampler and the younger inexperienced sampler.

3.3 Quantifying the size and shape of the material removed.

It is a very difficult to accurately quantify or measure the shape of the material extracted during the sampling process. The latest technology laser scanner was used to scan the face before and after each sample was chipped (Figure 3.7).This ‘before’ and ‘after’ (Figure 3.8) comparison is a useful visual tool for comparing the actual shape and size of the sample removed during the chipping process.



Figure 3.7: Faro laser scanner that was used to scan the actual shape of the material removed during the chipping process.



a) b)

Figure 3.8: a) A point cloud of the area scanned before sample extraction, and b) is a point cloud of the area after sample extraction.

Pipes and the confined space in the raise complicated the scanning process. A portion of the raise between the 5.3m and 6.9m point was scanned before and after the chip samples had been removed (Figure 3.9).

The two red lines in Figure 3.9 represent the channel width (reef) and the blue lines are the boundaries of the actual sample width of 7cm. The red irregular shapes in Figure 3.9 give a visual representation of the actual shape of sample that was removed during the chipping process. The white squares represent the demarcated samples and red irregular shapes are the boundaries of the actual sample material removed.

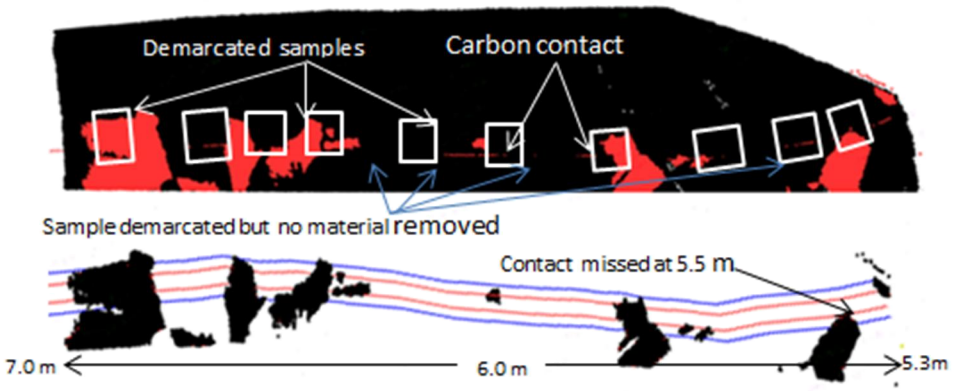


Figure 3.9: A software plot of points generated by the Faro laser scan, the irregular shapes of the samples removed during the extraction process highlights the irregular extraction compared to extracting pre-defined sample shapes from hard quartz reefs.

Some of the samples demarcated had no material removed, suggesting that the material was collected at a different position. Not a single sample extracted complied with the required geometric shape defined in the protocol. This means that there is significant Extraction Error (EE) associated with this sampling method. The first sample on the diagram at the ±5.5m position missed the reef contact completely (Figure 3.9). This observation is supported by the very low grade of 0.239 g/t reported for this sample (see variability plot Figure 5.3).

The scanner managed to capture the highly irregular shapes of the material removed during the sampling process. It provides a visual tool for comparing the actual shape against the demarcated shape. The outcome confirm observations made by other authors Sichel (1947); Storrar (1981); Lerm (1994); De Jager(1997); Freeze(2013) that sample extraction with the current tool is questionable. *Instead of achieving a representative groove (channel) at regular intervals, samplers are performing a variation of 'grab sampling 'at irregular intervals.*

3.4 Alternative Tool Tested

Like most of the previous authors it was decided to test an alternative tool as a possible replacement for the chip sampling method. The alternative sampling tool tested for this project is the DD130Diamond coring tool from Hilti. It is capable of drilling and extracting sample core with diameters of 8 - 162 mm. The tool's

capabilities were tested on surface and it managed to drill a 15cm core with a 65mm diameter from a basal reef slab in less than 15 minutes (Figure 3.10)



Figure 3.10: Drilling the core samples from a reef slab on surface was successful and promising.

Underground drilling was very difficult and the tool was heavy and cumbersome. Underground testing proved difficult because the power supply for the coring tool was initially incorrect. There were also difficulties mounting the drill in a confined space (Figure 3.11), and the combination of water and electricity created a serious safety hazard.



Figure 3.11: Securing the drill stand underground was much more difficult than anticipated.

Once these problems had been resolved it was only possible to extract five fractured samples in a period of three days. But if you have a look at the actual core extracted

you will see that it tends to break on the natural softer carbon contact (Figure 3.12).This resulted in most of the carbon being washed away with the water.

a)  b) 

Figure 3.12: a) Very fractured core sample, and b) fracturing visible on the softer contact.

Initial testing of the diamond drill on surface showed promise but underground operation was very difficult. It is heavy and cumbersome and the combination of water and electricity created a serious safety hazard. The tendency of the core to break along its carbon contact and the water that washed away most of the exposed carbon does not make this a viable substitute for the current chip sampling process.

Underground observation of chip sampling confirmed the finding by previous authors (Cawood, 2003; De Jager; 1997; Lerm; 1994; Sichel; 1961; Storrar, 1986) that the tool was unable to extract a good sample. Not even one sample extracted during the project could be classified as a good sample. All the samples extracted differed in shape size and volume. Since all of the samples were supposed to be of equal dimension the difference due to poor extraction makes them different in support. The different shapes extracted with the current tool introduce another problem that could be responsible for introducing error and bias that is unique to chip sampling.

The problem comes when the gram per tonne value obtained with the extracted material is converted to a centimetre gram per tonne value used in the valuation and composition processes. The methodology for converting from g/t to cmg/t is sound but it is based on the assumption that the sample was extracted perfectly over the demarcated area especially the sample width. It is clear from the scans taken during the investigation that the shapes of the samples extracted was haphazard and in some

cases a single sample was extracted from various positions. It is therefore impossible to apply a correct sample width to the extracted material and this is where additional error are introduced that has nothing to do with the material extracted.

The example of the oversampling of the carbon is a good example of how incorrect extraction of a demarcated sample when converting from g/t to cm.g/t could overestimate the grade. So the actual width of the material extracted does not match the width of the sample demarcated which is used for the cm.g/t conversion which will always introduce error. Oversampling of the soft carbon material was only observed at one section which makes this unlikely as a constant source for bias. Some reefs due to their composition could be more brittle and easier to extract. The basal reefs found at Bambanani are extremely brittle and soft at the contact and sample material could be extracted relatively effortlessly by only using the back of the chisel. Another area of concern is the observation made that the Samplers and Chippers are almost always discarding material after each extraction.

It was observed that they almost always discard the waste portions collected in the dish. This was happening frequently enough to introduce some serious error and bias. The alternative sampling method tested failed to extract proper samples and is not considered a suitable substitute for the current chip sampling method which despite its poor extraction capabilities, still managed to extract 120 samples in comparison with the 5 of the core drill. Chip sampling is better suited for the harsh underground conditions found on most South African gold mines but the quality of the results is questionable.

CHAPTER 4 – QA-QC AND STATISTICS

4.1 Descriptive Statistics

A total of 120 samples were collected from the raise with chip sampling and five fractured core samples were collected from the core drilling exercise, examples being shown in Figure 3.12. Below is a chronological sequence on all the tests performed on the samples with their results and findings.

4.1.1 Sample Grading

Pulps are produced by crushing and pulverizing the particle size of the chip sample material to a nominal size (eg 85% passing 75 μm). This will ensure proper fusion in the furnace. Descriptive statistics done for the size grading shows that all of the samples managed to pass well above the prescribed standard of 80% passing -75μ with an average of 93.57% passing -75μ (Table 4.1)

Table 4.1: Descriptive statistics for size grading percentage - 75μ.

Size Grading Percentage -75μ	
Mean	93.57
Standard Error	0.16
Median	94
Mode	94
Standard Deviation	1.71
Sample Variance	2.93
Range	7
Minimum	90
Maximum	97
Count	120

4.1.2 Sample Mass

The 120 samples were sent to Performance Laboratory situated in Allanridge for analysis and part of the request was to weigh all the individual sample masses. The results were very interesting and confirm the findings in Chapter 5.2 that each and every sample extracted was different in size, volume and mass. The individual results were plotted on a graph (Figure 4.1) against the expected mass of 389 grams, based

on the demarcated sample dimension of (7 cm x 10cm x 2cm) at a relative density of 2.78. The mean mass of the extracted material is 363 grams which is below the expected mass of 389 grams. The standard deviation of the mass is 97.41 grams and according Figure 4.1 almost 11 samples are plotting outside the 3rd standard deviation.

Table 4.2: Descriptive statistics of the extracted mass of the samples.

Mass of samples extracted	
Mean	363
Standard Error	9
Median	357
Mode	342
Standard Deviation	98
Sample Variance	9569
Kurtosis	0
Skewness	0
Range	511
Minimum	167
Maximum	677
Sum	43887
Count	120

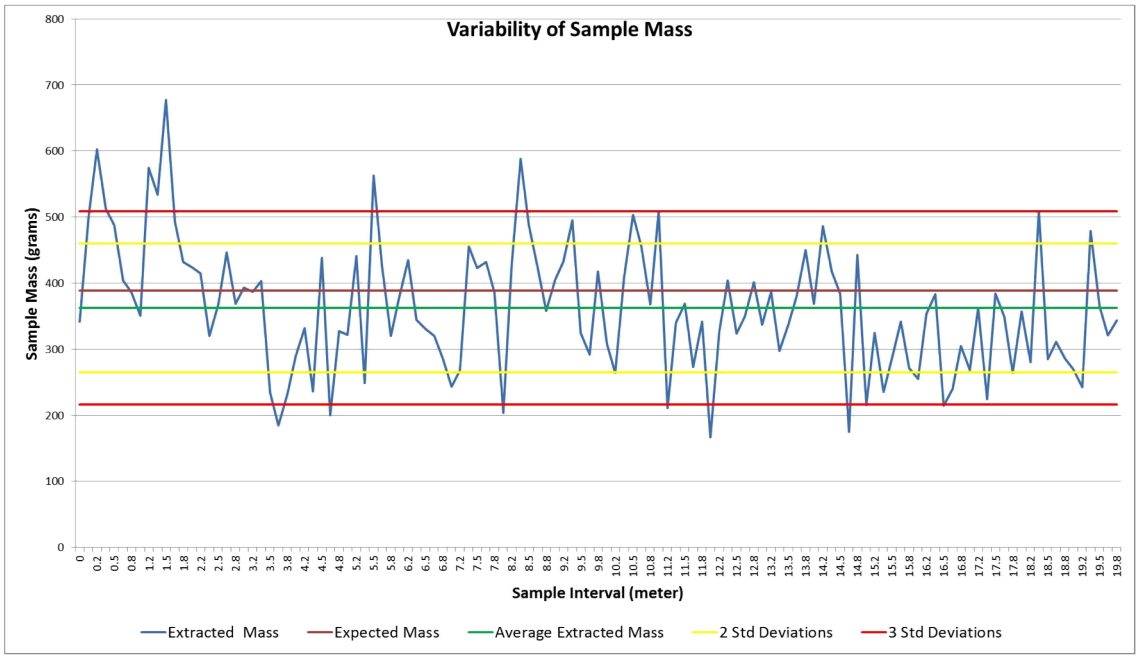


Figure 4.1: Variability of the individual mass of samples.

Variability of the individual mass of samples collected from the development raise indicates that a pre-defined sample mass cannot be adequately collected using the

'hammer and chisel' approach. The samples extracted at the start of the project up to 2.5 m is on average well above the expected mass of 389 grams. The average mass drops to below the expected mass. It is the author's opinion that samplers still had a lot of energy and did more than is expected because of the presence of a supervisor, but as the samplers tired work as per normal conditions continued.

4.1.3 Sample Grade

A summary of the descriptive statistics for the 120 samples chipped from the development raise and subjected to fire assay with gravimetric finish are presented in

Table 4.3: Descriptive statistics of 120 gold grades from raise

Statistic	Value
Mean grade (g/t)	70.10
Standard Error (g/t)	4.87
Median (g/t)	57.56
Mode (g/t)	28.57
Standard Deviation (g/t)	53.34
Sample Variance $(g/t)^2$	2845.30
Kurtosis	1.94
Skewness	1.37
Range (g/t)	266.63
Minimum (g/t)	0.24
Maximum (g/t)	266.87
Sum (g/t)	8412.49
Count	120
Confidence Level (95.0%)	9.64

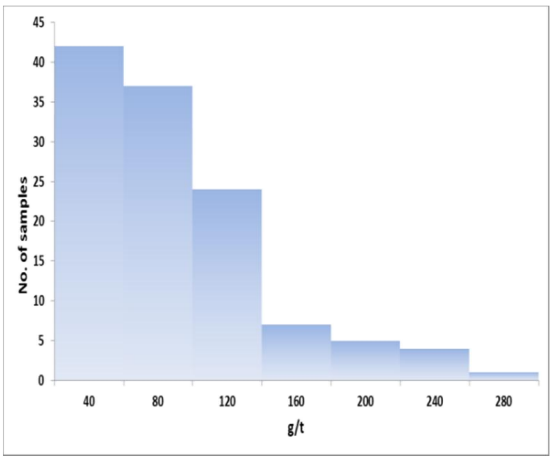


Figure 4.2: Positively skew distribution of chip sampling data

This specific raise was sampled on a previous occasion by the shaft sampler at the required interval of 5 m. Descriptive statistics of these gold assays (Table 4.4) shows that the average grade of 73.01 g/t from previous sampling was very similar to the average of 70.10 g/t obtained with the project.

Table 4.4: Descriptive statistics of original samples chipped at 5 m intervals

Grade of raise samples extracted	
Mean	73.01
Standard Error	10.5
Median	61.22
Standard Deviation	34.93
Sample Variance	1220.4
Kurtosis	0.13
Skewness	0.93
Range	108.6
Minimum	28.05
Maximum	136.62
Sum	803.12
Count	11

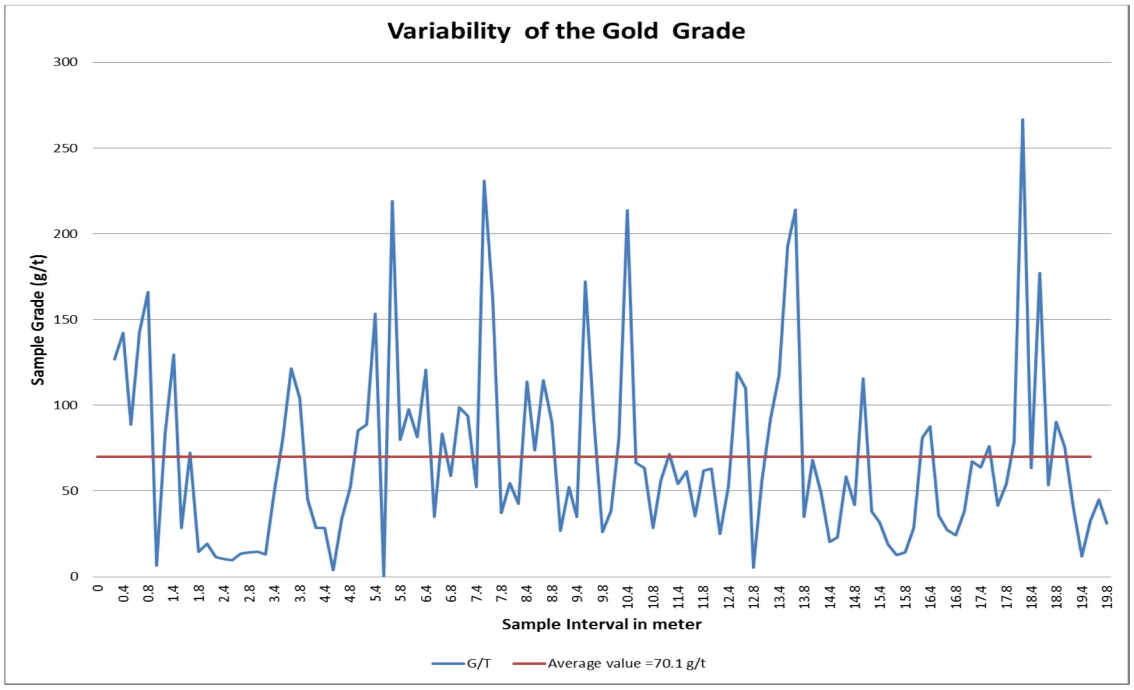


Figure 4.3: Variability of the 120 samples gold grade in the development raise

4.1.4 Effect of Aliquot Size On Precision

Work done by Hallbauer (1972) indicated that there are instances where larger gold grains, generally above 100 microns, do not become homogenized in the pulverized gangue during milling. Instead of breaking up gold particles, because of their extreme malleability will flatten out, they may roll up into cigar shaped particles, or they may incorporate gangue material in the gold grain. The gold grain itself does not break up

even under extreme milling conditions in which the gangues material is milled to less than 75 microns. As a result the assayer when selecting a 25 g aliquot from a packet of pulverized gold ore will select a gold grain that then returns a very high assay value. From a sampling perspective there is therefore uncertainty that a single 25 gram aliquot taken for the first sample is representative of the grade of the total sample milled. This uncertainty may arise because individual gold particles are selected in the aliquot and because the sample is not perfectly homogeneous.

To test the sub-sampling error a series of duplicate samples from the 120 samples had been assayed multiple times for gold content. The bulk of the samples had been analysed using 25g aliquots whilst a smaller number had been analysed using 50g aliquots. These duplicate samples will check the precision or the reproducibility of the initial result to determine if 50g aliquots gave better precision and thus potentially improved accuracy than the 25g aliquots (Figure 4.4). The mean value and the precision was calculated for each sample result were then plotted and a regression line calculated to determine if there was a significant difference between the 2 data sets (Figure 4.4).

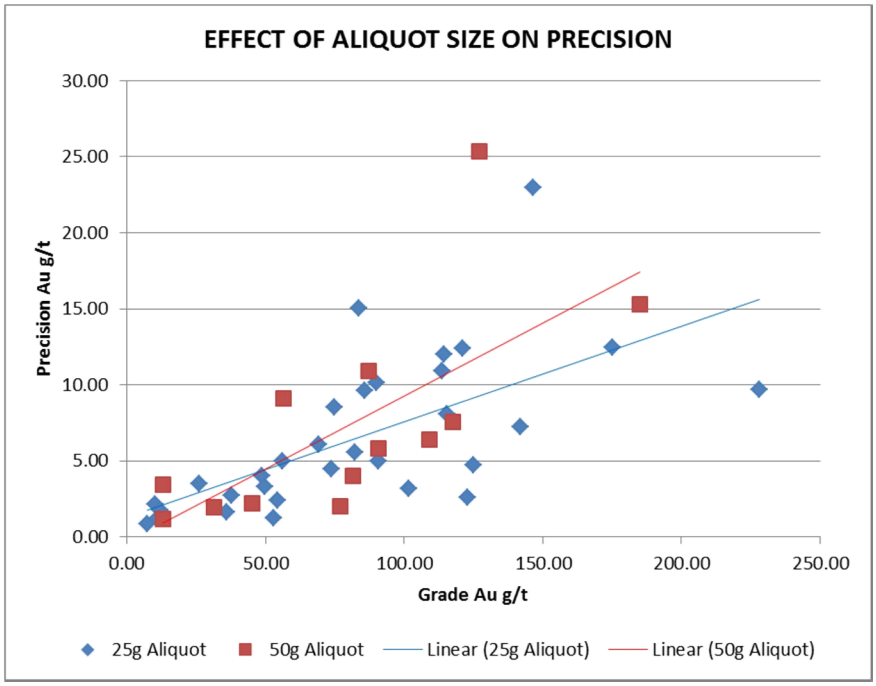


Figure 4.4: Effect of aliquot size on precision

Table 4.5: Summary output for 25 g aliquots

Regression Statistics	
Multiple R	0.65
R Square	0.42
Adjusted R Square	0.40
Standard Error	3.90
Observations	31

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	313.88	313.9	20.67200621	8.92E-05
Residual	29	440.33	15.18		
Total	30	754.22			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.259	1.340	0.939	0.355	-1.482	4.001
X Variable 1	0.063	0.014	4.547	8.9E-05	0.035	0.091

Table 4.6: Summary output 50g aliquots

Regression Statistics	
Multiple R	0.69
R Square	0.48
Adjusted R Square	0.43
Standard Error	5.15
Observations	13

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	264.98	265	10.008	0.009
Residual	11	291.25	26.48		
Total	12	556.23			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.322	2.805	-0.11	0.911	-6.496	5.852
X Variable 1	0.096	0.030	3.164	0.009	0.029	0.163

The conclusion of the Anova analysis is that the variation in the grade of the samples themselves masks the effect of the aliquot size. From the data processed it appears that the nature of the occurrence of the gold in the sample is resulting in no conclusive result being achieved on the data submitted.

Only one result out of the 461 assays, a value of 390.75g/t gold was considered an outlier and discarded from the calculation (sample TK10010) as a statistical outlier (Table 4.7). The Grubbs test was used to detect outliers. The Grubbs test is a statistical test that will detect outliers in a dataset assumed to come from a normal distributed population. Sample 8 in Table 4.7 is flagged as an outlier with a value of 390.75 g/t compared to an average of only 126.36 g/t for all the samples.

Table 4.7: Grubbs test is used to detect a significant outlier in a dataset.

Descriptive Statistics

Mean:	126.36768
SD:	60.0538
# of values:	22
Outlier detected?	Yes
Significance level:	0.05 (two-sided)
Critical value of Z:	2.75773516

Data

Row	Value	Z	Significant Outlier?
1	129.502	0.0522	
2	113.731	0.2104	
3	118.146	0.1369	
4	111.225	0.2522	
5	112.426	0.2322	
6	110.2	0.2692	
7	116.749	0.1602	
8	390.75	4.4024	Significant outlier. P < 0.05
9	107.561	0.3132	
10	150.398	0.4002	
11	115.854	0.1751	
12	97.059	0.488	
13	114.577	0.1963	
14	111.379	0.2496	
15	116.287	0.1679	
16	104.02	0.3721	
17	119.854	0.1085	
18	112.822	0.2256	
19	96.897	0.4907	
20	108.333	0.3003	
21	105.025	0.3554	
22	117.294	0.1511	

4.1.5 Precision of the analytical data

Precision error of the assayed samples is usually determined by comparing matching pairs of samples (i.e., original sample and duplicates) (Abzalov, 2008). The original sample is the first sample assayed, and the second is called the duplicate. The same rule used to collect the original sample from the pulverised pulp is used to collect the second sample. There are many statistical methods available to assess the precision error from paired data and the Half Absolute Relative Difference Plot was used as a graphic tool.

Half Absolute Relative Difference is a plot generated by calculating |x1-x2|/(x1+x2) of 472 samples expressed as a percentage and then sorted from smallest to largest (Figure 4.5). Pairs of data that are identical in grade will give a value of 0%. Grades completely different (i.e. 10g/t and 100g/t) will give a value of 100%.This is a very useful graph for assessing the precision of a set of duplicates.

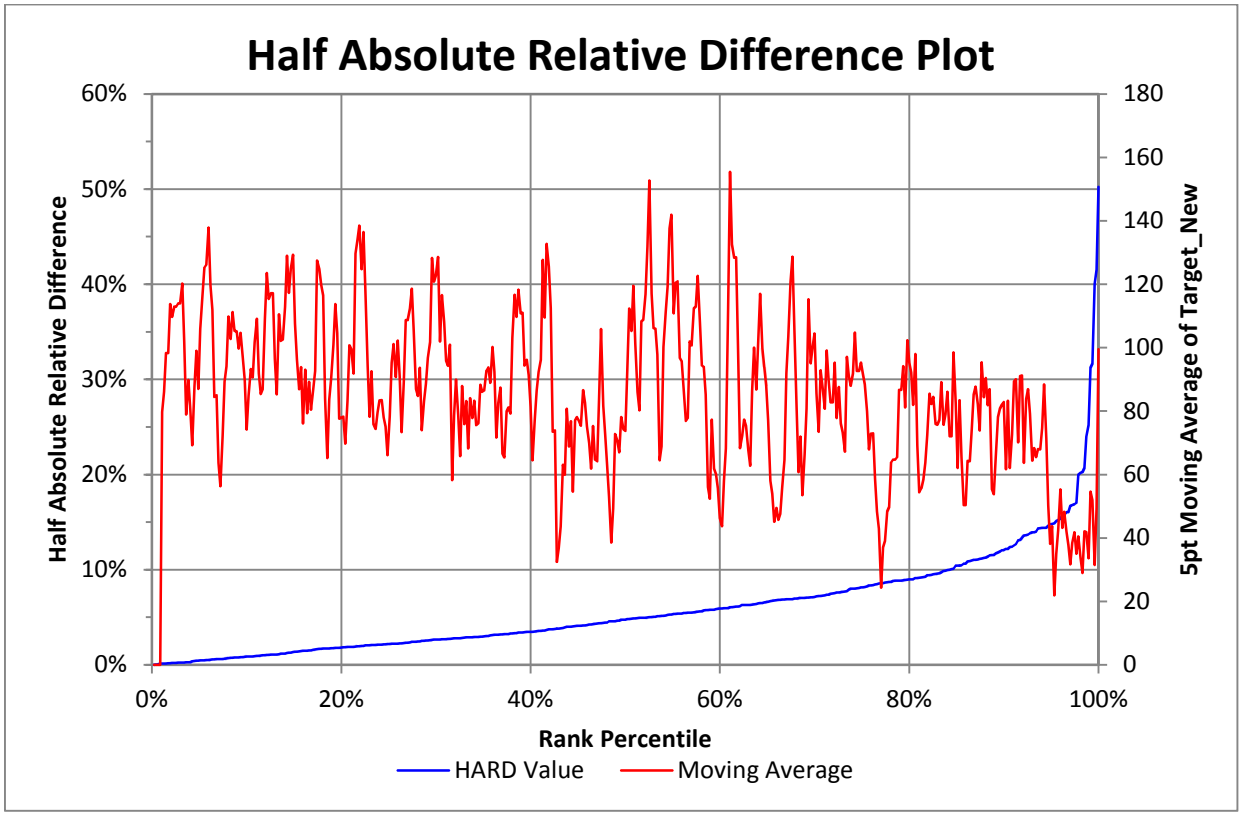


Figure 4.5: Half absolute relative difference plot for duplicate assays

As a rule of thumb the HARD for 90% of the pulp duplicates should be less than 10%. For coarse split duplicates the HARD for 80% of the pulp duplicates should be less than 10%, and for field duplicates the HARD for 70% of pulp duplicates should be less than 10%. The HARD vs. rank percentile plot shown in Figure 4.5 indicates that the variability of the assay process is within the acceptable standard. QA-QC indicates that the laboratory is not introducing additional error it just managed to produce precise inaccurate assays because the error introduced during extraction are far more devastating.

Statistical analysis of the grade of the samples extracted did not indicate anything significantly different when compared with statistics of historical sample data extracted

from the same area. The data is very variable over very short distances and could be the result of nugget effect usually associated with this reef. It could also indicate that the size of the sample is too small and not optimal for the population under investigation. It could also be the result of poor extraction. The sample variance, and standard deviation increased proportionally with the decrease in sample intervals. The skewness calculated for the 120 samples was also more positively skew than that calculated for the 11 samples. QA-QC performed on the 120 samples also indicates acceptable laboratory procedures with minimum change of additional error being introduced. Statistics done on the mass of the 120 samples extracted clearly indicated that the extraction process is flawed. Since all the samples demarcated were of equal dimensions it would be assumed that perfect extraction would result in samples of similar mass. The mass of the samples extracted was also very variable. Samples extracted at the start of the project were on average heavier than the samples extracted at the end of the project. The variability of the sample masses which should have been identical is a clear indication that the extraction error obtained with this sampling method was random and a probable source of error and bias.

CHAPTER 5 – IDENTIFYING THE ERROR ACCOCIATED WITH CHIP SAMPLING

5.1 Observed Sampling Error

Statistical analysis done on the grade and the mass of the samples indicates that the population is highly variable and lognormal expected from this reef type. Even though statistical analysis describes the nature of the data and the relation of the data to the underlying population it does not have the ability to determine the error introduced during the extraction process. That is why observation of the sample extraction underground becomes vital in understanding how error are introduced during this important process. Literature review found that practical implementation of the sampling protocol with the current tools of choice “the hammer and chisel” failed in all of the aspects defined in principles of sampling correctness. Instead of achieving a representative groove (channel) at regular intervals, samplers are performing a variation of ‘grab sampling ‘at irregular intervals. The following errors were observed during the underground sampling process, and have been classified according to the taxonomy of errors identified in the Theory of Sampling.

5.1.1 Increment Delimitation Error (IDE)

In order for a sample to be correct, every increment making up the composite sample must have exactly the same chance as every other increment of becoming part of the sample (Pitard, 2009). This principle can only be upheld when sampling zero- or one-dimensional lots. While the stope face or development raise may be thought of as a two dimensional object requiring a sampling module to be a cylinder, it better represents a continuous one-dimensional lot (Figure 5.1). According to Pitard (2009) it would require a complete and uniform slice, but it is not a lot that can easily be sampled or cut. In our understanding of particulate sampling one-dimensional lots are usually confined to a conveyor belt and the particulate nature of the materials on the belt means that they can easily be sampled using a cross-belt or cross-stream samplers. In the case of a solid in-situ stope face or raise the only portion of the face that has a chance of being sampled is that which is immediately exposed in the face. Whereas samples to be collected from such a lot may be considered to be

equiprobabilistic, the physical constraints on their extraction make equiprobabilistic sampling almost impossible.

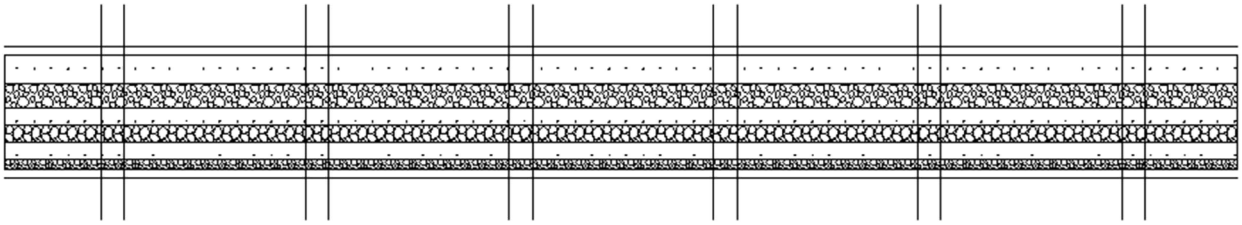


Figure 5.1: The underground stope face actually represents a heterogeneous 1-D 'stream' and the vertical lines represent the sample section (Fourie and Minnitt, 2013)

The difficulties associated with sampling in the given environment are amplified due to the limitations of the sampling equipment because only portions of the exposed face that are fractured or soft enough can be extracted other exposed portions on the face are unlikely to become part of the sample.

Even if the sides of the channel sample are defined using a rotary diamond saw it is not possible to chip the material within the channel sample to an even depth. Instead samplers actually undertake a form of grab sampling on selected areas of the 'stream' determined by how fractured it is (Figure 5.3 b). The deviation of the sample shape and volume extracted from that specified by the sampling standard is marked, and it contributes significantly to the bias or error of the sample.

5.1.2 Increment Extraction Error (IEE)

This error occurs when the sampling tool is selective or unable to extract a sample of the correct shape and volume as defined by the sampling standard (Pitard, 2009). The sampling equipment must be able to extract the correctly delimited sample. A comparison between sample mass extracted and sample mass required is also a good indication on the IEE (Figure 4.1).

All the samples were demarcated at the same dimensions of (7cm x 10cm x 2cm) because the channel width was +- 1.5 cm and the COP require a minimum sample width of 7cm when demarcating a contact sample. During the sampling exercise samplers did their best to comply with the requirements of the sampling standards but the tools did not allow for easy extraction. The expected mass was 389 grams based

on the dimensions of (7cm x 10cm x 2cm). The actual mass extracted ranged between 166.6 grams and 677.3 grams with an average of 362.7grams. Almost 65 % of the samples were below the required mass. The reason for this variability of the mass is because the samplers failed to extract the correct demarcated samples which are confirmed by the Faro scans in Figure 3.9. This relatively simple comparison between samples with equal support clearly shows the inconsistency of the actual masses obtained with the hammer and chisel. The tools are clearly not capable of extracting the required mass, shape and volume of a demarcated sample.

5.1.3 Increment Preparation Errors (IPE)

Increment Preparation Errors (IPE) are introduced between different stages of the sampling process or sample handling and arises because of contamination, material losses, and alteration of the physical composition of the sample, human errors, ignorance, carelessness, fraud, and even sabotage (Pitard, 2009). IPE observed during the sampling exercise were related mostly to contamination by fragments or pieces of reef that were dislodged from around the area being sampled. Where the reef was very hard or solid, the hammer was used directly on the reef face to loosen material for the sample. This introduced contamination and sample loss (Figure5.2).



Figure 5.2: Sample loss clearly visible when the chipper are using use a hammer to collect sample

It was also observed that when the sampler and his helper had collected sufficient material in the sample dish, they would select some of the bigger pieces and break them into smaller pieces by hitting them with the chisel on a leather glove. The primary reduction of the fragments underground is necessary because most of the laboratories are not equipped to do primary crushing on surface. They would then select some pieces, mostly waste, to discard. Discarding of sample material is considered standard practise on most mines and they do so to reduce the sample to about 350 grams.

Breaking the bigger pieces on the leather glove also increases the possibility of contamination as fine gold grains can be trapped in the leather and the seams of the glove. The collecting dish is cleaned after each sample with very little chance that fine gold will adhere to the metal surface of the dish compared to the leather glove. Sample losses of one form or another were observed at most stages of the sampling process.

5.1.4 Increment Weighting Errors (IWE)

Underground observation confirmed that extracting an acceptable sample from the hard reef material with the basic tools was very difficult indeed. Sampling of the thin reefs may only require a single sample to represent the section, but elsewhere thicker reefs like the Basal Reefs mined at Harmony's Bambanani shaft may have to be sampled using multiple composited samples, as shown in (Figure 5.3). A section across a composite reef such as that shown in (Figure 5.3) would consist of multiple samples that were cleanly cut sample across the entire channel width. Instead, because of the hardness of the ores, it would most likely consist of scattered portions of reef extracted in a haphazard way (patches shown in black) with highly irregular shapes and sizes. Poor extraction or recovery for each individual sample when composited may lead to a bias generated by an Increment Weighting Error (IWE). For in situ extraction this variance of the error can be very large in comparison to the small variance introduced in the lab when the increments selected is not constant (Pitrad, 2003)

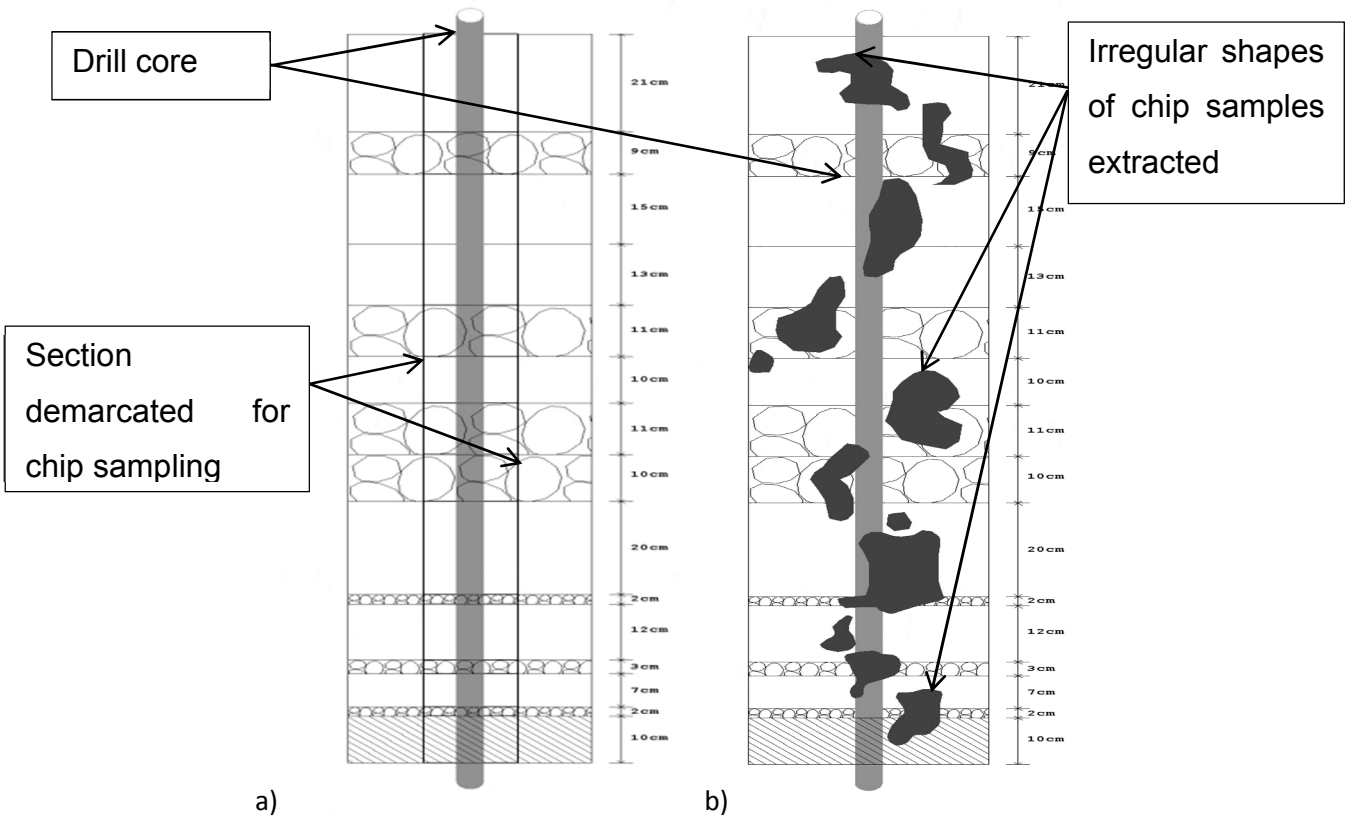


Figure 5.3: a) Diagram comparing the extraction capabilities between a drill core (grey) and the b) irregular shapes and sizes of the chip sampling (black) in a thick heterogeneous reef -type.

Sample extraction using the drill core method under perfect conditions may achieve 100% recovery, whereas the chip sampling method was observed to have poor recovery, as additionally, mixing of samples with different recoveries may introduce bias (Pitard, 2003)

5.1.4.1 IWE when compositing samples with different widths

The errors or variance introduced when samples of different support sizes are composited is better explained by using Cawood (2003) and Lerm (1994) proposed new protocol for sampling the thin carboniferous reefs. This proposal is specifically aimed to stop the oversampling of the softer material when sampling thin carboniferous reefs where the soft carbon portion is less than 3cm. Since the minimum sample width is 7cm some waste will be included in the demarcated sample if it has a carbon width of 3cm. If the carbon portion is over extracted simply because it's softer and the grade is now allocated to the full 7cm then the chances of overestimating the

grade increases. To avoid this from happening they suggested that the horizontal width of the portion of the sample containing most of the gold should be increased. It is believed that this effort would significantly reduce the variability and the possibility of over estimation. Figure 5.4 is a diagram used by Cawood to explain the new proposed method.

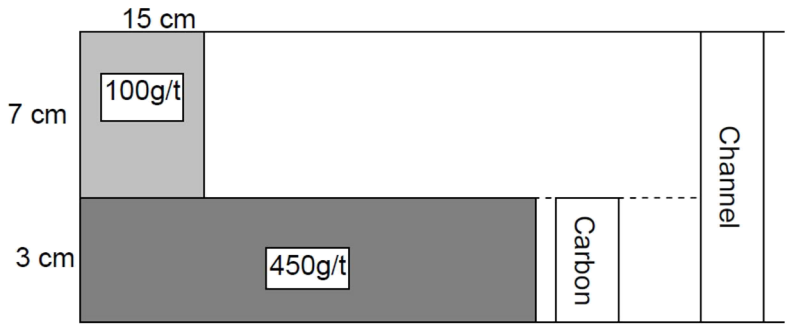


Figure 5.4: Diagram explaining the new method of sampling and how the variance could be reduced by simply increasing the sample width of the high grade contact portion (Cawood, 2003:28)

The method determines that all external waste should be excluded from the contact sample. The carbon-rich layer in the channel should be marked and extracted separately. The minimum horizontal width of a sample should be increased to 15cm instead of the required 10cm. The carbon–rich section of the sample should be chipped until a required mass of 600 grams is reached even if it means that the sample horizontal width for the contact sample will now be 45cm (Figure 5.4).The average value for the section is now calculated as follows: Average value (cm.g/t) = {450 x 3} + {7 x 100} = 2050cm.g/t (Cawood, 2003:28).Lerm (1994)in an experimental simulation calculated that the estimated method could lower the average face grade by up to 14%.

The new method proposed by Cawood and Lerm has some merit but it will only work if either all the sample sections consist of a single sample only, or if all the samples extracted have similar (width) dimensions. If you have to extract multiple samples from a section, then this new suggested method of increasing the sample mass for an individual sample only, will introduce significant IWE. The pay-off with this suggestion is that when you get one aspect right, the other aspects tends to go wrong.

Figure 5.4 will be used to explain the problems associated with the proposed method. The suggestion to increase the mass of the contact sample by increasing the horizontal width of the sample is a valid, but it in doing so it will also change the support size of that particular sample. Comparing samples with different support sizes may lead to incorrect assumptions (Pitard, 2009; Smith, 2001).

Table 5.1 is used to illustrate the variance introduced when the support of the samples in relation to their horizontal widths are not kept constant. The single contact sample at a horizontal width of 45cm and an average grade of 450g/t used in Table 5.1 could also consist of three individual samples (A, B and C) with a horizontal width of 15 cm each. For the demonstration three individual grades for the carbon samples A, B and C was assumed. The average value is now calculated (450 g/t x 3cm) + (100 g/t x 7cm) = 2050 cm.g/t and is the same as the grade in the original calculation in Figure 5.4. To be able to explain the issues of support grades was assumed for the channel samples B and C in Table 5.1

Table 5.1: Table with individual grades based on the new sampling method

Sample Composition	Sample Width	Sample A 15 cm	Sample B 15 cm	Sample C 15 cm	Avge g/t	Avge cmgt
Channel	7 cm	100	25	75	100	700
Carbon	3 cm	750	150	450	450	1350
Total	10 cm					2050

The problem comes in when you have multiple samples in the same section with different horizontal widths (even if they have the same mass) in this case the 15 cm horizontal width at 100g/t, especially if you have to composite the samples to get an average value for that section. Although the weights of the two samples are almost the same as stated by Cawood they are in fact representing a different support area for a specific part of the reef and are therefore not considered to be an equiprobablistic sample and is a classic example of IWE. The following tables are used to demonstrate the biases that are introduced with this specific sample method.

Table 5.2: Table represents what is considered correct sampling practices.

Sample Composition	Sample Width	Sample A 15 cm	Sample B 15 cm	Sample C 15 cm	Avge g/t	Avge cmgt
Channel	7 cm	100	25	75	100	700
Carbon	3 cm	750	150	450	750	2250
Total	10 cm					2950

The samples in Table 5.2 represent normal sampling practises where samples are demarcated and extracted at the same widths; in this case 15 cm. Perfect extractions of the two samples will return an average of 2950cmg/t. It is significantly higher than the 2050cm.g/t obtained with the proposed new method in Table 5.1, even though the vertical representation of the samples remained the same.

In Table 5.3 the width of the channel sample composition was also increased to 45cm the same as the carbon sample width. The average cm.g/t now calculated to 1819cm.g/t.

Table 5.3: This sampling will also be considered correct sampling practise and would be representative for the 45cm width.

Sample Composition	Sample Width	Sample A 15 cm	Sample B 15 cm	Sample C 15 cm	Avge g/t	Avge cmgt
Channel	7 cm	100	25	75	66.7	467
Carbon	3 cm	750	150	450	450	1350
Total	10 cm					1817

This simple example was used to illustrate how sensitive sampling is and if you try to fix one aspect of an error it may introduce other errors. These examples also highlight how important it is to understand how sensitive sample extraction from a vertical face is to the aspect ratio. Any deviation from this pre-determined aspect ratio or sample size will introduce bias. According to (Krige, 1999) increasing the sample mass will definitely reduce the material variation, and will also lower the variance, but if this increase in mass is not in relation with the aspect ratio and just selectively applied in this case the contact sample, then serious bias will be introduced. Every time when

this sample aspect ratio is changed it is considered to represent a different support and constitute a different variance. Let's consider applying this proposed method of increasing the sample mass of the contact sample of a core extraction. It is not practical (Figure 5.5).

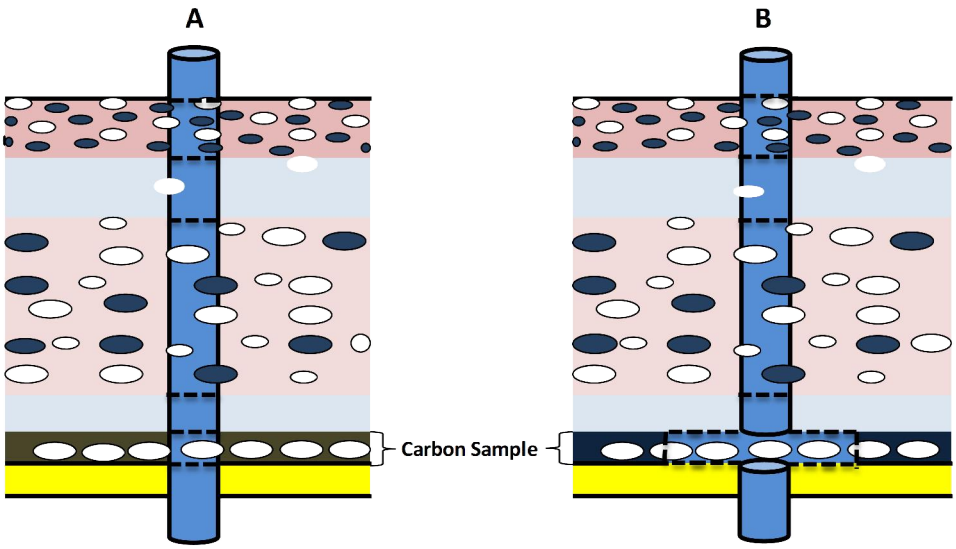


Figure 5.5: Diagram showing how impractical the proposed new method seem if applied to a drill core example. 'A' normal core extraction and 'B' proposed mass increase of the carbon portion only.

It must be stressed that the issue was never really about the sample weight or mass introducing error but more about the tool inability to extract a representative sample according to the demarcated area. So even if the extracted sample mass should increase tenfold, extraction with the current tool is probably going to remain poor, therefore the author believes that the new proposed method is not practical.

5.1.4.2 IWE when compositing samples with irregular shapes

The following is a practical example whereby a single sample collected from an underground face is used to demonstrate how poor extraction (which also constitute a different support) can aggravate the bias introduced by IWE. A sample of 16cm (Figure 5.6)was collected from the face during the sampling project and was cut into two individual samples, Sample A(Figure 5.7),consisting of a footwall waste and reef portion, and Sample B(Figure 5.7) consisting mostly of internal quartzite.

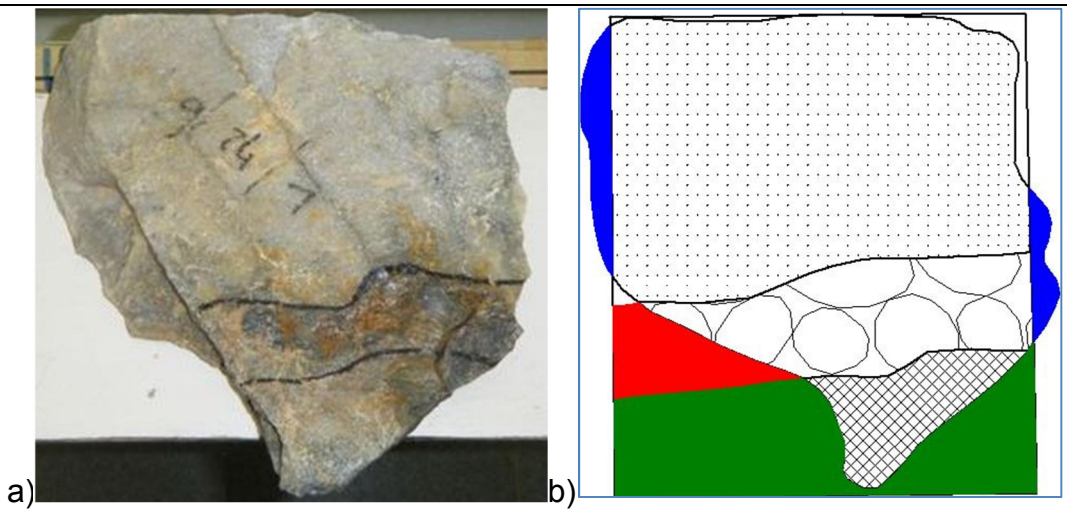


Figure 5.6: Irregular shape of the sample collected from the face, b) diagram of the sample showing the areas of under- and over-representation.

The sample diagram (Figure 5.6b) for this particular sample composition was constructed. It clearly indicates that the sample shape extracted does not correctly represent the sample dimensions at a locked aspect ratio represented by the rectangle. The portions shown in red and green colours are the under-represented areas of the reef and footwall respectively, while the blue area indicates over-representation of the internal quartzite. The width for the internal quartzite was approximately 10cm and for the footwall + reef portions was about 6cm (Figure 5.7).The two samples were weighed and assayed and the average result was weighted according to the sample mass(Table 5.4).

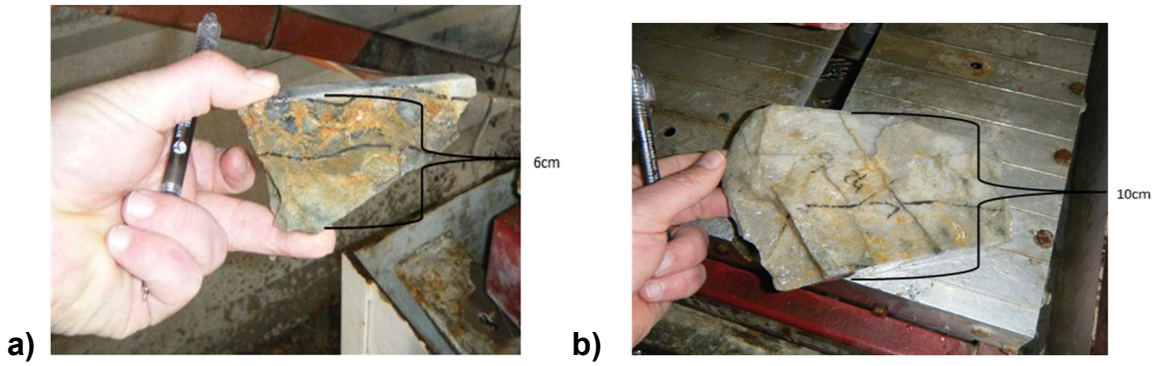


Figure 5.7: a) Sub-sample A consisting of reef+ footwall, and b) Sub-sample B consisting of internal quartzite.

The reef +footwall sample (Sample A) returned a grade of 143.7g/t. The internal quartzite sample (Sample B) retuned a grade of 0.2g/t. The average of the two

samples when composited {cm.g/t = {0.2g/t x 10cm} + {143.7g/t x 6cm} = 864cm.g/t (Table 5.4). This is normal procedure to calculate a section consisting of two or more samples. The two samples are in fact not really representative of the width used in the calculation above, based on the shape and the volume of the actual (Figure 5.6b).

Table 5.4: Comparison of the two individual samples A and B

	g/t	Width (cm)	cm.g/t
Sample A (Internal quartzite)	0.2	10	2
Sample B (Reef and footwall)	143.7	6	862
Total		16	864
Average g/t	**54.01 g/t**		

If the material of the two samples is combined and a new grade is obtained, based on the weighted mass, and then multiplied with the combined width of the two samples, the problem of poor extraction will become evident. The remaining pulps of the two samples were combined to form new “Sample C”. Sample C was then bottle rolled for 48 hours before being assayed, and it returned a new grade of 14.81g/t (Table 5.5).

Table 5.5: Grade for combined Sample C

	g/t	Width (cm)	cm.g/t
Sample C (Sample A + Sample B)	14.81	16	237
Total		16	237
Average g/t	**14.81 g/t**		

The content for the combined sample (Sample C) is {cm.g/t = {14.81g/t x 16cm} = 237 cm.g/t. The average value calculated for the individual samples A and B weighted on sample width only is 864cm.g/t (Table 5.4). The average value for the same material combined, and weighted on mass and width now returned a value of 237cm.g/t. It is a difference of 365%. This is a classic example of IWE, and this example is a clear indication how error is introduced if a vertical width is applied to an irregular shaped sample. Perfect extraction of the sample at a width of 16cm would have returned a different grade altogether. The values returned from the lab for the individual and the

combined material are correct, how we allocate this value back to a three dimensional shape or volume is where the actual error is introduced.

Underground observation has confirmed that proper extraction with the current tools is not possible. The Sampler and his team and the tool have absolutely no control over the shape size and volume of the material extracted. The samples extracted are by definition rather a grab sample. The problem of poor extraction is further aggravated when a sample width is applied in order to calculate a cmgt value which is mostly used in the valuation process on South African mines. It has been shown with a practical example how using an incorrect width in the cmgt calculation could overstate the value. Channel sampling it is particularly sensitive to this so it's important that the aspect ratio of the sample demarcated should be extracted accordingly. If not then unprecedented errors and bias could be introduced which would be difficult to quantify.

CHAPTER 6 - QUANTIFYING THE ERRORS

Observation of the underground sampling process as carried out by samplers on a day-today basis has shown that sample extraction using a hammer and chisel is beset by error especially IDE, IWE, IPE and IEE, but finding a method of quantifying the errors remained a challenge, especially in the light of Lord Kelvin's comment, "If you can't measure it, you can't improve it" (Lord Kelvin). Sichel (1947) mentioned that quantification of sampling errors is difficult because we always deal with varying quantities. The actual grade of the in-situ material represented in a demarcated (correctly delimited) sample is not known. If it were, then the error associated with sample extraction could be measured by calculating the difference in grade between the extracted sample and the expected grade. The erratic or nuggety distribution of gold grains in the reef is such that the grade varies from one sample to the next over very short distances. As a result duplicate extraction of samples, i.e. samples taken next to one another is a meaningless method of attempting to quantify the error.

6.1 Simulating the Perfect Sample

Quantification of the error introduced as a result of using a specific type of sampling equipment, especially the hammer and chisel, is almost impossible in a real world mining environment. The only possible solution to quantifying the error associated with sampling delimitation and extraction would be to eliminate the uncertainty associated with not knowing the expected grade. This is achieved by simulating the extraction of a 'perfect chip sample' at a known grade which in this study is referred to as the "Simulated Chip Sample Model" (Figure 6.1).This 'perfect sample' is used as a benchmark to simulate and quantify different scenarios of over or under extraction that could occur with the current hammer and chisel equipment. The difference between the extracted grade and the expected grade, is therefore the extraction error are calculated which can be expressed as a percentage.

The dimensions of the perfect simulated standard reference sample are based on current sampling protocols and measuring 10cm (Horizontal Width) x 7cm (Vertical Width) x 2cm (Depth). Although it has not been investigated in detail in this study, it is highly likely that the lithology of the particular reef being sampled can aggravate the

error introduced as a result of poor extraction. It was therefore decided to simulate the standard reference sample based on a generally observed underground lithology, with an internal quartzite width of 4cm, an average reef width of 1cm and a footwall width of 2cm as shown in Figure 6.1. A relative density (Rd) of 2.78 was used for the in situ reef material**.** The actual density for the carbon portion will be much higher than the allocated 2.78, but for this simulation it was assumed to be the same as the surrounding rock. The reef portion (Figure 6.1) is assumed to be homogenous with a grade of 150g/t. Extraction in the 3rd dimension, the depth, is assumed to be a perfect 2 cm, but in reality it is also considered to be a factor that could contribute to the error as a result of poor extraction.

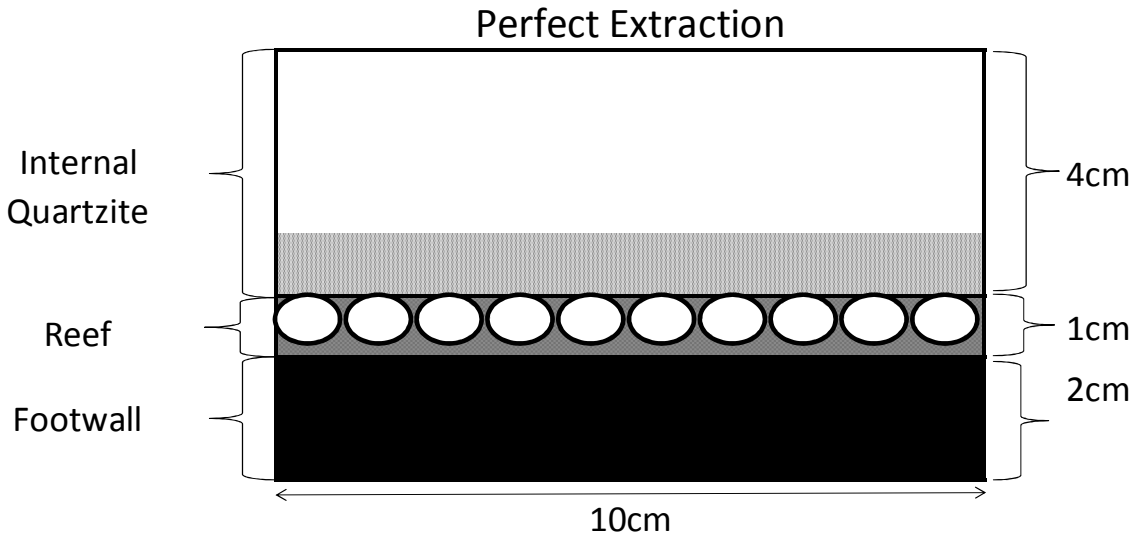


Figure 6.1: Lithology and components of the perfect standard reference or "Simulated chip sample model".

The average in situ grade of the simulated standard reference sample is calculated to be 21.43 g/t based on the sample dimensions and a grade of 150 g/t in the reef portion. Perfect extraction of the sample according to the demarcated dimensions will result in a grade of 21.43g/t, weighted by mass and width (Table 6.1). The results from the perfect sample can now be used as the benchmark to quantify the error involved with incomplete or over extraction of any of the units making up the sample.

Table 6.1: Standard reference simulated chip sample model based on the actual reef composition

Sample Composition	Width (cm)	Height (cm)	Depth (cm)	Rd	Mass (gram)	g/t	Weighted cm.g/t
Internal Quartzite	10	4	2	2.78	222.4	0	0
Reef	10	1	2	2.78	55.6	150	8340
Footwall	10	2	2	2.78	111.2	0	0
Total		7			389.2		8340
Average						21.43	150

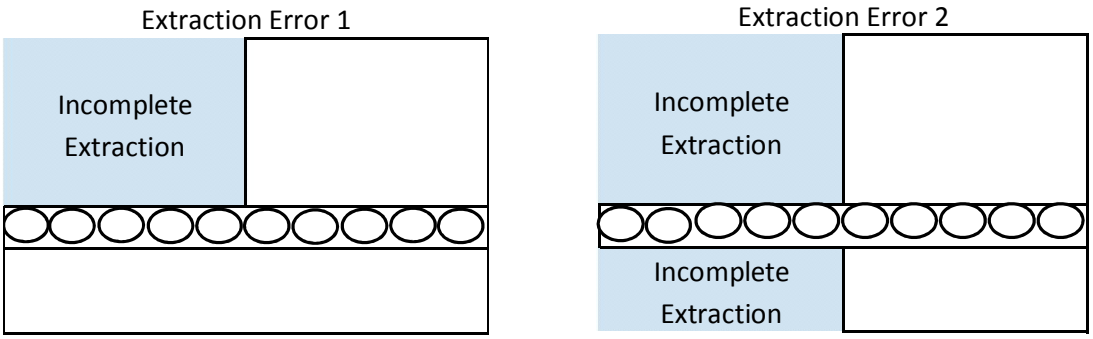
6.1.1 Effect of of Under-Sampling

The simulated chip sample model in Table6.1 can be used as a benchmark to quantify the effect of under or over extraction of certain material within the demarcated (delimited) sample. The error attributable to poor extraction only, can be calculated and quantified because the uncertainty of the inherent grade variability or nugget is removed. Numerous reasons could be called on to explain the over- or under-sampling of each component in the 'simulated sample' i.e. limitation of the tool, brittle or soft portions, blast induce fracturing etc. Quantifying all possible percentages of deviation from the perfect sample is not possible but in order to cover the main possibilities that could arise it was decided to simulate six probable cases for oversampling and six probable cases for under sampling of the reef. Under sampling refers to a situation where some material was not extracted from a pre-defined sample whereas oversampling refers to a situation where more than the required sample material was extracted.

Different extraction errors are simulated for each component of the perfect sample and the difference in value is then compared with the expected grade with the error being expressed as a percentage. The results obtained from these simulations helped to quantify the percentage error and bias introduced as a result of poor sample extraction, especially for this type of carboniferous reef with this specific reef-to-waste ratio.

The diagram **shown** in Figure 6.2 a, "**Extraction Error 1**"**,** simulates a probable outcome of sampling where the tool fails to extract all of the internal quartzite from the

demarcated sample. A second diagram shown in Figure 6.2 b, "**Extraction Error 2**" simulates the probable effect of both the internal quartzite and the footwall portion of the sample being under extracted. In both cases the grade of the reef portion is biased upwards (30.0 and 37.5 g/t), relative to the standard reference sample (21.43 g/t) due to the under extraction of the waste portions.



a) 40% Over estimation of the actual grade b) 75% Over estimation of the actual grade

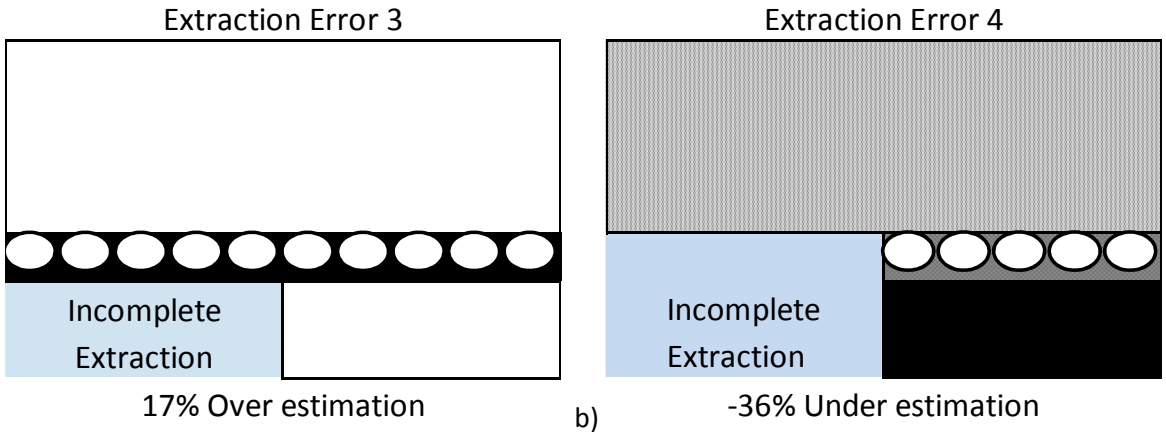
Figure 6.2: Diagram indicating the area of under extraction for; a) Extraction Error 1 and b) Extraction Error 2.

Table 6.2: Calculated grade for Extraction Error 1 and Extraction Error 2

	Extraction Error 1							Extraction Error 2						
Sample Composition	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**
Internal Quartzite	5	4	2	2.78	111.2	0	0	5	4	2	2.78	111.2	0	0
Reef	10	1	2	2.78	55.6	150	8340	10	1	2	2.78	55.6	150	8340
Footwall	10	2	2	2.78	111.2	0	0	5	2	2	2.78	55.6	0	0
Total		7			278		8340		7			222.4		8340
Average						**30.00**	210						**37.50**	262.5
True grade = 21.43 g/t	**% Difference**					**40%**		**% Difference**					**75%**	

The grade calculated for the material extracted in simulation "**Extraction Error 1"** is 30g/t (Table 6.2). This is a 40% increase in grade when compared against the actual in- situ grade of 21.43g/t (Table 6.1). Similarly, "**Extraction Error 2"** will also overstate the actual grade of the sample by a massive 75 % (Table 6.2). This confirms the belief that if the harder surrounding materials usually at low grades are underrepresented in relation to the gold bearing portion demarcated within a sample, then the actual grade of the extracted material will be over stated.

"**Extraction Error 3**" represented in Figure 6.3 a**,** simulates some under extraction of the footwall portion only. This type of extraction error will overestimate the in-situ grade by 17% (Table 6.3).



a) b)

Figure 6.3: Diagram indicating the probable area of under extraction for a) Extraction Error 3 and b) Extraction Error 4

Table 6.3: Calculated grades for Extraction Error 3 and 4.

	Extraction Error 3							Extraction Error 4						
Sample Composition	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**
Internal Quartzite	10	4	2	2.78	222.4	0	0	10	4	2	2.78	222.4	0	0
Reef	10	1	2	2.78	55.6	150	8340	5	1	2	2.78	27.8	150	4170
Footwall	5	2	2	2.78	55.6	0	0	5	2	2	2.78	55.6	0	0
Total		7			333.6		8340		7			305.8		4170
Average						**25.00**	175						**13.64**	95.5
True grade = 21.43 g/t	**% Difference**					**17%**		**% Difference**					**-36%**	

With the simulation in Extraction Error 4 (Figure 6.3b), under sampling of the reef and footwall portions are assumed. This resulted in the grade of the material extracted to under estimating the actual grade by 36% (Table 6.3).

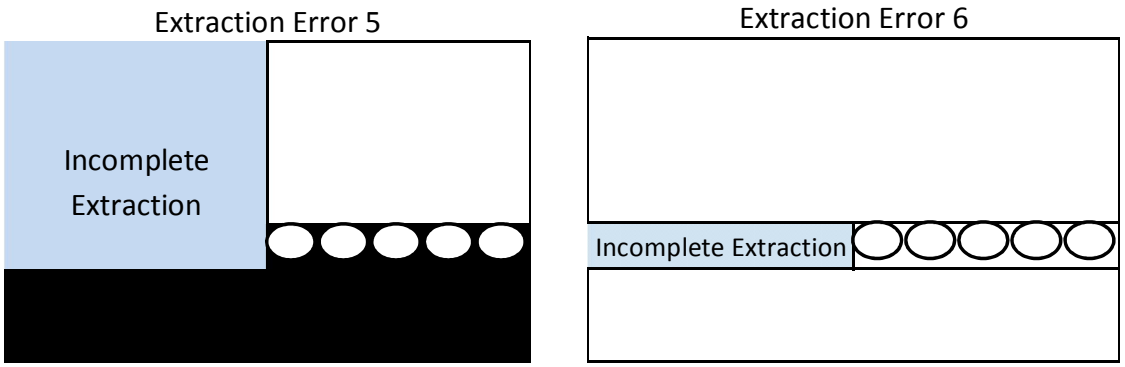


Figure 6.4: Diagram indicating the area of under extraction for a) Extraction Error 5 and b) Extraction Error 6

Table 6.4: Calculated grades for Extraction Error 5 and 6.

	Extraction Error 5							Extraction Error 6						
Sample Composition	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**
Internal Quartzite	5	4	2	2.78	111.2	0	0	10	4	2	2.78	222.4	0	0
Reef	5	1	2	2.78	27.8	150	4170	5	1	2	2.78	27.8	150	4170
Footwall	10	2	2	2.78	111.2	0	0	10	2	2	2.78	111.2	0	0
Total		7			250.2		4170		7			361.4		4170
Average						**16.67**	116.67						**11.54**	80.8
True grade = 21.43 g/t	**% Difference**					**-22%**		**% Difference**					**-46%**	

One might argue that the selection of the six probabilities itself was biased, especially if you compare the reef to waste ratio for each simulation. While this might be true the exercise nevertheless manages to capture the devastating effect that poor extraction can have on the assayed grade giving rise to both error and bias. Underground observation confirmed that it's possible for samplers to under or over sample certain units of the demarcated sample. The same simulation experiments were repeated with some of the units being over extracted.

6.1.2 Effect of Over-Sampling

Six different extraction errors were simulated for each component of the perfect sample, and the difference in value was again compared with the expected grade of the simulated standard reference sample (21.43 g/t) and expressed as a percentage error. "**Extraction Error 7**" represents a situation whereby the initial demarcated sample was perfectly extracted with some extra internal quartzite (Figure 6.5).

"**Extraction Error 8**" is assuming oversampling of both the internal quartzite and footwall portions (Figure 6.5).

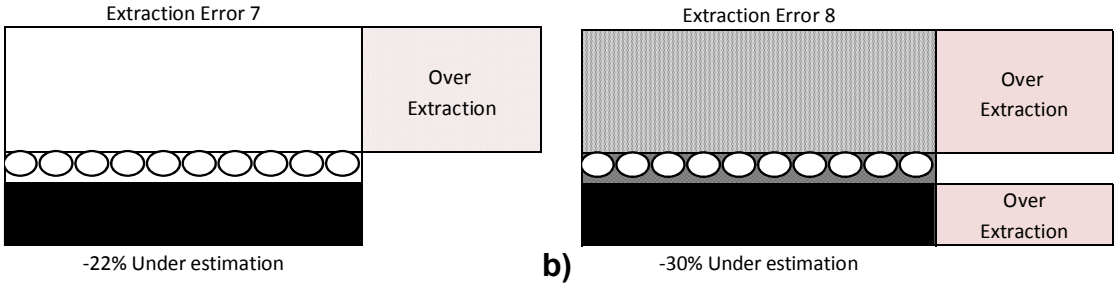


Figure 6.5: Diagram indicating the area of under extraction for a) Extraction Error 7 and b) Extraction Error 8

Both simulations indicate that over sampling gives rise to underestimation of the known in situ grade of -22% and -30% respectively (Table 6.5), compared to the simulated standard reference sample of 21.43 g/t. This indicates that oversampling of the waste portions over and above perfect extraction will tend to under estimate the true in-situ grade of the sample.

Table 6.5: Calculated grades for Extraction Error 7 and 8.

	Extraction Error 7							Extraction Error 8						
Sample Composition	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**
Internal Quartzite	15	4	2	2.78	333.6	0	0	15	4	2	2.78	333.6	0	0
Reef	10	1	2	2.78	55.6	150	8340	10	1	2	2.78	55.6	150	8340
Footwall	10	2	2	2.78	111.2	0	0	15	2	2	2.78	166.8	0	0
Total		7			500.4		8340		7			556		8340
Average						**16.67**	117						**15.00**	105.0
True grade = 21.43 g/t	**% Difference**					**-22%**		**% Difference**					**-30%**	

"**Extraction Error 9**" in Figure 6.6 a, assumes over extraction of the footwall portion only and resulted in a under estimation of 13 % (Table 6.6). "**Extraction Error 10**" in Figure 6.6b assume over extraction of both the reef and footwall portion, which resulted in an overestimation of the true grade by 24% (Table 6.6).

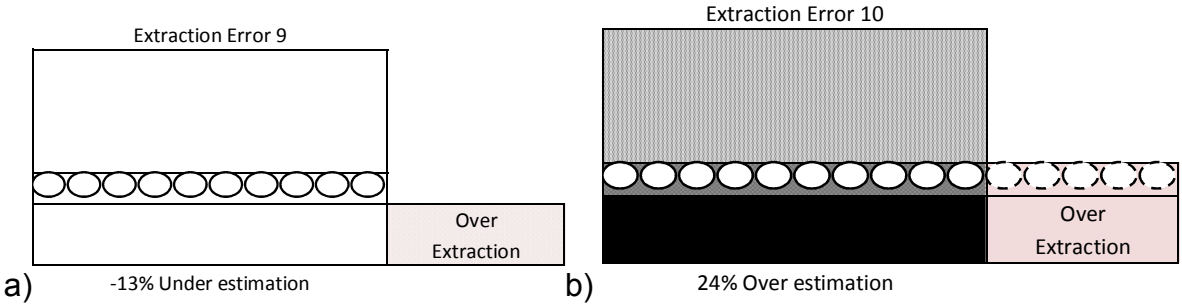


Figure 6.6: Diagram indicating the area of under extraction for a) Extraction Error 9 and b) Extraction Error 10

Table 6.6: Calculated grades for Extraction Error 9 and Extraction Error10.

	Extraction Error 9							Extraction Error 10						
Sample Composition	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**	**Width (cm)**	**Height (cm)**	**Depth (cm)**	**Rd**	**Mass (gram)**	**Value (g/t)**	**Weighted cmg/t**
Internal Quartzite	10	4	2	2.78	222.4	0	0	10	4	2	2.78	222.4	0	0
Reef	10	1	2	2.78	55.6	150	8340	15	1	2	2.78	83.4	150	12510
Footwall	15	2	2	2.78	166.8	0	0	15	2	2	2.78	166.8	0	0
Total		7			444.8		8340		7			472.6		12510
Average						**18.75**	131						**26.47**	185.3
True grade = 21.43 g/t	**% Difference**					**-13%**		**% Difference**					**24%**	

"**Extraction Error 11**" simulated the over extraction of both the internal quartzite and the reef portion (Figure 6.7 a). "**Extraction 12**" depicted in Figure 6.7 b, assumed over extraction of the reef portion only. This simulations calculated an over estimation of the true expected grade of 11% and 40% respectively (Table 6.7).

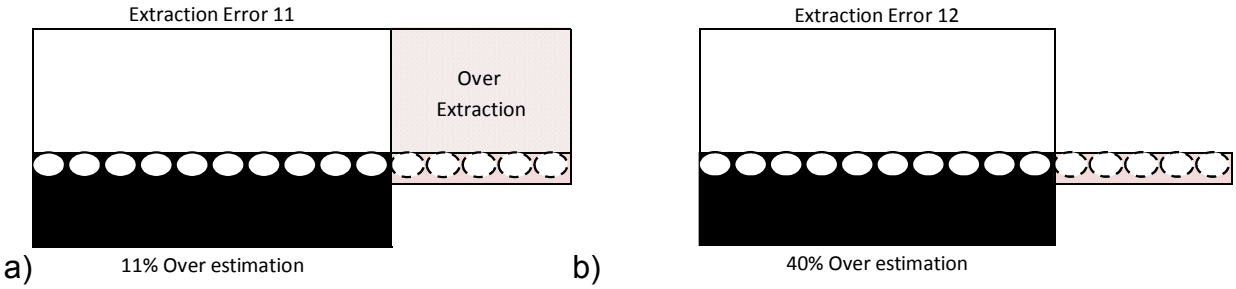


Figure 6.7: Diagram indicating the area of under extraction for a) Extraction Error 11 and b) Extraction Error 12

Table 6.7: Calculated grades for Extraction Error 11 and Extraction Error 12

	Extraction Error 11							Extraction Error 12						
Sample Composition	Width (cm)	Height (cm)	Depth (cm)	Rd	Mass (gram)	Value (g/t)	Weighted cmg/t	Width (cm)	Height (cm)	Depth (cm)	Rd	Mass (gram)	Value (g/t)	Weighted cmg/t
Internal Quartzite	15	4	2	2.78	333.6	0	0	10	4	2	2.78	222.4	0	0
Reef	15	1	2	2.78	83.4	150	12510	15	1	2	2.78	83.4	150	12510
Footwall	10	2	2	2.78	111.2	0	0	10	2	2	2.78	111.2	0	0
Total		7			528.2		12510		7			417		12510
Average						**23.68**	166						**30.00**	210.0
True grade = 21.43 g/t	% Difference					11%		% Difference					40%	

Over extraction of the various units of a sample over and above the required material also introduces error.

6.1.3 Summary of Simulated Chip Sample Results

This exercise confirms the devastating effect that poor extraction alone can have on the precision and accuracy of a sample value when it is compared to an expected value. The slightest deviation from the pre-defined sample size, shape and volume will introduce error. "**Extraction Error 2**"**,** represented by Figure 6.2b reveals that most of the waste-portions of the extracted material are under-represented. It was mentioned earlier that picking of reef and discarding of waste from the sample after the sampling activity was completed is a common practise amongst samplers. A sampling team that consistently performs reef-picking immediately before the sample material is bagged will introduce enormous biases to the assay results. Even if they do manage to extract a relatively good sample, selection of the visually better looking portions of reef (reef–picking) will transform the samples to a similar composition of reef to waste ratio present in "Extraction Error 1, 2 and 3", and they are all responsible for over valuation of the expected grade.

This exercise also indicates that the error incurred as a result of under extraction of certain units in a sample in relation to the demarcated sample may be more severe than that found with the over extraction of the same units. This could explain why the MCF reported by AngloGold Ashanti improved markedly after implementation of the quality assurance drive which implemented a significant increase in the mass of the samples extracted.

6.1.4 Unbiased extraction affecting precision.

Experiments using the simulated standard reference sample demonstrated that poor extraction influences the error, and is aggravated by the heterogeneity (reef to waste ratio) of the sample composition. The six examples used to demonstrate the error generated with poor extraction in Chapter 6.1.1 may not reflect normal extraction situations encountered underground. The portions selected could even be biased in that the waste portion, especially from the internal quartzite, was over represented. To avoid this type of selective bias, and to ensure that each component making up the sample either becomes part of the sample, some changes were made to the calculation.

A new “Simulated Chip Sample Model” with the same dimensions used in Figure 6.8 was constructed, but it was now sub-divided into 70 smaller units with each unit representing an area of 1cm^3, and each unit had its own expected grade (Figure 6.8).

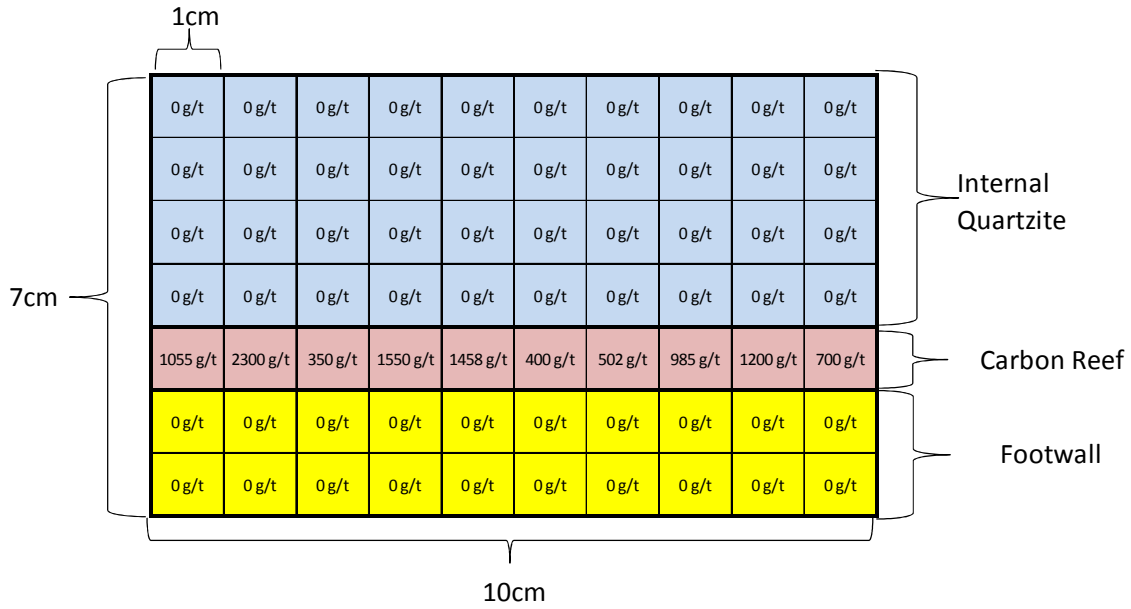


Figure 6.8: New “Simulated Chip Sample Model “generated and split into 1cm3 with corresponding grades.

The grade of the individual units in the Carbon Reef component were increased to simulate the high variability usually associated with this type of reef (Figure 6.8).The internal quartzite waste and footwall units were not allocated any grades. Perfect extraction of all the units in Figure 6.8 will result in an average grade of 150g/t at a

sample mass of 389.2grams.The simulation will allow a more realistic extraction error investigation free of any bias as a result of the units which were initially selected to be included or excluded in the calculations.

The grades representing the 70 units were plotted in a column in a Microsoft excel spread sheet. To simulate perfect (100%) extraction all 70 units will be selected and used in the calculation which will return a value of 150 g/t. To ensure that the selection process of units to be included or excluded from the calculation was unbiased, the following methodology was applied.

The RAND () formula available in Excel generated a random number next to each of the 70 units. The RAND formula returns an evenly distributed random number greater than or equal to 0 and less than 1. The 70 units will be sorted in ascending order based, on their calculated RAND () values. Extraction errors were calculated for various percentage material extracted per simulation. Each simulation will have a grade calculated for 100%, 90%, 80%.....30% of the material extracted. The difference between the actual grade of the material sampled and that of the expected grade is then expressed as a percentage. If an extraction error of 10 % is considered, then only 90% of the 70 units will be included in the calculation. The first (90%) or 63 of the units based on their random numbers sorted from small to high, will be included in the calculation. The last seven units (10%) will be excluded from the calculation. To calculate the error for 80% extraction only the first 56 units will be included in the calculation. All the extraction errors up to 30% will be calculated for a specific simulation. The RAND () function were run again to create a fresh number of random numbers for each unit. This process of calculating the grade associated with each percentage extracted error was repeated 31 times. The average, maximum and minimum percentage error for each percentage extraction error was calculated for all of the 31 simulations (Table 6.8).

Table 6.8: The percentage material extracted affects the precision and accuracy

Percentage Material Extracted	Average Grade	Total Percentage Error	Maximum Percentage Error	Minimum Percentage Error
100%	150	0	0	0
90%	154.72	3.46	11.11	-17.99
80%	150.44	2.73	25	-38.19
70%	149.97	1.49	36.03	-43.71
60%	146.78	-4.08	58.7	-53.3
50%	140.59	-7.21	51.28	-56.19
40%	134.18	-8.67	77.14	-63.1
30%	150.4	0.9	68.51	-66.51
Average	147.14	-1.42	46.82	-48.43

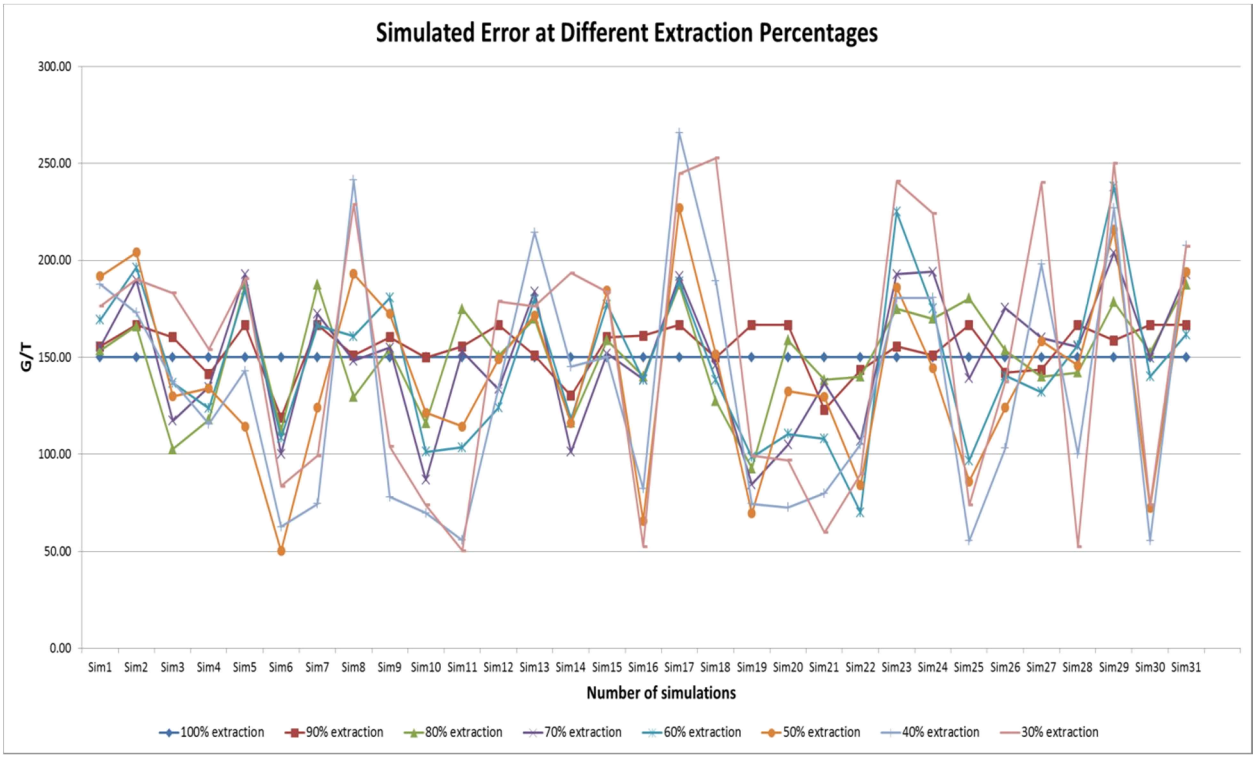


Figure 6.9: A graphical presentation on how the percentage material extracted from a delimited sample is affecting the precision of the grade.

Figure 6.9 is an indication of how poor extraction can influence the precision of the actual in-situ grade. If the expected percentage of sample material that will be extracted declines, so does the precision of the grades (Table 6.8). The simulation of

90% material extraction simulation has shown the best precision with a minimum error of -17.99% and a maximum error of 11.11%. Total error or accuracy for all the simulations is only -1.42% indicating that no bias was introduced with the simulation. As the percentage of sample material extracted decreases from the required mass, then the minimum and maximum error (or precision) increases proportionally. The average grade (or accuracy) calculated for each of the simulated extraction errors after 31 simulations is actually very close to the expected grade.

The simulation experiments illustrate that even with random, very poor extraction rates, the errors are self-correcting over a number of samples, if no bias is present when selecting the units to be included in the sample. The precision of the grade sampled is directly correlated to the percentage of the sample material removed. This leads to the quite somewhat counter-intuitive conclusion that if all available resources were to be sampled and mined then extraction error would have cancelled itself. This is not practical in most underground mines where most of the sampling is concentrated around pay areas only. So in such cases poor extraction may skew the actual grade to such an extent that over- or under-estimation of any panel is possible. This has important consequences for selective mining decisions that attribute pay or un-pay values to mining units at an SMU level. Most importantly this simulation has demonstrated that, despite poor extraction, the high waste to reef ratio of this specific sample does not introduce bias.

6.1.5 Importance of Sampling Shape

In Chapter 5.1.4 it was mentioned that the irregular shape of the samples extracted is a major source of bias and error. Any sample that deviates from the rectangular shape, even though the aspect ratio may change, will introduce bias. Although the underground drill core exercise failed to deliver any acceptable core for assay purposes, it was decided to test a theoretically correct piece of core to see if it would pass as being a representative sample. Most underground drilling, except for cover drilling, is aimed at intersecting the reef perpendicular to the bedding, whereas extracting core samples from a near-vertical stope face, means that the drill penetrates the reef parallel to the bedding. It is expected that this drilling orientation

combined with a highly heterogeneous reef-type could introduce extraction errors that would make this method unsuitable, even if a perfect cylinder of core is extracted.

The main reason for the bias is because the sample width, in this case 7cm for the core diameter, is used to weight the gold grade. In so doing the implication is that the aspect ratio of the sample is represented by the square (Figure 6.10a; b).This is better explained with the aid of a diagram (Figure 6.10) which represents a core sample that was drilled horizontally into a vertical stope face and parallel to the bedding of the reef.

The core diameter is 7cm but the area or sample width it represents is exactly the same as the square sample area it lies inside, which is expected to intersect a 1cm reef across its centre (Figure 6.10), i.e. the maximum possible volume. In terms of its volume the square sample represents a greater mass of material than is recovered by the core sample, and because the weighting is vertical, some units are biased in the way they are represented.

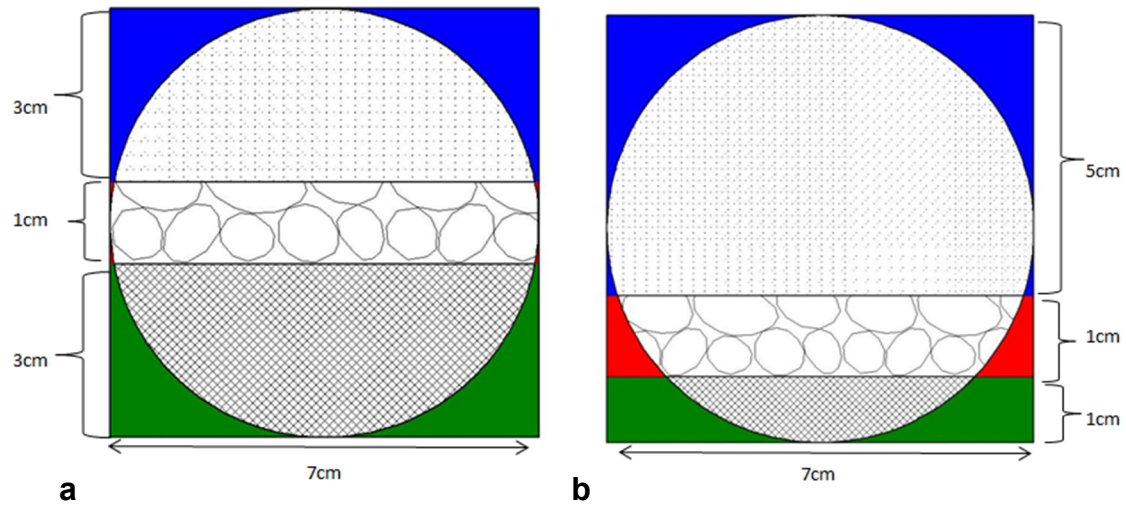


Figure 6.10: Diagram illustrating the Extraction Error introduced by the round shape of a core barrel when drilling parallel to a heterogeneous reef.

The blue and green portions represent the shortfall of material that would not be extracted as a result of the round shape of the sampling tool, compared to the rectangular shape of 7cm it is supposed to represent. In Figure 6.10**a** the exact same sample shape and volume is extracted as in Figure 6.10b**,** but changing the position of where the drill intersects the reef now indicates that the under-represented areas are

significant for the different lithological components of the sample, especially the reef component.

Table 6.9: Simulated chip sample model based on the actual reef composition for the core sample (Figure 6.10a)

Sample Composition	Width (cm)	Area (cm^2)	Depth (cm)	Rd	Mass (gram)	Value (g/t)	Weighted cmg/t (mass)	Weighted cmg/t (width)
Internal Quartzite	3	15.9	2	2.78	88.4	0	0	0
Reef	1	6.7	2	2.78	37.25	150	5587.8	150
Footwall	3	15.9	2	2.78	88.4	0	0	0
Total	7	38.5			214.06		5587.8	150
Average (Weighted on mass) Core						**26.10**		
Average (Weighted on width) Square 7cm x 7cm						**21.43**		

Table 6.10: Simulated chip sample model based on the actual reef composition for the core sample (Figure 6.10b)

Sample Composition	Width (cm)	Area (cm^2)	Depth (cm)	Rd	Mass (gram)	Value (g/t)	Weighted cmg/t (mass)	Weighted cmg/t (width)
Internal Quartzite	5	29.5	2	2.78	164.02	0	0	0
Reef	1	5.3	2	2.78	29.47	150	4420.2	150
Footwall	1	3.7	2	2.78	20.57	0	0	0
Total	7	38.5			214.06		4420.2	150
Average (Weighted on mass) Core						**20.65**		
Average(Weighted on width) Square 7cm x 7cm						**21.43**		

A "Simulated Chip Sample Model" was calculated for the theoretical core values and is reported in Table 6.9 and Table 6.10)**.** The only difference between the two diagrams is the position of the reef in the core. Perfect extraction of the core is assumed at a depth of 2 cm for both examples, thus they would be equal in volume, mass and shape. The grade for core sample in Table 6.9**,** is 26.10g/t which is an over estimation of 21.8% compared to the actual in situ grade of the 21.43g/t for the 7cm x 7cm sample. The grade for the core sample in Table 6.10 was calculated at 20.65g/t, which is an under-estimation of 3.6% compared to the actual grade of 21.43g/t for the 7cm x 7cm sample. The grade calculated for the square samples in Table 6.9 and Table 6.10 remained exactly the same even if the position of the reef

within the samples changed. It must be stated that the grade for the sample extracted with the core is 100 per cent correct for that shape and size (support), the error comes when the grade is weighted by the a vertical sample width of 7cm to calculate a cm/g.t value for the sample. The cm/g.t conversion assumes that the horizontal width of the sample was perfectly extracted at vertical width of 7cm, in other words a perfect square or rectangle; it's only then that the vertical representation of the different units within the demarcated sample becomes bias and introduces error (Figure 6.11).

If sampling perpendicular to a reef then the sample shape has to have a proportional relationship between its width and its height (aspect ratio).

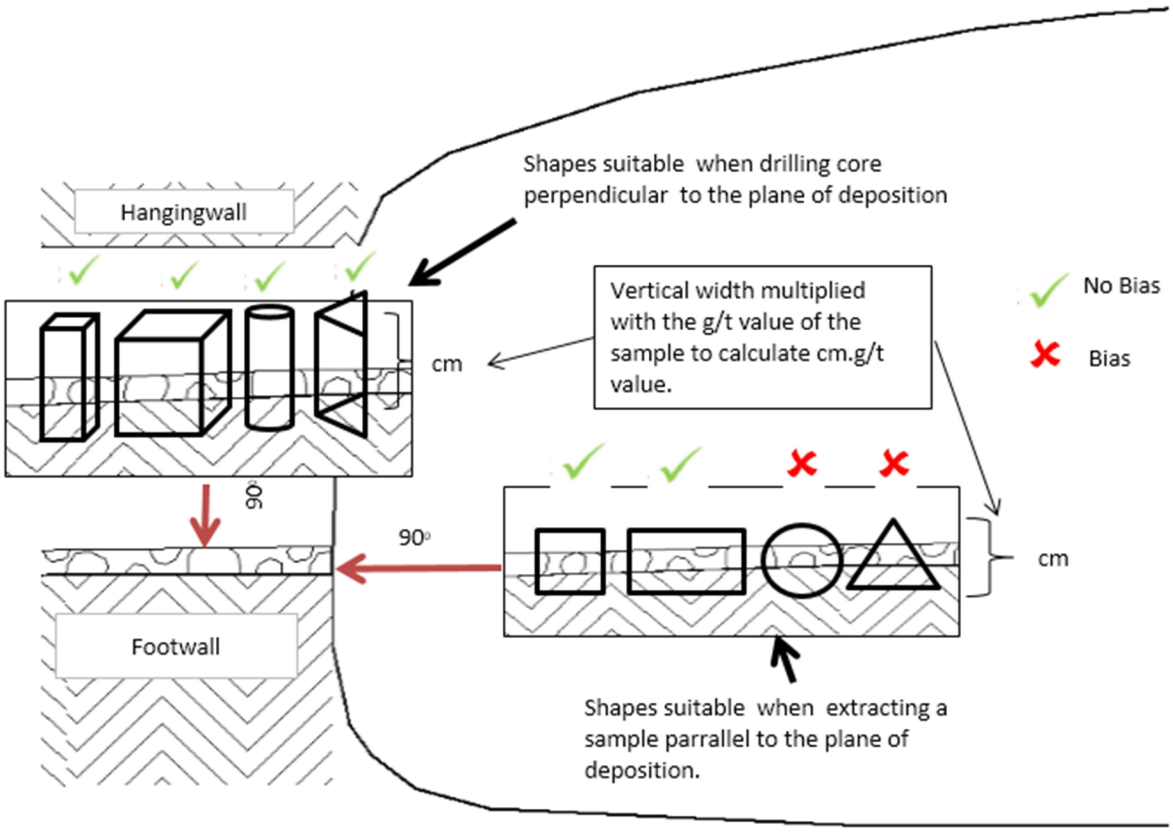


Figure 6.11: Diagram illustrating how sample shape can introduce a bias when extracting a sample parallel to the plane of a reef.

The grades for round core samples drilled horizontally into a reef that is exposed in a vertical face are sensitive to the position of the mineralised portion of the reef within the shape of the sample itself. The same goes for triangle, oval etc. sample shapes.

The only shape that will not introduce any error is a square or rectangular sample shape. It is concluded that even with perfect core extraction if it is taken parallel to the bedding of the reef, the very shape itself introduces error, therefore the author believes that core sampling if taken parallel to the bedding of the reef cannot be considered an acceptable sampling alternative to the traditional rectangular sample extracted using a hammer and chisel. The shape of the sample extracted can become a source of error when the grade obtained from such a sample are weighted with a vertical width depending on the heterogeneity of the material being sampled and its (angle of extraction relative to the strata).

6.1.6 Heterogeneity Experiment

By changing the reef-to-waste ratio in the simulation models of possible over- and under-extraction as demonstrated in Chapter 6.1.2 and 6.1.3, it was found that the percentage extraction error changed accordingly. Further experimentation revealed that the percentage error on the gold grade tends to decrease as the sample composition becomes more homogenous provided the extraction error remains constant. “Extraction error 1”, simulated in Figure 6.2, explains the rationale behind this simulation. “Extraction error 1” had a reef-to-waste ratio of 14.29% based on a 1cm reef and 6cm waste portion and incomplete extraction, resulting in an a grade error of 40% (Table 6.2).

The reef thickness was incrementally increased and the waste proportionally decreased as shown in Table 6.11.The percentage extraction error was kept the same, the Simulated Chip Sample Model was updated with changes in the component parts of reef and waste, and a new expected grade was calculated for each step change. The methodology applied in order to calculate the changes in gold grade error as a result of changes in the homogeneity of the reef components from zero to 100 per cent, while maintaining exactly same (Figure 6.12).

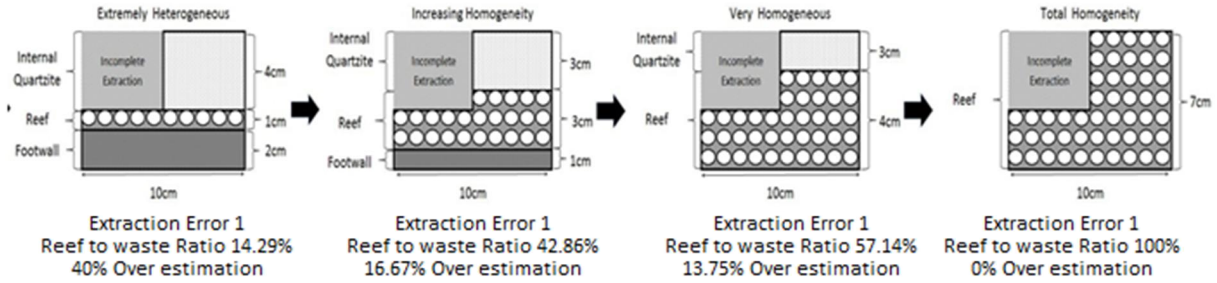


Figure 6.12: Percentage extraction error decreases as the sample becomes more homogenous.

Table 6.11: Comparison on the effect of 'under extraction' on a sample that increase in homogeneity.

Reef-to-waste Ratio %	100%	92.86%	85.71%	78.57%	71.43%	64.29%	57.14%	50.00%	42.86%	35.71%	28.57%	21.43%	14.29%
Reef (cm)	7	6.5	6	5.5	5	4.5	4	3.5	3	2.5	2	1.5	1
Footwall + Internal Quartzite	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
Perfect Extraction	0	0	0	0	0	0	0	0	0	0	0	0	0
Extraction Error1	0	2.31	5	8.18	12	12.78	13.75	15	16.67	19	22.5	28.33	40
Extraction Error2	0	0.96	2.08	3.41	5	6.94	9.38	12.5	16.67	22.5	31.25	45.83	75
Extraction Error3	0	-1.28	-2.78	-4.55	-6.67	-6.02	-5.21	-4.17	-2.78	-0.83	2.08	6.94	16.67
Extraction Error4	0	-2.1	-4.55	-7.44	-10.91	-11.62	-12.5	-13.64	-15.15	-17.27	-20.45	-25.76	-36.36
Extraction Error5	0	1.71	3.7	6.06	8.89	8.02	6.94	5.56	3.7	1.11	-2.78	-9.26	-22.22
Extraction Error6	0	-0.59	-1.28	-2.1	-3.08	-4.27	-5.77	-7.69	-10.26	-13.85	-19.23	-28.21	-46.15
(Min % Error)	0	-2.1	-4.55	-7.44	-10.91	-11.62	-12.5	-13.64	-15.15	-17.27	-20.45	-28.21	-46.15
(Max % Error)	0	2.31	5	8.18	12	12.78	13.75	15	16.67	22.5	31.25	45.83	75
Sum of the errors	0	1.01	2.18	3.57	5.24	5.84	6.59	7.56	8.85	10.66	13.37	17.89	26.93

The same was done for the over Extracting errors with similar results observed in under extraction (Table 6.12). The maximum and minimum errors is on average much lower when compared to similar under extracting errors, indicating that over extraction has a natural tendency to minimize the impact of poor extraction.

Table 6.12: Comparison on the effect of 'over extraction' on a sample that increase in homogeneity.

Reef-to-waste Ratio %	100%	92.86%	85.71%	78.57%	71.43%	64.29%	57.14%	50.00%	42.86%	35.71%	28.57%	21.43%	14.29%
Reef (cm)	7	6.5	6	5.5	5	4.5	4	3.5	3	2.5	2	1.5	1
Footwall + Internal Quartzite	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
Perfect Extraction	0	0	0	0	0	0	0	0	0	0	0	0	0
Extraction Error7	0	-1.28	-2.78	-4.55	-6.67	-7.1	-7.64	-8.33	-9.26	-10.56	-12.5	-15.74	-22.22
Extraction Error8	0	-0.38	-0.83	-1.36	-2	-2.78	-3.75	-5	-6.67	-9	-12.5	-18.33	-30
Extraction Error9	0	0.96	2.08	3.41	5	4.51	3.91	3.13	2.08	0.62	-1.56	-5.21	-12.5
Extraction Error10	0	1.36	2.94	4.81	7.06	7.52	8.09	8.82	9.8	11.18	13.24	16.67	23.53
Extraction Error11	0	-0.81	-1.75	-2.87	-4.21	-3.8	-3.29	-2.63	-1.75	-0.53	1.32	4.39	10.53
Extraction Error12	0	0.51	1.11	1.82	2.67	3.7	5	6.67	8.89	12	16.67	24.44	40
(Min % Error)	0	-1.28	-2.78	-4.55	-6.67	-7.1	-7.64	-8.33	-9.26	-10.56	-12.5	-18.33	-30
(Max % Error)	0	1.36	2.94	4.81	7.06	7.52	8.09	8.82	9.8	12	16.67	24.44	40
Sum of the errors	0	0.36	0.77	1.26	1.85	2.06	2.32	2.65	3.1	3.72	4.66	6.21	9.33

Figure 6.13 is a diagrammatic representation of the changes in extraction error calculated for "Extraction Error 1" in Table 6.11and Table 6.12, moving from a highly heterogeneous composition(on the left) to a very homogenous composition (on the right). The total Homogeneity represents a 100% reef-to-waste ratio and an extraction error would have zero influence on the true actual grade.

6.1.7 Summary of the Simulation Experiments

Figure 6.13 is a graphical representation of all the extraction errors calculated from Table 6.11and Table 6.12. It is moving from a highly homogenous composition (on the left) to a very heterogonous composition (on the right). The total Homogeneity on the left represents a 100% reef-to-waste ratio and an extraction error would have zero influence on the true actual grade. It clearly indicates how the error percentages (positive and negative) are increasing proportionally with an increase in sample heterogeneity (waste t reef).

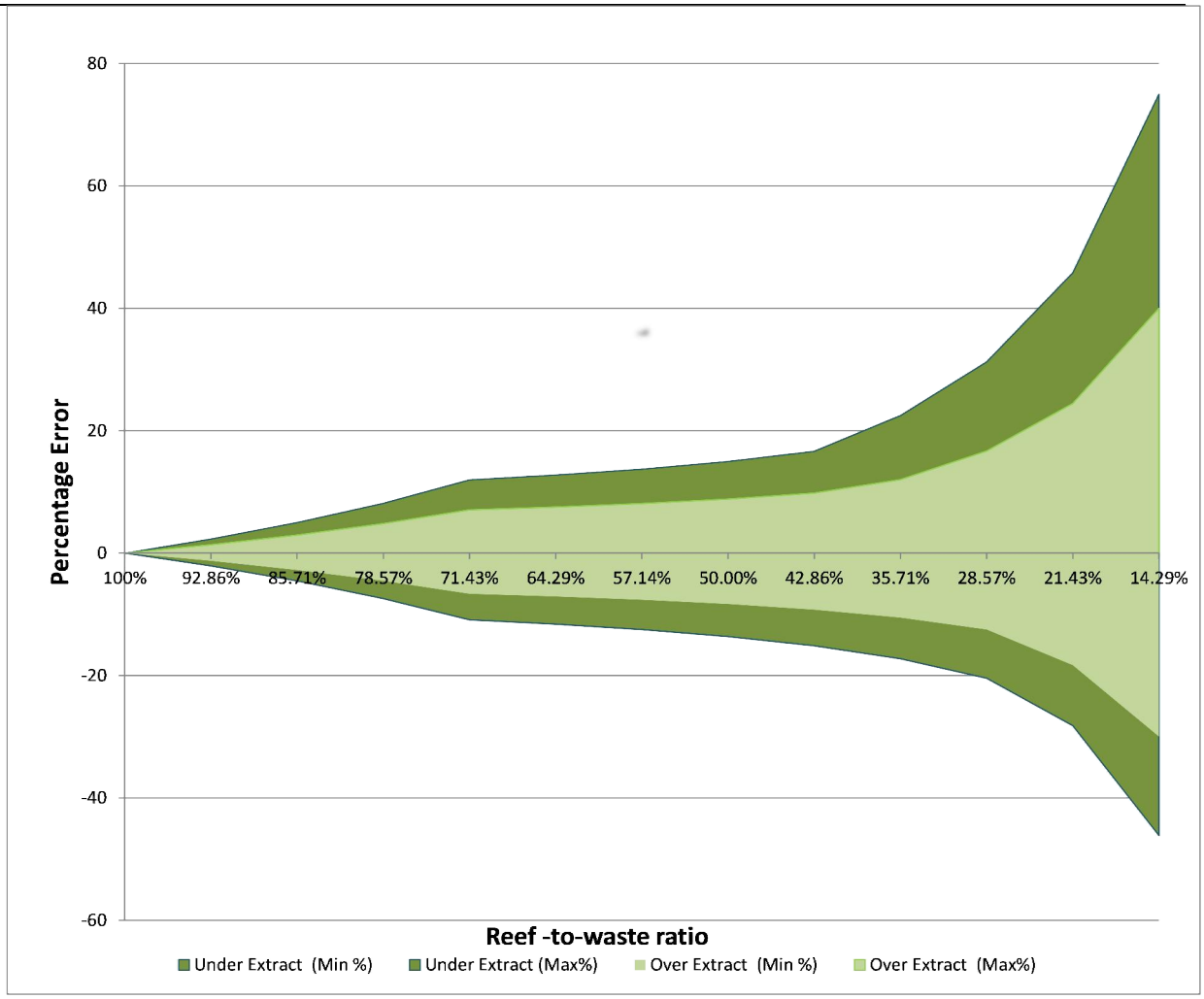


Figure 6.13: Graphical depictions on how errors increase from a very homogenous (on the left) to a highly heterogeneous (on the right composition).

The outcome of the simulation exercise confirms the likelihood that the percentage extraction error for samples extracted in the same manner will decrease as the sample composition and grade becomes more homogenous. This may well explain why shafts mining the more homogenous reefs i.e. VCR, A, and Elsburgs can maintain Mine Call Factors close to 100% even though they use an identical sampling technique. Although they probably incur the same extraction errors as other shafts, the inherently more homogenous nature of their reefs means that the effects of heterogeneity are not as severe as those experienced by mines extracting thin carboniferous reefs. It also indicates that a sample should be demarcated within homogenous lithologies or areas of the reef and not across heterogeneous reef sections, as per the example in Figure 6.11 d. In doing so the error introduced with poor extraction will be minimized.

6.1.8 Nugget Effect or Sampling Error

The “nugget effect” is a geostatistical term which takes on different meanings depending who is using the term (Clark, 2009). Geologists refer to it as the difference in grade between two closely spaced locations in a rock specimen, while to the geostatistician it is the discontinuity in the semi-variance between zero and an infinitesimal increase in the lag at the origin of the semi-variogram. It is a random variability related to the location and distribution of gold nuggets in the rock being sampled. The size of this discontinuity depends on the variance between pairs of samples at short lag distances. From a samplers point of view the nugget effect is a combination of the geostatistical definition of the nugget effect, plus a component of random variability that arises from errors related to both measuring and positioning (spatial) error (Pitard, 2009). Measurement error is also referred to as the Increment Materialisation Error IME (Pitard, 2009), and includes all the errors IDE, IEE, IWE and IPE generated during sampling and assaying (Pitard, 2009).

Because of the constraints on extracting a perfectly repeatable volume and shape for all chip samples extracted from a rock face, the support for all samples differs. This is mainly due of the hardness of the rock and the equipment used for its extraction. Thus the difference in grade between closely spaced samples is a combination of true variability in the gold content from one place to the next, as well as sampling error (IME). These multiple sources of sampling error introduced during sample extraction, contribute to the true in situ variability, the “nugget effect” of the ore. In the case of chip sampling where extraction is very poor the error obtained from poor extraction will destroy the true inherent nugget actually existing between samples. An example of the way in which poor sample extraction affects the true “nugget effect” is illustrated in Figure 6.14.

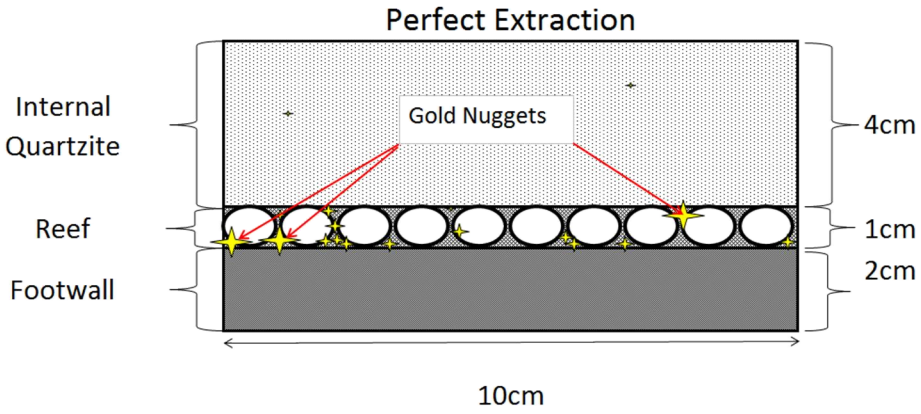


Figure 6.14: Illustration of gold nuggets (gold stars) in a correctly demarcated sample

Perfect extraction of the demarcated sample in Figure 6.14 would include all the particles of gold. Such a sample would reflect the true grade of the ore at this support. Assume for the purposes of this illustration that the six samples shown in Figure 6.15 are identical samples. If each sample is extracted perfectly the grade of each sample would be identical and the variance between them would be zero. The six scenarios shown in Figure 6.15 simulate some possible combinations and permutations of incomplete extraction that could arise from chipping a sample from a typical Witwatersrand-type reef.

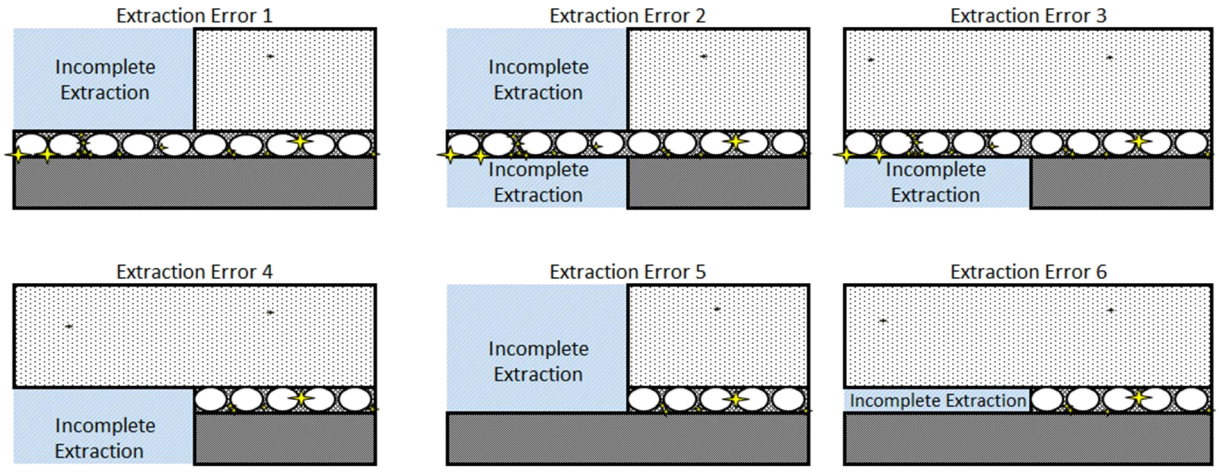


Figure 6.15: Six probable combinations of lithological components illustrate the effect that incomplete extraction may have on the true “nugget effect” of a sample

Any form of incomplete extraction will result in different grades for each sample and a large between-sample variance even though the samples, for the purpose of this illustration, are considered to be identical. The variance between samples in this case

is entirely due to the extraction error and unrelated to the presence or absence of nuggets of gold.

6.1.9 Effect of Extraction Error on the Variogram

An experiment to illustrate the effects of poor sampling extraction on the nugget effect in the experimental semi-variogram was undertaken. In a simulated exercise fifty samples of varying grade were collected in a raise at intervals of 1m to represent actual samples. The grade of the samples varied from 13.39g/t to 830.94g/t. The same methodology for evaluating the effect of extraction error at percentages between 10 and 80 per cent, as that presented in Chapter 6.1.3, using a sample divided into 70 units of known grade was applied. This process was repeated for each of the 50 samples simulated at different grades. Each of the fifty simulated samples has an actual grade for perfect extraction and a grade for each of the different extraction error percentages, EE1 up to EE7 (Table 6.13). This was done to simulate the effect of poor extraction on the nugget value when calculating the experimental variogram. The nugget effect in this case has nothing to do with the true in situ nugget effect that existing between perfectly extracted and adjacent samples. The values for the actual sample grades representing perfect extraction were sorted from low to high as shown in Table 6.13

Table 6.13: Simulated grades with various extraction errors percentages.

XPT	YPT	ZPT	SECTION	Actual Grade g/t	EE1 g/t	EE2 g/t	EE3 g/t	EE4 g/t	EE5 g/t	EE6 g/t	EE7 g/t
0.00	1.00	0.00	Section42	13.39	8.17	8.07	12.38	8.14	10.18	8.55	8.27
0.00	2.00	0.00	Section6	16.57	18.89	17.02	7.43	16.98	19.29	17.14	3.57
0.00	3.00	0.00	Section30	18.97	16.89	14.61	11.69	18.80	21.24	9.74	15.86
0.00	4.00	0.00	Section39	35.80	35.25	37.33	23.62	39.60	50.92	28.20	44.55
0.00	5.00	0.00	Section43	38.94	49.00	35.54	11.71	47.88	44.43	42.56	48.40
0.00	6.00	0.00	Section15	39.81	26.48	44.05	39.16	50.35	55.89	44.71	53.64
0.00	7.00	0.00	Section49	41.47	67.06	58.21	50.82	58.29	46.50	44.46	42.33
0.00	8.00	0.00	Section10	43.70	25.86	13.59	12.30	19.50	17.74	24.86	15.86
0.00	9.00	0.00	Section35	47.53	88.76	51.76	58.23	66.55	71.43	62.64	59.37
0.00	10.00	0.00	Section31	50.79	36.70	66.05	40.17	41.90	41.12	49.54	56.43
0.00	11.00	0.00	Section27	62.21	67.60	48.76	69.13	69.19	42.66	56.88	61.00
0.00	12.00	0.00	Section24	69.14	74.91	23.79	48.95	62.98	54.43	31.71	47.63
0.00	13.00	0.00	Section3	70.76	33.96	31.46	43.86	65.33	26.21	68.27	75.44
0.00	14.00	0.00	Section23	78.63	58.82	36.43	47.76	51.46	33.10	29.14	71.71
0.00	15.00	0.00	Section47	79.99	43.53	83.14	62.36	88.87	57.46	46.05	50.79
0.00	16.00	0.00	Section21	80.81	94.23	104.76	0.10	89.79	1.18	92.46	100.96
0.00	17.00	0.00	Section37	81.19	81.59	4.00	0.00	83.64	95.43	111.07	3.20
0.00	18.00	0.00	Section46	88.21	98.02	110.27	122.33	125.12	129.40	161.75	215.67
0.00	19.00	0.00	Section33	91.80	33.18	43.43	37.92	73.81	55.36	95.00	52.11
0.00	20.00	0.00	Section29	95.20	85.51	90.30	100.03	100.33	101.71	71.26	83.55
0.00	21.00	0.00	Section32	112.84	193.00	26.76	140.84	125.38	179.33	83.00	160.96
0.00	22.00	0.00	Section14	115.30	33.31	28.67	29.00	126.56	25.04	27.57	21.29
0.00	23.00	0.00	Section4	121.07	134.52	170.80	213.50	166.02	272.76	151.34	180.17
0.00	24.00	0.00	Section25	122.96	132.56	83.86	67.09	83.16	72.36	75.35	36.24
0.00	25.00	0.00	Section22	142.10	203.00	157.89	324.48	213.55	177.63	263.07	217.74
0.00	26.00	0.00	Section19	148.29	164.76	246.10	184.93	308.86	210.94	394.24	247.09
0.00	27.00	0.00	Section1	150.00	133.93	69.05	168.66	136.63	147.45	176.94	166.67
0.00	28.00	0.00	Section28	156.33	230.74	36.04	204.33	48.05	173.63	146.09	178.79
0.00	29.00	0.00	Section38	166.49	278.26	199.70	425.29	177.51	228.22	343.89	255.67
0.00	30.00	0.00	Section34	171.20	259.10	208.20	185.06	222.08	310.91	292.04	364.10
0.00	31.00	0.00	Section9	175.23	0.29	0.23	0.40	182.70	0.35	0.00	124.54
0.00	32.00	0.00	Section2	180.33	200.37	214.70	240.82	275.00	330.00	369.64	492.86
0.00	33.00	0.00	Section40	181.10	158.80	57.05	95.79	113.43	99.25	132.33	190.11
0.00	34.00	0.00	Section48	191.27	368.43	230.20	180.29	157.75	210.33	276.32	140.22
0.00	35.00	0.00	Section16	199.84	438.19	192.94	224.36	163.52	269.23	336.54	169.84
0.00	36.00	0.00	Section45	227.69	236.78	266.16	286.21	304.18	309.67	354.88	425.86
0.00	37.00	0.00	Section26	231.90	60.83	47.52	64.40	54.14	35.64	170.46	151.52
0.00	38.00	0.00	Section8	236.86	373.07	283.54	682.67	447.69	514.68	263.17	321.51
0.00	39.00	0.00	Section12	260.47	264.17	402.57	289.41	337.14	316.09	239.47	212.16
0.00	40.00	0.00	Section5	270.71	189.13	44.64	35.71	298.02	59.52	246.90	213.67
0.00	41.00	0.00	Section41	319.97	456.88	559.07	399.77	533.02	576.77	480.90	355.35
0.00	42.00	0.00	Section18	344.50	700.86	372.70	419.29	463.27	525.64	428.90	484.40
0.00	43.00	0.00	Section36	358.76	398.62	191.03	0.79	1.05	269.68	308.20	195.40
0.00	44.00	0.00	Section13	380.39	465.39	655.26	546.07	1092.10	468.06	415.30	819.07
0.00	45.00	0.00	Section20	388.11	435.51	508.10	252.43	431.24	654.11	404.38	596.83
0.00	46.00	0.00	Section7	408.14	703.23	608.21	433.59	606.31	810.95	545.20	477.05
0.00	47.00	0.00	Section11	429.93	465.76	646.43	762.66	632.75	843.67	569.20	498.05
0.00	48.00	0.00	Section44	453.16	196.00	261.33	494.68	545.89	553.93	633.06	719.74
0.00	49.00	0.00	Section50	516.54	573.94	825.46	670.35	1137.57	645.68	864.64	741.12
0.00	50.00	0.00	Section17	830.94	1212.24	925.14	1795.04	923.27	2219.05	1057.31	1436.03

Semi-variograms for each percentage of extraction error as well as for the actual known grades (perfect samples without error) were calculated at an assumed sample interval of 1 m and are shown in Figure 6.16.

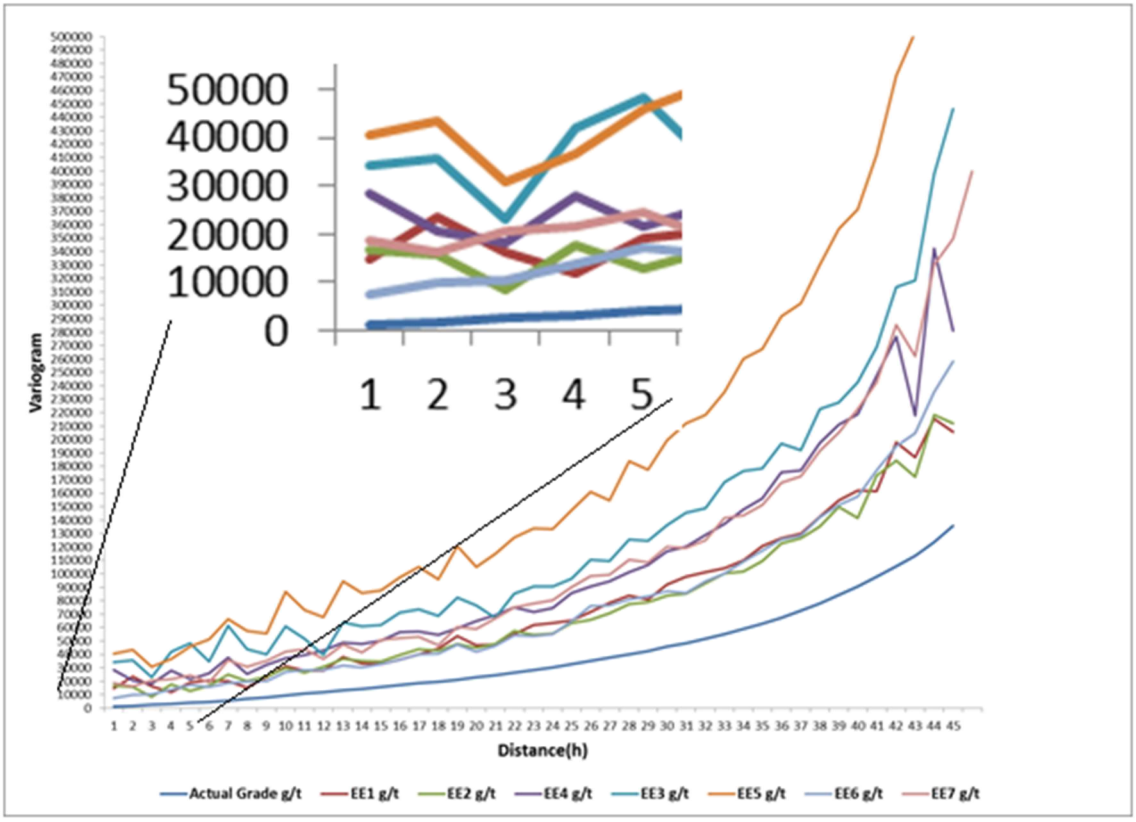


Figure 6.16: Semi-variograms for each of the simulated samples calculated; the inset shows the nugget effect of the variograms near the origin.

The semi-variogram of the actual known grades is the only one that has no nugget effect, and originates close to zero at a 1 m lag. All other semi-variograms calculated for various percentages of extraction error display the presence of a nugget effect at the origin of the semi-variogram (Figure 6.16). The increase of the nugget effect a result of extraction error is shown in detail by comparing semi-variograms calculated for the true grade and for extraction error 5 (EE5, Figure 6.17). The true grade of the samples (purple squares) and the grade of samples having a percentage of extraction error (blue squares) show the influence of higher variances associated with higher grades (the Proportional Effect). As the grade increases so does the variability and there is a sympathetic rise in the steepness of the variogram. Thus the effect of extraction error EE5 is to cause the semi-variogram to rise more rapidly than that for the true grade (Figure 6.17).

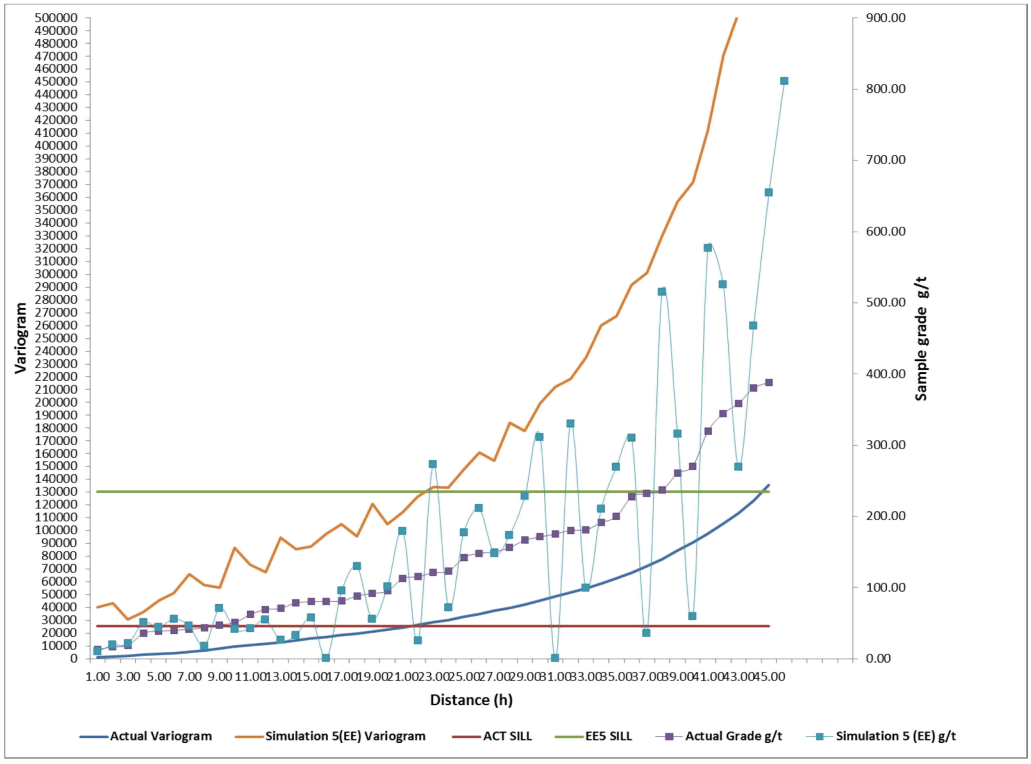


Figure 6.17: Comparing the differences of two semi-variograms and their grades at individual distances.

The variance of the EE5 semi-variogram (EE5 Sill, Figure 6.16) is also substantially higher than that for the true population variance (ACT Sill), but both variances reach their individual sills at almost the same distance of 23m (Distance h). Figure 6.17 is a comparison done to observe the relationship and differences existing between the sill and the shape of the two variograms, EE5 and Actual. This was achieved by aligning the objects relative to each other's sills (Figure 6.18)

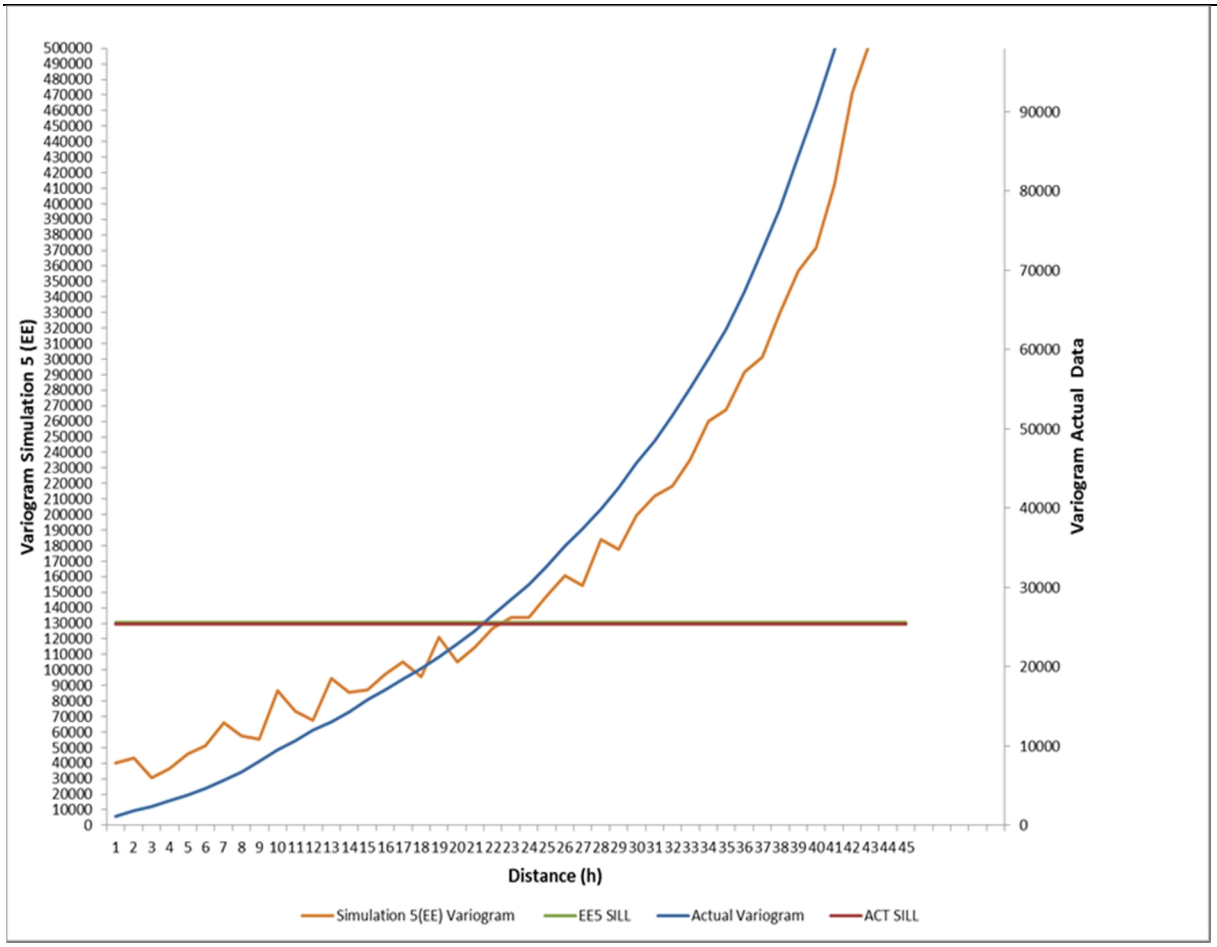


Figure 6.18: Actual shape of the semi-variograms with their sills aligned.

The EE5 semi-variogram is much more irregular than that for the actual samples and lies above the variogram for the actual grades while it is below the sill. After reaching the sill the variogram for the actual grades lies above that for the variogram whose values have an associated extraction error. The erratic shape of the EE5 semi-variogram shows that at short lag distances samples with associated extraction error are more variable than those without any extraction error. According to Morgan (2005) a nugget effect means that data further away will receive a greater proportion of the available kriging weight, and consequently greater smoothing of the estimates during the kriging process which could have serious financial implications.

6.1.10 Effect of Poor Extraction and a High Nugget on Estimation

Morgan (2005) illustrated the problem of excessive smoothing due to a high nugget effect by kriging 16 minable square blocks with an accurately modelled semi-variogram as shown in Figure 6.18a. Almost half the blocks can be profitably extracted. The grades in the same area were then estimated using the same semi-variogram with a high nugget effect (Figure 6.19).

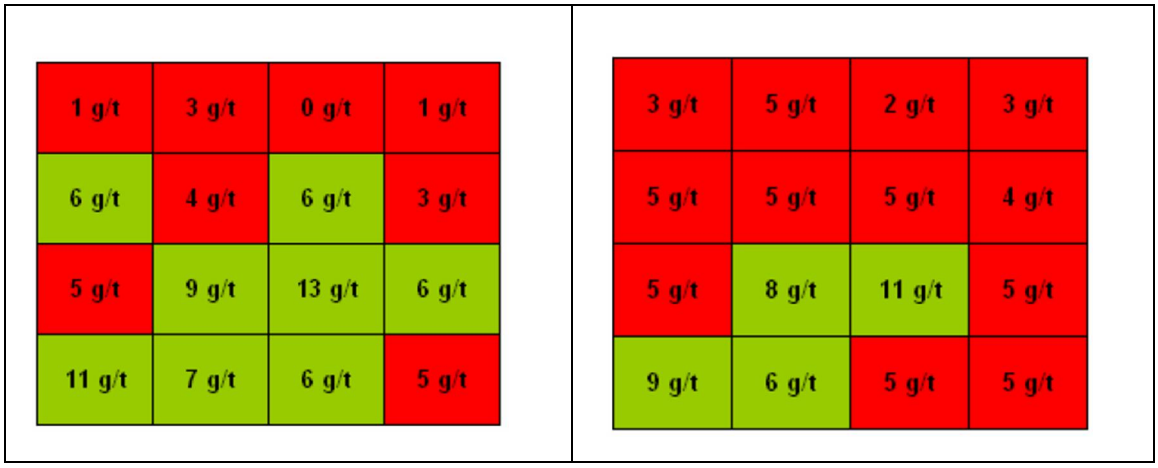


Figure 6.19: a) Estimated grade distribution of the 16 minable block, assuming that the semi-variogram is accurately estimated and modelled b) Estimated grade estimation of the 16 minable blocks, assuming that the semi-variogram's nugget effect is now too highly estimated (Morgan, 2005:41).

According to Morgan (2005) using a variogram with a high nugget effect results in overly smooth kriged estimates and only four blocks were above the pay limit even though the size of the areas and average grade in Figure 6.18a and Figure 6.18b are the same. Extraction error therefore increases the nugget effect at short variogram lag distances resulting in estimated grades that are overly smoothed and consequently affects mining selectivity. This simulated example illustrates that the nugget effect may be derived entirely as a result of sampling errors related to the extraction of the increments (IME) and may have little or nothing to do with the occurrence of actual nuggets (particles) or clusters of gold grains (~100 microns) in the ore.

CHAPTER 7 – POTENTIAL SOURCES OF BIAS

7.1 Review on what we know

The previous chapter investigated the principal errors introduced during sample collection using the chip sampling method. Simulation models provided a means for understanding the main factors that give rise to sampling error. The “Simulated Chip Sample “model has demonstrated its value on two counts. Firstly, it allows the effect of poor extraction to be quantified, and secondly it explains why errors associated with poor extraction are severe if the sample composition is heterogeneous and almost negligible when the sample composition is homogenous. The model showed that although the percentage extraction error significantly affects the precision of the individual grades, the accuracy for the total dataset remains similar irrespective of the percentage extraction error observed.

Simulation models used in the previous chapter were all based on the notion that extraction process was random and free from any bias. However it is known from previous research and underground observations that some bias is always present especially when sampling thin carboniferous reefs. The bias leads to overstating the grade of the extracted material which in turn overstates the face grades. This is one of the principal causes of a low (~50%-70%) MCF. Several workers have suggested that the bias is linked to the observation that samplers tend to oversample the softer well-mineralised portions of a reef, while under-sampling the harder waste portions (Cawood, 2003; De Jager, 1997; Freeze, 2013; Sichel, 1961). While this type of bias, which is referred to here as a ***soft-reef bias*** to distinguish it from other types of bias, always leads to an overstatement of the in-situ grade, it has never been quantified in the historical research (De Jager, 1997; Lerm, 1994; Freeze, 2013).

It is widely believed that improved sample extraction will eliminate this soft-reef bias, but most of the historical comparisons between chip sampling and other sampling methods that extract samples of higher quality, were all inconclusive. A very comprehensive study on the effects of poor sample extraction was undertaken by AngloGold Ashanti (Freeze, 2013) in work that compared sampling results of near perfect “text book“ type with chip sampling. The results indicated very little or no bias

between the two methods with the inherent variability of the reef and the number of comparisons tests being offered as the explanation for these results (Freeze, 2013). However if soft-reef bias, leading to oversampling occurs at all sample extraction sites, common sense would suggest that the average grade of chip samples should be noticeably higher than that of the text-book-type samples cut with diamond saws etc. This does not appear to be supported by the results obtained in the study undertaken by Freeze (2013).

7.2 Another bias responsible for overestimation?

A possible source of bias that has not yet been quantified in any study of underground chip sampling is the change in quality of sampling under direct supervision. The well-known saying “when the cats away the mice will play” means that most of the evidence for a decline in the quality of the samples when no one is looking is anecdotal. People tell of the way in which empty bags are filled with sample material that is simply collected from the floor of the same stope when no one is watching. Where direct supervision is lacking the usually very hot, wet, noisy, unwelcoming environment means that human stamina and resilience declines over an eight-hour shift and the quality of the sampling tends to decline.

If the quality of chip samples extracted under supervision is higher than that of the samples taken under the inhospitable normal day-to-day conditions described above then another type of bias, the absent-supervisor bias, is introduced (Magri and McKenna, 1986, Sichel, 1961. If this is indeed the case and comparisons between “text-book-type” sampling and chip sampling show no major differences as suggested by Freeze (2013), then we must assume that ***chip sampling done under supervision, even if the shape is not correct and more of the softer reef (usually considered to be richer in grade) is extracted, is just as good as samples extracted perfectly***. This is indeed good news, but it does not answer the question as to the source of the bias causing an overstatement of grade? In the study by Freeze (2013) it should be asked if improved supervision by AngloGold Ashanti was the only variable that led to a reduction of the bias or is there a further, as yet, unaccounted for influence. Besides improved supervision, the only other variable that changed significantly as a result of the implementation of the “Quality Index” was an increase in

the sample mass. Data collected before and after implementation of the individual sample mass was used to construct Table7.1.

Table 7.1: Data of the minimum and maximum sample mass before and after implementation of the "Quality Index".

Year	Average Mass of Samples	% Difference	Maximum Mass of Samples	% Difference	Minimum Mass of Samples	% Difference	No Samples
2011	360	0%	591	0%	226	0%	127
2012	595	39%	1137	48%	291	22%	775
2013	611	3%	1112	-2%	294	1%	1001

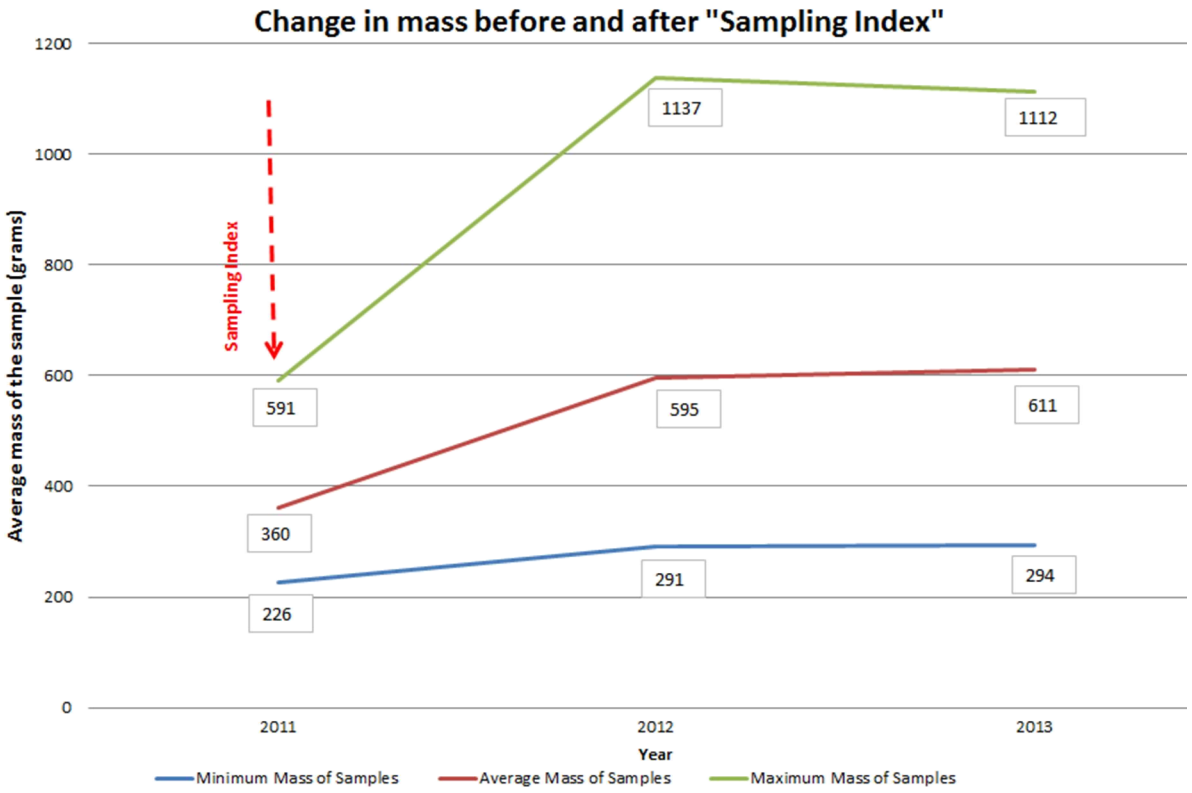


Figure 7.1: Data collected from underground sampling depicting the change in average sample mass before and after implementation of the "Quality Index" by AngloGold Ashanti

As shown in Figure 7.1 the average mass of the samples extracted increased by almost 39 % after implementation of the Quality Index in 2011. Freeze (2013) is of the opinion that the increase in sample mass is because samplers are now extracting a better quality sample. The Quality Index requires that the mass of the sample material extracted should meet the calculated mass of the sample based on its width; if not the sample will be rejected. The increase in sample mass could be contributed to the fact that samplers are indeed taking more care when extracting a sample, but it may also

indicate that samplers stopped discarding excess sample material after extraction. The likelihood that the Quality Index resulted in improved sample extraction, as well as samplers desisting from discarding excess sample material after extraction and an increase in sample mass after its implementation is now investigated.

7.2.1 Extract a more representable sample

The Quality Index procedure requires that 'before and after' photos of the sample extracted be used as a means of accepting or rejecting a sample. Although this is a good initiative, comparative photography may not be possible depending on the sample location and lightning conditions. The time spent by the samplers in their daily task of extracting a sample before and after the Quality Index was implemented could act as a benchmark to determine if the improved quality is a result of more time spent extracting the sample. Table 2.15 in Chapter 2 shows that samplers took between 3 and 5 minutes to chip a sample after implementation of the Quality Index; a time which is still very fast. Literature mentioned that samplers used to spend a full shift collecting a single sample of about 1-3kg (Storrar, 1987). Notwithstanding the fact that improved quality was responsible for the increase in sample mass, other factors were responsible for the increase in sample mass.

7.2.2 No more sample reduction underground

It was mentioned in Chapter 5 that observation of samplers in underground workings revealed that samplers and chippers all reduced the initial sample material extracted to end up with a sample mass of about 350 grams. If they ceased discarding excess material in order to meet the required quota determined by the "Quality Index", this could account for the improvement in sample mass (sample quality). In this case the factor responsible for the increase in sample mass was not an improvement in the extraction process, but rather that samplers were no longer discarding what they considered to be excess sample material underground. Reduction of the sample mass after extraction is common practise on most of South African mines. The samplers reduce the collected mass to ± 350grams which is the minimum required mass for most sampling protocols. It also means that the sampler's assistant is able to carry more samples per bag per shift from the workplace to surface. The following recorded

data of the total mass of the samples collected per sampler per shift was obtained from Tshepong mine.

The data are collected for a report required by the Department of Mineral Resources (DMR) as to how much gold bearing material is sent to the laboratory on a daily basis. Since the number of samples per shift was also recorded, the average mass per sample per shift could be calculated as shown in Table 7.2.

Table 7.2: Table calculating the average mass of a sample per shift and the frequency of occurrence

No of samples extracted per shift			Sum of the sample masses	Frequency of shifts	Average mass per sample	Expected mass per sample
0	-	10	66610	164	406.2	389.2
10	-	20	68338	151	452.6	389.2
20	-	30	101348	223	454.5	389.2
30	-	40	107414	285	376.9	389.2
40	-	50	88846	250	355.4	389.2
50	-	60	76825	241	318.8	389.2
60	-	70	59325	203	292.2	389.2
70	-	80	40712	158	257.7	389.2
80	-	90	25685	100	256.8	389.2
90	-	100	17755	72	246.6	389.2
100	-	110	11876	52	228.4	389.2
110	-	120	11490	52	221.0	389.2
120	-	130	11636	49	237.5	389.2
130	-	140	5223	23	227.1	389.2
140	-	150	5332	22	242.4	389.2
150	-	160	6459	27	239.2	389.2
160	-	170	3178	13	244.4	389.2
170	-	180	2809	11	255.4	389.2
180	-	190	1450	5	290.0	389.2
190	-	200	1282	5	256.3	389.2
200	-	210	658	3	219.5	389.2
210	-	220	408	2	204.2	389.2
220	-	230	605	3	201.6	389.2
230	-	240	399	2	199.6	389.2
240	-	250	120	1	120.4	389.2
250	-	1000	178	1	177.5	389.2

Plotting the number of samples per shift against the combined mass of the samples indicates that the average mass per sample decreases as the number of samples per shift increases as shown in Figure 7.2. This graph shows that where the number of samples extracted per shift is less than 50 the average sample mass is above the expected mass of 389 grams. However, as the number of samples extracted per shift rises above 50, the average mass per sample send for assay decrease proportionally. The interpretation from the data in this graph highlights the way in which discarding of sample material affects the mass of a sample.

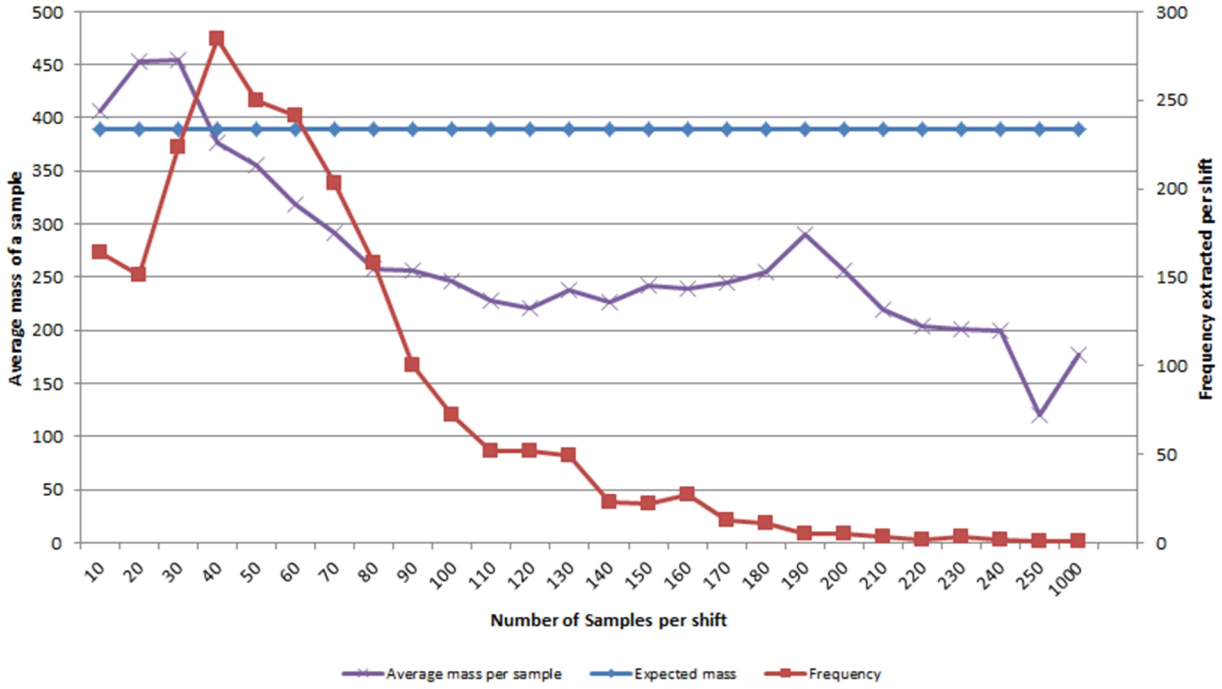


Figure 7.2: Graph indicating that the sample mass is inversely proportional to the number of samples taken per shift

7.2.3 Historical procedure for sample reduction.

It should however be remembered that traditionally chip samples were always reduced in mass before the samples were assayed. The reduction method has changed significantly over the last few decades, but historically the process took place on surface under strictly controlled conditions. Samples extracted from the reef face underground were between 1 kg and 2.5 kg each (Storrar, 1987) and were reduced by quartering to about 350 g after being crushed (Watermeyer, 1932). Quartering is a

tried and tested method for reducing particulate materials and is considered to be free of bias if done correctly (Jackson, 1946).

Improvements in assay procedures mean that less sample material was required to carry out high quality assays and at some point the mining industry as a whole made a decision to perform the sample reduction underground rather than on surface. It's not clear from historical literature where or why this decision was implemented, but it was probably done to reduce costs and the number of labourers required to transport the heavy bags to surface. The minimum mass required for an individual underground sample was approximately 350 grams and was even written into the operating procedures. Samplers were still expected to extract a well-balanced sample and where necessary the variable sample masses were reduced to a standard 350 grams. The Theory of sampling and the formula for the Fundamental Sampling variance suggests that even though this is impossibility samplers were nevertheless expected to reduce the sample mass without introducing a bias? Reducing the mass of broken sampled ore after each sample has been extracted is an ideal opportunity to introduce sampling error which is completely unrelated to the primary process of sample extraction from the face.

7.2.4 Current procedure for sample reduction

Investigations during the course of working experience indicates that the true source of sampling error is due to the way in which the samplers are selectively keeping and discarding sample material immediately after taking the sample. If they are selective in the way they discard or keep the sample material that is caught in the sample dish then significant sampling error is almost certain to be introduced. A survey was carried out across a spectrum of anonymous sampling personnel involved with underground sample extraction at the Harmony operations. The survey consisting of five simple questions was aimed at determining the methods used by samplers and chippers to reduce the sample mass during normal underground sampling procedure. The questions were presented and explained to the samplers and their teams at the shafts and they were asked to complete the questions honestly without the fear of being victimised. The questionnaire was completely anonymous and it is believed that the responses reflect the honest opinion of samplers about the way they conduct business

on a daily basis. A total of 76 respondents from nine shafts participated in the survey, the numbers from each shaft being reported in Table 7.3.

Table 7.3: Number of respondents from each shaft

Shaft	No of Participants
Target1	6
Target 3	3
Tshepong	7
Pakisa	10
Bambanani	6
Joël	12
Unisel	12
Masimong	12
Kusasahlethu	8
Total	76

7.2.5 Sampling Survey

The five questions asked of the samplers are listed Annexure A. The questions were simple and short to avoid confusion or misleading the respondents. The main aim of the survey was to identify a predilection among samplers for the types of materials they are likely to keep and what they are likely to discard. In the sections which follow the question is stated and the answers received are tabulated and plotted in a rose-diagram which provides a useful visual aid for comparing the results.

7.2.5.1 Question 1 -The Sampler has marked the sample area to be chipped. How easy is it to chip a sample with the hammer and chisel?

The majority of the respondents indicated that it was difficult to very difficult to chip a sample with the current tools (Table **7.4**).

Table 7.4: Answers to Question 1

Shaft	% Easy	% Difficult	% Very Difficult
Target1	17%	67%	17%
Target 3	0%	33%	67%
Tshepong	29%	57%	14%
Phakisa	40%	50%	10%
Bambanani	50%	50%	0%
Joël	0%	92%	8%
Unisel	8%	58%	33%
Masimong	17%	58%	25%
Kusasahlethu	13%	63%	25%
Totals	19%	59%	22%

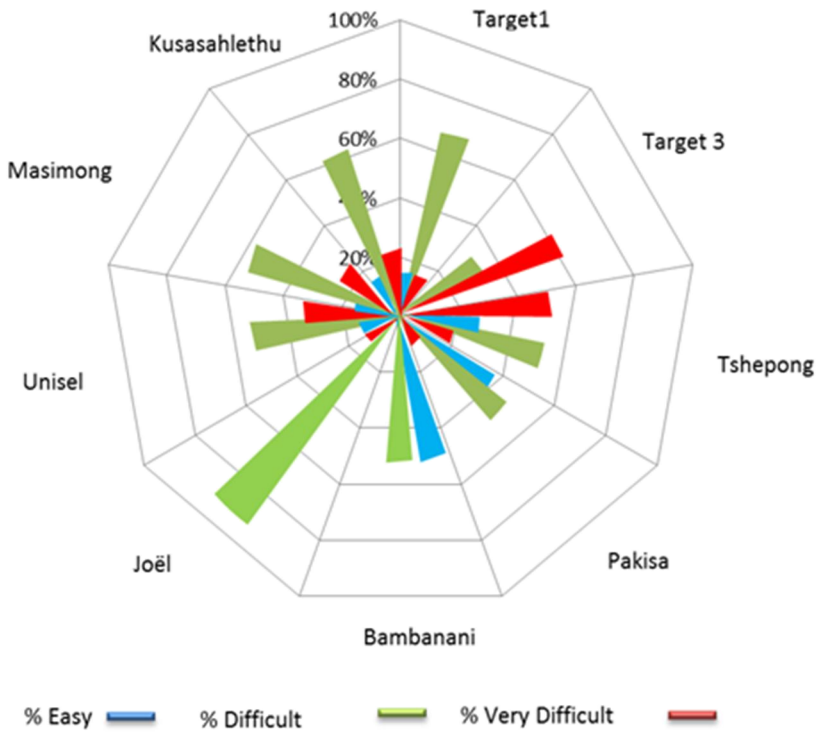


Figure 7.3: Rose-diagram indicating that most respondents believe it is difficult to extract samples with current tools.

7.2.5.2 Question **2 –** In this question the participants were asked if they think that perfect extraction of a sample with the current tools is possible as per the requirements of the Standard Operating Procedures. Perfect extraction refers to a sample that is extracted with square corners at a certain depth exactly within the demarcated lines. Almost 50 per cent of the respondents do not think it is possible as

illustrated in the rose diagram showing the different responses from the shafts, but the results are shaft specific and may relate to the type of reef they are required to sample.

Table 7.5: Answers to Question 2

Shaft	% Yes	% No	% Sometimes
Target1	0%	100%	0%
Target 3	33%	0%	67%
Tshepong	29%	43%	29%
Phakisa	20%	50%	30%
Bambanani	17%	33%	50%
Joël	17%	33%	50%
Unisel	0%	67%	33%
Masimong	17%	50%	33%
Kusasahlethu	13%	50%	38%
Totals	16%	47%	37%

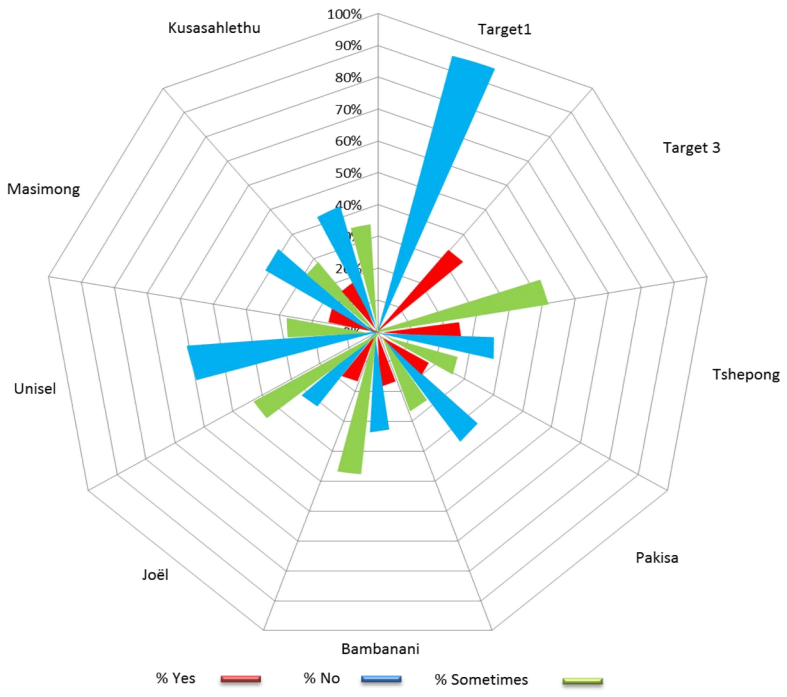


Figure 7.4: Results indicate that perfect extraction is seldom obtained with the current tools allocated to the job.

7.2.5.3 Question 3- Samplers were asked if they occasionally extracted sample material outside the demarcated lines. The majority of participants selected 'No' or

'Sometimes' and provided a good indicator of the degree of difficulty involved extracting a representative sample (Table 7.5).

Table 7.6: Answers to Question 3

Shaft	Most of the times	Sometimes	Never
Target1	17%	83%	0%
Target 3	33%	0%	67%
Tshepong	14%	57%	29%
Phakisa	0%	20%	80%
Bambanani	17%	50%	33%
Joël	0%	67%	33%
Unisel	25%	67%	8%
Masimong	8%	75%	17%
Kusasahlethu	0%	88%	13%
Totals	13%	56%	31%

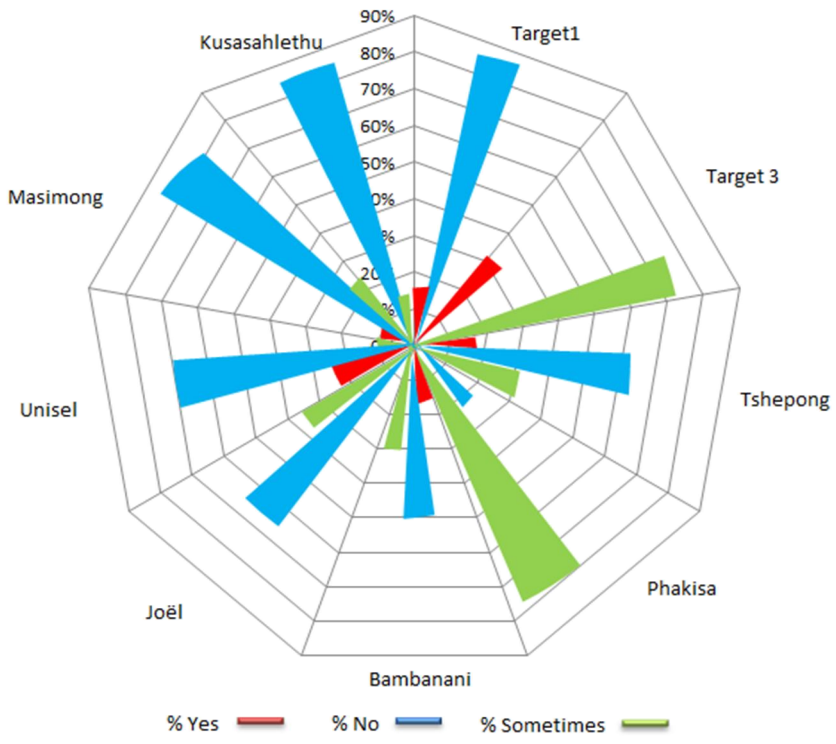


Figure 7.5: Rose-diagram showing that samplers at some shafts find it easier to extract between the lines probably because the reef type allows for easier extraction.

7.2.5.4 Question 4- Participants were asked if they managed to collect enough material in the dish and if there were large fragments that needed to be reduced in size before selecting which material to be discarded. The choices were between

waste, reef or bigger pieces to select for discarding when they reduced the mass of sample material. The majority of the respondents (74 per cent) indicated that they visually identify and discard the waste rock in the sample material collected in the dish; this is followed by “Bigger Pieces” at 19 per cent (Table 7.7).

Table 7.7: Answers to Question 4

Shaft	Reef	Waste	Biggest Pièces
Target1	33%	33%	33%
Target 3	0%	100%	0%
Tshepong	29%	57%	14%
Phakisa	0%	80%	20%
Bambanani	0%	67%	33%
Joël	8%	75%	17%
Unisel	0%	83%	17%
Masimong	0%	67%	33%
Kusasahlethu	0%	100%	0%
Totals	8%	74%	19%

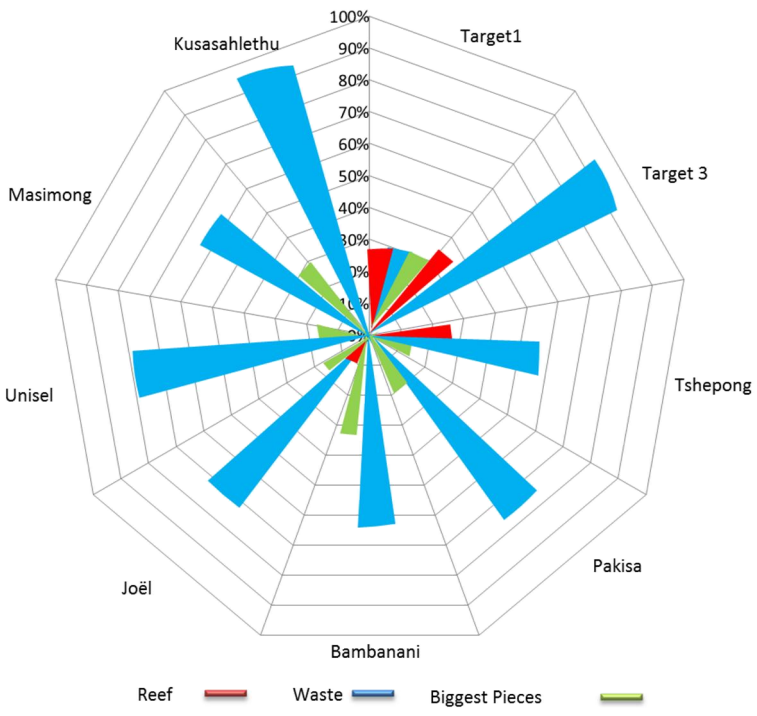


Figure 7.6: Rose-diagram showing the strong bias towards waste materials when deciding what portion of a sample to discard

The data in Figure 7.6 are a clear indication that the most samplers and chippers are biased towards the waste portions in their selection of what materials to discard. It's interesting to note that Target1 is the only shaft where samplers are not biased in selecting which components of sample material to discard. Perhaps this could be explained by the fact that Elsburg reefs, consisting of thick conglomerates with little or no internal quartzite, are sampled at this mine. If the reefs are uniform and do not contain barren bands of internal quartzite then the sample consists primarily of ore with little or no waste to discard. Bands of barren internal quartzite are easily identified and removed during sample reduction Most of the times it will consist of only reef and discarding will now depend on bigger pieces first and then some of the remaining material. Samples with no waste are unlikely to be biased as there is little choice about which materials to discard. If the extracted sample material contains a large proportion of waste, as in the case when sampling the thin carboniferous reefs, then the preference for discarding waste will increase significantly.

7.2.5.5 Question 5 – Samplers were asked which type of material they would retain if they only had to choose between reef and waste. Surprisingly almost 93 per cent of samplers said that they would keep the reef and discard the waste. Although this question is very similar to Question 4, it isolated and emphasised the inherent bias amongst samplers towards keeping the reef.

Table 7.8: Answers to Question 5

Shaft	Reef	Waste
Target1	83%	17%
Target 3	100%	0%
Tshepong	100%	0%
Phakisa	100%	0%
Bambanani	100%	0%
Joel	92%	8%
Unisel	92%	8%
Masimong	83%	17%
Kusasahlethu	88%	0%
Totals	93%	6%

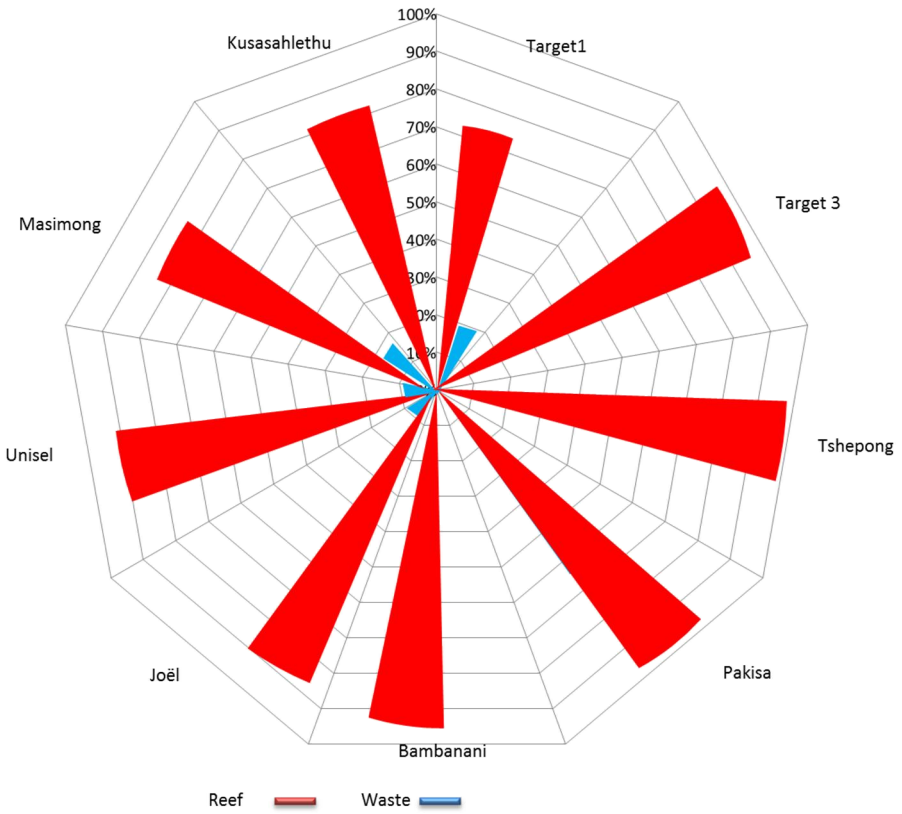


Figure 7.7: Rose-diagram showing the overwhelming tendency amongst samplers to retain the fragments of reef and to discard waste rock.

The survey revealed that under normal sampling conditions samplers and chippers are cogitatively biased when selecting materials to retain or discard. When faced with such a decision during the reduction of the sample mass underground, and if there is no one to maintain an unbiased view on what to keep and what to discard, samplers prefer to keep mineralised reef and to discard the waste rock. Consistent biasedness in selection will almost certainly lead to overestimation of the reef grade because reef is always preferred over waste rock. In addition if the initial material was extracted as carefully as possible and by some chance of nature happened to be statistically representative of the in-situ reef, then the standard procedure of sample mass reduction, which is totally incorrect, would immediately undo all the good work performed during initial extraction.

The composition of the sample material extracted from the thin carboniferous Basal reefs has higher waste to reef ratio than that of the Elysburg's or South Reefs. The sampler extracting thin carboniferous reefs would have no problem identifying the waste and discarding it. Those sampling the thicker, more homogenous reef-types with

high reef to waste ratios will have difficulty finding pieces of waste amongst the reef and would therefore probably select the larger pieces for discarding, irrespective of its composition. It was also shown with the homogeneity model that the error associated with poor extraction increases as the waste to reef ratio increases even without a bias.

7.2.6 Quantifying the bias due to incorrect sample reduction

Interpretation of the data presented in the previous section suggest that overestimation of the face grade is due to human factors – the "rational man" wanting to keep the components that are known to be more valuable. Since it was determined that it was mostly waste being discarded we could use the simulation model in Figure 6.9 to test the effect of selective discarding on the overall error. The same simulation and results obtained was used to calculate the effect that systematic reduction of waste material after the initial extraction will have on bias introduction.

Although it is not known what percentage of the initial mass is discarded during the sample reduction stage, a figure of 18 per cent is assumed for this simulation. If waste only is discarded after the initial sample extraction then it is possible to calculate a new grade for the sample after mass reduction for waste only, by dividing the total content of the sample by the new reduced mass. Table 7.9 is an example of how the effects of selective reduction of waste in "Simulation 1"after the initial extraction process are causing the remaining material to be overstating the actual grade.

Table 7.9: Effect of selective waste reduction on the grade

	Simulation 1			Simulation 1 : Less 18% Waste Reduction		
% Material extracted	Mass of sample (grams)	Content (cm.g/t)	Weighted grade (g/t)	Mass of sample (-18% waste)	Content (cm.g/t)	New weighted grade (g/t)
100	389	10500	150	319	10500	182.93
90	350	9800	155.56	287	9800	189.7
80	311	8600	153.57	255	5600	187.28
70	272	7615	155.41	223	7615	189.52
60	234	7113	169.36	191	7113	206.53
50	195	6713	191.8	160	6713	233.9
40	156	5255	187.68	128	5255	228.88
30	117	3705	176.43	93	3705	215.16
Average			167.47			204.24

The experiment was repeated for all the initial 31 simulations (Table 7.10)

Table 7.10: Selective waste reduction introduces bias.

	Extraction error simulated at different extraction percentages					Same Simulation (-18% waste reduction)			
% Material extracted	No. Simulations	Average grade (g/t)	Total percentage error	Maximum percentage error	Minimum percentage error	Average grade (g/t)	Total percentage error	Maximum percentage error	Minimum percentage error
100	31	150	0	0	0	182.93	21.95	21.95	21.95
90	31	154.72	3.46	11.11	-17.99	188.68	26.17	32.5	0.01
80	31	150.44	2.73	25	-38.19	183.46	25.28	52.44	-24.62
70	31	149.97	1.49	36.03	-43.71	182.9	23.77	65.89	-31.36
60	31	146.78	-4.08	58.7	-53.3	179	16.97	93.53	-43.05
50	31	140.59	-7.21	51.28	-56.19	171.45	13.16	84.48	-46.57
40	31	134.18	-8.67	77.14	-63.1	163.63	11.37	116.03	-54.99
30	31	150.4	0.9	65.51	-66.51	183.42	23.05	105.5	-59.16
Average		147.14	-1.42	46.82	-48.43	179.43	20.22	71.92	-29.72

In Table 7.10 the overall percentage error after 31 simulations was -1.42 per cent which indicates a slight negative bias. The same extraction error mass were discounted by 18 per cent waste to simulate selective sample reduction after the initial sample collection. The total percentage error now changed from slightly negative to a positive 20.22 per cent (Table 7.10).

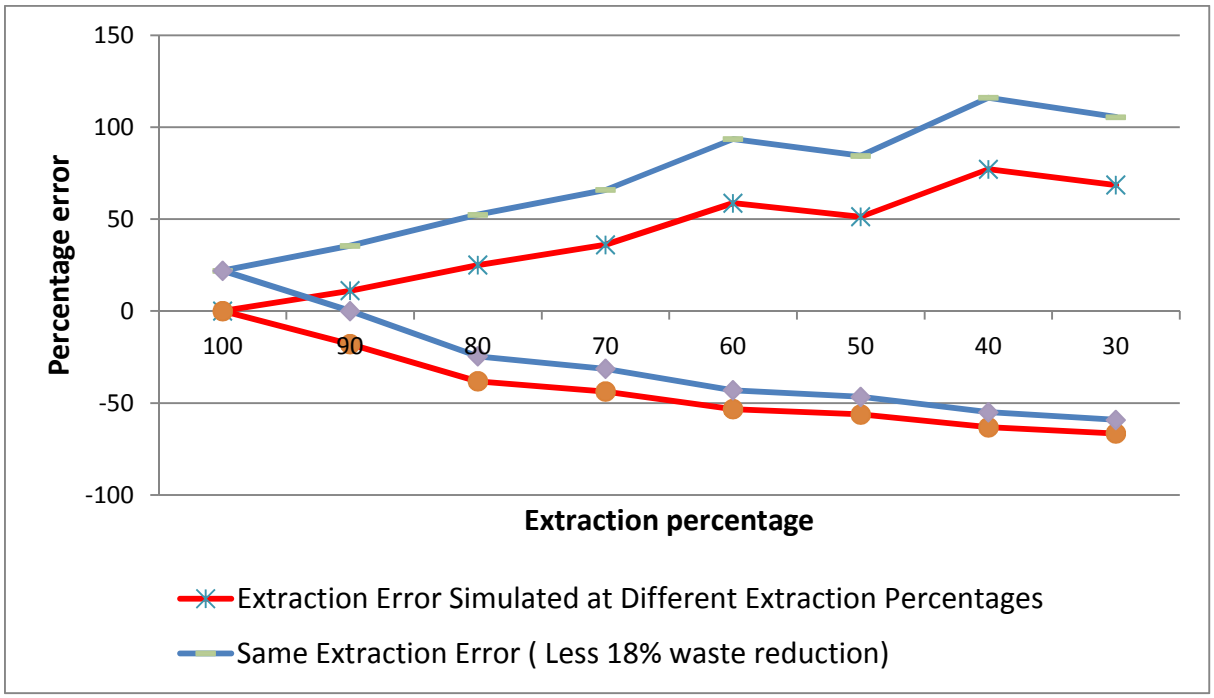


Figure 7.8: Selective discarding of waste responsible for bias

This table clearly captures the fact that the errors as a result of poor extraction is not introducing any bias, but if selective discard of waste is occurring after initial extraction

then serious positive bias are introduced. Even if a sample was extracted 100 per cent but selective discard of waste occurred in this simulation 18 per cent then this would not only undone the effort achieved with good extraction but will overestimate the true grade by almost 22 per cent.

The percentage bias introduced after the initial extraction is directly proportional to the amount of waste discarded and is a classic example of IPE. Shafts mining heterogeneous reefs with high waste to reef ratios will be more affected by this selective sample reduction method that is common practice on most mines today.

CHAPTER 8 – RECOMMENDATIONS

Extraction capabilities of the chip sampling method are far from desirable, and introduce error with each sample extracted that is not meeting the required standard. The magnitude of the errors is proportional to the amount of material over extracted or under extracted in relation to the demarcated area. Due to the limitations of the tool allocated to extract the sample material, errors will always be present. But it was found that despite the poor extraction obtained with this method, that samples of acceptable quality can be achieved if the following conditions are met.

- On-going training and supervision - AngloGold Ashanti has successfully managed to improve the quality of their sampling by focussing on on-going underground training. Part of the focus includes regular underground visits from experienced personnel to ensure that samplers are working to standard.

- Implement controls - It's important to have daily controls in place to monitor and check the quality of the samples extracted from underground panels. AngloGold Ashanti successfully implemented the "Quality Index" to use a standard checklist together with the aid of photos taken before and after extraction to determine if a sample extracted is within acceptable limits based on size, mass and extraction.

- As far as possible samplers must try to demarcate the sample according to the composition of the mineralised and un- mineralised portions of the reef. This is difficult to achieve in some carboniferous reefs where the carbon contact is only a couple of mm thick. It is suggested that in such a case that the actual width of the conglomerate housing the carbon contact should be recorded. Samples extracted from waste portions of the reef should be spot checked on surface to see if any reef material is present which could indicate contamination.

- Sample widths must be measured to a high degree of accuracy before and after extraction.

- Focus should shift away from "Quantity" to "Quality"

- Sample reduction underground is a source of concern and if not done according to the correct principles of sampling, then serious bias can be introduced at this point.

Due to the haphazard nature of the shape and size of the material extracted with the current tool, some sort of material reduction may be warranted especially in the case where massive over extraction of material laying outside of the demarcated area occurred. Sample reduction done blindly and selectively after each extraction should be stopped and it is therefore important that the samplers are made aware of the impact of selective material reduction underground. Some sort of control is needed to ensure that the mass of the sample extracted is equivalent to the expected mass based on the sample size. Maybe the practise of sample reduction on surface should be re-looked. It will not only reduce the error currently introduced but will also allow the valuator or senior sampler to visually observe the material extracted. Sampling error associated with chip sampling can never be completely eliminated due to the tool currently used, but the errors may be reduced to acceptable levels if the above steps are followed.

CHAPTER 9 – CONCLUSION

Chip sampling has been practised for more than a century on all South African gold and platinum mines over which time samplers have collected hundreds of thousands of samples. Despite this extended period and number of data collected little is known today about the quality of the samples extracted by this method. Visual observation of the extraction process and capability of the sampling tools employed clearly indicates that errors of one sort or another are bound to be introduced. Many researchers Beringer, (1938); Cawood (2003); De Jager (1997); Fourie and Minnitt (2013); Freeze (2013); Harrison (1952); Hallbauer and Joughin (1972); Jackson (1946); Lerm (1994); Magri and Mckenna (1986); Muller (1950); Sichel (1961) and Storrar (1987) collectively agreed that perfect sample extraction by this method is not possible with the current tools, a hammer and chisel, that have been used since chip sampling was first attempted. Extraction of a sample with the required geometrical shape and volume demarcated on the face is almost impossible to achieve in practice. Observations made during sample extraction of extremely hard, fine grained quartzite using the hammer and chisel indicates that only fractured, loose material or soft portions (carbon or brittle conglomerates) are recovered from the face.

The thesis consists of two parts the first of which includes a historical review of the findings concerning the errors introduced by sampling. The second part consists of an underground investigation aimed at confirming the findings highlighted in the literature review. The aim was to understand and quantify exactly how different variables, present during and after extraction, are responsible for introducing error and bias. This has never before been done successfully. The introduction of the simulated chip sampling model made it possible to quantify how the components of sampling error introduced by extraction, contribute to the total error.

1. Learnings from the Simulated Chip Sample Model

a. Effects of Sample extraction on Grade and Precision

The simulated chip sample model made it possible to quantify the error introduced as a result of poor extraction. The reason that this has not been successful in times past is because the nugget effect made comparative studies between samples taken at

exactly same location, but using two different sampling methods, questionable. The simulated chip sample model allows one to remove the uncertainty arising from the nugget effect. This provides a clearer understanding of the means by which substandard sample extraction with the hammer and chisel introduces sampling error. The model was designed to represent the underground lithology of a carboniferous reef, typical of the Basal or Carbon Leader reefs. The percentage error introduced as a result of poor extraction was estimated by comparing the calculated accumulation value with the known standard from the model. The method of multiplying reef grade and reef thickness is a traditional engineering approach that captures the ideas of reef grade and thickness in a single statistic commonly known as the accumulation value (cmg/t). Despite poor sample extraction the average grade, over many samples, remains relatively constant, even though the precision may be highly variable. According to the required shape and mass of the demarcated sample, extraction could be perfect if 100% of the material is extracted. For every percent not extracted, the error tends to increases proportionally, depending on the heterogeneity of the material in the sample. However the variability depends critically on the percentage of reef and/or waste material extracted, for example the precision decreases proportionally with the percentage material not extracted. The simulation model allows one to calculate the extraction error over a range of the percentage of material over- and under-extracted. This means that even in the case of poor sample extraction from a very heterogeneous material, there is no evidence of a bias that could explain the extent of over estimation.

b. Effect of Sample shape on Error

The shape of the demarcated (delimited) sample extracted from a stope face is also very important. Simulation also indicated how the shape of a sample can become a source of error even if it was perfectly extracted. If sampling perpendicular to a reef then the sample shape has to have a proportional relationship between its width and its height (aspect ratio) as shown in Figure 6:11. The only shape that will not introduce an error is a square or rectangular sample shape. Even with perfect core extraction, a sample taken parallel to the bedding of the reef, will incur error simply as a result of the shape of the sample extracted and will be aggravated by the heterogeneity of the

reef. This finding disqualified core sampling as a potential replacement for the method of chip sampling.

c. Effect of Homogeneity of the Reef on Extraction Error

A further important contribution was made through an investigation of how the same extraction error can result in different percentages of error if the ratio of reef to waste within the demarcated sample changes. Simulating the chip sample indicated that the accuracy and precision increases as the composition of the sample becomes more homogenous despite having the same extraction error as discussed previously. This indicates the importance of demarcating samples on the face according to their lithology i.e. waste and reef, and to avoid including waste with reef within a demarcated sample. It was found that in the case where a sample is highly heterogeneous that the average error seems to be less severe if more than the required material is extracted, than to extract less material. If the sample composition is homogeneous then it did not matter.

d. Effect of Calculating Accumulation Values on Bias and Error

When a sampler prepares for sample extraction he is careful to ensure that exact widths and chip sample lengths are marked on the face and then measured and carefully recorded. Where there is failure to extract a sample exactly according to the demarcated area error is introduced, but the problem is compounded because the grade of the sample, which is known to be incorrect (biased), is then multiplied by the recorded sample width. A classic example of such and error occurred and lead to an overestimation of the grade by 365%.

A different form of error arising from the use of accumulation values occurs if one assumes that the reef material was extracted to the prescribed geometric shape of the sample, when in fact it was not. As mentioned earlier sample width is used to calculate the product of reef thickness and reef grade, a cm.g/t value, which is composited and used in most estimation models. The sample width can generate an error because it assumes that perfect extraction was achieved when it was not, so any bias incurred during extraction will be applied to the demarcated width of the sample. Any bias present in the sample due to poor extraction is then amplified by a ‘width demarcated’ and not the ‘width extracted’.

The width demarcated has nothing to do with the extraction process, but is nevertheless capable of inflating the error inherent in the extracted material. In a case such as this the grade allocated to the sample material extracted is correct, the error is only introduced when a sample width is multiplied with the grade to calculate an accumulation value (cm.g/t). This error is amplified if the heterogeneity of the material inside the demarcated sample is large. This error is always present during chip sampling because of the historically poor extraction and it is never possible to eradicate this source of error completely. With deeper understanding of this problem properly designed protocols could be introduced to prevent a systematic bias from being introduced during sample extraction. Even though comparisons between chip sampling and saw sampling were inconclusive the author is of the opinion that any improvement in extraction capability will reduce this error and improve accuracy and precision per sample and section.

e. Relationship between Extraction Error and Nugget Effect

It has also been shown in the thesis that the error associated with poor extraction will over-ride the true underlying nugget effect existing between samples of equal support. A simulation indicated that the variance calculated between six identical samples of known grade was entirely due to the extraction error and unrelated to the presence or absence of nuggets of gold. It is only possible to calculate the nugget effect existing between samples of similar sizes if no IDE or IEE was introduced during extraction. If any form of IDE or IEE was present during extraction then what is considered nugget effect is actually due to extraction error. Simulating the impact of the extraction error on the calculation of a variogram indicates that the extraction error leads to an increase in the nugget effect at short lags. This resulted in estimated grades that are overly smoothed and consequently affects mining selectivity.

2. Identifying sources of bias

The second part of the Thesis used the knowledge gained about the effects of poor extraction on error and bias, to simulate and test actual underground sampling conditions and to identify behaviours amongst samplers that could be responsible for introducing bias during and after sample collection.

Early investigations into the sampling procedures identified “soft-reef” bias and inclusion of waste in the demarcation of the sample as the main sources of error and bias. The literature review indicated that early investigators were more focused on attributing over estimation to sampling bias than understanding the sources and reasons for bias and error in general. Soft reef bias is a major error and bias generator whereby the soft carbon material is always over extracted compared to the harder adjacent host materials inside a demarcated sample area. This form of bias always results in an over estimation the grade of the in situ sample. Investigations into this type of bias concluded that it may be responsible for over estimating the overall grade by as much as 26 per cent (Cawood, 2007). Unfortunately the perception that chip sampling causes over estimation of the in situ grade was used by mining personnel as an easy and obvious explanation as to why certain shafts were reporting low MCF’s. This perception and misunderstanding masked other sources of error such as dilution, sweepings and incorrect tramming etc. that were actually responsible for the deterioration of the MCF to go by unchallenged.

The effects of fragmentation of the ore due to blasting, ore handling and tramming distance on the deterioration of the MCF is also a clear source of the introduction of gold loss, not covered by sampling or estimation. Historically the average MCF at the Bambanani mine was in the vicinity of 65 per cent. However since the commencement of pillar extraction the average MCF is almost 100 per cent. In the shaft pillar the reef type mined and its characteristics are identical to that which was mined historically and the sampling and the estimation methodology have remained the same. The only factor that has changed is the decrease in tramming distance and the amount of ore handling before it reaches surface.

There is no dispute that soft-reef bias introduces serious error and bias into the MCF, but, it has to be introduced during the extraction of every sample at any particular shaft. The possibility of this happening in practice is unrealistic. The existence of the soft reef bias was confirmed during the underground investigations that are reported on page 72, but this type of bias was only observed once out of a total of 120 samples extracted. Another variable that influences the incidence of soft-reef bias is the thickness of the carbon seam in the stope face, a variable that has been very rarely reported in the history of sampling data capturing, and even today is not recorded. The

size of the chisel used to extract the sample would require a carbon seam of at least 1cm or more to allow for easy extraction. It is difficult to imagine the chisel that causes over extraction of carbon material in seams less than 3mm thick. Another important point to consider is that some of the in situ carbon exposed on the surface of the stope face will be lost during the impact of blasted fragments on the face, during washing, and during barring of the face that must take place before the sampler can do his work.

The author is therefore of the opinion that the extent of soft-reef bias decreases rapidly as the carbon seam becomes thinner and will occur only occasionally, but with far less frequency than previously thought. Furthermore the rate of occurrence of this type of bias is not significant enough to cause the deterioration of the MCF. This was confirmed by AngloGold Ashanti in a project where chip sampling was initially considered to be responsible for the declining MCF because of soft-reef bias. Statistical comparisons between samples extracted by chip sampling compared to 'coffin sampling', thought to be the "perfect sample", did not find any bias. The text book examples of perfect coffin samples were compared to chip sampling for which the extraction was not so perfect. It was anticipated that because of the existence of the soft-reef bias the mean grade of the chip samples should be higher than the average grade of the coffin samples. The comparisons did not indicate any bias and it also confirmed that chip sampling actually compared well with alternative methods capable of extracting better samples. It was argued that chip sampling carried out under careful supervision produced samples of better quality than what might normally be expected.

3. Survey of the in-stope sample discard process

This implies that samplers under supervision extract better quality samples or are doing something other than they normally do during or after sample extraction. The fact that samplers have a free hand in adjusting both the sample mass and the sample content in the period between taking the sample and it reaching the surface is a completely new insight. The process of discarding sample material after extraction because there was an excess of sample material, was observed by the author during the underground investigations. In the case of AngloGold Ashanti the average sample mass increased drastically 'after' the implementation of the "Quality Index" compared

to the ‘before’ situation. Increase in sample mass according to AngloGold Ashanti was accredited to improved extraction obtained with stricter supervision either in person or by comparing photos taken before and after sample extraction.

It is difficult to quantify the increase in sample mass from the before and after photos taken at the face. The increase in the average mass, (the time taken to extract a sample basically remained the same, yet the mass increased a lot) as well as the increase in the average time spent extracting a sample before and after implementation of the “Quality Index”, could not be explained. It is the author’s suspicion that discarding sample material in the stope was the only activity that was not controlled by the Standard Operating Procedures, and this was the reason for the increase in sample mass. Samplers were therefore not discarding excess material in order to comply with the rules of the “Quality Index”. Data obtained from Tshepong Mine indicated that the average mass of the sample extracted was proportional to the number of samples collected per sampler, per shift. A very important conclusion is that the average sample mass decreases as the number of samples extracted per sampler, per shift, increases. Prior to the introduction of the “Quality Index”, the amount of material sent to the assay lab depended not only on the material extracted, but also on the amount of material discarded after sample extraction. Since discarding of material after initial extraction was occurring at each and every sample site it was the prime suspect as a possible source of not only error, but bias. This is a possible reason that no bias was discernible between the chip samples and the ‘coffin samples’ analysed by Flitton and Freese (2013).

4. Identification of the “waste-discard bias”

If the sampler and his team were unbiased in their selection of the material to be discarded then this factor would not have introduce bias. In order to determine if the samplers and their crew were indeed selective when discarding what they considered to be excess material, a survey was conducted amongst 70 participants. They were asked to honestly answer five questions designed to determine if a bias existed with the discarding process. The survey concluded that the samplers not only found sample extraction with the tools difficult, but 93 per cent of the respondents indicated that they select waste rather than reef when faced with the choice of what to discard. The simulated model used to show that highly heterogeneous sample compositions, on

average, were unbiased irrespective of the quality of extraction, was also used to test the effect of selective waste discard after the extraction process. The results clearly indicated that selective discarding of waste portions from a broken ore sample collected with waste and reef present will result in a serious bias responsible for over estimating the grade of the extracted material. Even the most perfectly extracted sample will overestimate the true in situ grade if this error is introduced by preferentially discarding waste. This “waste-discard bias” will severely affect reefs with high waste to reef ratio such as the carboniferous reefs present in the demarcated sample shape. Since most of the channel samples taken on carboniferous reefs consist of only a single sample this type of error will introduce a severe bias. In fact the bias generated from this error will resemble “soft-reef bias”, but unlike soft-reef bias that is introduced during extraction the waste-discard bias is introduced after extraction. The effect of “selective discard” diminishes when the composition of the reef within the demarcated sample becomes more homogenous. If the exposed stope faces consist mainly of conglomerates with little internal waste then demarcation of the sample is done according to observed lithology i.e. reef and waste. In such a case the extracted material will consist of either reef or waste. When sampling the conglomerates the sampler and his team will only select bigger pieces of reef to discard since there will be no waste present, so it is unlikely that the discards will introduce a bias. The selection process in such a case will be totally random and free from bias. When extracting a sample demarcated in the waste portion the tendency of the samplers is to discard any reef (rather than waste) and/or the bigger pieces of waste.. This may explain why shafts that mine lithologically homogenous reefs compared to those mining carboniferous reefs, experience a better MCF despite the extraction error being fairly similar.

This “waste-discard bias” error may also be the source of higher grade in samples that have included a larger proportion of waste, rather than a decrease as might be expected because of dilution. This is because extra waste from a correctly demarcated and extracted sample will be removed from the sample during selective discarding of the waste. This will result in a grade similar to a sample extracted with no waste included, giving the perception that the error was as a result of inclusion of waste.

The percentage of error introduce with the “waste-discard bias” error depends on the reef to waste ratio of the demarcated sample, and on the percentage of waste discarded after extraction. It is impossible to determine what the percentage of discarded waste is because extraction is never constant and discarding is randomly determined by the sampler and the number of samples collected during the shift. The author feels strongly that this error, as well as other errors such as “soft reef “bias, is major contributors to the bias responsible for over estimating the grade. The only way to prevent this error completely would be to develop a tool that is able to extract a sample exactly to the shape and volume demarcated on the face. Since no such tool exists the only way to mitigate this bias will be to discourage any form of material discarding after the initial extraction process. However this is easier said than done in practice because there are occasions when extraction may include material outside the demarcated area that needs to be discarded. AngloGold Ashanti has shown that improved focus on standards, one of which included an increase in sample mass, resulted in samplers being discouraged from discarding any material after extraction. Since it is assumed that the increase in mass was not necessarily as a result of improved extraction, it is safe to conclude that the bias expected with “selective discard” was kept to a minimum, leading to an improvement in MCF.

There is evidence in the literature that our predecessors acknowledged the existence and introduction of bias during chip sampling especially on the thinner carboniferous reefs. Methods introduced to minimise the error included selective capping and even the exclusion of results during the estimation process which helped to lower the ‘gold called for’ and improving the MCF. This allowed the responsible persons to reduce the MCF, but it failed to solve the problem; it was purely a cosmetic exercise. The author is not suggesting that MRM’s revert to the earlier outdated practises of sample exclusion or capping, as this is accommodated in the kriging algorithms, but soft-reef and waste-discard bias cannot be eliminated; they are forever embedded in the bias sample data. Only in this way will it be possible to identify other factors that may actually be responsible for the deterioration of the MCF. Current estimation methods make provision for capping of data during variography and estimation, but this only eliminates the extreme errors. The question is “Do the automatic bias adjusting algorithms in the kriging equations adjust sufficiently for the bias present in the bulk of the data?” It should be accepted that the data on some mines are more affected by

error and bias. It should be acknowledge that our current estimation methods may not always be sufficient to successfully ameliorate the problem of bias inherent in the data. Even if the new sampling tools and equipment could minimise the bias, the sampling error and bias inherent in the historical data will still influence the estimation.

It is therefore important that implementation of sampling improvement initiatives such as the “Quality Index” should be maintained and adjusted if early results do not indicate an improvement in the estimation of resources and reserves. The impact on the MCF may take time to become manifest, but it is likely that it will improve in the longer run and that the amount of improvement will be equivalent to the bias introduced by sampling that was present before implementation. The focus can then be shifted to other areas such as the assay methods etc. in a quest to improve the MCF even further. Unfortunately it is not uncommon for more than one initiative to be introduced simultaneously to improve the MCF for a certain shaft, especially if the shaft is under investigation. If intervention does result in an improved MCF it is often difficult to determine which of the many interventions contributed the most to improvement.

Chip sampling in terms of its in-situ extraction capabilities is probably one of the worst sample recover methods, but in the difficult, confined, hot and unwelcoming environment in which samplers are expected to operate, it is probably the most best suited and only consistent reliable and cost effective method for underground face sampling. Despite its poor extraction capabilities, it was found that if no bias is introduced it is the best available method. A comparative study with other methods have shown that under certain conditions and despite its poor extraction capabilities that chip sampling is still considered the best sampling method.

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ANNEXURE

Annexure A- Questions for Sampling Department

1. The Sampler has marked the sample area to be chipped. With your tool “hammer and chisel” how easy is chip a sample.

Very easy ☐ Difficult ☐ Very difficult. ☐

2. The **picture 1** shows a well extracted sample from a soft material. Do you think it is possible to achieve the same extraction from the face with the hammer and chisel?



Yes ☐ No ☐ Sometimes ☐

3. Do you sometimes sample outside the yellow crayon marks?

Most of the times ☐ Sometimes ☐ Almost never ☐

4. You have chipped enough material in the dish. There are some big pieces and the sample is a bit heavy. You have to break the big pieces into smaller pieces and throw away some of the material. What pieces do you usually select to throw away?

Reef ☐ Waste ☐ Biggest pieces ☐

5. You have to choose between a piece of waste and a piece of reef to keep in your dish. Which one will you choose?

Reef ☐ Waste ☐