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Statistical size analysis of potholes: an attempt to estimate geological losses ahead of mining at Lonmin's Marikana mining district

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Mapped pothole data from the UG2 and Merensky reefs in Lonmin's Marikana mining operations were analysed for size variability and abundance. The UG2 Reef potholes have a greater proportion of larger potholes relative to that in the Merensky Reef. However, the proportions of potholes with diameters greater than 70 metres are comparable. Another characteristic identified, is that the maximum pothole diameters were generally found to decrease from west to east for both reef types. A visual inspection of the pothole occurrences revealed that clustering and abundance characteristics can be used to delineate broad domains, which have useful application in quantifying unknown pothole loss in unmined areas.

By analysing mapped pothole information and subsequently integrating these features into the grade models, the technical mining systems are now able to benefit from the prediction of unknown geological losses more reliably and serve as a single source of information for mineral resource reporting and mine planning.

Introduction

Potholes within the Merensky and UG2 reefs of the Bushveld Complex are well known geological features that are problematic in mining. They occur as depressions or slumps on the reef horizon normally existing as severe disruptions which prevent economic extraction and are thus characterized as geological losses. Given the adverse impact of potholes on ore extraction, considerable effort has been made by mine geologists to understand the pothole distributions such that their occurrences or abundances may be predicted.

In mineral resource modelling, potholes may be characterized either as known losses, where the data acquisition activity has allowed reasonable definition, or as unknown losses, where there is an expectation that potholes will be present with some statistical proportion. Typically, the global average abundance of a shaft block is applied to the unmined areas. In the case of known losses, the pothole dimension and shape may be constrained through partial or complete exposure in mine excavations. In contrast, the unknown pothole losses were estimated by applying average abundances from areas where potholes were well constrained (i.e. from the known pothole loss domains) or through the interpretation of high resolution seismic surveys. Refined mine planning and production forecasting arises from the ability to delineate the potholes into suitable domains and to estimate their likely abundance within acceptable error limits.

At Lonmin's Marikana mining operations, the sizes and percentage losses attributable to potholes have been analysed along the strike and dip directions of the reefs, which revealed trends that were useful for geological loss prediction. This study examines the pothole size variability which was used to gain some insight into the pothole distribution. Thereafter, known potholes were delineated into domains and then the average abundance was applied to the adjacent unmined areas. The pothole outlines and domains were then incorporated into a grade block model to obtain a final mineral resource model. The benefit of such an integrated resource model allows the mine design to exclude areas within known potholes and to quantify the parameters required to mitigate the likely effect of unknown potholes for unmined shaft blocks.

Geological setting

Potholes have generally been described by many geologists as synmagmatic circular depressions or slumps below the PGE-and/or Cr-rich mineralized horizons of the Merensky and UG2 reefs. Carr *et al.* (1994) described potholes to be one of several types of discontinuities that affect the Bushveld Complex, which range in extreme sizes from several kilometre scale regional gaps to minor ten centimetre discordant structures along the reef. Typically, potholes on a scale that affect mining operations can vary from five metres to several hundred metres in diameter. In some areas, such as the northwest part of the western Bushveld Complex, conformable Merensky Reef occurs within 'regional potholes' despite large-scale elimination of parts of the stratigraphy over areas of several square kilometres (Viring, 1998). Within these regional potholes, second order potholes occur as exhibited by the local development of the Merensky chromitite layer below the Upper-pseudo Reef chromitite layer (Smith and Basson, 2005).

Generally, the reef development within the potholes is irregular in both thickness and dip, and the reef horizon is

usually unconformable with the immediate footwall stratigraphic units. The Merensky and UG2 reef PGE mineralization within potholes is variable and disrupted, and the high dilution rates associated with the hangingwall layers, as well as complex mining configurations to follow the irregular reef shape results in little or no incentive to extract. The overlying stratigraphic layers that fill the pothole dip towards the centre and are commonly discordant with the reef layering. The depth and extent of the pothole base into the footwall layers, as well as the hangingwall unit contact angle to the reef and attenuation of the reef, has been used by geologists at the Impala Mines to classify UG2 pothole types (Hahn and Ovendale, 1994).

Potholes have been exposed throughout the mining operations in the Bushveld Complex and can vary dramatically in their abundance. Geological losses associated with the potholes in the western Bushveld Complex range from about 4% to 20% (Figure 1) but may reach 30% in certain areas. The controls on the pothole abundance may be examined in terms of distance from the magma's feeder or point of entry, or the affect of palaeo-topography, where the degree of turbulence within the magma would be greater. In the case of the palaeo-topography effect, several studies have correlated the increase in pothole abundance with reef characteristics such as steeper dip, as found at Lonmin's Western Platinum Mine (Carr, 1994) and Anglo Platinum's Rustenburg Mines (Chitiyo *et al.*, 2008).

Along the 26 km strike length of Lonmin's Marikana mining operations, potholes are pervasive on the reef horizons, but occur with varying abundances (Figure 2). Average mapped pothole abundances for the Merensky and UG2 reefs were estimated at 9.2% and 7.8% respectively. However, these may range from between 3% and 12% for individual shaft blocks. The general distribution of these potholes appears random; however, local clustering of the potholes was evident. These clusters have a northwest-southeast orientation on both reef horizons, which suggests that the processes responsible for forming these concentrations were active during the formation of both Merensky and UG2 reefs.

Data acquisition and validation

The information in this study was based on the routine underground mapping data collected by mine geological personnel over a period of over 20 years. The raw data consisted of mapped contacts of the potholes both fully and partially exposed during the mining process. The pothole edge or contact is broadly constrained by the interpretation of information from the mine plans, which results in the final pothole shape and dimensions to be an approximation of its true contact. As a result of this, the true pothole dimensions can be expected to be fractionally smaller or larger than the outline shown on the plans.

The data used for the study consisted of perimeters which defined the mapped pothole outline. The data clean up proceeded with the removal of incomplete mapped potholes usually of small crescent shapes or refining the interpretation of potholes where it was thought that the potholes have coalesced or where duplicate data existed. Furthermore, potholes with areas less than 20 m^2 (or 5 m diameter) were excluded. The integrity of the final data-set relied largely on the diligence applied to the original mapping. In total 1 043 Merensky Reef potholes and 3 585 UG2 Reef potholes were defined.

Pothole size and frequency variability

Mapped potholes are generally near circular features as shown by the good correlation found between the maximum north-south (YINC) dimension and the maximum east-west (XINC) dimension (Figure 3). This relationship gradually changes for potholes with diameters greater than 100 metres in both reef types where the larger potholes have a greater XINC length and thus the pothole shape tends towards an oval elongated in an approximate east-west direction, which is sub-parallel to the reef strike.

In mining operations, potholes may be characterized into broad categories based on their size. This approach has been documented at several mining operations, e.g. the Union Section Mine (Lomberg, 1998) and Rustenburg Section Mines (Chitiyo *et al.*, 2008) where the size of the

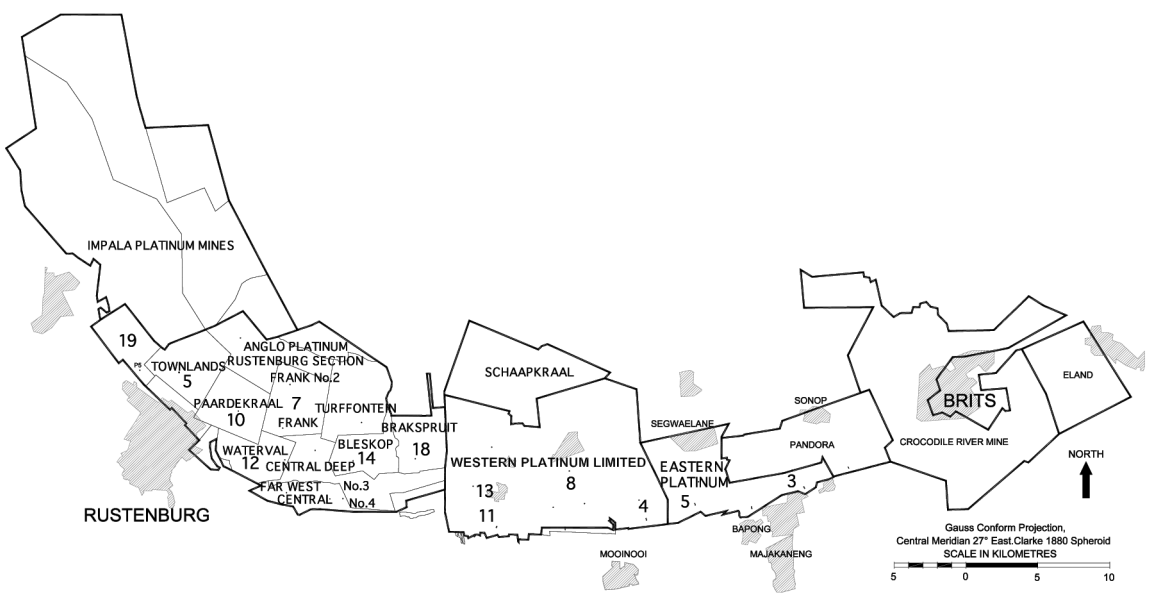


Figure 1. Location of the Lonmin mining operations (Western and Eastern Platinum Limited stipple shading) in relation to the surrounding mining district for the south western part of the Bushveld Complex. Also shown are the percentage potholes for the UG2 Reef by mining district. The data from the Anglo Platinum operations were extracted from Chitiyo *et al*. (2008)

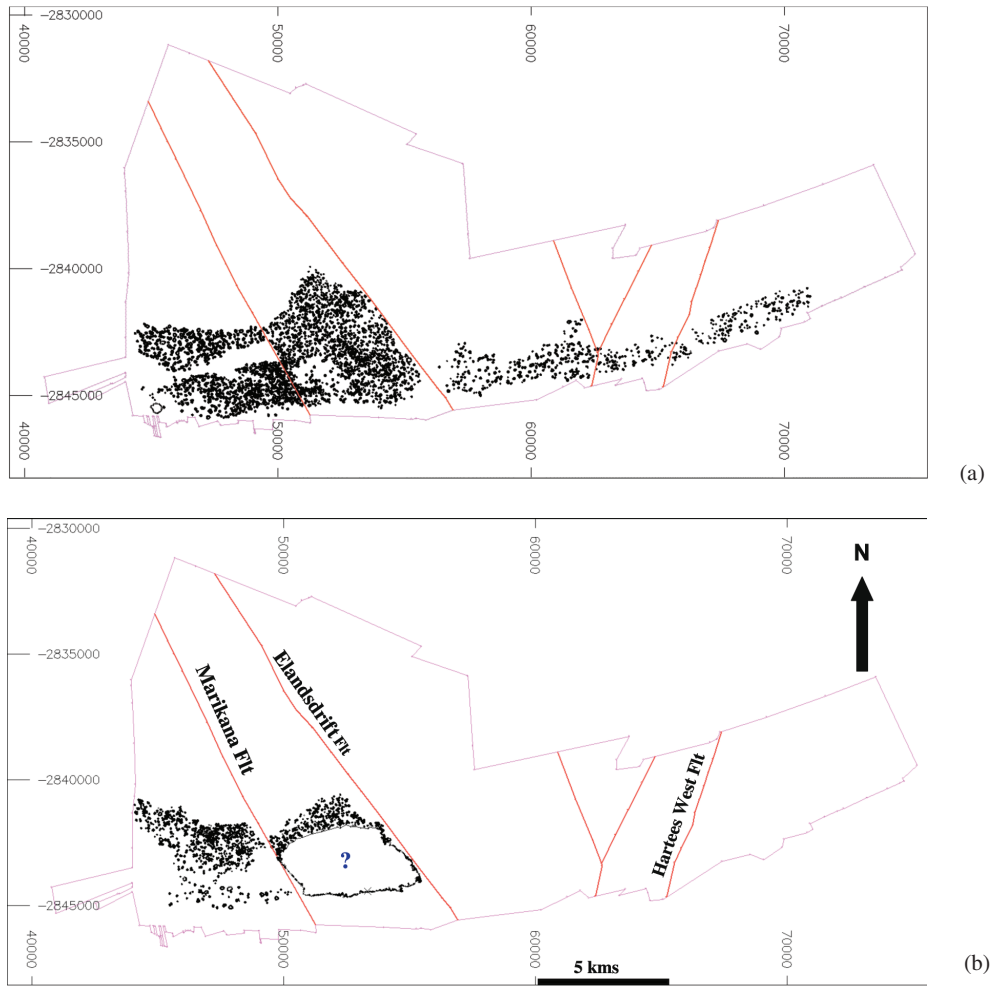


Figure 2. Occurrence of UG2 (a) and Merensky Reef (b) potholes within Lonmin's Marikana Leases including the Pandora Joint Venture to the East. The more significant NW-SE and NNE-SSW faults are shown. North is towards the top of the plan, which is also the down-dip direction, and scale can also be measured from grid. The blank areas beyond (down-dip) the concentrations of potholes are unmined areas. The domain denoted by '?' is unavailable data for the mined-out area. Compare with Figure 1

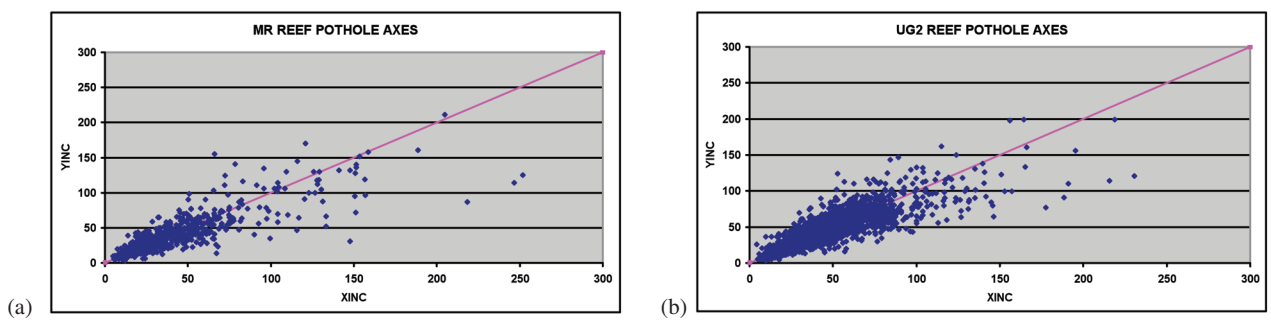


Figure 3. Scatter plots of maximum pothole length in east-west (XINC) and north-south (YINC) directions for the Merensky (a) and UG2 (b) reefs

pothole is related to the degree of disruption of the economic horizon. A similar approach was taken in this study and four size intervals were used to categorize a broad range of pothole diameters from 10 to 200 metres. Small potholes with diameter of less than 11 metres (approximately 100 m^2) have an effect of reducing the local stoping efficiency where a 15 metre wide up-dip panel is reduced to 4 metre. However stope faces may be abandoned where its length is <10 metres. Medium size potholes of 36 metres (1 000 m^2) reduce the face availability and force significant costly redevelopment and even sterilization of reserves. Large potholes up to 115 metres (<10 000 m^2) eliminate several stopes and usually require interventions such as acceleration of development to compensate for the lost potential ore reserve area. The extreme sized potholes, referred to as catastrophic potholes, may reach over 200 metre diameters and eliminate multiple stoping blocks and start to have an impact on the mining strategy. Massive potholes associated with large slump features can even occur superimposed on the two reef horizons.

The pothole size distributions, using the aforementioned mining impact size intervals, were broadly similar for both reef types (Figure 4). It was observed that medium size potholes are about twice as common as large potholes in the Merensky Reef, whereas the percentage frequency of large potholes is greater in the UG2 Reef than the Merensky Reef.

The percentage frequency of UG2 Reef potholes for each shaft/s block area per mining impact category is shown in Table I. No consistent trend in pothole frequency was revealed from west to east.

Cumulative frequency plots of pothole size reveal strongly skewed distributions for both reef types and also show that the smaller potholes are more abundant in the Merensky Reef relative to the UG2 Reef (Figure 5). Both reef types, however, have similar proportions of potholes with diameters greater than 70 metres. A further distinction noted within the UG2 Reef is that the potholes to the west of the Elandsdrift Fault (EDF) with diameters between 20 and 40 metres are significantly more abundant than those towards the east of the EDF. The position of the EDF also coincides with a sudden decrease in pothole percentage to the east. A general trend of decreasing pothole size is noted when plotting the pothole footprint along the X-axis (near strike; Figure 6). The maximum pothole size (with the exception of a few outliers) reveals a general decrease in size from west to east.

Pothole abundances and domains

It was considered that defining boundaries to zones of mapped potholes defined by similar abundances and/or size variability would prove useful in attempting to extrapolate pothole loss percentages into the unmined areas. In this study, only a visual inspection of the pothole distribution was made, and some obvious clustering was identified where abundant small and medium-sized potholes were scattered in varying proportions around a lesser population of large potholes.

Potholes on the Merensky Reef have an increased abundance of smaller potholes in the north-western sector of Marikana operations and this was similarly seen in the data from Carr *et al*. (1994) for the central part of the Marikana mining district. These two areas were thus joined to form a single inner domain, MR_DOM1 (Figure 7). This domain is enclosed by a more regular domain, MR_DOM2, which contains decreased potholes abundance. A sparsely populated domain, MR_DOM3, was assigned to the south-western area. It is interesting to note that potholes with areas greater than 10 000 m^2 appear to be more regularly spaced throughout the Merensky Reef. Further filtering of potholes by area greater than 5 000 m^2 revealed a higher abundance of large potholes in the western portion relative to the south-western and central parts of the Marikana operations. The macro trend of these northwest–southeast

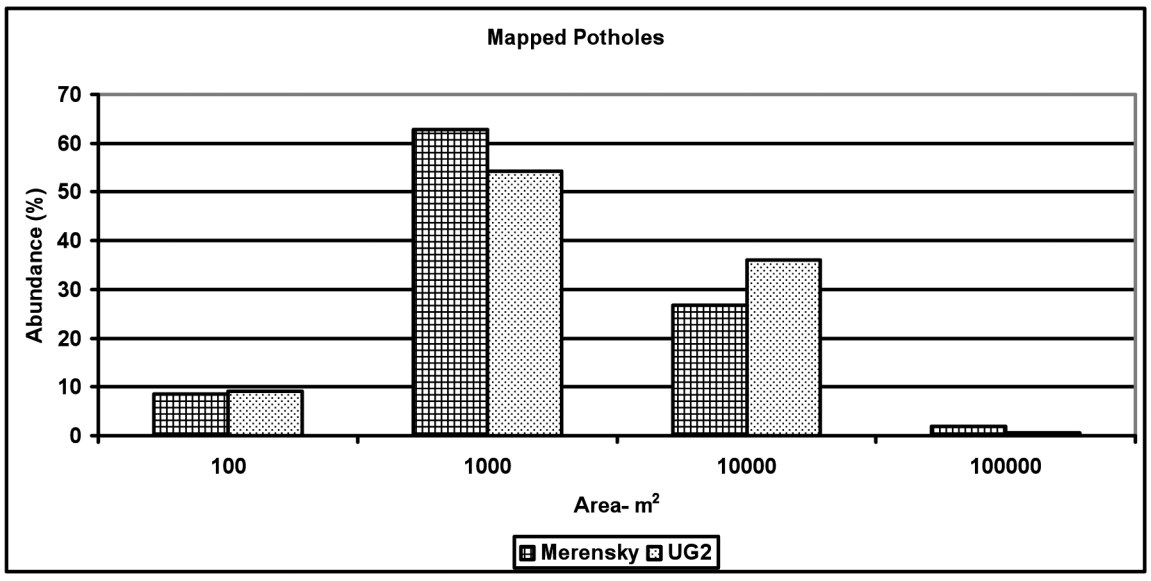
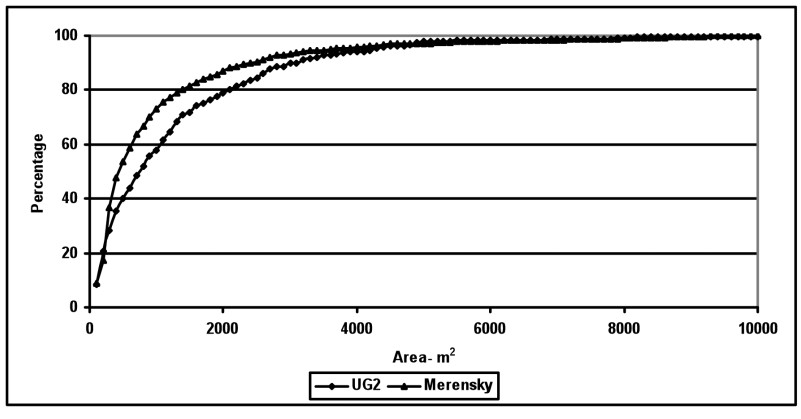


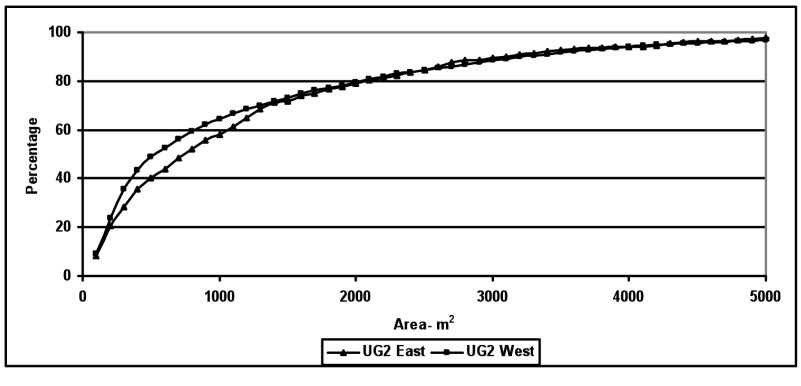
Figure 4. Histogram of mapped potholes of each reef type using the mining impact intervals (small, medium, large and catastrophic) for the pothole sizes

Table I
Percentage frequency of UG2 potholes by mining district at Marikana

Shaft	PH % <100 m^2	PH % 100 m^2	PH % 1 000 m^2	PH % 10 000 m^2
Western	3.48	72.17	21.74	2.61
South western	9.31	55.83	34.74	0.12
Central western	9.64	54.10	35.51	0.74
Central eastern	3.03	39.39	57.58	0.00
Eastern	6.56	45.00	47.81	0.63
Far eastern	13.51	59.91	26.13	0.45

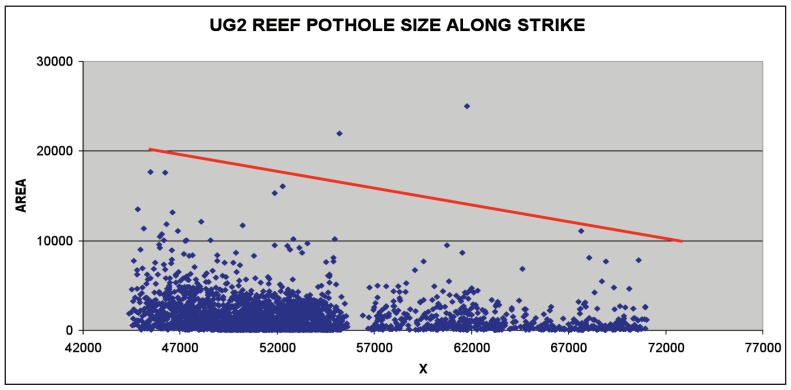


(a)

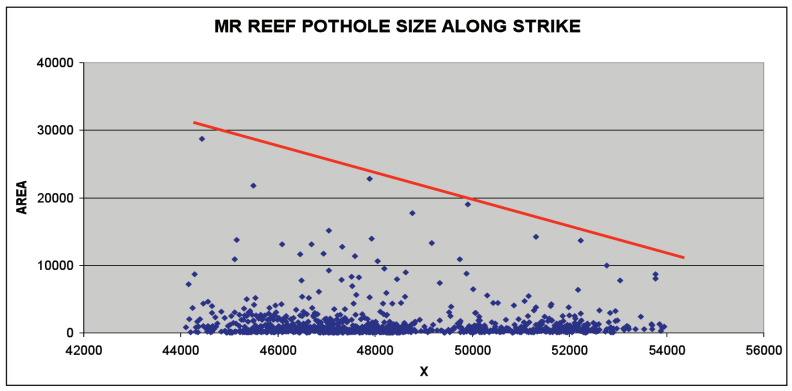


(b)

Figure 5. Cumulative size frequency plot of pothole areas for UG2 and Merensky reefs (a), and split of UG2 Reef into east and west domains along the Elandsdrift Fault trace along the X easting of 56 000 (below). See Figure 2 for position of EDF trace



(a)



(b)

Figure 6. Scatter plots of pothole area versus northing for UG2 Reef (a) and Merensky Reef (b) potholes. Note different X-axis scales for each reef type

oriented pothole domains shown in Figure 7 is slightly oblique to the regional east-west strike; however, it is approximately orthogonal to the orientation of the facies domains.

In the analysis by Carr *et al.* (1994), it was concluded that an increased abundance of Merensky Reef potholes was coincident with steeper dip domains in the central part of Marikana. This was not tested for the western part of the Marikana operations.

On the UG2 Reef horizon, the Elandsdrift Fault Zone appears to separate high and low pothole abundance (Figure 8), so that two broad pothole domains were defined. Potholes occupy 10.7% of the western area and 3.9% of the eastern area. The sudden change is not thought to be genetically related to the fault as the discontinuity is younger and its position is perhaps coincidental. A further distinguishing feature between the east and west is that the reef dip has a greater average dip on the east (11–13°) compared with 9–10° in the west, which is a contrary to the findings on the Merensky Reef in other studies (Carr *et al.*, 1994, and Chitiyo, 2008).

Two other prominent zones of pothole clustering were identified in Figure 8 which has orientations sub-parallel to the major fault structures, and also compare well with the pothole domains defined on the Merensky Reef.

Integration into grade block models

The mapped pothole outlines were integrated into the grade block model using a technique where the pothole perimeters were filled with blocks (cells of various sizes)

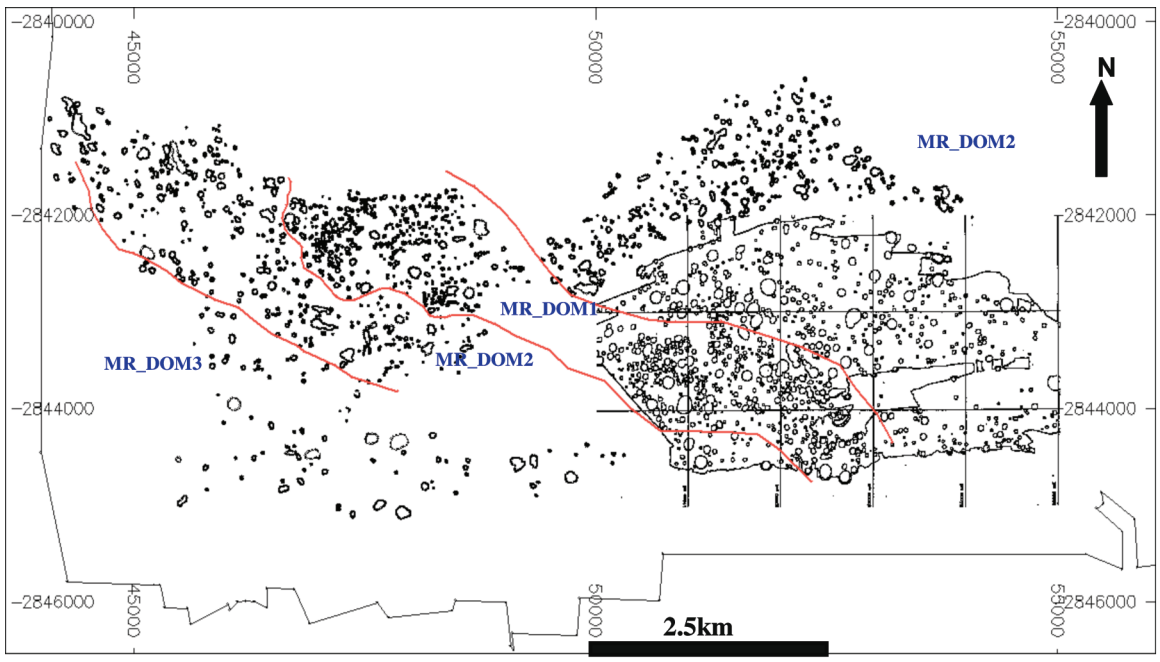


Figure 7. Merensky Reef potholes and domains (with insert of Rowland Shaft block potholes from Carr *et al*. (1994). North is towards the top of the plan, which is also the down-dip direction, and scale can be measured from grid. Compare with Figures 1 and 2

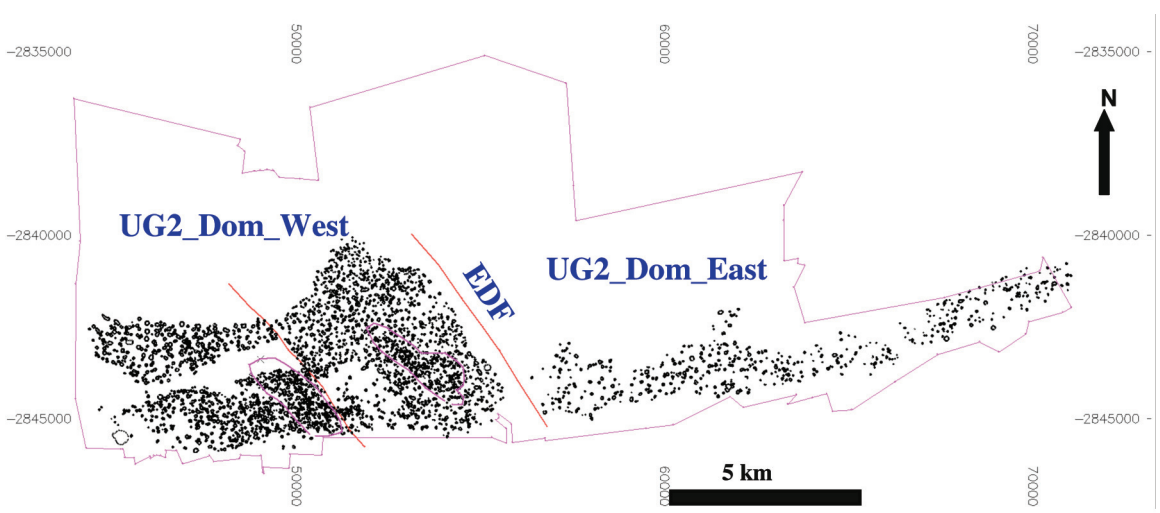


Figure 8. UG2 Reef potholes and domain east and west of the Elandsdrift Fault (EDF). North is towards the top of the plan, which is also the down-dip direction and scale can be measured from grid. Compare with Figures 1 and 2

and then superimposed onto the grade model. The pothole cells were assigned a 100% geological loss and these replaced the cells previously estimated with grade attributes. The pothole cells were characterized as known losses. In the areas where there was no geological information to define the potholes, the average domain value pothole loss was assigned. These assumed losses with no spatial component are referred to as unknown losses.

It is likely that a more refined estimate of the pothole losses can be obtained using pothole domains rather than averages for shaft blocks. In some cases, the difference is minor when considering a large area. To illustrate this, the average pothole loss for the Merensky Reef in the western part of Marikana is 9.0% whereas the area weighted average of the individual pothole domains in the immediate unmined down-dip block is 10.3%. The value of delineating pothole domains thus becomes important when required to obtain a local pothole loss value in an adjacent unmined block. For example, pothole loss for the western part of Marikana in Table II, has a wide range of values from 4 to 12% for the pothole domains along the strike of the reef.

A further benefit of incorporating both known and unknown pothole losses with the grade block model is that a single mineral resource model is made available for mine planning and scheduling. The single model delivery allows improved governance of information transfer between disciplines.

Discussion

The analysis of potholes from mapped geological information has been an enticing challenge for mine geologists for many decades. The value of understanding the pothole abundances and their size distribution becomes possible only after many years of arduous data collection, and it is anticipated that a statistical account will provide a good estimate on the future geological losses. Such practice is widely used in the Bushveld platinum mining industry. The information sharing study presented here is an initial attempt to quantify the variability of pothole size and distribution, and by incorporation of the pothole outline into the resource models, these have strategic benefit in mine planning and may even have some tactical merit for predicting potholes in the immediate production years.

The regional trend of increasing UG2 Reef pothole abundance per major shaft block towards the Spruitfontein Arch is a significant feature and needs to be examined in terms of geological control. This general trend of increased pothole abundance is also concomitant with larger pothole diameter on the eastern flank of the monocline. No investigative analysis has been done to offer an explanation for this trend; however, effects of footwall control related to the Spruitfontein palaeotopography is thought to have some effect on the increased pothole abundance (pers. com. RG Cawthorn, 2010). It has been shown for the Merensky Reef that the reef dips, either using dip domains (Carr, 1994) or a slope index (Chitiyo *et al.*, 2008), has a positive correlation with the percentage pothole abundance. The steeper reef dip is related to a more inclined cumulate pile that was susceptible to gravity induced parting and thus slumping and later scouring intensified the pothole development. In contrast, the UG2 Reef at Lonmin's Marikana district appears to have a negative correlation with the average shaft block reef dip, where the fractionally more shallow average dip of the reef is correlated with greater pothole abundance. This negative correlation may be due to the fact that the average reef dip is too generalized; however, this requires further examination to understand the controls on pothole distribution.

A sudden change in the pothole size distributions and or abundances serves as a useful interface to define domain boundaries. The boundaries at Marikana are generally gradational over several hundred metres (Figure 7); however, in some cases such as the UG2, they appear to be sharp (Figure 8) and in this study the abundance change coincides with the major Elandsdrift Fault zone. The significance of the pothole domain orientation has not been analysed in any detail; however, the Merensky Reef pothole domain orientation appears to be sub-parallel to that of the Spruitfontein Arch and it is possible that footwall folding or undulation may have had some controlling influence.

The compilation of pothole domains constrains potholes with similar abundances and size distributions, which serves as a valuable tool for predicting unknown geological losses in adjacent unmined areas. However, caution should be exercised if the pothole domains are parallel to the unmined shaft blocks. In such cases a global shaft block average would be more appropriate. The construction of pothole domains using the mapping raw data has benefited Lonmin's mine planning and reporting through a more refined understanding of pothole abundances. The further inclusion of the potholes as known and unknown losses in the mineral resource models allows for practical reporting and also results in an improved level of integrity for making geological information available through a single source.

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Table II
Estimated pothole percentage losses for Merensky Reef showing total sector and domain averages within the shaft block

Mining sector	Total sector average	Mer_Dom 1 average	Mer_Dom 2 average	Mer_Dom 3 average
Western	9.09	11.73	8.60	3.98
Central	10.89	-	10.89	-
South Western	6.44	-	-	6.44
Average	9.01	11.73	9.49	5.89

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During my 20 years in the mining industry I have been privileged to have worked in a technical role on a broad range of world class deposits on the African continent, which include reading for an MSc on the metamorphism of the Broken Hill deposit while employed as a mine geologist at Black Mountain Minerals, exploration at the Tarkwa gold mine, production geology at Northam Platinum and BCL Limited in Selebi Phikwe, resource extension at the Jwaneng and Orapa diamond mines, and mineral resource modelling at Lonmin's Marikana mining district.