



Predictability of pothole characteristics and their spatial distribution at Rustenburg Platinum Mine

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Synopsis

Prediction of pothole characteristics is a challenging task, confronting production geologists at the platinum mines of the Bushveld Complex. The frequency, distribution, size, shape, severity and relationship (FDS³R) of potholes has a huge impact on mine planning and scheduling, and consequently cost. It is with this in mind that this study was initiated.

Quantitative analysis of potholes indicates that pothole size (area covered) can be described by two partly overlapping lognormal distributions. These are referred to as Populations A (smaller) and B (larger). The range of observed pothole sizes conforms to a simple double exponential growth model based on Newton's Cooling Curve. A third size range of very large potholes (Population C) that could not be modelled properly within the proposed growth model is interpreted as to represent a very early phase of aggressive regional thermo-chemical erosion and potholing.

In general, potholes are dominantly quasi circular with only a subordinate tendency of elongation. In the UG2, potholes with elongated forms are more prevalent in the size range between 20 and 500 m diameter. In the Merensky Reef elongated potholes are more common in the size range above 50 m in diameter. Although not distinctly visible, elongation of potholes in both the UG2 and the Merensky Reef show a net north/south orientation. Using shapes of pothole rims and floor areas, documented for the UG2 in the Waterfall Shaft area, it is demonstrated that the northern, down-dip edges of potholes have steeper dips than the southern, up-dip edges.

Spatial distribution studies using a uniform quadrant method suggest that in both the UG2 and the Merensky Reef, the potholes are randomly distributed, with a tendency towards clustering. Clustering appears to be more prevalent in the smaller Population A potholes.

Bearing all findings in mind, it is found that the model of

thermo-chemical erosion of the cumulus floor by new influxes of superheated magma best explains the observed data.

Partial to complete melting of the cumulate floor occurred in three phases. The first represents the emplacement of hot magma. This magma, due to turbulent flow and high chemical and physical potential, aggressively attacks the existing floor (crystal mush on the magma/floor interface). Regional erosion is manifested by large, often coalescing potholes. During the second phase, when the magma emplacement process ceased and cooling *in situ* started, two distinct periods of pothole formation ensued. The first is related to rapid cooling along the relatively steep part of the Newton Cooling Curve, when Population B potholes nucleated randomly and grew rapidly with concurrent convective overturn and largely laminar flow condition. The second period of cooling occurred on the shallow-dipping part of the Newton Cooling Curve. Population A pothole growth became more subdued and nucleation appears to have been, at least locally, clustered. The final phase of this proposed 'super magma cycle' was introduced when chromitite crystallization and precipitation terminated pothole formation. This was followed sequentially by pyroxene and plagioclase crystallization to form the typical cyclic units of the Critical Zone.

No suitable proxy could be found for the prediction of pothole density of potholes associated with the UG2 (likely due to limited spatial data coverage), and these are best predicted by extrapolation. The Merensky Reef slope index, in contrast, provides a proxy for pothole density, enabling prediction with reasonable confidence. This predictive model has been verified using underground information. The findings made during the course of this investigation have, when implemented, significant impact. Successful implementation will not only allow enhanced resource and reserve definition, but also better mine planning and scheduling.

Introduction

The Bushveld Complex of South Africa is host to about 70% of the world's platinum group metals (PGMs) resource. PGMs are hosted by two orebodies, the UG2 and the Merensky Reef. The major structural features that disrupt the reefs are faults, dykes, joints, potholes, domes, iron rich ultramafic pegmatoids (IRUPs), rolls, and dunite pipes. Potholes are by far the most pronounced nightmare of geologists and miners because of their

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Predictability of pothole characteristics and their spatial distribution

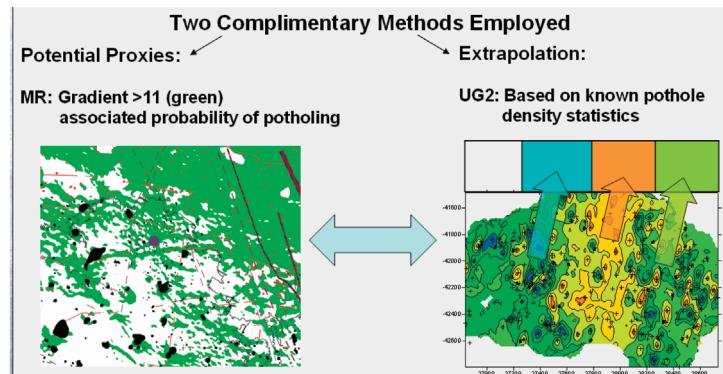


Figure 1—Prediction through extrapolation and/or proxies

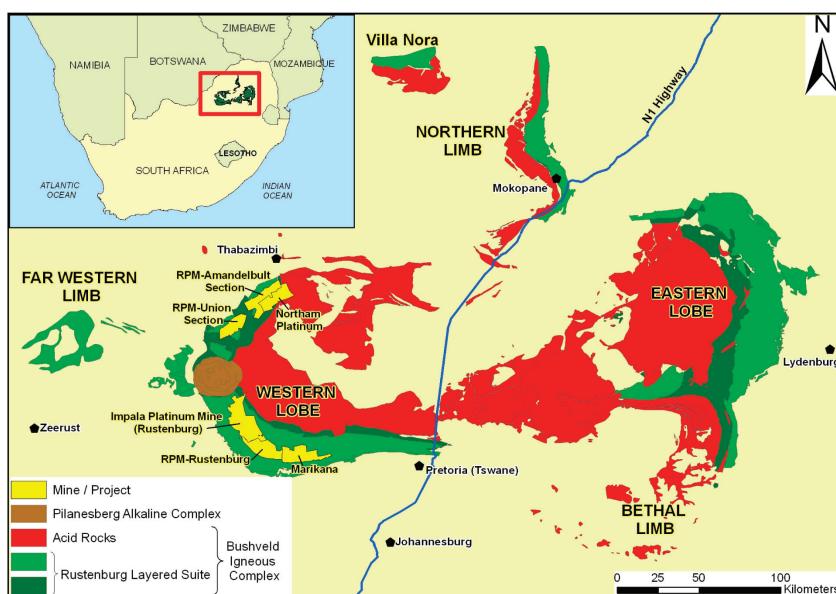


Figure 2—Geological map of the Bushveld Complex. Also shown is the location of Rustenburg Platinum Section (RPM—Rustenburg)

unpredictable nature. The aim of this project, which was conducted in conjunction with Shango Solutions (de Waal *et al.*, 2008), is to quantitatively analyse the frequency, size, shape, severity and relationship (FDS³R) of UG2 and Merensky Reef potholes. Findings are then utilized to predict pothole characteristics ahead of the mining face. The following data sources were considered: literature, historical data, underground mapping, underground and surface exploration drillhole information, and assay information.

The overwhelming opinion of the Rustenburg Section shaft geologists is that potholes in the absence of boreholes or predictive geophysical techniques, such as borehole radar, are unpredictable (Table I). Similarly, these geologists suggest, except for Bleskop, that no correlation exists between UG2 and Merensky Reef potholes.

Geology and mining

Rustenburg Section is located on the south-western Limb of the Bushveld Complex (Figure 2). Both, UG2 and Merensky Reef are mined. Production from the Merensky Reef began in

the late 1920s with the UG2 coming into production during the early 1990s. The majority of underground exposure therefore derives from the Merensky Reef horizon. The Upper Critical Zone of the Bushveld Complex comprises seven cyclic units that grade from chromitite (at the base) over pyroxenite and norite to anorthosite (at the top). The vertical separation

Table I
Rustenburg Section representative perceptions of pothole predictability

	Are potholes predictable?
Waterval	No
Turffontein	No
Bleskop	No
Townlands	No*
Brakspruit	No*
Paardekraal	No*
Frank	No
Boschfontein	No

(* = yes in the presence of borehole and geophysical information)

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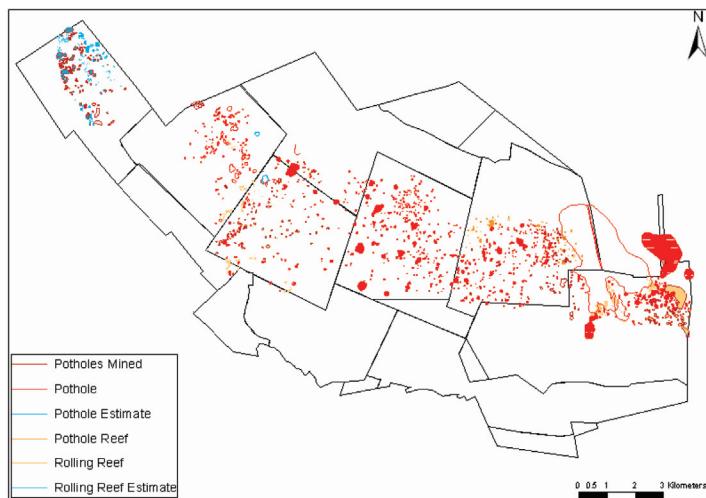


Figure 3—Electronically captured (since late 1990s) Merensky Reef potholes

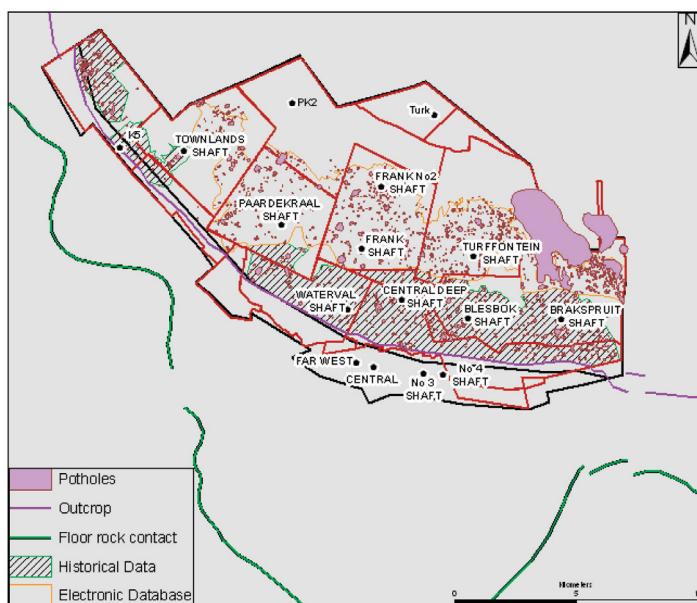


Figure 4—Newly compiled Merensky Reef pothole plan

between the UG2 and the Merensky Reef is on average 140 metres. Both reefs dip generally between 10 and 12 degrees to the north. Localized areas where the dip steepens to 14 to 15 degrees are common. Potholes are widespread in the Rustenburg Section.

Data sources

Underground mapping

Electronic capturing of underground mapping data at Rustenburg Section began during the late 1990s (Figure 3). Integration of this data with information contained on old stope plans, and historical pothole maps (e.g. Viljoen and Hieber, 1986), resulted in the compilation of a comprehensive Merensky Reef pothole plan (Figure 4). Due to a shorter production history, the UG2 provides a smaller sample of underground mapping data (Figure 5).

Borehole information

Underground and surface exploration drilling has, over the last five years, received increasing attention at Rustenburg Section (Figure 6). This has led to improved structural models for both UG2 and Merensky Reef and the localization of some potholes. However, other predictive tools are required to complement the drilling results.

Geophysical surveys

Rustenburg Section has applied several geophysical techniques, such as aeromagnetic, radiometric and 3D seismic surveys (Figure 7). High resolution 3D seismic, in particular, has been instrumental in delineating large potholes. Aeromagnetic and radiometric surveys have so far been inconclusive in delineating potholes.

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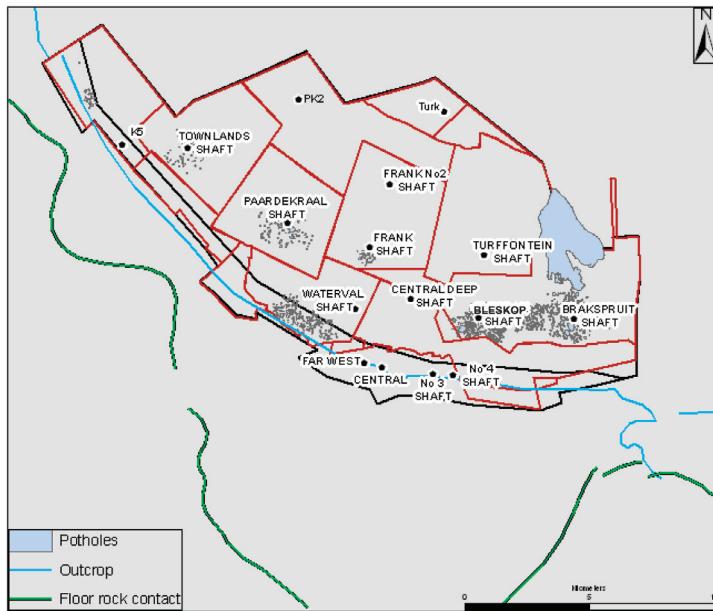


Figure 5—UG2 pothole plan

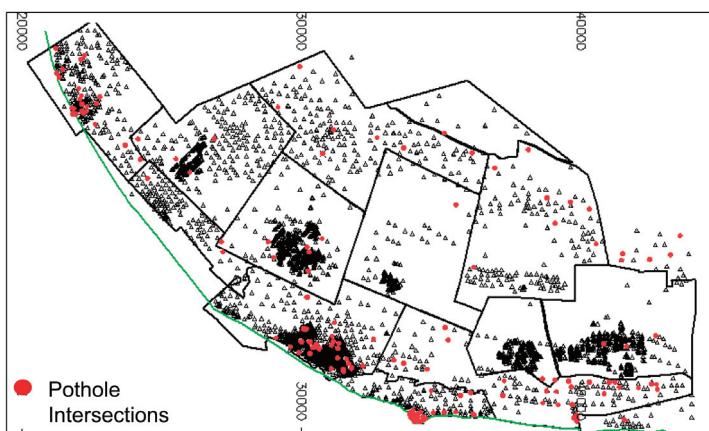


Figure 6—Rustenburg section exploration drilling also showing pothole intersections

Pothole characteristics

Three pothole populations are defined at the Rustenburg Section of Rustenburg Platinum Mine. These are A, B and C, in order of increasing size and from young to old. Population A, the small potholes, less than 20 metres in diameter, are randomly distributed and are generally clustered. Population B with diameters between 20 to over 500 metres are evenly randomly distributed. Population C is characterized by significant Merensky Reef and UG2 depressions that have diameters in excess of 1 kilometer, and that can erode in excess of 40 m of stratigraphy.

Frequency

Data analysis confirms that the UG2 is characterized by a higher frequency of potholes when compared to the Merensky Reef (Table II).

Distribution

In the UG2, Population A potholes are generally randomly

distributed and clustered, whereas Population B potholes are randomly distributed with less clustering (Figure 8). The Merensky Reef is dominated by Population B potholes, with Population A being less prevalent (Figure 9).

Size

As mentioned before, two pothole populations are prevalent at Rustenburg Section, i.e. populations A and B (Figure 10), with Population C occurring only at Brakspruit Shaft (Figure 9). Pothole growth modelling confirms that populations A and B are genetically related, whereas population C is genetically unrelated to the former. Pothole size frequency data tend to support two independent variables, pothole growth rate and pothole nucleation rate. Pothole growth rate is a function of magma-cumulate temperature differential whereas nucleation rate is a function of magma floor properties, e.g. stability of lag layers. The average diameter of Population A and B potholes are 27 m and 83 m, respectively, for UG2, and 55 m and 129 m, respectively, for Merensky Reef.

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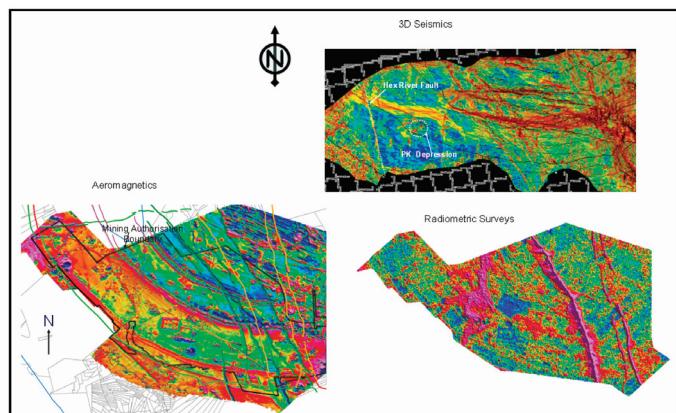


Figure 7—RPM geophysical surveys

Table II

Comparison of pothole statistics for Merensky Reef and UG2

	% Potholed	n	Potholes/km ²
<i>Merensky Reef</i>			
Zone A*	7.5	101	16
Zone B	6.7	117	23
Zone C	6.2	166	14
Zone D	4.8	475	34
Zone E	15.3	130	21
<i>UG2</i>			
Boschfontein	18.8	25	107
Townlands	5.0	28	33
Paardekraal	9.7	49	28
Waterval	11.5	417	219
Frank	6.7	91	264
Bleskop	13.7	261	126
Brakspruit	17.7	281	85

*Zones selected for study

n = number of potholes observed

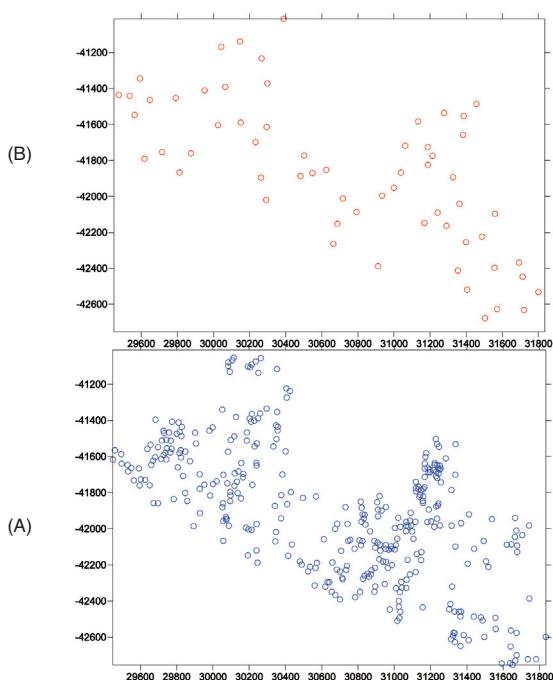


Figure 8—UG2 pothole distribution, populations A and B, Waterval Shaft

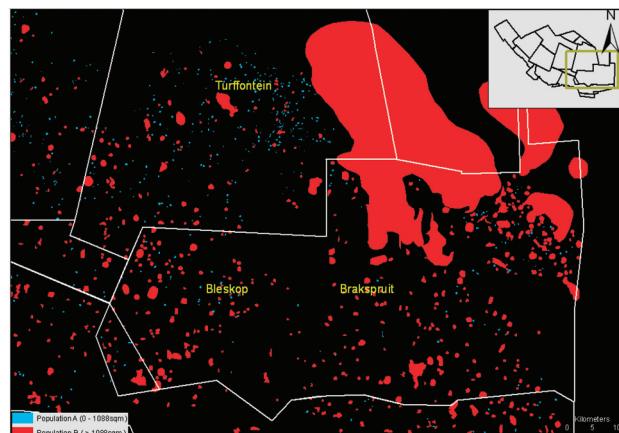


Figure 9—Distribution of Population A (white speckles) and B (grey speckles) potholes at Bleskop, Brakspruit and Turffontein Shafts, Merensky Reef

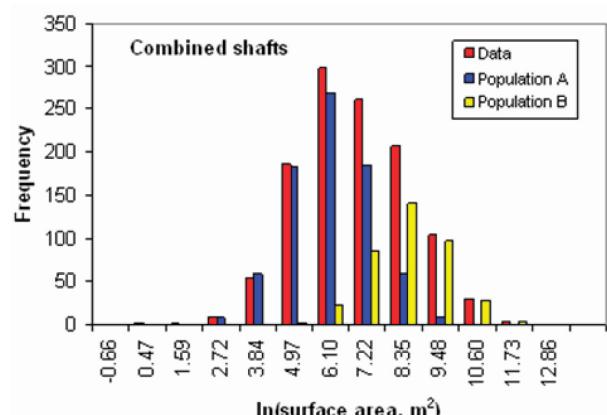


Figure 10—Histogram showing bimodal pothole size distribution

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Table III

Percentage potholed by shaft, UG2

Shaft	% Reef potholed	n	Potholes km ²	Population A			Population B		
				Fraction	Mean	stdev	Fraction	Mean	stdev
Boschfontein	18.8	25	106.5	0.603	6.34	1.12	0.397	8.23	0.37
Townlands*	5.0	28	33.4	0.960	6.64	1.10	0.040	9.34	1.22
Paardekraal	9.7	49	27.6	0.812	7.17	0.89	0.188	9.52	1.00
Waterval	11.5	417	218.5	0.814	4.93	1.02	0.186	7.60	1.09
Frank	6.7	91	264.2	0.937	4.34	1.48	0.063	7.90	0.14
Bleskop	13.7	261	126.3	0.567	5.67	1.12	0.433	7.41	1.28
Brakspruit	17.7	281	84.8	0.000			1.000	7.03	1.44

Shape

Pothole shapes at RPM are generally quasi-circular (Figure 11). Perfectly circular potholes are rare. Near circular and elliptical potholes are dominant. Small potholes tend to be circular whereas larger ones tend to be irregularly shaped and sometimes amoeboid. Coalescing potholes tend to lead to irregular amoeboid shapes.

Severity

Severity of potholes is directly related to pothole size. Increased prevalence of Population B and C potholes results in pronounced severity. The severity measure is the percentage pothole loss at individual shafts. Inspection of Table III reveals that the percentage potholed area varies significantly from shaft to shaft. Population A potholes dominate in frequency across the mine. The highest percentages of pothole losses (Table III, Boschfontein, Brakspruit and Bleskop) are associated with the highest frequency fractions of Population B.

Relationship

Analysis of the potential relationship of UG2 and Merensky Reef potholes is hampered due to the limited spatial overlap of data from these orebodies (Figure 12). However, comparing pothole frequency, size and location between the two reefs at Bleskop Shaft (Figure 13, Table III) indicates that genetically independent potholing events resulted in the UG2

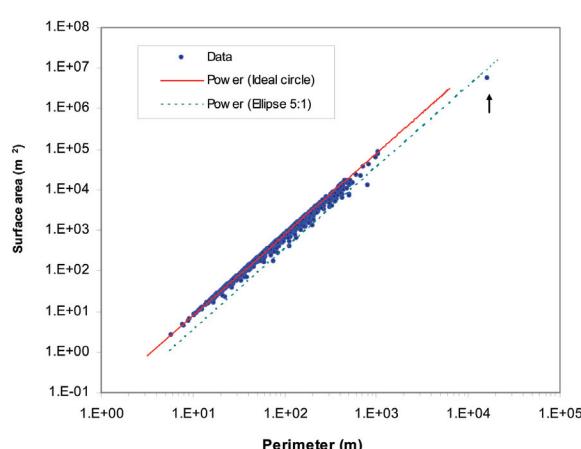


Figure 11—UG2 pothole shapes. Data point at arrow is a Population C Merensky pothole that cuts through the UG2

and Merensky Reef potholes.

For the Merensky Reef, a pronounced relationship between the slope index and the location of potholes exists (Figure 14), suggesting that an increased frequency of potholes is encountered at elevated slope indices. Utilizing

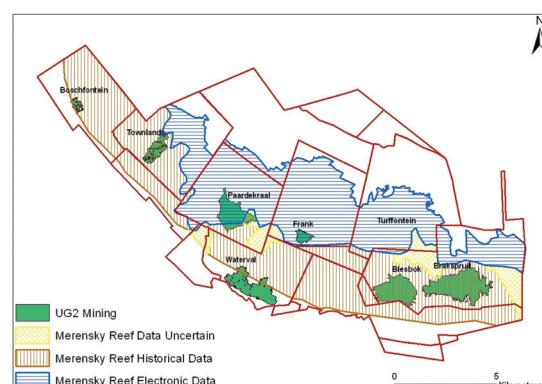


Figure 12—Areas of UG2 and MR overlap



Figure 13—Pothole relationship between Merensky Reef (white circles) and UG2 (grey circles) at Bleskop Shaft

Table IV

Area potholed and percentage pothole loss for the UG2 and the Merensky Reef at Bleskop Shaft (also see Figure 13)

	Total area	Merensky Reef loss	UG2 loss
Area (m ²)	2 066 564	117 547	450 117
% Loss		5.69	21.78
No. of potholes		32	473

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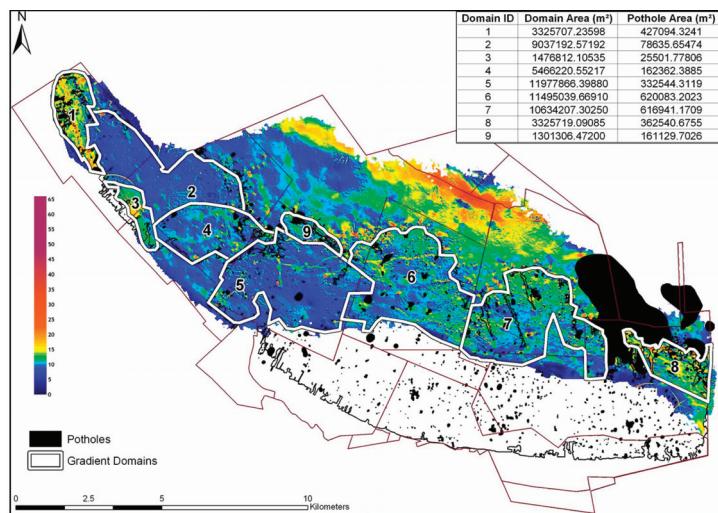


Figure 14—Merensky Reef slope index versus pothole intensity

Table V

Prediction of percentage potholed into the unmined, Bleskop Shaft (see Figure 16 for zones)

Zone	n	% potholed Upper 95%	Confidence limit		Relative error	
			Lower 95%	Upper %	Lower %	
Bleskop West*	111	17.64	19.58	16.13	10.19	9.22
Bleskop Central	45	10.78	13.42	8.18	28.15	21.90
Bleskop East	105	18.68	20.86	17.43	9.99	8.08

*alternative method used

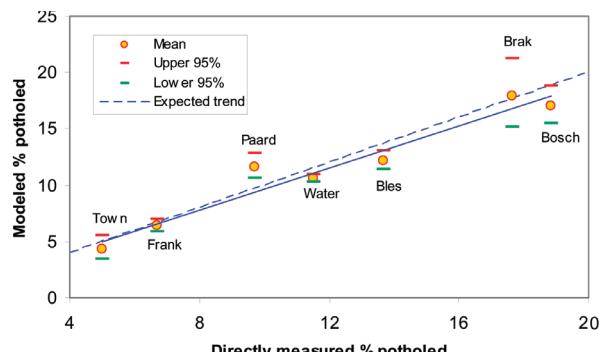


Figure 15—Measured versus predicted percentage UG2 potholes. Regression line compares well with expected trend

exploration borehole results, the slope index can be extrapolated into the unmined areas. Proper care should be taken that the slope index has not been significantly influenced by faulting or folding.

Predictive modelling

Two differing predictive models are applicable for the UG2 and Merensky Reef:

- Prediction through extrapolation is applicable for the UG2. Considering the limited amount of data and their confined spatial distribution, it was not possible to

- identify a proxy
- Prediction of pothole density by proxy can be confidently performed for the Merensky Reef.

Prediction by extrapolation (UG2)

Pothole size, density and distribution analyses, as discussed earlier, yield relevant pothole statistics. These statistics are utilized to predict pothole characteristics, especially distribution density, in unmined areas. It is found that modelled and observed pothole densities across Rustenburg Section compare favourably (Figure 15).

The UG2 at Bleskop Shaft describes distinct, north/south trending zones of differing degrees of potholing (Figure 16). These zones of varying pothole densities can be extrapolated into the unmined at a 95% confidence level (Table V).

Prediction by proxy (Merensky Reef)

The slope index of the Merensky Reef (Figure 14), serves as a suitable proxy for pothole density (Figure 17). This facilitates enhanced prediction of pothole density. Verification of this predictive model, utilizing underground data, has been successfully completed.

Summary and conclusions

Prediction of pothole characteristics is a challenging task, confronting production geologists at the platinum mines of the Bushveld Complex. The frequency, distribution, size,

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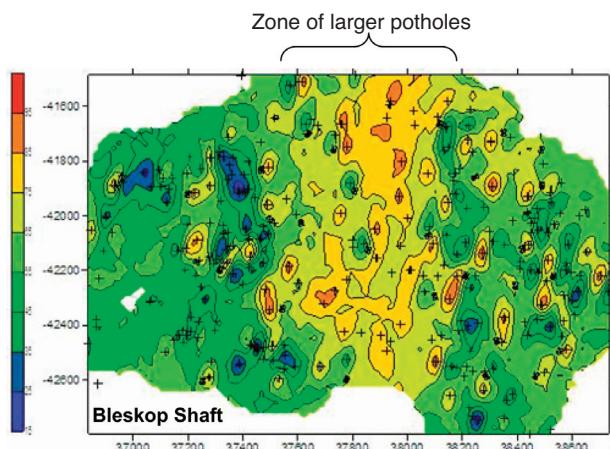


Figure 16—Zones of differing UG2 pothole densities, Bleskop Shaft

shape, severity and relationship (FDS³R) of potholes has a huge impact on mine planning and scheduling, and consequently cost. It is with this in mind that this study was initiated. The following conclusions are drawn:

Frequency

- The UG2 is more densely potholed, considering predominantly Population A potholes, as opposed to the Merensky Reef.

Distribution

- Population A potholes are generally randomly distributed and clustered.
- Population B potholes, dominant in the Merensky Reef, are randomly distributed and less clustered.

Size

- The average diameter of Population A and B potholes are 27 m and 83 m, respectively, for UG2, and 55 m and 129 m, respectively, for Merensky Reef. These two populations are genetically related.
- Population C potholes (colloquially also referred to as depressions) are genetically unrelated to Populations A and B and represent major erosion features.

Shape

- Pothole shapes are generally elliptical or near circular.
- Large and coalescing potholes tend to be irregular in shape.

Severity

- The severity of potholes, expressed at the mine as pothole loss, is obviously directly related to pothole size, which increases from Population A through to C.
- Pothole losses vary significantly from shaft to shaft.

Relationship

- UG2 and Merensky Reef potholes do not exhibit any genetic relationship, as is to be expected.
- Merensky Reef Population C potholes erode deeply into the footwall, excess of 40 m and may effect UG2 reef.

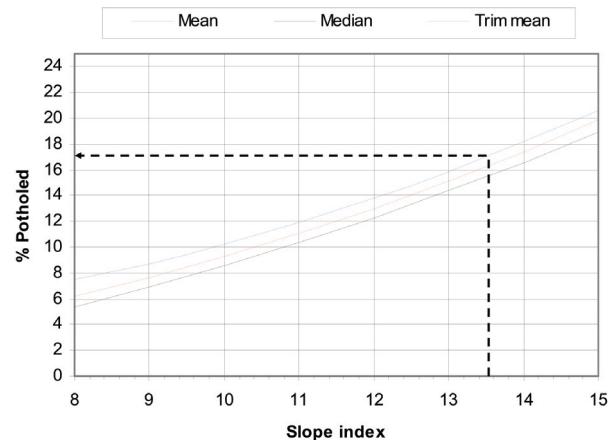


Figure 17—Percentage potholed versus slope index

- Pothole relationships to associated reef characteristics could not be ascertained for the UG2, possibly due to the limited, spatial distribution of the data.
- Pothole relationship with the slope index is confidently established for the Merensky Reef, thereby defining a proxy for prediction purposes.

The above findings facilitate the establishment of the following prediction methodologies for the UG2 and the Merensky Reef. These methodologies consider the prediction of pothole density ahead of the mining horizon, and are unable to predict the exact location of potholes:

- UG2 pothole densities are predicted through extrapolation of zonal features that are characterized by distinct percentages of pothole densities.
- Utilizing the slope index as extrapolated from the mining horizon and as deduced from exploration boreholes, Merensky Reef pothole densities can be confidently predicted into the unmined areas.

The findings made during the course of this investigation, when implemented, can have significant impact. Successful implementation will allow enhanced resource and reserve definition, but also better mine planning and scheduling.

Acknowledgements

Numerous Anglo Platinum employees participated during the course of this investigation. The shaft geologists of Rustenburg Section are especially thanked for their willingness to share information, knowledge and expertise. Theo Pogram and Bruce Walters from Anglo Platinum Head Office are also acknowledged for their input into this investigation.

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