COUTO, P.M. and THERON, W. Flexural slip thrust faulting on Booysendal Platinum Mine and the implications for rock engineering. *The 6th International Platinum Conference, 'Platinum–Metal for the Future'*, The Southern African Institute of Mining and Metallurgy, 2014.

Flexural slip thrust faulting on Booysendal Platinum Mine and the implications for rock engineering

P.M. COUTO and W. THERON
Northam Booysendal Platinum

This paper evaluates the extent of flexural slip thrust faulting within the Bushveld Complex. Information from the literature is compared with the geological conditions observed on Northam Platinum's Booysendal Platinum Mine during the shaft sinking process as well as stoping. Observations were taken from multiple working ends underground during the decline development stages and continuing into the early stoping stages over the past 2 years. Flexural slip thrust faulting was found to occur throughout the mining area at Booysendal, with different intensities and under different conditions.

This project will assist the rock engineering and geology departments to identify and support these featuresahead of mining.

Introduction

This paper combines two scientific fields; namely geology and rock engineering, which have a mutual relationship in combating large falls of grounds (FOGs) in some cases. FOGs are a result of geological conditions associated with the formation of the Bushveld Complex (BC). This paper investigates specifically the conditions associated with flexural slip thrust faulting observed within the BC. Flexural slip thrust faulting (FSTF) may occur throughout all the stratigraphic layers of the BC. FSTF has been observed in chrome mines, which mine the Lower Group 6 (LG6) horizon, as well as platinum mines which mine both the Merensky Reef and the Upper Group 2 (UG2) Reef. This paper will highlight the possible risks associated with these unique conditions in the BC. FSTF will be explored in more detail, highlighting the occurrence as well as the predictability of the locality. Data on FSTF was collected on Booysendal Platinum Mine (BPM). The geotechnical environment of BPM can provide trends or guidance on related structures.

Geology (Smith and Van der Schyff, 2008)

The BC, situated within the north-central portion of the Kaapvaal Craton in South Africa, is the largest layered igneous intrusion in the world, with an estimated area of 66 000 km² and ranging from 7 to 9 km in thickness. The Complex, which is dated at approximately 2 052 Ma, is subdivided into three distinct limbs, namely the northern, western, and eastern limbs, and comprises a range of igneous rocks from ultramafic to felsic. BPM is situated on the southern portion of the eastern limb of the BC. Figure 1 indicates the position of Booysendal in relation to the BC and neighbouring mines.

The structural geology within the area in which BPM is situated comprises two major joint sets with a third random joint set. These joints do not normally contain an infill, but if present the infilling consists of a calcite/quartz material. Although separation of joints is not common, it occurs in some instances. These joints are planar and have a high degree of roughness, although close to surface it is possible that some of these natural joints are slightly weathered due infiltrating groundwater. The weathering forms serpentine, which reduces the cohesional force along the joint plane.

A minor joint set was identified during the development stages of the project. This joint set is flat-dipping (less than 30°) and is found in the hangingwall. The norite tends to weather in a foliated manner, which results in the rock mass visually appearing competent, even though structurally the norite is weaker than anticipated.

Exploration has revealed numerous other geological features that influence the structure within the mining area.

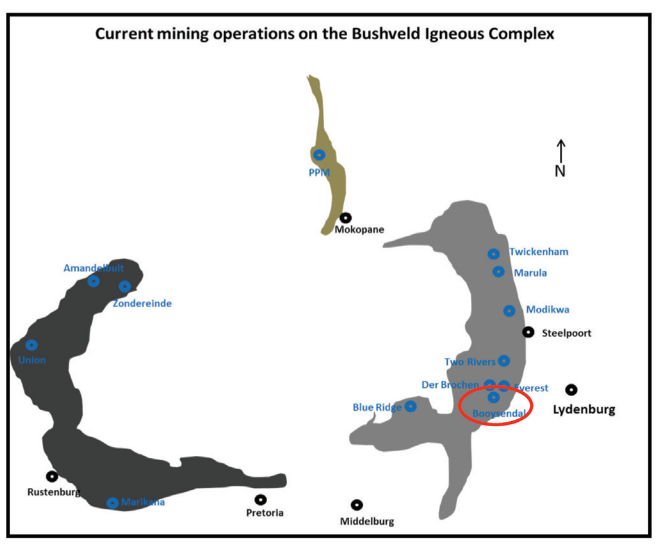

Figure 1. Some of the mining operations on the Bushveld Complex in South Africa

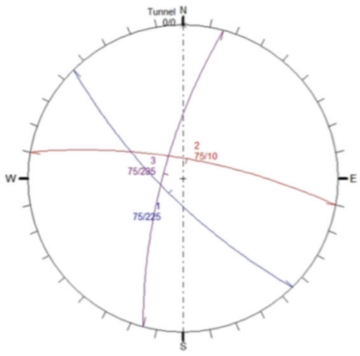

Figure 2. Stereonet projection of joints mapped on Booysendal Platinum Mine

These features include dolerite dykes, faults, and potholes. Exploration drilling has identified only two major dykes and one pothole within the area. No shear zones have been identified during exploration drilling, but they could be present within the mining area.

The data has indicated that all three of the joint sets dip at an average angle between 75° and 85°. The joint sets are depicted in the stereonet projection in Figure 2.

Flexural slip thrust faulting (Billi and Salvini, 2003)

Flexural slip thrust faulting (FSTF) develops in fold limbs early during deformation if extensional fibre stresses in the flexure flanks exceed the tensile strength of the flexed rock.

Flexural slip thrust faults are difficult to identify due to the fact that on BPM they do not exceeded a dip of 30°. These flexural slip thrust faults have to be identified on the sidewalls of the excavation in a geological section or via a borehole drilled into the hangingwall, whereby they can be investigated with a borehole camera. The average angle at which these features dip on BPM is between 10° and 30°. A geotechnical survey of exploration holes has indicated that 60% of the hangingwall jointing ranges between 0° and 30° on both the Merensky and UG2 reefs. The immediate hangingwall on both reefs is pyroxenite.

Flexural slip thrust faults are not distinctly visible in every working end throughout the mine, with more prominent examples present in geologically challenging areas. FSTF is more prominent at the edge of the BC close to the outcrop of the both economic reefs and the edge of major geological features, namely the potholes, reef slumps, and dykes that occur in the UG2 Reef.

Flexural sip thrust faults have an infilling of gouge material ranging in thickness from 1–10 mm depending on the exposure of the contact to flexural stresses. Striations along the planes can clearly be seen, indicating movement.

Rock engineering challenges

The effect of the joint sets in the BC coupled with the FSTF poses challenges for rock engineering departments in terms of the correct support design and implementation. Weakening of the pillars occurs when the fault contact contains a striated gouge material that is susceptible to water. This can result in movement between the contacts. Pillar monitoring on BPM consist of monitoring the size of the pillars according to the design as well as monitoring the geological conditions of the pillars. This information is incorporated into a programme that monitors every pillar after it has been cut. If the monitoring indicates that failure is likely to occur, then additional secondary support will be installed to confine the pillar. Contact planes with no infilling have a slightly higher cohesional force due to the direct contact between the planes. Joints with a calcite/quartz infill also have a higher shear stress component and do not fail as easily as joints contain soft gouge material.

The second threat of FSTF is deemed as the 'ultimate failure' by the Rock Engineering Department, in which a FOG could occur due to wedge failure. Monitoring is conducted on a daily basis by the Rock Engineering Department and the Geology Department. The Geology Department works closely with the Rock Engineering Department on BPM in order to identify areas that have FSTF present from geological sections of the underground workings. The Rock Engineering Department also ensures that they are proactive in trying to identify these faults with the use of borehole cameras. Boreholes are drilled into the hangingwall after every blast. These camera holes are drilled to 4.5 m as the average upper pyroxenite contact (UPC) between the anorthosites ranges between 2.5 m and 3.5 m if the mining cut is executed correctly. Thus the camera hole is drilled in order to monitor the geological discontinuities in the hangingwall pyroxenites.

Results

Observations have been made throughout the entire Booysendal underground workings, with particular attention to geologically challenging areas and areas close to the outcrop.

Daily observations were made in every end on Booysendal by means of borehole cameras, which assisted with the identification of FSTF in the hangingwall. Mapping of the sidewalls of the excavation clarified the structures located in the hangingwall. The local geology that was established during the exploration process was also a good indicator of areas in which FSTF is most likely to occur.

FSTF is a common feature in both the BC and the platinum-rich Great Dyke in neighbouring Zimbabwe (Roberts and Clark-Mostert, 2010). Various technical publications have highlighted the risk that FSTF poses to the stability of mine excavations from a rock engineering perspective. However, there is no information in the literature as to how these faults are formed, nor regarding the identification of areas that could be susceptible to FSTF, so that mining personnel could be warned before they begin mining these areas. Figure 3 shows the dip of a flexural slip thrust fault in a stoping section on BPM.

Observations in terms of a regional perspective were made during decline sinking at BPM from the first blast. FSTF was prominent in the first 56 m of development, after which it was less prevalent, and eventually became insignificant at 103 m.

On a more localized scale, areas that indicated possible reef slumps or potholes were identified as being most likely to contain FSTF. These areas were monitored extremely closely while being mined, although monitoring also continued throughout the mine in order to ascertain whether FSTF occurred in other areas not challenged by geological factors.

On BPM, potholes have a radius of approximately 10 m on the edge, and thrust faulting is present in the rock mass.

Figure 3. Flexural slip thrust fault on the sidewall of an excavation on BPM

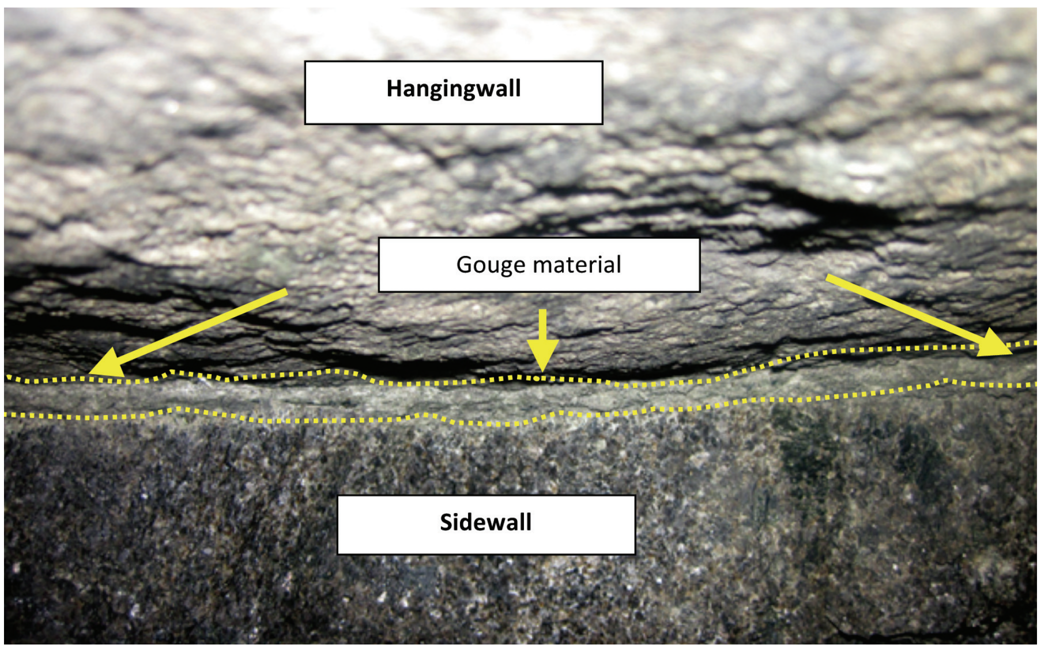

Figure 4. Gouge material in a flexural slip thrust fault on BPM

This has been ascertained by means of borehole camera observations in the hangingwall as well as daily inspections in these areas. The thrust faulting can be seen on the sidewall as all three rock types within the mining cut are affected. Figure 4 illustrates the gouge material formed by movement between the two planes.

The borehole camera observations identify these thrust faults, but they do not indicate an orientation or an accurate dip. These parameters needs to be determined using the sidewall projections performed by the Geology and Rock Engineering departments. The camera observations do, however, indicate when a thrust fault is present and the condition of the contact (weathered, competent, or separated). These boreholes observations are documented and recorded by the Rock Engineering Department in order to identify potential stability problems as well as implement precautions to ensure a safe working environment.

Thrust faulting also occurs at the edges of reef slumps, although the intensity of the faulting is less than that around potholes. The faulting associated with reef slumps has minimal throw – approximately 1–2 cm on average compared with 5–7 cm on thrust faults associated with potholes. The conditions of the thrust faulting are also not as intense – there is no gouge material present in most of the faults; instead, there is a smooth planar surface that is welded. The pothole thrust faults tend to exhibit separation and in some cases, when close to other geological features like dykes, have a calcite infilling. Calcite crystals have been found on occasions that clearly indicate a separation of at least 2 mm is required in order for the crystals to grow.

Flexural slip thrust faults can have undulating planes. This is an indication that these features formed during flexural stages early in the formation of the BC.

Figure 6 illustrates the possibility of separation between the planes forming a wedge structure in the hangingwall, while Figure 7 shows striations on the hangingwall plane that indicate the direction of slip.

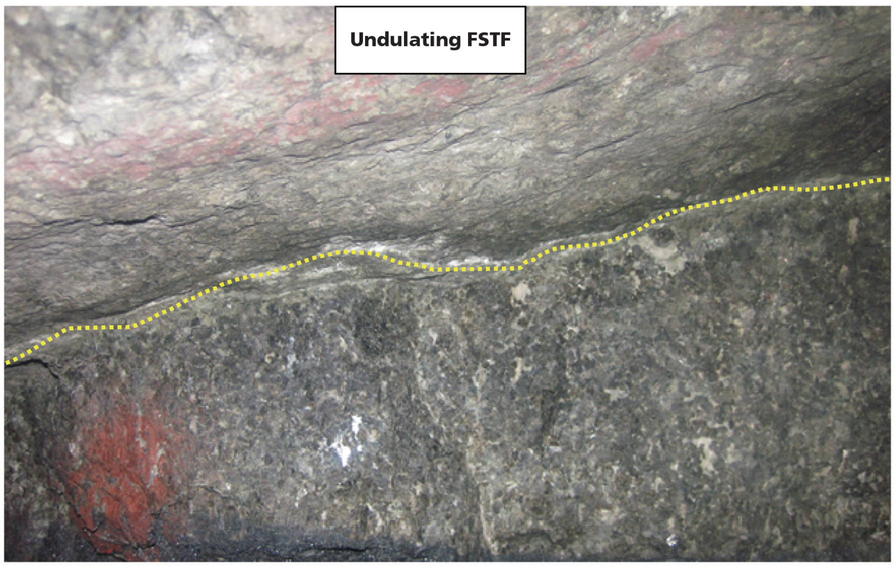

Figure 5. Undulating flexural slip thrust fault on BPM

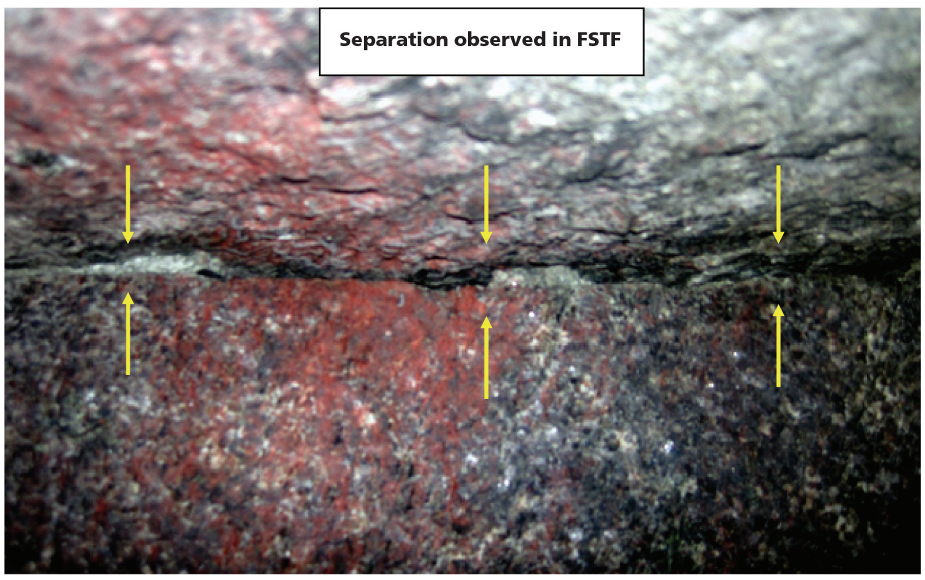

Figure 6. Separation on a flexural slip thrust fault at BPM

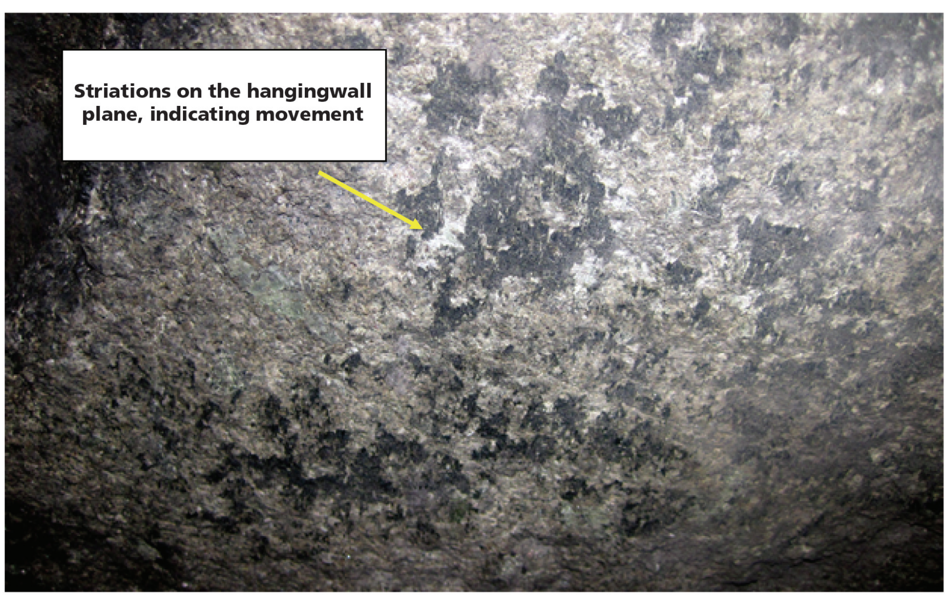

Figure 7. Striations on fault plane indicating movement

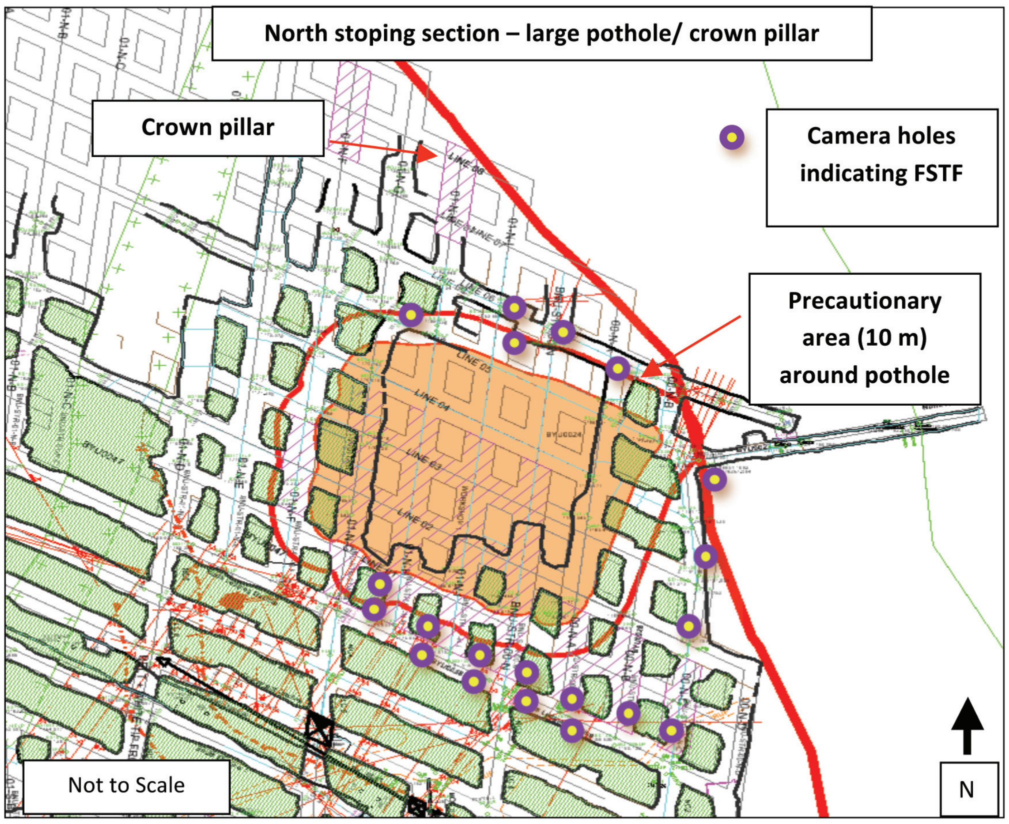

Figure 8. Plan view of pothole and crown pillar on North stoping section

Underground observations have revealed instances of thrust faulting whereby brows have formed in the areas that contain major geological features. The wedges that form are welded and thus a lot more competent; however, the support is increased to stabilize these brows as they still pose as a FOG threat.

The dyke areas on BPM also indicated a change in ground conditions that affect the UPC. This was discovered while advancing through a large dyke at the shaft barrels, as well as in some stoping ends on the northern section of the mine. Underground observations revealed tightly spaced (approximately 32 cm) joints radiated outwards from the dyke, which was expected. However, there was joint infilling consisting of calcite, quartz, and biotite. The UPC had weathered due to the action of water infiltrating along the joints, resulting in the hangingwall becoming unstable. This was confirmed by borehole camera observations on panels in close proximity to the dyke.

Data was collected from borehole camera observations and underground mapping over a 2-year period in different geological environments. The borehole camera information was documented and summarized in order to assist the Rock Engineering Department to identify areas that require particular attention in order to ensure the safety of mining personnel, as well as the overall stability of the mine.

Analysis and evaluation of results

The results have clearly indicated that areas in close proximity to geological features such as dykes, potholes, and jointing tend to be weathered or contain unusual geological conditions. This finding will alert the Rock Engineering Department to the possible presence of geological features ahead of the excavation that will require appropriate support. Figure 8 shows an example of the borehole camera data that has indicated the presence of FSTF, together with the areas that have been identified as requiring special precautions.

Observations indicate that FSTF is found predominately within 10 m of the edges of potholes. Thrust faults can also be found around large slumps, but are not as common as thrust faults around potholes.

Borehole cameras have indicated that weathering of the UPC occurs up to approximately 16 m from the dykes. Edge weathering is observed on the Upper Pyroxenite Contact (UPC), which is the contact plane between the hangingwall pyroxenites and anorthosites. Weathering is thus a good indicator for the Rock Engineering Department that a dyke is within close proximity and there is water present on the dyke.

The high temperature of the magma chamber at the centre of the BC caused melting of the country rock. The increased crustal loading deformed the originally horizontal layering of the BC strata into a basin-fold (saucer-shaped) geometry. This process resulted in shear stresses, concentrated around the edge of the Complex but occurring throughout, which generated the FSTF. This model indicates that FSTF will be encountered across the entire BIC, although the intensity will vary from area to area, depending on other geotechnical influences.

Conclusions

The results of this study will enable rock engineers and geologists to understand the hazards of hangingwall wedge failures associated with FSTF features, and assist in preventing such failures from occurring in the future.

Borehole camera monitoring and mapping of geological features enable precautionary areas to be demarcated on the mining plan in order to warn mining personnel of potentially instable hangingwall conditions ahead of mining. Changes to the support layout can be put in place before the excavation enters the precautionary area.

References

BILLI, A. and SALVINI, F. 2003. Development of systematic joints in response to flexure-related fibre stress in flexed foreland plates: the Apulian fore bulge case history, Italy. *Journal of Geodynamics*, vol 36. pp. 523–536.

PERRITT, S. and ROBERTS, M.K.C. 2007. Flexural-slip structures in the Bushveld Complex, South Africa. *Journal of Structural Geology*, vol. 29, no.. 9. pp. 1422–1429.

ROBERTS, M.K.C. and CLARK-MOSTERT, V. 2010. Is there some commonality between the geological structures in the Bushveld Complex and the Great Dyke? *4th International Platinum Conference, Platinum in Transition 'Boom or Bust'*, Sun City, South Africa, 1–14 October 2010. Southern African Institute of Mining and Metallurgy, Johannesburg.

RYDER, J.A. and JAGER, A.J. 2002. A Textbook on Rock Mechanics for Tabular Hard Rock Mines. Safety in Mines Research Advisory Committee, Johannesburg.

SMITH, D. and VAN DER SCHYFF, W. 2008. Booysendal pre-feasibility review – Geology and Resource report.

VILJOEN, M.J. and SCHURMANN, L.W. 1998. Platinum group metals. The Mineral Resources of South Africa. Anhaeusser, C.R. and Wilson, M.G.C. (eds). *Handbook 16*, Council for Geoscience, Pretoria. pp. 532–568.

Paul Michael Couto

Senior Rock Engineer, Northam Platinum: Booysendal Division

In 2009 I completed my B.Sc Geology Degree at the University of Johannesburg. In 2010 I began my career in Rock Engineering, whereby I worked on Vaal Reefs for Open House Management Solutions as a Strata Control Observer. In October 2010 I obtained my COM Strata Control Certificate and was promoted to a Strata Control Officer, whereby I took up a position in January 2011 at Two Rivers Platinum under Open House Management Solutions. In June 2011 I was transferred to Booysendal Platinum with Open House Management Solutions, whereby I assisted with the implementation of the Rock Engineering Design at a project level. In March 2012 I was appointed as a Strata Control Officer for Northam Platinum: Booysendal Division. In March 2013 I obtained my final COM Rock Engineering paper and was promoted to Senior Rock Engineer. In 2011 I was appointed the Secretary of the SANIRE Eastern Bushveld Limb and have remained so to date. Currently I am furthering my studies through the University of Pretoria with a B.Sc (Hons) Applied Science.