Remnants and isolated blocks of ground in the Klerksdorp Goldfield

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Dates:
Received: 25 Nov. 2019
Revised: 10 May 2022
Accepted: 17 Oct. 2023
Published: February 2024

How to cite:
J.P. Gouvea. 2024
Remnants and isolated blocks of ground in the Klerksdorp Goldfield.
Journal of the Southern African Institute of Mining and Metallurgy, vol. 124, no. 2. pp. 75–84

DOI ID:
http://dx.doi.org/10.17159/2411-9717/1653/2024

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Synopsis

Back-analysis of two mining-induced tremors in 2011 was used to determine a modelling criterion for the entire Klerksdorp Goldfield (*i.e.*, Vaal Reefs region). At that time, most mining operations in the region were owned by AngloGold Ashanti (AGA) and shared many geotechnical similarities. By 2018 AGA had sold off all its Klerksdorp operations to different mining companies, which continued applying the 2011 modelling criterion. As mining activities became more remote, scattered, and isolated, the extraction of isolated blocks of ground and remnants became increasingly necessary. However, the inherited criterion allowed only minimal or no mining activities at these areas.

Keeping in mind that safety is the overriding consideration, an innovative numerical modelling approach, which includes the application of peak particle velocity designs, was developed to provide practitioners in the Klerksdorp Goldfield with a suitable criterion to justifiably and safely mine isolated blocks of ground and remnants. This would not always be possible if a conformist approach was used.

Keywords

seismicity, potency, PPV, remnant, isolated block of ground, bracket pillar.

Introduction

The Witwatersrand Basin in South Africa comprises nine distinct goldfields, namely the Central Rand, West Rand, West Wits, South Rand, East Rand, Evander, Free State, Vredefort, and Klerksdorp goldfields. Mining activities were first established in the Klerksdorp Goldfield in the late 1800s, and by the early 1930s, mainstream mining companies started conducting large-scale operations in the area.

AngloGold Ashanti (AGA) owned most operational mines in the Klerksdorp Goldfield in 2011. The area is notorious for hard-rock narrow tabular mining, and most operations applied a scattered mining method at depths ranging between 800 m and 3000 m below surface. At that time, back-analysis of two mining-induced rockbursts was used to define a numerical modelling criterion for the entire Klerksdorp Goldfield (Hofmann and Scheepers, 2011). This entailed using modelled seismic potency as a quantitative criterion to determine the seismic hazard assiciated with geological structures.

In 2018, AGA sold all its underground mining operations in the Klerksdorp Goldfield region to Harmony Gold and Village Main Reef (refer to district 3 in Figure 1). As the glory days of the Klerksdorp Goldfield mining sector faded, companies started mining in more remote, scattered, and isolated areas than before. The numerical modelling criterion derived in 2011 became impossible to apply in practice as the modelled seismic potency for geological structures surrounding these areas, typically referred to as isolated blocks of ground and remnants, was rarely within 'acceptable' limits.

Remnants and isolated blocks of ground (IBGs) are terms commonly applied to remaining pieces of ground (typically less than 1000 m² in size) entirely or partly surrounded by extensively mined-out areas. In practice, the term remnant is reserved for IBGs that have only one egress or ingress to a workplace and are characterized by difficult mining conditions (*e.g.*, seismicity, poor ground conditions).

Through a case study approach, this paper details an innovative numerical modelling approach, using elastic boundary element code, which includes the application of peak particle velocity designs, that was developed to enable companies in the Klerksdorp Goldfield to justifiably and safely mine IBGs and remnants.

Location and geological setting

The mine where the initial study was conducted (Hofmann and Scheepers, 2011) is a hard-rock, narrow tabular operation situated in the Klerksdorp Goldfield. The Klerksdorp gold mining district is situated approximately 160 km southwest of Johannesburg, covering a total area of 200 km² (Figure 2). Large-

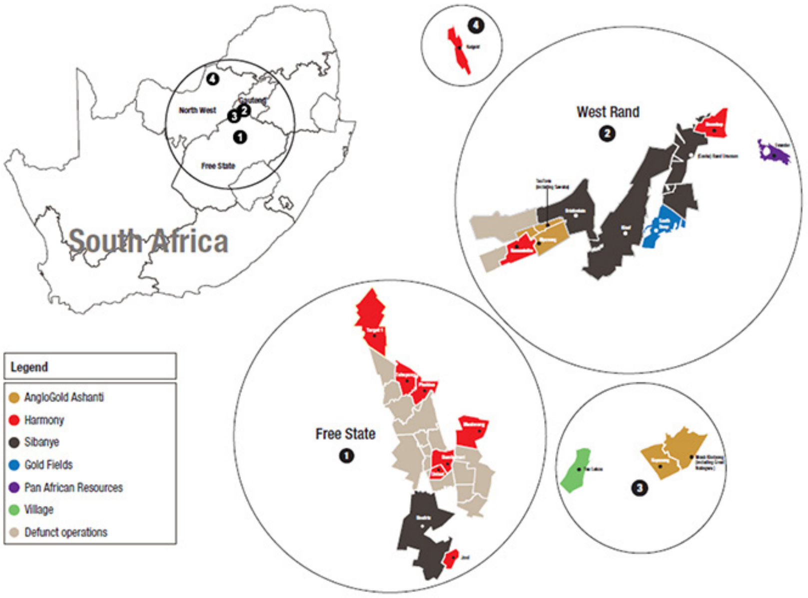

Figure 1—Gold-producing mines in the Witwatersrand Basin (Minerals Council, 2023)

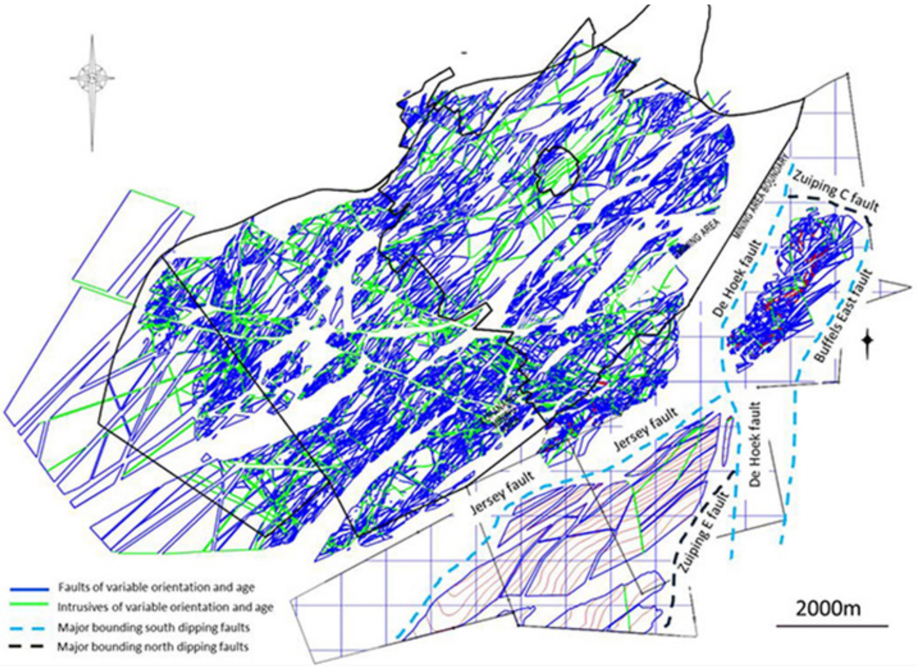

Figure 2—Vaal River regional structure depicting major bounding structures

scale mining activities in the region started in the early 1930s, and by 1970 the region was experiencing substantial mine-related seismicity (Gay and van der Heever, 1982), especially along geological structures, which necessitated further research.

The case study mine uses a twin shaft system to access the orebody and operates over eight main production levels. A scattered mining method is applied, similar to neighbouring mines. Stope and panel configurations may be breast, up-dip, down-dip, or on an apparent dip, depending on mining conditions and the presence of nearby geological structures. Mining takes place from pre-developed, dip-orientated raise lines, approximately 150 m to 180 m apart on strike, depending on the position of, and displacement on, nearby geological features.

It is important to note that scattered mining requires regular final extraction when mining approaches holing. This is inherent to scattered mining and does not necessarily constitute remnant mining conditions.

The Vaal Reef, the primary economic horizon, occurs in a well-bedded argillaceous environment and is stratigraphically located near the middle of the Central Rand Group. The orebody is structurally complex and is predominantly transected by normal, graben, and horst structures (including bedding-plane faults). These structures have displaced the orebody to mineable depths of between 1000 m and 2300 m below surface. The reef channel varies between 30 cm and 200 cm in thickness and dips 10° to 35° in a southeasterly direction. The Main Bird series MB4 forms the hangingwall of the reef package, with the MB5 forming the immediate footwall (see the stratigraphic columns in Figures 3 and 4). The uniaxial compressive strength of these rock types on average ranges between 170 and 220 MPa.

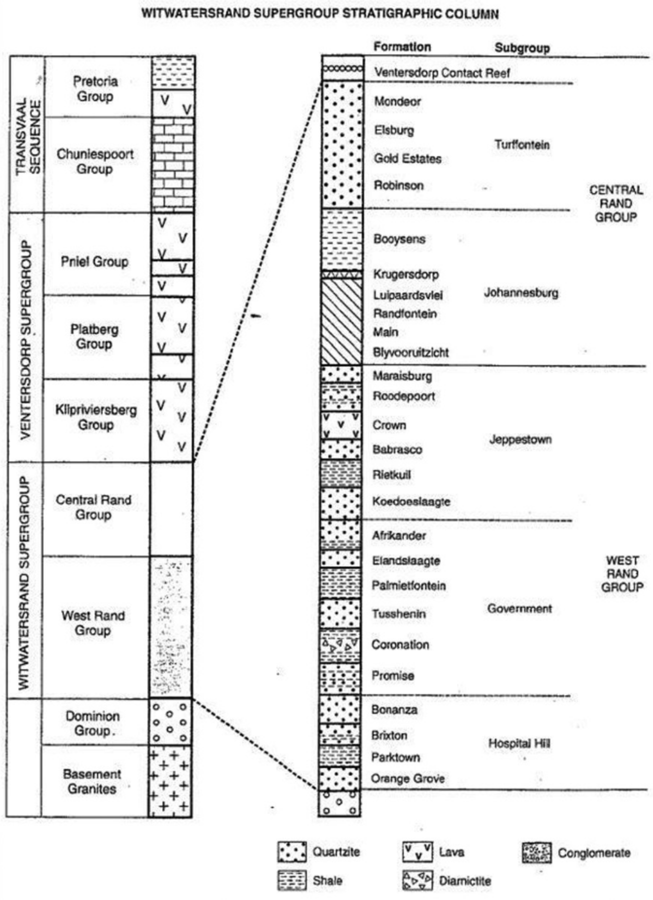

Figure 3—Generalized stratigraphy of the Witwatersrand Supergroup (from the mine's Code of Practise)

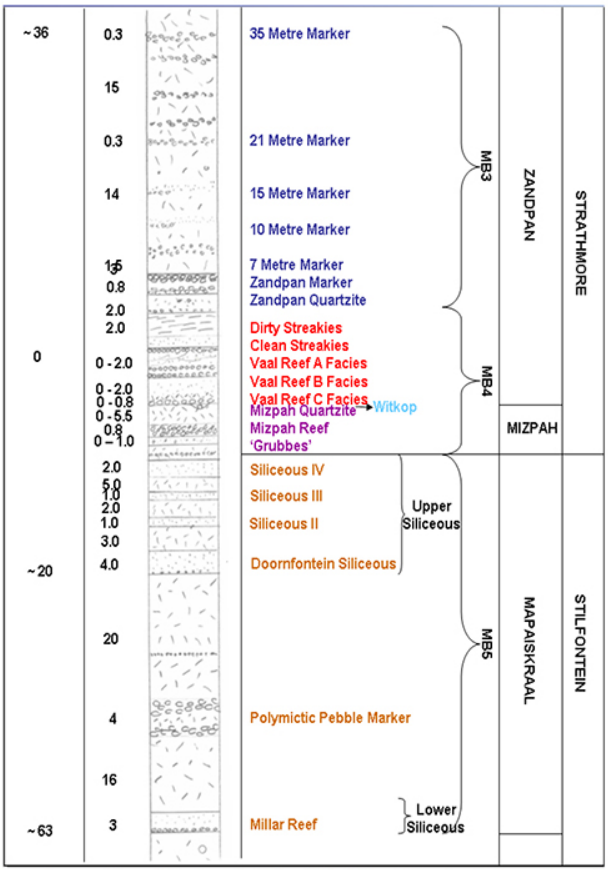

Figure 4—Immediate hangingwall and footwall of the Vaal Reef (from the mine's Code of Practise)

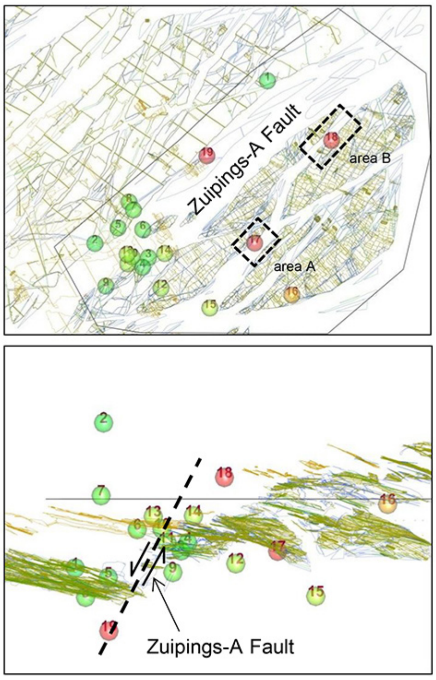

Figure 5—Plan and section views of seismic events numbered 17 (m_L 3.0) and 18 (m_L 4.0)

Historical modelling criterion

The historical modelling criterion was determined by back-analysing two seismic events of local magnitude 3.0 and 4.0 that occurred at the mine on 15 October 2009 and 29 November 2009, respectively (Figure 5). These events resulted in significant damage to underground workings.

Boundary element numerical modelling software was used to simulate shear slip on the geological structure where the seismic events occurred. The coseismic slip was simulated using non-zero cohesion and friction angle (as part of the Mohr-Coulomb failure criterion), (Hofmann and Scheepers, 2011). After successful calibration and simulation of shear slip on the geological structure, the need for a forward modelling methodology for the mine was identified and assessed (after Hofmann, 2011).

The assessment was not an attempt to predict seismic events under planned mining, but rather to quantify the conditions under which seismicity can occur. For this purpose, seismic potency was used to quantify coseismic deformation, estimated from the low-frequency plateau in the displacement spectrum. Seismic potency (P) is given by:

$$P = A \times \bar{D} \qquad [1]$$

where A is the source area and $\bar{D}$ is the weighted average displacement on a particular geological feature.

Seismic potency was calculated at two different positions along the geological structure (areas A and B on Figure 5) for mining executed between January 2009 and October 2009. From the historical modelling methodology, input parameters, and spatial analysis polygon, it was concluded that a total modelled seismic potency exceeding 775 m^3 indicated a potentially unstable geological structure response (Hofmann, 2011).

One can appreciate that the modelling criteria that originated from the initial work by Hofmann and Scheepers (2011) were never divulged in a public forum due to the lack of case studies. Nonetheless, other practitioners in the Klerksdorp Goldfield applied the P = 775 m^3 criterion in the absence of any other quantitative or qualitative criteria.

Operations in the Klerksdorp Goldfield resorted to abandoning blocks of ground or implementing substantial bracket pillars where the seismic potency on geological structures exceeded the P = 775 m^3 criterion. The effectiveness of these stability pillars in risk mitigation was rarely considered, and as a result, the extraction of many IBGs and remnants was deemed not feasible.

Proposed methodology for extracting remnants and IBGs

Since risk is an integral part of mining, 'acceptable risk' becomes a necessary and significant consideration when assessing the mineability of a block of ground. A practical approach is to implement measures that result in acceptable levels of reliability and safety. One of the measures is thorough design, to ensure that all likely hazards have been satisfactorily addressed (after Stacey, 2009).

Figure 6 is a simplified process outline of the different geotechnical considerations that make up a remnant or IBG assessment. Decision gates determine if a block of ground should be considered further for possible extraction.

Considering all the functional requirements and constraints, the objective of the approach or methodology is to determine if a pillar or remnant can be extracted.

Plan assessment

Unfortunately, the reason for remnants and pillars being left intact is not always known, mostly due to the length of time elapsed since these areas were last actively mined. In the absence of accurate and definitive information, numerous inferences can be made from assessing historical mine plans and consulting persons who were working in the area at the time when the pillar or remnant was last mined (alternatively, persons who last visited the area). Factors can include a financial decision (grade, gold price, production costs) or rock mass conditions (large falls of ground, compromised access ways, seismicity). The assessment can provide valuable insights into anticipated rock mass behaviour that directly impacts on the potential mining of a remnant or isolated pillar.

Over and above contemplating the likely reasons that led to the creation of a particular remnant or IBG, numerous other geotechnical factors need to be considered during the plan assessment phase. Singh *et al.* (2006), as well as Rangasamy and Jager (2002), summarized several geotechnical factors to consider when assessing the potential extraction of a remnant or IBG (ground control district, structural and stratigraphical interpretation, access way stability, mining method, and layout, *etc.*). These geotechnical aspects are relatively well understood in the mining industry; however, they are more critical when dealing with remnants and isolated pillars, which are geotechnically more hazardous and proverbially unforgiving.

After the mine plans have been holistically reviewed; the grade, size of the block, and ease of access will ultimately determine if the block is worth pursuing further (decision gate 1, Figure 6).

It is important to develop conceptual layouts and designs for remnants or isolated pillars prior to the underground visit. Technical and practical considerations during this phase will, to a large extent, influence, and guide future assessments. In this regard, the Witwatersrand Rock Burst Committee (Durrheim and Riemer, 2012) made numerous practical suggestions regarding remnant and pillar mining layouts (Jeppe, 1946):

- Pillars or remnants should not be left where this is avoidable
- Efforts should be made to avoid the formation of IBGs, and to that end, panels should lead against mined-out areas or boundaries
- Where multi-reef mining takes place, one reef should be worked out as completely as possible in advance of the other
- Main haulages should be situated a considerable distance into the footwall of the reef package
- Final remnants should be positioned away from potentially seismically active geological features
- Mining should proceed away from the mined-out area towards solid ground wherever possible.

In terms of remnants, it was suggested that:

- The number of persons at the working face should be kept to a minimum
- The panel face should advance rapidly and continuously
- The direction of face advance should be carefully selected to ensure safety
- Sufficient yielding support should be kept close to the advancing face.

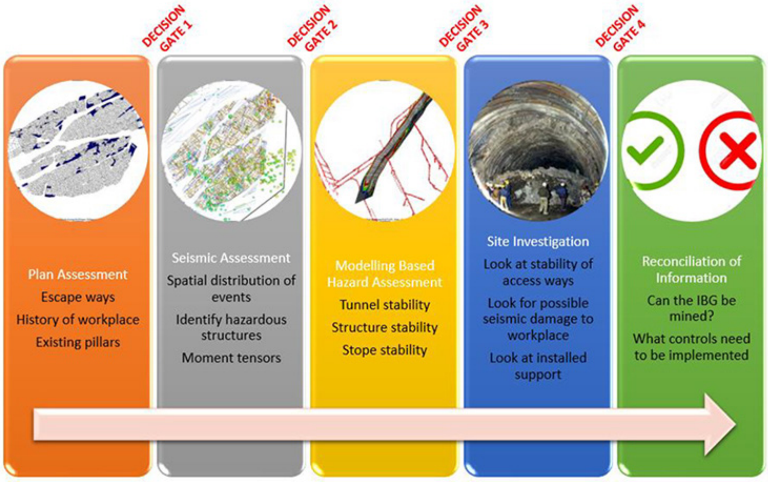

Figure 6—Process outline

These guidelines are still valid and used in the industry today.

Seismic assessment

In terms of seismic energy release, the primary risks associated with the Vaal Reef in the Klerksdorp Goldfield are seismic emissions associated with geological structures in the form of 'slip type' events, with faceburst type events rarely being observed. True facebursts are rare and do not demonstrate a trend; however, this should be confirmed by conducting a seismic analysis of the area in question.

Seismic source parameters in the space, time, and volume mined domain need to be assessed (Figure 7). This would assist in quantifying seismic sources and provide useful insights into seismic source mechanisms. These interpretations may impact the overall extraction of a pillar or remnant and its extraction sequence on a local and regional scale.

Seismic data, in conjunction with site-specific experience, influences if the block of ground is worth pursuing further (decision gate 2, Figure 6).

Modelling-based hazard assessment

Design criteria typically used to assess mining of pillars and remnants do not necessarily apply to the Klerksdorp Goldfield. Typical methods, including average pillar stress (APS) and energy release rate (ERR), have limited use in the Klerksdorp Goldfield, as they primarily focus on burst-type events.

Jooste and Malan (2020) remarked "As many of the older mines exploit remnants, the question should be asked" to what extent these criteria are valid in remnant areas, and if they are not, what alternative method should be used to estimate the stress distribution and associated hazard.

The modelling methodology considered in this paper assesses seismic potency induced by the extraction of remnants or IBGs. It attempts to position and simulate the largest anticipated seismic event associated with the extraction of a particular pillar or remnant. Seismic hazard is inferred from the damage potential of the associated event, which is directly related to the location and distance of the seismic source with respect to a workplace.

Figures 8 and 9 are typical examples of model geometries in a boundary element numerical model.

Seismic potency and excess shear stress (after Ryder, 1987) are modelled for different geological structures near remnants and IBGs. Similar to the historical modelling approach, structures with a total modelled seismic potency below 775 m^3 are deemed mineable. However, contrary to the historical modelling methodology (Hofmann and Scheepers, 2011), further analysis is conducted where the total modelled seismic potency on a geological structure exceeds 775 m^3.

In principle, the severity of a potential rockburst theoretically decreases the further away a workplace is from the seismic source. To better quantify the effects of distancing workplaces from sources of potentially damaging seismic events, the process starts with assessing the most probable location of an event. This is done by assessing seismic data and modelled potency on geological structures (Figure 10).

As a continuation of the process outlined above, mining step results are subtracted from each other to obtain differential results. Considering that blocks of ground were separately staged during the model construction, this assists in quantifying the seismic impact an individual pillar or remnant will have on a particular geological structure. The magnitude of selection is not considered absolute; however, a conservative approach is advocated where individual remnants and IBGs are extracted in a single mining step.

Equations provided by Jager (1988), Jager and Ryder (1999), as well as the Hanks Kanamori moment magnitude formula (Grandin *et al.*, 2011) make it possible to convert modelled values (shear stress, displacement, area) to anticipated seismic moment and magnitude. Once the most likely location of failure (*i.e.*, lobes of ride on the modelled geological structure) and magnitude have been determined, peak particle velocity (PPV) equations are used to determine anticipated ground motion at surrounding workplaces. The following equations were considered:

- McGarr, Green, and Spottiswoode, 1981
- Spottiswoode, 1984
- Potvin and Wesseloo, 2013
- Kaiser *et al.*, 2010
- Kaiser, Tannand, and McCreath, 1996
- Butler and van Aswegen, 1993
- Mendecki, 2019.

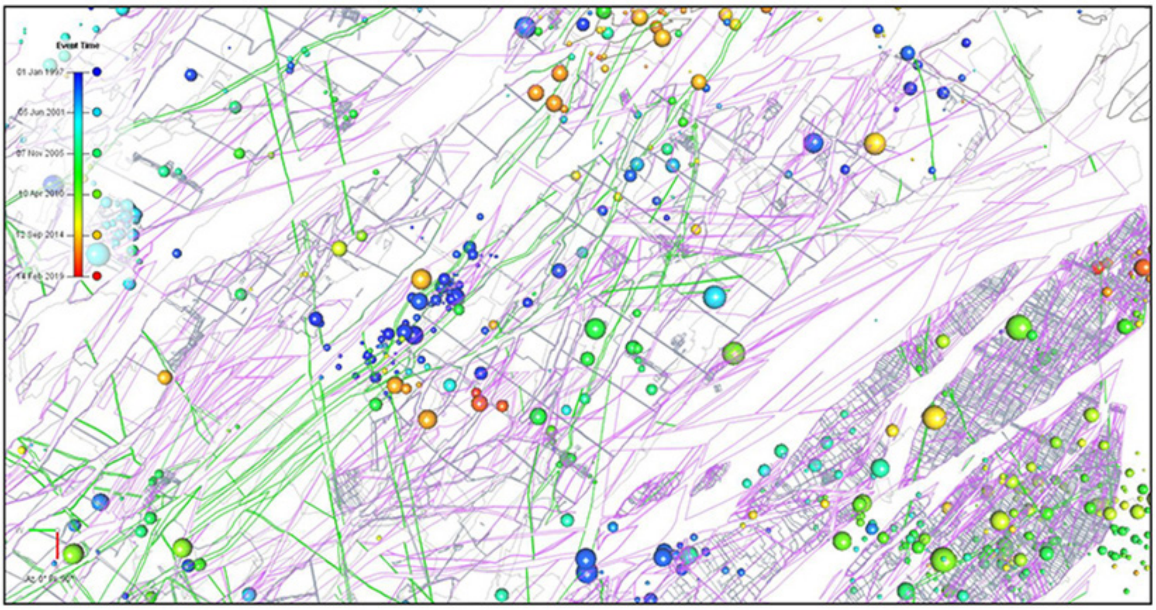

Figure 7—Spatial-temporal seismic hazard assessment

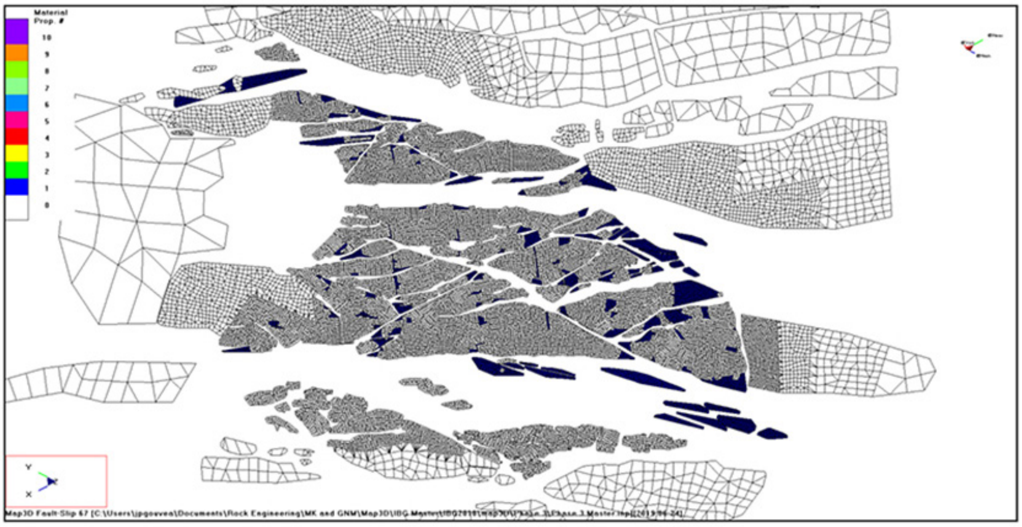

Figure 8—Model geometry (blue blocks indicate remnants and pillar mining areas)

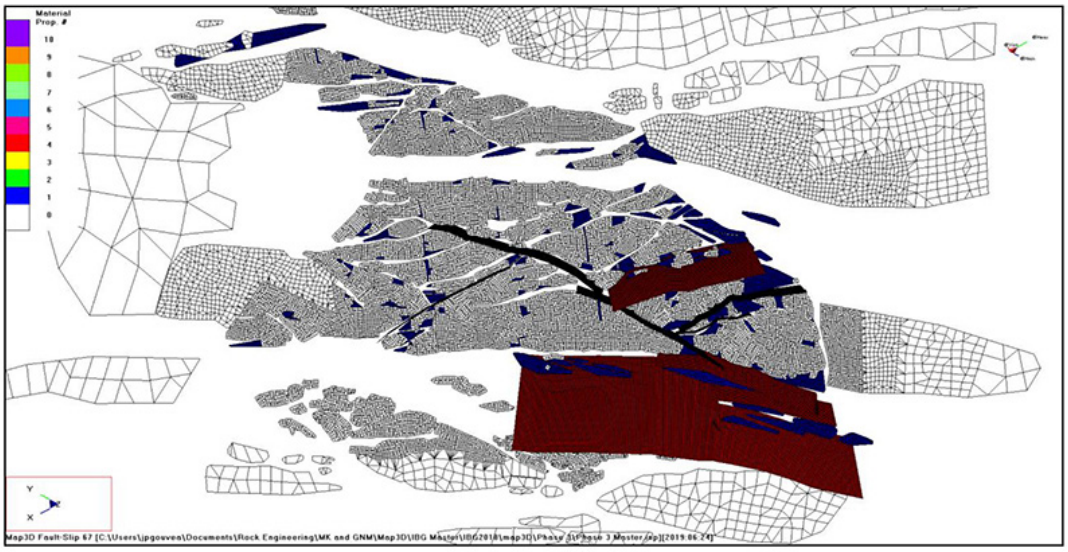

Figure 9—Model geometry (red planes are modelled geological structures)

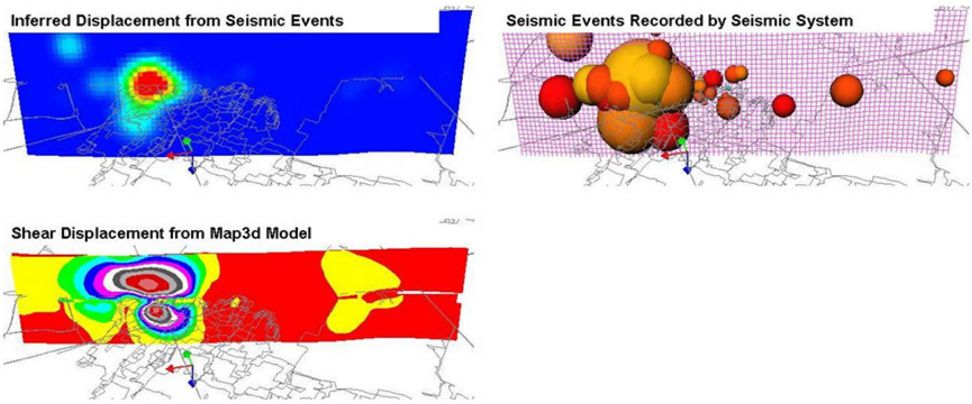

Figure 10—Example of modelling results on a geological structure (Wiles, 2020)

Figures 11 and 12 depict anticipated ground motion, for a range of seismic event magnitudes, at locations that are 10 m and 100 m away from the seismic source, respectively.

The energy absorption criteria for ground support in narrow tabular mines are calculated based on an initial hangingwall velocity of 3 m/s arrested within 0.2 m (Daehnke, van Zyl, and Roberts, 2001). At first, it can be tempting to consider 3 m/s (or 300 cm/s) as the design cut-off. However, studies have shown that damage can be experienced at lower velocities for different operations (Table I: Potvin and Wesseloo, 2013; Kaiser *et al.*, 2010).

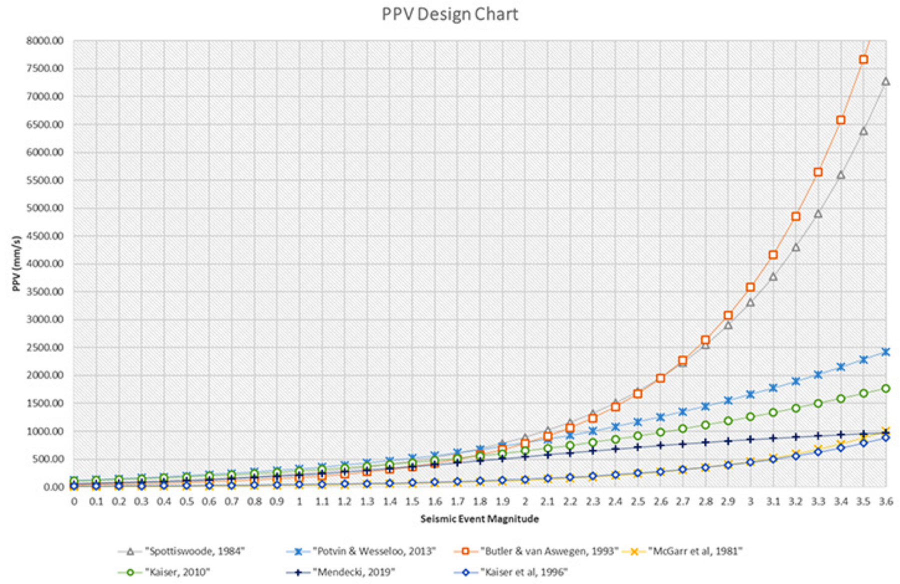

Figure 11—Anticipated peak particle velocity for different magnitude seismic events – 10 m from the seismic source

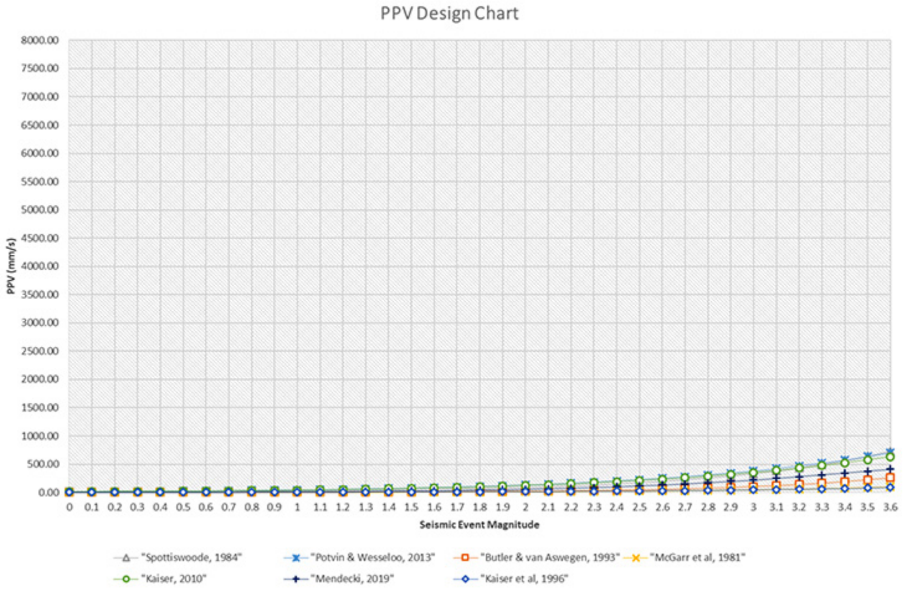

Figure 12—Anticipated peak particle velocity for different magnitude seismic events – 100 m from the seismic source

Table I

Anticipated seismic damage for different PPV ranges

PPV range	Anticipated damage
<50cm/s	No damage
50cm/s–100cm/s	Minor damage (shakedown)
100cm/s–300cm/s	Falls of ground
>300cm/s	Severe damage

As the proposed ranges for anticipated seismic damage require further research, conservative PPV ranges should be considered when designing bracket pillars. As more case studies are back-analysed and become available, higher PPV ranges can be considered.

Rockburst mitigation strategies deployed in the Klerksdorp Goldfield can be broadly classified into two categories. The first set of controls is aimed at reducing the likelihood of experiencing potentially damaging seismic events by implementing safety and bracket pillars. Bracket pillars reduce the seismic hazard of a geological structure by providing sufficient clamping forces (normal stresses acting on the plane). In addition, bracket pillars effectively increase the distance between a workplace and the seismic source. A larger distance from the seismic source can reduce the maximum ground velocities that stope support is exposed to and makes it possible for support to protect workers more effectively. Unfortunately, very little engineering effort goes into defining this suitable distance or bracket pillar size. The size of bracket pillars is typically based on engineering judgement and experience. Safety pillars reduce the seismic hazard of a geological structure by effectively limiting mining spans and providing regional support, subsequently reducing closure. Past research has indicated that high levels of closure are associated with increased seismicity along surrounding geological structures.

After reviewing the modelling results, a decision is made whether the block of ground is worth pursuing further (decision gate 3, Figure 6).

Site investigation

Remnants and pillars are typically highly stressed, densely fractured, subject to high closure rates, and seismically active. Due to these prevailing conditions, the probability of rock-related incidents and accidents is higher than in 'normal' mining areas (higher risk). This makes the extraction of remnants and pillars unique, requiring improved designs, planning, and execution of extraction to reduce the risk.

Remnants and pillars are generally not situated near active mining areas. These old or sealed-off areas are likely to contain high-temperature air and noxious gases that could have potentially fatal consequences if due precautions are not taken prior to and during inspection.

When any abandoned or unventilated excavations or areas are to be re-opened (refer to Figure 13), an official request must be submitted, and permission granted from a responsible and appointed person (Section 3.1 of the Mine Health and Safety Act) before any seal is broken. Where possible, through-ventilation must be established a day prior to entry by opening seals on the intake and return side of the abandoned area. The return air from the abandoned area is then checked for gases and high air temperatures prior to entry.

There shall be a minimum of three persons in every investigation. A typical investigation team should consist of a blasting certificate holder (required), Ventilation Officer (required), Mine Overseer (required), Geologist (optional), Rock Engineer (optional), and assistants (optional).

No investigation into previously sealed off areas may be attempted unless the following items and equipment are available:

- GDIs (gas detection instruments)
- Whirling hygrometer
- Bottled aluminium dust (better known as 'puff-puff')
- Tins of spray paint
- Sufficient drinking water for each person
- Two identical plans, one for surface and one for underground
- Velocity meter
- Measuring tape
- Drager and tubes
- Self-Contained Self Rescue (SCSR) pack for each person
- First aid equipment
- PPE (personal protective equipment)
- Vent seal (also referred to as Versi-Foam).

Due consideration should be given to the health and safety of the investigating team members. Underground investigations of remnants or isolated pillars typically involve the removal of walls, travelling far distances on foot, carrying heavy equipment and negotiating steep inclines and restricted areas. This is further exacerbated due to the majority of activities taking place in humid and poorly ventilated conditions.

Figure 13—Opening sealed off workplaces

Under no circumstances may any member take part in a visit if he or she:

- Is feeling sick or ill
- Is under the influence of alcohol or using strong medication (preceding 48 hours)
- Did not eat breakfast
- Was off sick from work the day before
- Has an expired certificate of fitness;
- Is classified heat-intolerant by a medical practitioner
- Was not underground for more than five consecutive days prior to the planned investigation.

Actual workplace conditions are unknown to investigating team members beforehand. When level-to-level investigations are conducted, the possibility exists that one of the accessways may be compromised (refer to Figure 14) and unplanned deviations from the proposed route are required (refer to Figure 15). From experience, this was the case on multiple investigations, and air flow was found to be an unreliable indication of whether accessways are still open.

Figure 14—Compromised accessways along investigation routes

Figure 15—Investigation team planning routes and escape ways

Rehabilitation and 'upgrading' of support at historically mined-out workplaces is a contentious topic for different operations. Not only did the extent of serviceable infrastructure increase, but these excavations were supported according to support standards in force at that time (refer to Figure 16). Mines continuously attempt to improve health and safety, and as a result, several support standards have been amended over the years. More often than not, these amendments were made to further improve health and safety at the mine, and not because previous standards were regarded as unsafe or insufficient. The mine should review these historically applied standards and their effectiveness before deciding to rehabilitate or 'upgrade' installed support to modern-day standards. The alternative can be costly and negatively affect the mine's ability to extract remnant and pillar areas.

Once a site investigation has been completed, it is crucial that these areas are re-sealed (refer to Figure 17) to prevent access by unauthorized personnel and to maintain the integrity of the ventilation flow to the rest of the mine workings.

Considering the conditions of the support and excavation (overall stability) at the remnant or pillar mining area, a decision is made as to whether the block of ground is worth pursuing further (decision gate 4, Figure 6).

Performance tracking

A total of 113 remnants and pillar mining areas were assessed over 2 years at the case study site. Applying the historical modelling methodology, 80 of the 113 remnants or pillars were deemed mineable (71%). Applying the new methodology, 107 of the 113 remnants or pillars were deemed mineable (95%). This improvement was significant considering the mine's operational strategy of balancing remnant and pillar mining with mining at newly developed raise lines.

Since the implementation of the new methodology at the study site, production personnel have prioritized and safely extracted numerous remnants and IBGs close to serviceable infrastructure. Notwithstanding the favourable results in the short term, the mining sequence being executed may inadvertently have negative implications in future, especially as regards remnants and isolated blocks at more remote areas of the mine where retreat mining sequences are critical. Well planned mining and support strategies are fundamental to the successful extraction of remnants and IBGs.

Discussion

In a recent annual report submitted by the Mine Health and Safety Inspectorate (MHSI), it was recognized that mining operations are running out of virgin ground as they are approaching the end of their life. As a result, mining companies rely on mining IBGs and remnants that are prone to seismicity and are likely to pose a higher probability for falls of ground.

The MHSI went on to state that preliminary investigations into mine disasters (a term typically reserved for a mine accident that results in the death of four or more employees) in the Klerksdorp Goldfield suggested that a lack of safe mineable ground and companies resorting to pillar mining without comprehensive risk management plans contributed to the disasters.

As a strategy to improve the *status quo*, the MHSI committed to more frequent and purposeful inspections at operations mining pillars and remnants. Furthermore, they have requested mines to submit detailed and comprehensive risk management plans for pillar areas and remnants before any mining of these can be allowed. These documents should be submitted to the MHSI at least 6 months prior to mining the area in question to allow for proper review and further work, should it be required. This is a well-considered initiative.

Figure 16—Historically applied mine support standards.

Figure 17—Re-sealing workplaces once an investigation is completed

In a changing mining industry adopting emerging technologies, past practices may become obsolete, and the lack of rigorous reviews of these designs may result in systems that are neither optimized, nor effective (Gouvea and Stacey, 2019). This is the case considering the modelling criteria used in the Klerksdorp Goldfield.

Conclusions

Due to the higher risk inherent in mining remnants and pillars, it is in the best interest of all stakeholders (mine management, mine employees, goverment regulators, and associated unions structures) to ensure that these areas are properly investigated and the risks assessed prior to attempting extraction. The health and safety of workers remain integral to the long-term sustainability of the mining sector.

From a general point of view, the approach proposed in this paper is sound but it only covers fault-slip seismic events on known geological structures. Fault-slip is generally the most hazardous and common event, especially in the case study region (Klerksdorp Goldfield).

Numerical modelling approaches utilizing APS and ERR to assess remnants and pillar mining areas are obsolete when considering fault-slip on geological features. This notion was seconded by other industry geotechnical engineers that are involved with the assessment of remnants and pillar mining (after le Roux and Stacey, 2008): "The results of the study suggest that the use of average pillar stress, energy release rate and hydraulic radius is ineffective for the evaluation of the potential dynamic failure of remnants".

The approach in this paper can be deemed conservative in the long term. The shorter the 'prediction' period and the smaller the remnant or pillar mining area, the more uncertainty exists; hence back-analyses and more case studies are required for further calibration.

The results from the case study mine indicate that where the innovative approach for assessing the mineability of remnants or pillars looks promising.

References

Butler, A.G. and van Aswegen, G. 1993. Ground velocity relationships based on a large sample of underground measurements in two South African mining regions. *Proceedings of the 3rd International Symposium on Rockburst and Seismicity in Mines*, Kingston, Ontario, Canada. CRC Press. pp. 41–49.

Daehnke, A., van Zyl, M., and Roberts, M.K.C. 2001. Review and application of stope support design criteria. *Journal of the South African Institute of Mining and Metallurgy*, vol. 101. pp. 135–164.

Durrheim, R.J. and Riemer, K.L. 2012. History of endeavours to mitigate the rock burst risk in South African mines. *Proceedings of the 9th International Mining History Congress*, Johannesburg, South Africa, 17-20 April 2012. Society for Mining, Metallurgy, and Exploration, Englewood, CO. pp. 156–171. http://hdl.handle.net/10204/5990

Gay, N.C. and van der Heever, P.J. 1982. *In situ* stresses in the Klerksdorp gold mining district, South Africa - A correlation between geological structure and seismicity. *Proceedings of the 23rd U.S Symposium on Rock Mechanics (USRMS)*, Berkeley, California. American Rock Mechanics Association, Alexandria, VA. Paper no. ARMA-82-176

Gouvea, J.P. and Stacey, T.R. 2019. An approach to determine the effectiveness of tendons in a support system. *Proceedings of the 7th African Young Geotechnical Engineers Conference*. South African Institution of Civil Engineering Geotechnical Division and the International Society of Soil Mechanics and Geotechnical Engineering.

Grandin, R., Jacques, E., Nercessian, A., Ayele, A., Doubre, C., and Socquet, A. 2011. Seismicity during lateral dike propagation: Insights from new data in the recent Manda Hararo- Dabahu rifting episode (Afar, Ethiopia). *Geochemistry, Geophysics, Geosystems,* vol. 12, no. 4. doi: 10.1029/2010GC003434

Hofmann, G.F. 2011. Numerical modelling back-analysis of two large seismic events associated with Zuipings-type faults. AngloGold Ashanti.

Hofmann, G.F. and Scheepers, L.J. 2011. Simulating fault slip areas of mining induced seismic tremors using static boundary element numerical modelling. *Mining Technology*, vol. 120. pp 53–64.

Minerals Council. 2023. https://www.mineralscouncil.org.za/sa-mining/gold [qccessed: 12 March 2023].

Jager, J.A. 1988. Excess shear stress in the assessment of geological hazardous situations. *Journal of the South African Institute of Mining and Metallurgy*, vol. 88. pp. 27–39.

Jager, A.J. and Ryder, J.A. 1999. A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines. Creda Communications, Johannesburg, South Africa.

Jeppe, C.B. 1946. Gold Mining on the Witwatersrand. Transvaal Chamber of Mines, Johannesburg. pp. 805-806.

Jooste, Y. and Malan, D.F. 2020. The need for improved layout design criteria for deep tabular stopes. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 120. pp. 23–32.

Kaiser, P.K., Tannant, D.D., and McCreath, D.R. 1996. Canadian Rock Burst Support Handbook. Geomechanics Research Centre, Laurentian University, Sudbury, Ontario.

Kaiser, P.K., Kim, B., Bewick, R.P., and Valley, B. 2010. Rock mass strength at depth and implications for pillar design. *Proceedings of the Fifth International Seminar on Deep and High Stress Mining.* Australian Centre for Geomechanics, Perth. pp 463–476.

Le Roux, P.J. and Stacey, T.R. 2008. Establishing a methodology for the assessment of remnant stability using recorded seismic events on Harmony mines. *SHIRMS 2008: Proceedings of the First Southern Hemisphere International Rock Mechanics Symposium*, Potvin, Y., Carter, J., Dyskin, A., and Jeffrey, R. (eds), Australian Centre for Geomechanics, Perth. pp. 679–691, https://doi.org/10.36487/ACG_repo/808_95

McGarr, A., Green, R.W.E., and Spottiswoode, S.M. 1981. Strong ground motion of mine tremors: Some implications for near-source ground motion parameters. *Bulletin of the Seismological Society of America*, vol. 71, no. 1. pp. 295–319.

Mendecki, A.J. 2019. Frequency range, log E, log P and magnitude. *Proceedings of the 8th Rockburst and Seismicity in Mines Symposium*, Russia. https://www.imseismology.org/doc/publications/Mendecki-2013-Frequency-Range-logE-logP-and-Magnitude.pdf

Potvin, Y., Wesseloo, J., and Heal, D. 2013. An interpretation of ground support capacity submitted to dynamic loading. *Proceedings of the Fifth International Seminar on Deep and High Stress Mining.* Australian Centre for Geomechanics, Perth, Australia. pp. 251–272.

Rangasamy, T. and Jager, A.J. 2002. A selective review of remnant definitions and creation in the South African gold mining industry. *Proceedings of the SANIRE Symposium, Re-Defining the Boundaries.* South African National Institute of Rock Engineering.

Ryder, J.A. 1987. Excess shear stress (ESS): An engineering criterion for assessing unstable slip and associated rock burst hazards. *Proceedings of the 6th ISRM Congress*, Montreal, Canada. International Society for Rock Mechanics and Rock Engineering. Paper no. ISRM-6CONGRESS-1987-224.

Singh, N., Kataka, M., Milev, A., and Sellers, E. 2006. Remnant mining in South African gold mines. *Proceedings of the 41st U.S. Symposium on Rock Mechanics*, Golden, CO. American Rock Mechanics Association, Alexandria, VA. Paper no. ARMA-06-1038.

Spottiswoode, S.M. 1984. Source mechanisms of mine tremors at Blyvooruitzicht Gold Mine. *Rockbursts and Seismicity in Mines: Proceedings of the First International Symposium on Rockbursts and Seismicity in Mines*, South African Institute of Mining and Metallurgy, Johannesburg, pp. 29–37.

Wiles, T. 2020. Map3D user's manual – Version 67, www.map3d.com/ftp/Map3D_Help.pdf.

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