

ROCKBURST DAMAGE MECHANISM AT IMPALA PLATINUM MINE

L S Ledwaba and J Scheepers
Impala Platinum Holdings Limited

R J Durrheim
CSIR Centre for Mining Innovation and University of the Witwatersrand

S M Spottiswoode

Abstract

Impala Platinum Mine (Impala), situated north of the town of Rustenburg in the North West Province of South Africa, has experienced an increase in seismicity from ~841 seismic events in the year 2005 to ~1588 seismic events in 2008. The Seismologists and Rock Engineers need to understand the underlying mechanisms and driving forces responsible for seismicity to develop and design mining layouts and support strategies to eliminate or mitigate the risks posed by rockbursts. However, most previous studies of seismicity conducted on Impala and other Bushveld Complex mines in the Rustenburg area provided limited information regarding the source parameters and mechanism due to insufficient data.

The study is designed to investigate the seismic hazard on Impala Platinum Mine by means of two approaches: an investigation of seismic spatial distributions and the study of the rockburst damage mechanism of seismic events. A number of detailed investigations of rockbursts were conducted whereby damage was mapped and photographed. The investigations include reviews of the seismic history, short-, medium- and long-term seismic hazard assessment methods, and an analysis of the source parameters of the seismic event and associated ground motions. The study has revealed that most of the seismic events occur close to the reef plane, and are the result of the failure of a volume of rock that includes a pillar and the host rock that forms the foundation of the pillar.

1 Introduction

1.1 Seismicity at Impala

Impala Platinum Mine (henceforth referred to as Impala), is situated near the town of Rustenburg in the North West Province. Impala was established in the early 1960s. Seismic hazard on Impala has not been an acute problem in the past. Fortunately, only a few seismically-related fatalities have taken place, the last recorded incident on 30/12/1997. However, seismic activity on Impala is on the increase, which poses a risk to the workforce. It is expected that with increasing mining depth, the number and magnitude of seismic events may also increase, suggesting that the frequency and severity of seismic related collapses could increase (Gay, Durrheim, Spottiswoode & Van der Merwe, 1995).

On Impala, the number of seismic events with $M_L > 0.0$ almost doubled, from 841 events per year in 2005, to 1588 events per year in 2008. The reduction in the number of seismic events in 2009 and 2010 was due to production rates on the Merensky reef (where Impala experiences most of its seismicity) being reduced and production from UG2 reef being increased.

Seismologists and Rock Engineers need to understand the underlying mechanisms and driving forces responsible for seismicity to develop and design mining layouts and support strategies that will lessen such problems. Most previous studies of seismicity conducted on Impala and other Bushveld Complex mines in the Rustenburg area, provide limited information regarding the seismic source parameters and mechanism due to insufficient data from underground investigation.

1.2 Methodology

The Impala PRISM seismic network was used to collect the data to investigate the source parameters and rockburst mechanisms. The seismic network consists of 34 sites spread around the lease area, of which 23 are underground and 11 are surface sites. Underground investigations are routinely conducted for all $M_L \geq 1.0$ seismic events to quantify rockburst damage and establish the damage mechanism. Information gathered from these investigations formed part of the research work. Details of the Impala seismic network can be found from Scheepers and Ledwaba (2012)

The following methodology was applied:

- a) A Seismologist, Rock Engineering Officer, Geologist and Section Manager visited the rockburst site prior to rehabilitation. The damage to the excavation and support system were carefully studied, dynamic closure was estimated, and mining-induced fractures, joints and other geological features were recorded.
- b) The seismic history of the area in the vicinity of the rockburst was assessed, carefully noting the existence of nearby geological structures (e.g. dykes, faults and potholes).

2 Literature Review

The first investigation of mining related seismicity within the Bushveld Complex was conducted by Aref et al. (1994a and 1994b), using GENTEL seismographs at Impala No.10 Shaft (previously Wildebeesfontein North Mine) and Frank Shaft of Rustenburg Platinum Mine (RPM). Data were recorded between January and December 1992. Aref et al. (1994a) concluded that the relationship between seismicity and mining activity varied from area to area. Some areas showed a close correlation between seismicity and mining rate, while in other areas the mining activity was aseismic. No. 10 Shaft showed potential for large seismic events and the greatest rate of seismic energy release with mining. The Aref et al. (1994a and 1994b) study clearly indicated that a more comprehensive seismic network and more underground observations of movements on geological structures and excavation damage were required.

Data collected between September 1993 and August 1994 from a Portable Seismic System, installed at No. 10 Shaft, were analysed by Van der Merwe (in Haile and Jager, 1995) and Durrheim et al. (1997). They found that the majority of the seismic events (50%) located on pillars in the back area of mined-out areas. Approximately 35% of seismic events located at faces of active stopes, the remaining 15% of the events located in the back areas of actively mined panels. Some seismic activity correlated with old falls of ground (FOG) that occurred prior to the seismic event.

Haile and Jager (1995) found that most events occurred during the blasting period and shortly thereafter. The majority of larger magnitude events, which tend to occur outside the blasting time, were associated with observed pillar failure and pillar foundation failures. Durrheim et al. (1997) concluded that the level of seismic activity in the Bushveld Complex is a function of many factors, including the regional support system, size and spacing of pillars, geotechnical conditions, depth of mining and stress regime.

Brink et al. (2000) evaluated current and future seismic hazard by assessing seismic activity in Bushveld Complex platinum mines and its effect on support systems. They concluded that strain bursting on highly stressed pillars is a form of mining-induced seismicity or pillar bursting, and a number of fatalities were linked to these seismic events. Brink et al. (2002) conducted a further assessment of the seismic risk in the Bushveld Complex platinum mines through analysis of seismic data from recently installed seismic networks. In areas described as shallow to medium depth (< 1500m), mining seismicity is found to occur in or around highly-stressed pillars or remnants.

Spottiswoode et al. (2006) analysed five seismic events recorded by the Impala No. 10 Shaft seismic network that were associated with pillar burst mechanisms. The seismograms were found to be compatible with pillar failure caused by many shear planes within the pillar and driven by stope spans much larger than the pillar sizes.

3 Spatial distribution of seismicity

The PRISM systems at Impala recorded 6917 seismic events with $M_L \geq 0.0$ between 01 January 2005 and 31/12/2010. The following observations emerged:

- The seven biggest seismic events have $2.0 \leq M_L < 2.5$. They locate on, or are very close to the reef plane, and are associated with pillar burst and foundation failures. They are also correlated with falls of grounds, total panel collapse and haulage sidewall collapses.
- Fifty three seismic events have $1.5 \leq M_L < 2.0$. They locate in, or very close to the reef plane, 40% are correlated with pillar foundation failure, 30% are correlated with pillar bursts, 25% are correlated with falls of ground but unknown source mechanism, and the remaining 5% correlate spatially with geological features.
- 431 seismic events have $1.0 \leq M_L < 1.5$. Most locate within previously damaged areas, 90% are pillar bursts, and the remaining 10% are a mix of events associated with falls of ground, geological features, and pillar foundation failures.
- 6426 seismic events have $0.0 \leq M_L < 1.0$. They mostly locate within active stope faces, and previously damaged areas. These events also pose a risk to workers.

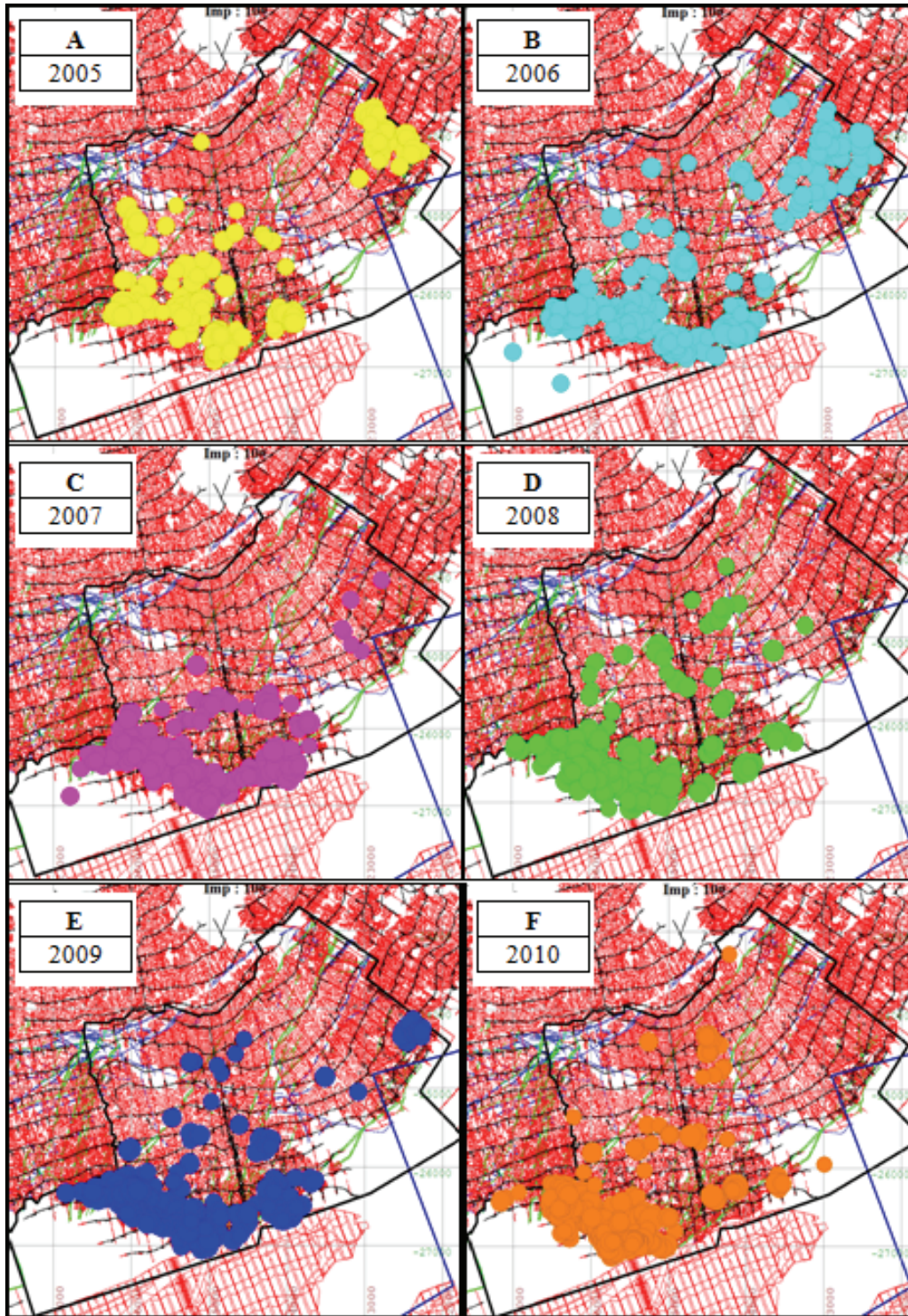


Figure 1. Seismic events locations with $M_L \geq 0.0$ per year at 10 Shaft. (Note that background plan shows face positions at the end of 2010)

A number of annual “snapshots”, showing the spatial distribution of seismicity at No. 10 Shaft, are shown in **Error! Reference source not found.** The seismicity is closely associated with the panels that were being mined during that period, with some events still occurring in the previously active areas (see **Error! Reference source not found.** where events are recorded in an area that was mined out in 2005).

Most of the recorded seismic events located on, or very close to the reef plane, some in the back areas of active and older/mined-out panels. Much of the yielding in and around pillars is of a stable nature. In some instances, fairly large seismic events were experienced in the mined-out area, followed by a short burst of events (aftershocks), during which there was significant rockburst damage over several panels. In general, seismic events that located in the back areas have higher magnitudes than the events located close to the working faces. Furthermore, the frequency of large events is greater in the back areas or old mined-out panels, and also results in extensive failure, causing damage in centre gullies. Few seismic events were located in the previously damaged areas, which suggest that at this stage in the failure process, the area has probably been completely de-stressed (Hildyard et al., 2005).

Diurnal variations of seismicity

A diurnal variation in the occurrence of the seismic events at No. 10 Shaft is shown in **Figure 2**. There is a threefold increase in the number of small seismic events during blasting time, between approximately 17h00 and 21h00. Large seismic events tend to occur independently from blasting, apparently occurring randomly throughout the day.

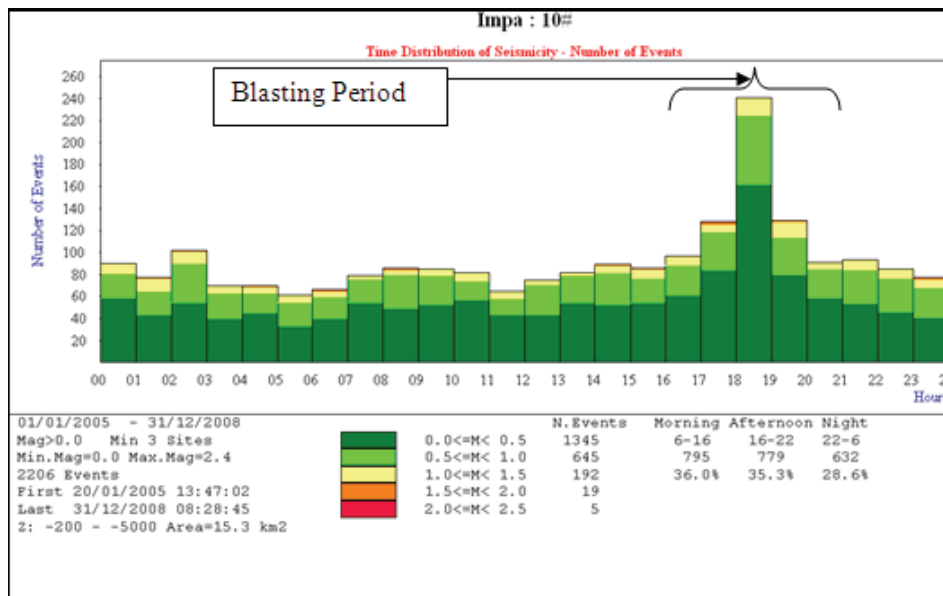


Figure 2. Diurnal distribution of seismic events recorded at 10 Shaft.

4 Seismicity in relation to depth

Figure 3 shows the relationship between seismicity and depth. The concentration of seismic events between 400 m and 1400 m is due to the fact that the bulk of the mining operations are concentrated in this depth range. Magnitude and number of seismic events tend to increase with depth. This increases the potential for damage, implying greater hazard as mining progresses deeper.

Figure 4 shows the comparison of E and M_o with depth of the $M_L \geq 0.0$ seismic events (from 2005 to 2010) for all shafts at Impala. The concentration of seismic events ranges from 600 m to 1400 m in depth, which is due to the fact that most of the mining is concentrated at this depth. Both moment and energy tend to increase with depth.

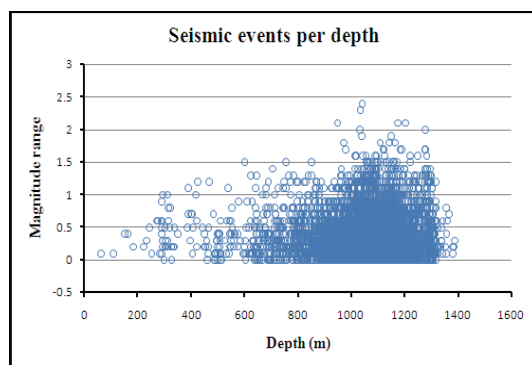


Figure 3. Seismicity in relation to depth.

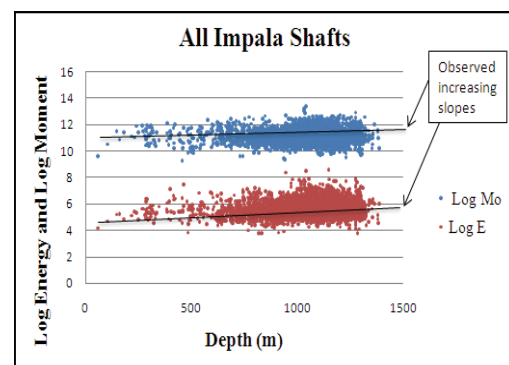


Figure 4. Log Energy and Log Moment in relation to depth for all Shafts.

4.1 Energy - Moment relations.

The local seismic event magnitude calculation in the mining industry is commonly based on both moment and energy derived from Fourier spectra. The PRISM system at Impala calculates magnitude from seismic energy only as follows (equation 1):

$$M_L = 0.667 \log E - 3.267 \quad (1)$$

The reason for this magnitude calculation is explained by Hildyard et al (2005). For both pillar crush failure and pillar foundation failure the entire stope converges, yielding a moment much larger than in the pillar region, thus the local magnitudes calculated using seismic moment only are larger than may be expected, particularly for the failure of small pillars.

Figure 5 shows that seismic moment estimated from P-waves is consistently higher than seismic moments estimated from S-waves, which suggest that the source has a high component of volume change (Spottiswoode et al., 2006).

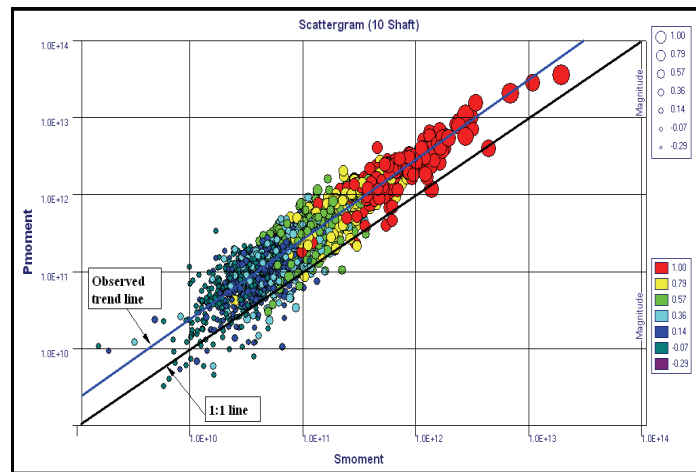


Figure 5. Relation of P- and S-wave moments at No. 10 Shaft.

5 Waveform and Spectral Analysis

The common way of displaying spectra is in terms of displacement, in which case frequencies above the corner frequency fall off rapidly (Spottiswoode et al., 2006; Mendecki et al., 1997). The displacement spectrum then falls off with frequency (f) as f^{-2} until elastic attenuation absorbs energy at high frequencies (Spottiswoode, 1993). f^{-2} fall-off for the displacement spectrum above the corner frequency is equivalent to a flat acceleration spectrum. Table 1 lists seismic events with $M_L \geq 1.0$ associated with damage observed through underground investigation at Impala with their source parameters. Waveform analysis was conducted on some of the events in Table 1. The highlighted seismic events represent events interpreted to have a slip source mechanism based on the E_s/E_p ratio. Generally a low E_s/E_p ratio (below 10) indicates a burst or pillar/abutment failure, while a high ratio indicates slip on plane of weakness.

Figure 6 shows the displacement seismograms for a pillar burst and a slip event respectively. For the shear slip event (EventID 9987 in Table 1), relative displacement between the dyke and host rock was observed during an underground investigation. Note that the amplitude of the P-wave is smaller compared to that of a pillar burst in

Figure 6. In

Figure 7, the amplitude of the spectrum falls off rapidly above f_0 for the $M_L=1.9$ slip event, while the acceleration spectra for the $M_L=2.1$ pillar burst event are flat from f_0 to f_l . Features of spectra displayed as displacement, velocity and acceleration are listed in Table 2.

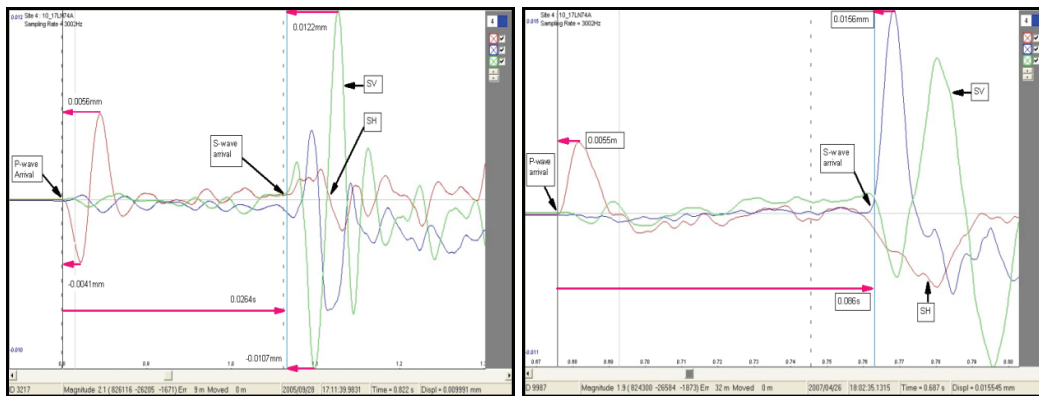


Figure 6. Displacement seismograms for $M_L=2.1$ pillar burst seismic event (left) and $M_L=1.9$ dyke slip seismic event (right)

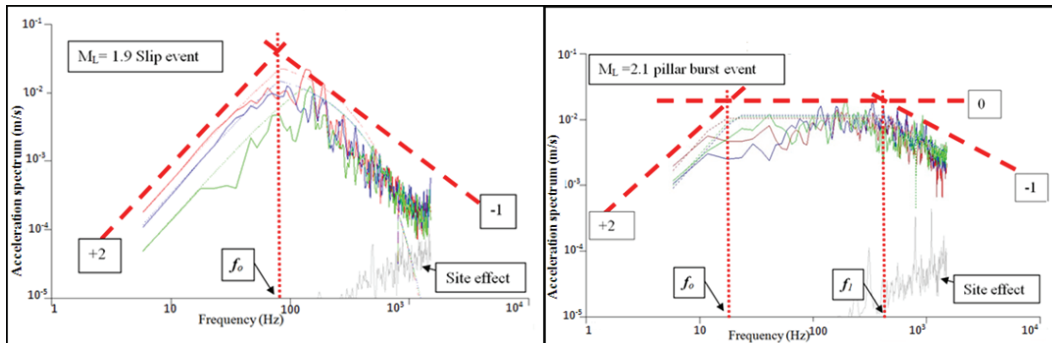


Figure 7. S-wave acceleration spectrum for slip and pillar burst seismic events. Site effect means background noise from the geophone.

Table 1 Source parameters of damaging seismic events with $M_L \geq 1.0$ at Impala

EventID	EventDate	Time	M_L	E_z/E_s	M_{zsf}/M_{zsf}	M_{OP} ($\times 10^{12}$)	E_p (MJ)	M_{OS} ($\times 10^{12}$)	E_s (MJ)	Stress Drop (MPa)	Radius AvVol (m)	Energy index	M_{MO}
3217	2005/09/28	17:11:40	2.1	10.4	0.30	10.1	19.2	3.04	200	11.1	59.7	4.12	2.2
8782	2006/12/22	03:24:23	1.2	3.3	0.17	6.23	0.54	1.07	1.76	0.019	285	0.07	2.2
9459	2007/03/09	12:08:55	1.3	6.1	0.30	4.03	0.38	1.34	2.55	0.033	214	0.13	2.1
9826	2007/04/11	21:10:48	1.2	16.5	0.35	1.60	0.25	0.57	4.07	0.119	103	0.64	1.9
9987	2007/04/26	18:02:37	1.9	97.3	1.19	1.21	3.87	1.64	440.	8.544	24	43.57	2.0
10697	2007/06/22	14:08:08	1.6	6.6	0.45	3.98	1.15	1.80	7.62	0.0911	156	0.37	2.2
10954	2007/07/11	19:06:15	1.3	2.1	0.41	1.38	0.31	0.50	2.85	0.089	130	0.42	1.8
11139	2007/07/24	11:01:53	1.2	6.1	0.41	2.35	1.65	0.97	3.28	0.17	266	0.07	2.0
11321	2007/08/06	04:47:05	2.4	12.2	0.54	6.57	2.72	10.90	262	0.313	219	0.65	2.8
12122	2007/10/04	18:05:10	1.1	4.6	0.19	1.55	0.41	0.29	1.87	0.074	114	0.42	1.8
12551	2007/11/02	23:50:08	1.2	3.1	0.38	1.70	0.56	0.65	1.76	0.059	133	0.31	1.9
12636	2007/11/07	15:29:24	1.1	6.3	0.35	1.22	0.26	0.42	1.36	0.059	118	0.34	1.8
14716	2008/04/07	20:43:55	1.3	7.3	0.25	1.68	0.39	0.41	3.01	0.098	108	0.53	1.8
14766	2008/04/10	23:14:02	1.3	9.0	0.45	1.80	0.26	0.69	2.76	0.321	77	1.65	1.9
15620	2008/05/23	19:11:50	1.4	6.4	0.38	3.94	0.84	1.49	5.38	0.069	168	0.28	2.1
15732	2008/05/29	15:46:39	1.8	15.2	1.12	3.97	1.86	4.45	28.2	0.214	133	0.77	2.3
15922	2008/06/06	18:28:38	1.0	5.7	0.36	1.77	0.35	0.63	2.41	0.040	147	0.22	1.9
16167	2008/06/19	07:33:30	1.0	3.2	0.28	1.80	0.45	0.50	1.47	0.05	140	0.26	1.9
16491	2008/07/03	02:37:07	2.1	7.3	0.25	11.20	2.93	2.78	21.4	0.105	200	0.33	2.4
17700	2008/09/08	08:53:57	2.1	4.6	0.31	5.68	9.14	2.79	41.6	0.360	112	1.30	2.3
23540	2009/09/14	06:08:29	1.1	125	1.65	0.25	0.47	0.41	58.1	2.32	183	1.08	1.6
24976	2010/01/14	06:33:58	1.7	25.7	0.76	1.67	2.35	1.27	60.3	10.90	38.3	0.78	2.0
28928	2010/11/17	13:25:07	1.6	8.9	0.53	3.5	1.4	1.85	8.77	2.68	73.1	1.87	2.2

Table 2. Features of spectra when shown in different ways (Spottiswoode et al, 2006).

X	Y	Slope in range of frequencies		
		$f < f_0$	$f_0 < f < f_1$	$f > f_1$
Log (f)	Displacement: $\tilde{u}(f)$	0	-2	-3
Log (f)	Velocity: $\tilde{v}(f)$	+1	-1	-2
Log (f)	Acceleration: $\tilde{a}(f)$	+2	0	-1

6 Rockburst case studies

6.1 Statistical summary

Damage associated with seismic events was observed only in Merensky reef stopes, no significant damage related to seismic events within UG2 reef occurred at Impala during the course of this study. Seismic events locate close to the Merensky reef plane, mostly within 10 m. Usually the source is related to the failure of a volume of rock that includes the pillar and the host rock surrounding the foundation of the pillar.

The types of rockburst damage observed at Impala include a wide range of phenomena ranging from violent rock ejections, buckling disruption and displacement, shakedown, to falls of ground associated with large distant seismic events. A total of 491 seismic events with $M_L \geq 1.0$ were recorded between 2005 and 2010 throughout Impala. The following summary of the rockburst mechanisms observed at Impala through underground investigations emerged:

- No strain bursts are discussed because they are associated with small ($M_L \leq 1.0$) seismic events at Impala.
- One hundred and six seismic events were identified to have pillar burst as the source mechanism.
- Twenty four seismic events were identified to have pillar foundation failure as the source mechanism.
- Nine seismic events were identified to have slip on geological structures as the source mechanism.
- The source mechanism of eighty seismic events that produced falls of ground could not be identified due to hazardous conditions in the area.
- Forty nine seismic events could not be investigated because they located within mined out areas, which were sealed off for ventilation purposes.
- One hundred and fifty one seismic events located in or close to previously investigated falls of ground and damaged pillars.
- Seventy two seismic events were not associated with any damage.

6.2 Rockbursts associated with slip on geological structures

A seismic event with $M_L = 1.9$ was recorded at No. 10 Shaft on the 26/04/2007 at 18h02 (henceforth referred to EventID9987) and was located near panel 1W, which was in the midst of negotiating a dyke intersections. **Figure 8** shows the locations of the seismic events and the distribution of damage. The panels in the proximity were mined up-dip. The right side of **Figure 8** depicts a photograph of shear movement of approximately 4 cm between the dyke and the host rock. The yielding pillar within panel 1W sustained damage, and also rock fragments fell from the hangingwall as part of the shake out.

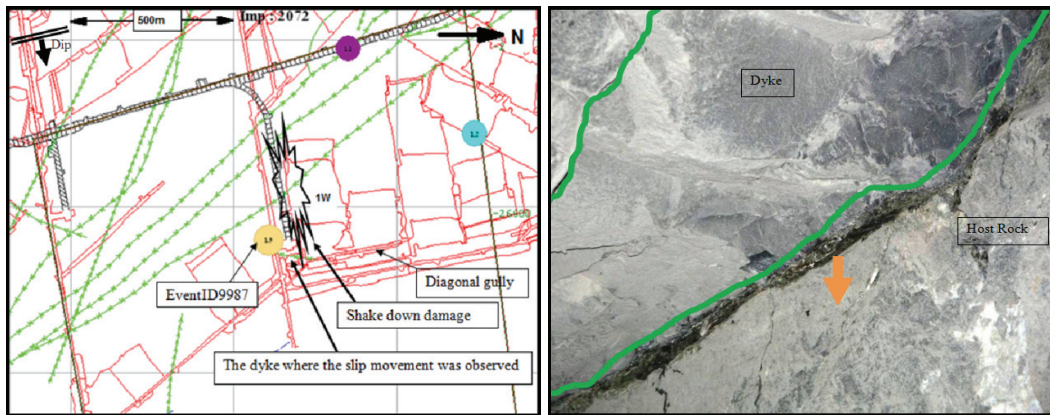


Figure 8. Locations of seismic event and the associated damage. On the right, view upwards towards the hangingwall; the dyke is contained within the green lines. The host rock moved about 4 cm in a downward direction indicated by the arrow.

6.3 Rockburst associated with pillar burst seismic events.

Impala uses 6 m × 3 m (strike × dip) in-stope pillars separated by 2 m long ventilation holings, which are carried on strike, adjacent to each panel, as part of the overall support of the stoping horizon. The original design was extensively researched and tested by Lougher (1994) and Spencer and York (1999). Rockburst damage resulted from a $M_L = 1.3$ seismic event that occurred on 03/09/2010 at No. 10 Shaft, 1962 panel 5N/S at 01h36, henceforth referred to as EventID27867 (see **Figure 9**).

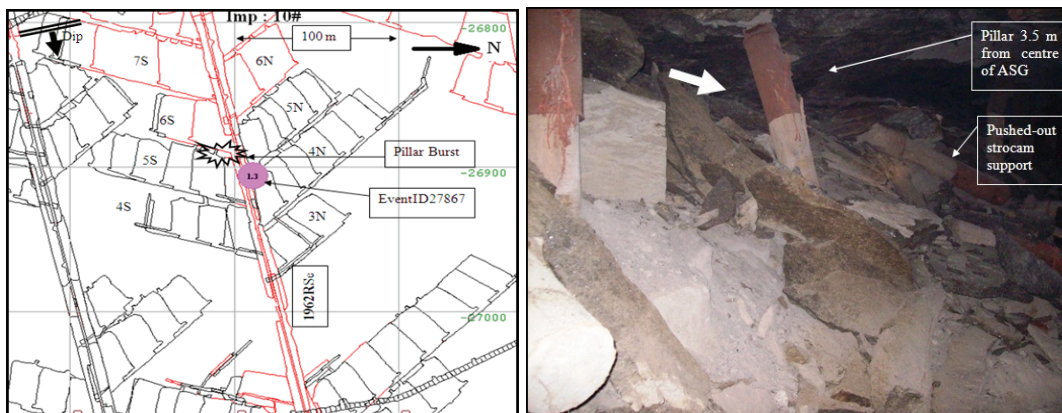


Figure 9. Locations of seismic events and associated damage (number within event represent the local magnitude). On the right figure, view south-westerly within the ASG towards panel 6S ASG face, pillar burst observed within panel 1962 6S. The damaged pillar is on the left side behind the support. Rock fragments were ejected from first pillar (4.1 m × 10 m) from 1962 RSE between panels 1962 5S and 6S. Ejected rock fragments rolled out of the siding into the ASG, indicated with a white arrow. Some of the support units along the 1962 4S ASG were pushed-out and not broken.

6.4 Severe shakedown damage associated with pillar bursts or slip events.

Rockburst damage resulted from a seismic event with $M_L = 2.1$ (henceforth referred to as EventID16491) and a series of 22 seismic events with magnitudes ranging between 0.0 and 1.6 that occurred within an hour on 03/07/2008 located within No.10 Shaft

(Figure 10). A complete collapse of 1973 crosscut and scattered damage in the nearby panels was observed. Two months later, two seismic events with $M_L = 2.1$ (henceforth referred to as EventID17700) and a $M_L = 1.8$ occurred on 08/09/2008 (Figure 10) and contributed to the total collapse and complete sealing off of 1973 crosscut.

The 1973 Xcut (4.3 m wide by 3.2 m height) intersects the reef at the end of the tunnel, meaning that the raise is in a very close proximity to the tunnel. A 2.8 m thick pillar was left on the south side and 5 m thick pillar on the north side of the 1973 Xcut. Mining around the Xcut was in all directions, including up-and down-dips. Pillar shapes ranged from triangular to rectangular

The sidewall of the 1973 Xcut was shattered into small fragments. The support that had been installed (2 m × 2 m diamond mesh and lace, with 1.9 m tendons) was ineffective in supporting the sidewall. The observed damage was interpreted to be the result of a pillar bursts which led to a number of falls of ground in the nearby panels. Rocks were ejected from the pillar within panel 2073 6W and 5W (see Figure 11 to 13).

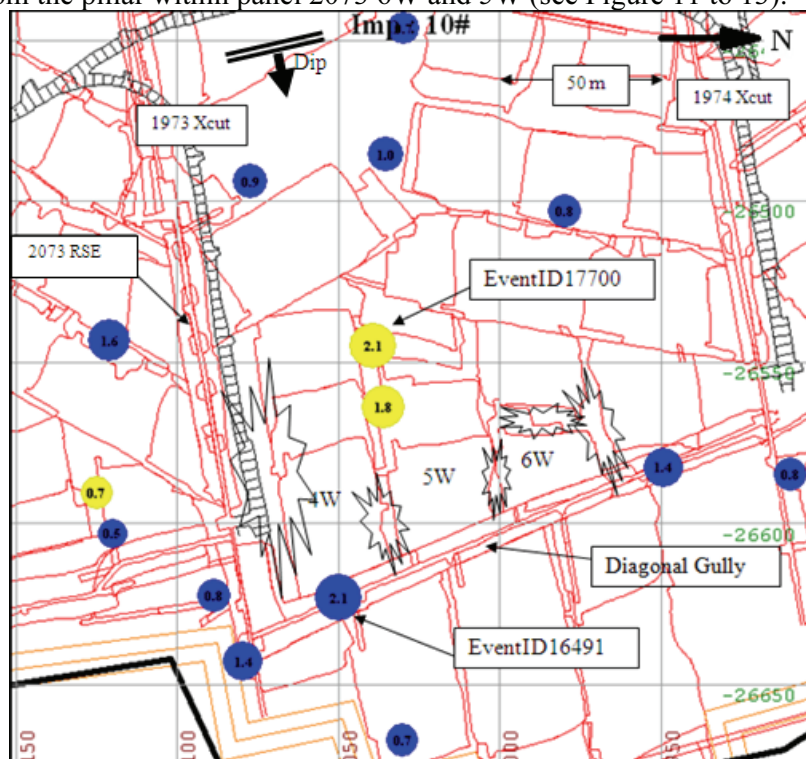


Figure 10. Locations of seismic events and associated damage. Black spheres represent seismic events recorded on the 03 July 2008 and the light shaded spheres represent events recorded on 08 September 2008.

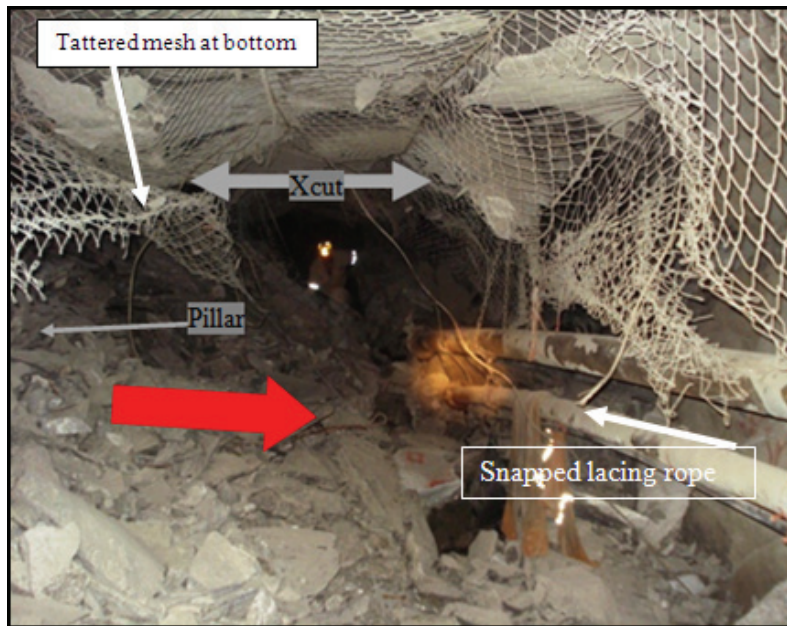


Figure 11. Rock fragments ejected from the pillar between 1973 Xcut and 2073 panel 4W into the Xcut. View easterly towards the end of the Xcut. Red arrow illustrates the direction in which rocks were ejected. The tunnel wall on left side is intensely fragmented and has suffered severe dilation. Tendons on the hanging wall appear not to have failed. Lacing rope has snapped and meshing was torn by ejected rocks. Slabs are caught up in the overhead mesh.



Figure 12. FOG next to the tip area within 2073 RSE

View westerly towards the 2073 gully and 1973 Xcut intersection. The pipes and cables that run across the centre gully are damaged. The winch is completely covered by fragmented rocks that fell from the hanging wall and were ejected from the nearby pillar. The pipes and cables that lead towards the face are damaged.



Figure 13. Extensive damage at the 1973 X/Cut due to EventID17700

View easterly towards the end of the Xcut. The tunnel wall on left side is intensely fragmented and has suffered severe dilation. Tendons and meshing on the hanging wall appear too loosened. Cables and pipes are completely destroyed. When comparing with Figure 11, it should be noted that this photo was taken ± 3 m away from damage, and the damage is more extensive (complete closure of the Xcut).

6.5 Pillar foundation failure

Rockburst damage resulted from a seismic event with $M_L = 1.2$ on 22/12/2006 at 03h24 at No.14 Shaft 1995 South area, hence forth referred to as EventID8762 (**Figure 14**). It caused footwall uplift between the 5N and 6S pillars (right side of **Figure 14**).

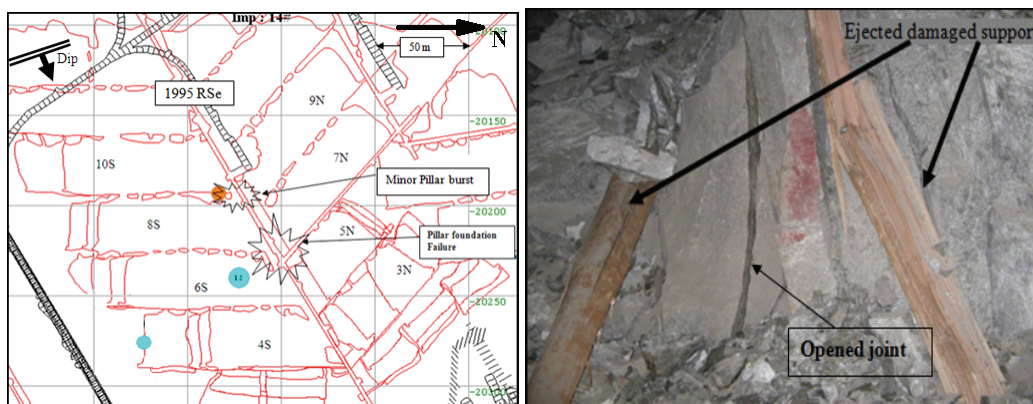


Figure 14. Locations of seismic events and associated damage. On the right, viewing south towards the entry of panel 6S, footwall damage observed on the pillar at the entry to panel 6S. 3-Sticks cluster pack pushed out by fragmented and jointed rocks from the pillar footwall. Open joints on the pillar footwall.

6.6 Pillar-associated rockburst mechanism

Most of the rockburst damage observed at Impala is a result of pillar burst and foundation failures. **Figure 14** shows the relationship between the magnitude of events and the effective pillar width determined by Mokgalaka (2006) who analysed seismic events with $M_L \geq 0.5$. The effective pillar width (equation 2) is used to establish the effect of the pillar shape on strength.

The effective widths of pillars were calculated using the following equation (Jager and Ryder, 1999):

$$W_{eff} = \frac{4 \times \text{Area of the pillar}}{\text{Perimeter of the pillar}} = \frac{2w_1w_2}{(w_1+w_2)} \quad (2)$$

where w_1 and w_2 pillar dimensions in meters

The study by Mokgalaka (2006) shows that the oversized pillars (i.e. effective pillar width 4.8 m and above) tend to store energy, thus not scaling until there is sufficient energy to burst. Pillars with effective pillar widths between 3 m and 3.5 m tend to respond by releasing energy progressively and hence are associated with fracturing, and events have smaller magnitudes that usually cause little damage.

The area of high risk is from 0 to 3.5 m from the pillars where most equipment and personnel are vulnerable to damage and injuries leading to production loss, which is why most panels in the seismically-declared ground control district have sidings cut up to 3.5 m.

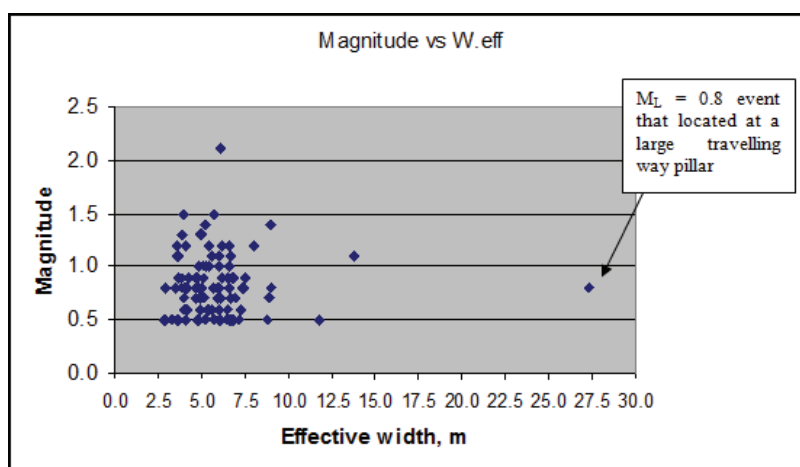


Figure 15. Seismic magnitude in relation to effective pillar width (Mokgalaka, 2006)

Pillar burst mechanisms observed at Impala shows that pillars of widths greater 3 m are loaded to high stress and can generate events of considerable magnitudes as the whole pillar releases the stored energy. Pillar foundation failure is usually associated with large pillars, remnants left due to poor ground conditions and potholes, which have a core that can sustain higher stresses (Hildyard, et al., 2005).

7 Conclusions

The primary goal of this study was to gain a thorough understanding of seismic source parameters and mechanism of the potentially hazardous seismic events at Impala, and provide an understanding to the mechanisms involved in the violent failure of pillars and structures like lamprophyre and dolerite dykes. This was achieved by gathering information from underground investigations, where the support systems were studied, dynamic closure estimated, and mining-induced fractures, joints and other geological features were recorded. The Impala PRISM seismic network was used to collect the data used to investigate the source parameters and rockburst mechanisms. Seismograms of the incident were used to determine the source parameters.

The source mechanisms of events that caused significant damage at Impala were pillar bursts, pillar foundation failure and slip on geological structures. In general, the intensity of shaking decreases with distance from the source, and damage mechanisms vary accordingly. The observed damage mechanisms included violent rock ejections, buckling disruption and displacement, shakedown, and FOG associated with distant seismic events.

Most seismic events locate close to the Merensky reef plane (within 10 m) and most often the source is related to failure of volume of rock involving the pillar and the host rock surrounding the foundation of the pillar. The bi-directional ground displacement recorded at the geophone sites is explained by partial elastic rebound of the stope

hangingwall following pillar failure. In contrast, a seismic event produced by slip between a dyke and the host rock produced a uni-directional pulse.

Seismic moment estimated from P waves was found to be higher than seismic moments estimated from S waves, which suggest that the source has a high component of volume change, as previously suggested by Spottiswoode et al. (2006). The analysis of P- and S-wave acceleration spectra for slip and pillar burst seismic events plotted as a function of $\log(f)$ showed that the amplitude of the spectrum falls off rapidly above f_0 for the $M_L=1.9$ slip event, which is in agreement with the theoretical spectrum. The acceleration spectra for the $M_L=2.1$ pillar burst event show a flat spectrum, and the rate of the frequency fall off increases to a second corner frequency (f_i), which is in contrast to the theoretical spectrum. All the seismic events that are compatible with the second corner frequency (f_i) increased fall-off rate show that it is a source effect and it is not being caused by attenuation along the ray paths.

Rectangular pillars with a width ≤ 3 m and 6 m length yield in a more stable manner than the triangular and square pillars. Pillars of widths greater 3 m are loaded to high stress and can generate events of considerable magnitudes as the whole pillar releases the stored energy. Larger pillars, remnants left due to poor ground conditions and potholes have a core that can sustain higher stresses and the failure usually results in foundation failure.

8 Recommendations

The level of seismic activity in the Bushveld Complex is a function of many factors, including the regional support system, size and spacing of pillars, geotechnical area, depth of mining and stress regime. Although Impala is still officially classified a “shallow depth” mining environment, the signs of the change into an “intermediate depth” mining environment are already being experienced in the deeper mining sections (No. 10 Shaft). Signs observed to date include increased closure rates, fracturing of the stope hangingwall, and seismic activity. The number, magnitude, moment and energy of seismic events were found to increase with depth. This increases the potential for rockburst damage, implying greater hazard as mining commences on deeper levels, unless mining methods and support systems are adapted. Geological structures (faults, dykes and potholes) are not considered to pose significant seismic hazard risk at Impala. Pillar bursting and foundation failure pose a greatest risk. The strategy adopted by Impala to address the hazard associated with pillar bursting involves:

- Designing pillars using industry-accepted formulae and representative values.
- Cutting the pillars to the specified dimensions.
- Monitoring cut pillars to assess whether they behave as anticipated.

9 Acknowledgements

This paper is based on work towards an MSc Dissertation by the first author. Thanks to management and the rock engineering department at the Impala Platinum Mine for permission to publish this paper.

10 References

- Aref, K., Jager, A.J. & Spottiswoode, S.M. (1994a). A comparison of seismicity from two mines in the Bushveld Igneous Complex using different pillar systems. *The 1994 ISRM Int Symp. and VIth South American Congress on Rock Mechanics*, Santiago, Chile.
- Aref, K., Jager, A.J. & Spottiswoode, S.M. (1994b). The nature and possible source mechanisms of seismic events from a shallow pillar supported, platinum mine in South Africa. *Proc. 1st North American Rock Mechanics Symposium*, pp.895-902.
- Brink, A.v.Z., Hagan, T.O., Roberts, M.K.C. & Milev, A. (2000). Preliminary assessment of seismic hazard and risk in the Bushveld Complex platinum mines. *SIMRAC Report GAP 711*, Department of Mineral and Energy Affairs, South Africa.
- Brink, A.v.Z., Roberts, M.K.C. & Spottiswoode, S.M. (2002). Further assessment of seismic hazard/risk in the Bushveld Complex platinum mines and the implication for regional and local support design. *SIMRAC Report GAP 821*, Department of Mineral and Energy Affairs, South Africa.
- Durrheim, R.J., Spottiswoode, S.M., Jager, A.J. & Van der Merwe A.J. (1997). Seismic Monitoring of Pillar System performance in Bushveld Complex Platinum Mines. In R.G. Gurtunca and T.O. Hagan (Eds.), *SARES97, ISRM Regional Symposium*, Johannesburg, pp. 56-61
- Gay, N.C, Durrheim, R.J., Spottiswoode, S.M. & Van der Merwe, A.J., (1995). Effect of geology, in-situ stress, and mining methods on seismicity in Southern African gold and platinum mines. In T Fuji (Ed.), *Proc. 8th Int. Cong. on RockMechanics, ISRM*, vol. 8, pp. 1321- 1325
- Haile, A.T. & Jager, A.J. (1995). Rock mass condition, behaviour and seismicity in mines of the Bushveld igneous complex, *SIMRAC Report GAP 027*, Department of Mineral and Energy Affairs, South Africa.
- Hildyard, M.W., Milev, A., Linzer, L.M., Roberts, Jager, A.J. & Spottiswoode, S.M. (2005). Assess the hazard posed by dynamic failure of pillars in the back areas of platinum mines, *Platmine Task 3.7*, CSIR Division of Mining Technology.
- Jager, A.J. & Ryder J.A. (1999). *A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines*, SIMRAC Johannesburg 370 pages.
- Mendecki, A. J., (editor) (1997). *Seismic monitoring in mines*, Chapman & Hall. London, 262 p.
- Mokgalaka, L. (2006). *Relationship between Merensky Pillar Size and Seismic Magnitude*, Unpublished internal report. Impala Platinum Limited.

- Spencer, D. A. & York, G. (1999). Back analysis of yielding pillar system behaviour at Impala Platinum Ltd, *Proceedings of the Second South African Rock Engineering Symposium – SARES 99*, Johannesburg.
- Spottiswoode, S.M. (1993) Seismic attenuation in deep-level mines, *3rd Intl Symposium on Rockbursts and Seismicity in mines*, Balkema, pp. 409-414.
- Spottiswoode, S.M., Scheepers, J.B. & Ledwaba, L.S. (2006). Pillar Seismicity in the Bushveld Complex, *Proc. of SANIRE 2006*, Rustenburg, pp. 140-158.

The Authors



Lesiba Ledwaba, Mine Seismologist, Impala Platinum Mine

I studied my matric in Limpopo province in 1991, then went on to Wits and obtained a BSc degree in Physics and Geophysics in 1998 and BSc with Honours in 2000. I worked as Geodesy surveyor for 3 years at HartRAO, from 2002 I joined Geohydroseis as a Mine seismologist for the Welkom Mines. I joined Impala Platinum Mine as a Mine Seismologist in 2004.

