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# Seismicity at Big Bell Mine

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## Abstract

*Big Bell Mine started experiencing relatively large mining related seismic events, and accompanying rockbursts, from February 1999. Twelve rockbursts damaged access development from February 1999 to June 2000, with severe damage extending for up to 100m along footwall drives.*

*Five seismic events associated with the rockbursts were recorded by the AGSO, measuring 1.9, 2.2, 1.7, 2.4 and 2.2 on the Richter scale. These events affected 485 and 460 footwall drives in August and November 1999 and 535 footwall drive in June 2000 (drive level nomenclature is equivalent to the depth below surface and RL).*

*After the third event (July 1999) it was apparent that the seismicity was not a once-off phenomenon. This (sudden) onset of seismicity required management to implement a series of precautionary measures:*

- *to ensure the safety of the workforce*
- *to maintain continuity of production*
- *to reduce rockburst damage rehabilitation*

*The measures included extended re-entry periods and exclusion zones in high-risk areas, improved rockburst resistant support systems in areas prone to damaging seismic activity and improved support systems in areas prone to shakedown damage.*

*A full-scale minewide ISS seismic system was ordered in October 1999 and commissioned in February 2000. A portable eight-channel CSIR-Miningtek system was installed at short notice as an interim measure in August 1999. This CSIR system covered the northern producing stopes, where the majority of the rockbursts had occurred.*

*The objective of the seismic monitoring was to monitor relative activity and to determine trends with regards to time and location. MAP3D numerical modelling was used to investigate the relationship between seismicity and various combinations of stress components to assess the relative seismic risk in both current and proposed working areas. This information is used to determine where and at what stage in the mining cycle the rockburst resistant support is required.*

*Analysis of the seismicity has determined two distinct modes of seismicity - small scale localised, high frequency events in high stress areas and larger events related to shear along previously intact foliation surfaces.*

*This paper includes a summary of the seismic history, seismic data analysis, support system design, mine design adjustments and management action to minimise the effects of seismic activity at Big Bell Mine.*

## Location and History

The Big Bell Mine is located in the Murchison Province of Western Australia, approximately 30km west of Cue, 120km south-east of Meekathara, and 540km north-north-east of Perth.

The Big Bell deposit was discovered in 1904 and the mine has been in operation on and off since 1913. The mine currently produces around 168,000 ounces from 1.8mtpa of 3.1 g/t ore, using a longitudinal sub-level caving method. New Hampton Goldfields Ltd purchased Big Bell from Normandy Mining Ltd in January 2000. Big Bell Operations employs 364 people, of which 194 are contract workers associated with the underground mine. The majority of the people employed at the mine work on a fly-in-fly-out roster from either Perth or Geraldton.

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## Geology

The Big Bell deposit is located within a greenstone and sedimentary sequence within the Murchison Province of the Archaean Yilgarn cratonic block. The lithological contacts adjacent to the orebody generally strike at around 30° from magnetic north and dip 72° to the east. The orebody dip varies locally from 55° to 80°. Mineralisation is hosted within potassium-feldspar-schist (KPSH), altered schist (ALSH) and biotite schist (BISH). Footwall excavations are located in amphibolite schist (AMPH), a basalt equivalent (Figure 1).

A graphitic shear structure is located in the footwall of the orebody, varying in thickness from 2cm to 45cm and located from 5m to 20m in the footwall of the orebody. A cordierite schist (CRSH) is the footwall marker unit to the deposit.

The Big Bell lode system (KPSH, ALSH, BISH) has been defined along strike for over 1,000m and to a depth of 1,430m. In plan view the lode system is lenticular in shape varying from five to eight meters in width at the extremities and up to fifty meters in the central area of the deposit.

## Production and Mining

A longitudinal sub-level caving (SLC) method is used at Big Bell, using a top-down approach. The wider, central 350m section is mined from a central slot in the orebody out. The extremities of the economic mineralisation are developed on ore and retreated back onto a pillar, termed a "limit retreat".

Once the main SLC and the limit retreat faces close onto the pillar, a mass blast is initiated to retrieve ore within the pillar.

The sub-level interval is 25m and the orebody width varies from 10m to 40m, with twin ore drives developed in the central section where the orebody widths exceed 22m. The mine is currently (mid to late 2000) producing from 485, 510 and 535 Levels (metres below surface).

102mm blastholes are used for production drilling and blasting, with a ring burden of 2.5m, toe spacing at 3.6m, and holes angled forward at 20°. Holes are charged with bulk gassed emulsion, with two rings fired per shot with an historic powder factor of 0.56kg/t (Yeung, C., Player, J. R, and Braddon, K.

1999). Longhole drilling equipment consists of two Simba 4356 rigs. Elphinstone loaders (2 x R2800 and 2 x R2900) and trucks (7 x 73D) are used for loading and hauling the ore to surface.

## Geotechnical Considerations

### Rockmass properties

The rockmass properties at Big Bell vary markedly between the orebody and the footwall amphibolite (Table 1). Ductile failure in the orebody generally commences with excavation and is aseismic (Sandy and Player, 1999). The more brittle amphibolite footwall is more massive, with few west-striking structures. Whilst foliation is tight and healed the orientation relative to load direction is critical in rock sample testing (also valid for larger scale failures during seismic activity).

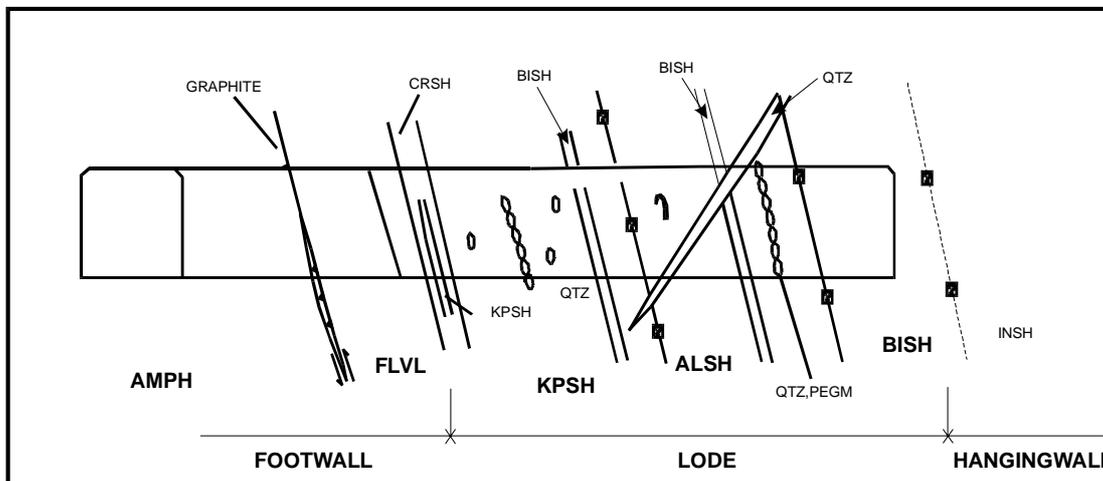
Table 1 - Rockmass properties (mean)

Rock Type	UCS 50	Young's Modulus (GPa)	Poisson's Ratio	density (kg/m <sup>3</sup> )
AMPH	123.11	67.12	0.28	2870
ALSH	121.13	44.51	0.21	2800
BISH	103.42	51.42	0.23	2900
CRSH	136.5	51.7	0.18	2820
KPSH	141.2	43.4	0.27	2738

Table 2 - Measured principal stresses

Level	Principal Stress	Magnitude (MPa)	Dip (°)	Bearing (°)
350	Major	74.3	06	215
	Intermediate	38.1	07	306
	Minor	19.3	81	086
380	Major	52.5	16	242
	Intermediate	29.6	19	338
	Minor	22.8	65	114
485	Major	69.1	27	274
	Intermediate	34.3	06	007
	Minor	29.9	63	109

Figure 1 - Schematic geology section



**Table 3 - Stress components**

Level	Stress Components	Normal (MPa)			Shear (MPa)		
		N-S	E-W	Vert	NS-EW	EW-Vert	Vert-NS
350	Magnitude	61.92	49.43	20.15	16.82	-5.06	-3.20
	Standard error	(1.65)	(0.92)	(0.72)	(0.77)	(0.42)	(0.76)
380	Magnitude	33.92	45.13	25.87	9.12	-7.91	-1.81
	Standard error	(7.58)	(4.49)	(3.44)	(4.40)	(2.31)	(3.72)
485	Magnitude	34.36	61.16	37.78	-1.70	-15.58	1.58
	Standard error	(3.29)	(4.49)	(2.35)	(2.85)	(2.16)	(1.95)

### Stress Regime

The stress has been measured at various depths using the Hi-cell overcoring method. The results for 350, 380 and 485 Levels have indicated high, deviatoric stresses (Tables 2 and 3). The majority of tests resulted in a high degree of confidence for the calculated stress levels. The most recent measurement, on 485 Level, indicated the maximum principal stress was orientated perpendicular to the orebody. An additional measurement is planned for 585 Level to provide an updated stress gradient for modelling.

### Seismic History

The Australian Geological Survey Organisation (AGSO) have recorded seismic events in the Big Bell region from at least prior to 1988 ( $M_L=3$  on 25/12/88). The threshold magnitude for the AGSO in the Big Bell area is around  $M_L=1.8$ , with the closest regional sensor located 120km from the mine at Meekatharra. Events at Big Bell can only be located accurately by the AGSO generally if the magnitude is greater than approximately  $M_L=2.5$ , and if a total of three sensors detect the event. Events between  $M_L=1.8$  and 2.4 at Big Bell can only be confirmed with a given time and location, and have to be manually processed by the AGSO using P and S arrival time differences.

The mine itself has also had a history of small scale strain bursting and rock noise. These strain bursts have been located

in deeper sections of the decline, cross-cuts, ore drives and footwall drives and have been related to the main pegmatite, flat dipping joints, and apparently high stress zones and/or strain burst prone rock zones.

### Rockburst History

Major mining related seismic activity at Big Bell commenced in February 1999, with seven major rockbursts occurring in 1999 and five in 2000, to June. These are detailed in Table 4.

The majority of the events have many similarities regarding failure mode, location, location relative to stoping, and timing relative to stope blasts. The rockbursts generally occur:

- along the hangingwall shoulder of the footwall drives,
- with foliation forming the hangingwall surface of the rockburst,
- either side of cross-cuts,
- on the level below main production levels where the mined out span on strike exceeds 100m,
- within 25m north or south of a production blast on the level above,
- within 24 hours of the production blast on the level above.

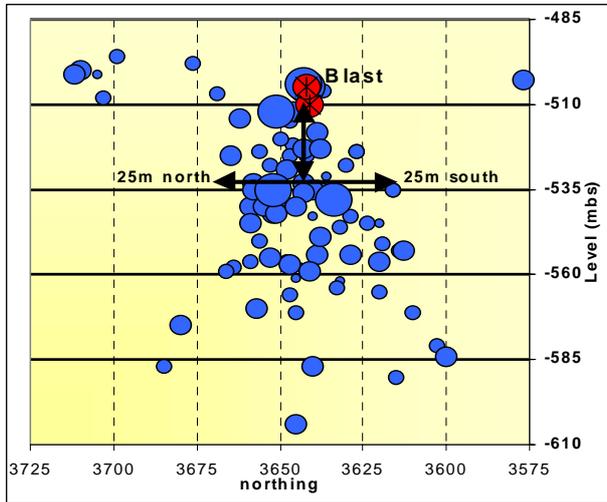
**Table 4 - Recent rockburst history**

Date of Rockburst	$M_L$ (AGSO)	m <sup>3</sup> fallen/ejected	Level	Location (northing)
12 February 1999	nr	4	460	Ore Drive (3655N)
16 June 1999	nr	5	435	Footwall Drive (3475N)
7 July 1999	nr	2	485	Footwall Drive (3775N)
9 August 1999	1.9	12	485	Footwall Drive (3790N)
22 August 1999	2.2	20	460	Footwall Drive (3805N)
25 November 1999	1.7	8	460	Footwall Drive (3820N)
25 November 1999	2.4	40	485	Footwall Drive (3845N)
6 <sup>th</sup> April 2000	nr	3	510	Footwall Drive (3775 N)
11 <sup>th</sup> April 2000	nr	1	485	Footwall Drive (3840 N)
8 <sup>th</sup> May 2000	nr	15	535	Footwall Drive (3665N)
23 <sup>rd</sup> May 2000	nr	0.2	535	Footwall Drive (3775N)
17 <sup>th</sup> June 2000	2.2	60	535	Footwall Drive (3765N)

nr=not recorded by AGSO

A typical distribution of seismicity following production blasting (510 Level south) is shown in Figure 2 with the size of the circles related to the magnitude of the event. The concentration of larger, possibly damaging events within 25 m down dip and north and south is evident and is in line with exclusion zone limits on 535 Level.

**Figure 2 - Long section with events 0 to 24 hours after blast of 7 June 2000**

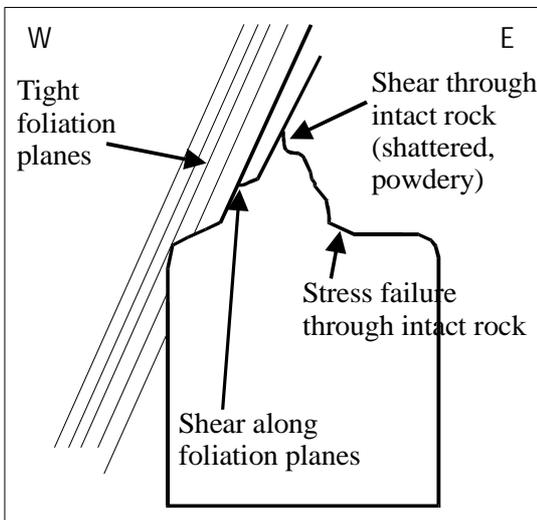


A number of events have been felt on surface and/or recorded by the AGSO which have not been related to damage to underground excavations, possibly being related to the cave in the hangingwall or movement on larger scale regional geological structures.

**Rockburst Failure Mode**

The majority of the rockbursts to date have been in the footwall drives, and have involved shearing of intact rock along the west surface of the rockburst and shearing of previously intact foliation along the east surface of the rockburst, close to the hangingwall edge of the footwall drives. Shear failure is evident in most rockbursts at the apex of the fall, and along foliation to the north and south of the fall (in the backs of the footwall drive) (Figure 3).

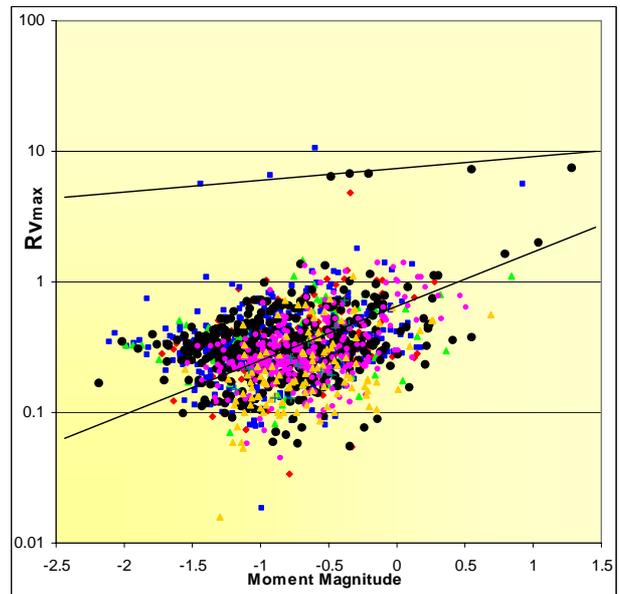
**Figure 3 - Typical rockburst failure geometry**



There has been no evidence to date of shear movement along structures such as the graphite shear that could be a primary source of seismic activity remote from the excavations. Location of events with the mine based seismic systems also indicates the primary source is very close to the footwall drives and sites of rockburst damage. Shear failure of intact rock and tight foliation surfaces is proposed as the main source/mode of seismic activity at Big Bell. The magnitude of the larger seismic events is relatively large for mine based intact rock/shear failure events. This is due to a combination of very high stress levels, a competent rock mass capable of storing a significant amount of energy prior to failure, and the orientation of footwall drives which were parallel to foliation and maximum shear stress below stope face positions.

High ground velocities up to 10m/s were indicated in certain zones by the sensors used with the CSIR seismic system, which were mounted on the sidewalls of excavations. A summary graph of the results for  $Rv_{max}$  analyses on quality data from August 199 to March 2000 shows the possible presence of two series of events, one of which involves very high velocities (Figure 4), (Mendecki Dr AJ, 1997, pp 1 to 4 and Jager AJ and Ryder JA, 1999, pp 303 to 304). These results are in line with previous findings in South Africa at Blyvooruitzicht Gold Mine and also confirm a requirement for support systems capable of yielding at velocities in excess of 2m/s (Spottiswoode SM, *et al.*, 1997). Note that data analyses to this extent are probably at the limit for a system using only uni-axial sensors.

**Figure 4 -  $Rv_{max}$  August 1999 to March 2000**



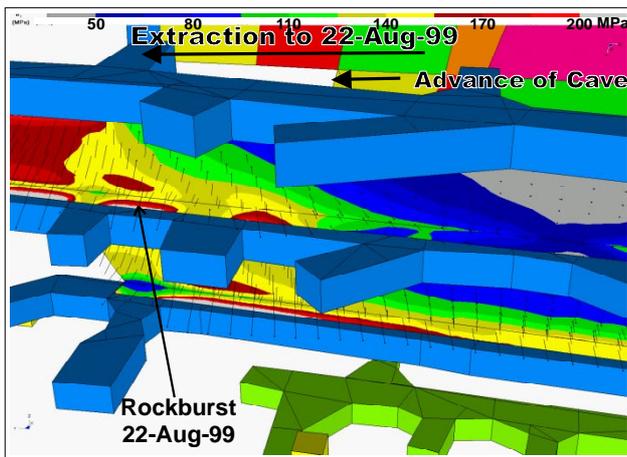
Water is commonly observed seeping from foliation in the backs following rockbursts in previously dry areas. The water comes from the upper footwall drives and can only seep through the rock once there has been a significant drop in stress levels in the east-west direction. Seismic data analysis has indicated this stress drop could be up to 10 to 50 MPa during a large seismic event (Mendecki Dr AJ, 1997).

**Modelling**

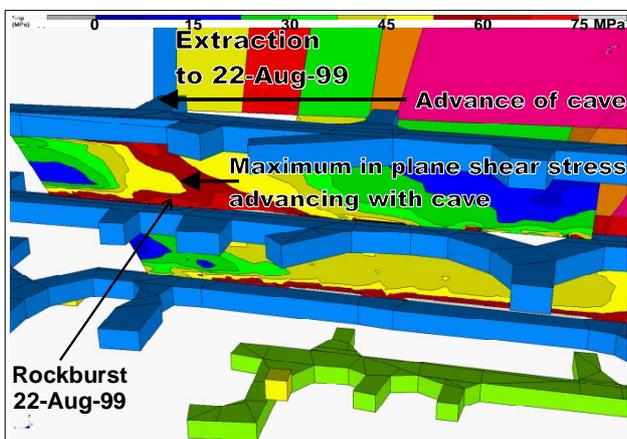
The changes in underground stresses due to mining have been modelled utilising MAP3D, with measured stresses and rock properties as input parameters. The high virgin stresses and the extent of stoping and the caved zone result in very high

indicated stress levels ahead of and below stoping abutments. Back analyses of all rockbursts have been undertaken and a number of stress components have been assessed to determine if there are any indicators or predictors of seismic activity. The two stress components which indicate peak zones around rockburst sites are the maximum principal stress (Figure 5) and the in plane shear stress along foliation (Figure 6). The maximum principal stress peaks in the footwall drive below the stope faces, and either side of east-west intersections off the footwall drive (e.g. cross-cuts). Back analysis has provided benchmark indicator levels for use in assessing the seismic risk in mine design proposals.

**Figure 5 - MAP3D maximum principal stress, rockburst of 22 August 1999**



**Figure 6 - MAP3D in plane shear stress, rockburst of 22 August 1999**



## Management of Seismicity

Management objectives covering seismicity include quantification of the hazard, and managing the risk by restricting access, modifying support and adjusting mine designs.

### Seismic Monitoring

An eight-channel CSIR-Miningtek (GMM) seismic system was installed at Big Bell in August 1999, and an 18-channel ISS system in February 2000.

The CSIR system was operated with daily downloads onto a notebook PC and covered the northern producing stopes, centred around the July and August 1999 rockburst sites on 485 Level. This system incorporated 14Hz geophones attached to the sidewalls of excavations with epoxy resin and located events from 435 to 535 Levels, with local magnitudes from -3.0 to 0.5. Waveforms were clipped for events greater than -0.5. Aura32 software was used for analysis of the data and events visualised in Aura32 and on Datamine.

The ISS system covers all the current working areas on a real time basis, with a range of local magnitudes from -1.8 to 1.5. The system includes three MS6A units, each with one tri-axial and three uni-axial accelerometers.

Seismic monitoring is primarily being undertaken to ensure Big Bell remains a safe and consistent producer for the owners. Use of the data includes the determination of re-entry times, exclusion zones and the extent of development requiring rockburst resistant support.

### Support Systems

The support system installed up to late 1999 included split sets, end anchored rockbolts (replaced with Stelpipe tubular bolts (TGBs) in January 1999), mesh (RF81), with cable bolts at intersections. The support system was strengthened following observed failures due to rockbursts throughout 1999.

Rockbursts sites typically included failure of split sets rings, pulling out of split sets, failure of end anchored bolts, TGBs and separation of mesh from the hangingwall shoulder and at mesh overlaps. Upgrading of the support system included grouting of cable bolts in split sets, and subsequent plating of these cables following continued failure of the split sets rings and the mesh.

These stronger, but relatively stiff, support elements continued to prove ineffective in rockburst conditions. In particular, the major rockburst on 485 Level on 25 November (Figure 7) destroyed all support elements in an area with a calculated static support resistance in excess of 230kN/m<sup>2</sup>. This section included split sets at 50kN/m<sup>2</sup>, twin strand cable bolts at 125kN/m<sup>2</sup>, end anchored bolts at 25kN/m<sup>2</sup> and mesh at 30kN/m<sup>2</sup>, (Jager AJ and Ryder JA, 1999, pp 147 to 160).

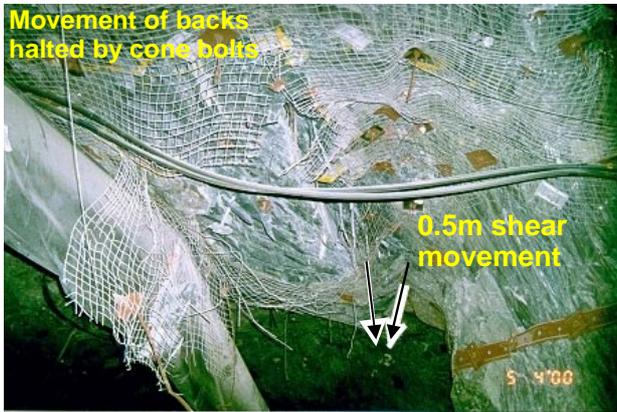
**Figure 7 - Rockburst of 25 November 1999, 485 footwall drive**



In contrast, an additional second pass support was introduced in certain areas from October 1999, including cone bolts in highly stressed rockburst prone areas and debonded Gewi bars in areas

prone to seismic shakedown damage. The rockburst of 25 November in 460 footwall drive was contained by this upgraded system and led to an acceptance that cone bolts could control the seismic related rapid rock mass deformations. The rockbursts of 6 April on 510 footwall drive and 23 May on 535 footwall drive were also satisfactorily controlled by cone bolts (Figure 8).

**Figure 8 - Rockburst of 6 April 2000, 510 footwall drive**



Strain bursting on 560 footwall drive during April-June 2000 has also led to a change in the timing of cone bolt installation for footwall drives. The cone bolts are to be installed as part of the development cycle, two cuts behind the face. Mesh and 1.8m, SS46 split sets are installed to the face of footwall drives, with split sets installed on a 1.1m row spacing along the drive and 1.2m across the drive. The mesh was changed in late 1999 from RF81 to M61 (6mm, 100 x 100mm, with additional strength welds specifically for mining applications) and is installed in 6 x 2.4m sheets. One sheet is installed across the drive starting at the hangingwall shoulder and an additional sheet cut to size to the footwall shoulder. Mesh is designed to extend down to 3m from the floor on both sides.

Six cone bolts are to be installed per row, starting from the hangingwall shoulder through 1.8m split sets, with hole lengths drilled to suit the cone bolt length. The two outer cone bolts are 2.4m and the four central bolts 3.0m in length. 4.0m bolts are installed through intersections.

**Strainburst Management**

Strainbursting of the face and immediate backs of the 560 footwall drive has necessitated sacrificial meshing of the face, with split sets to safeguard personnel during scaling, drilling and charging operations.

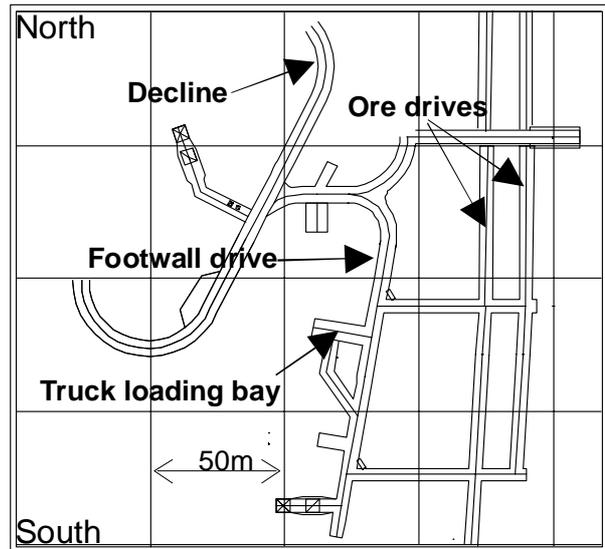
De-stress blasting ahead of the development face is also being undertaken in the footwall development and the decline to reduce the strainburst hazard. Two 4.2m holes are drilled up and out at 45° from the top corners of the drives. Each hole is charged with 1 x 700mm packaged emulsion, initiated with the first hole in the cut.

**Design**

A series of changes have been made to the design of footwall drives and associated excavations to reduce stress concentrations and exposure to large-scale damage from rockbursts.

Footwall drives have been moved further from the orebody, and diverge from the orebody away from the central access. This design increases the distance from the orebody to the footwall drive in the higher stress abutment zones from 20 to 40m and also places the footwall drive at a 10° angle to the foliation. The length of exposed foliation susceptible to rockburst shearing is minimised by ensuring the footwall drive is not parallel to foliation. Truck loading is no longer planned in the main footwall drive, with new truck loading bays orientated east-west off the footwall side of the footwall drives (Figure 9), and accessed via short (20m) loading ramps.

**Figure 9 - 560 South Level layout**



Service excavations such as sample bays and stockpile bays are also no longer planned off the hangingwall side of the footwall drives. These shorter excavations resulted in additional stress fracturing and stress redistribution shown to be detrimental to stability. The dimensions of footwall drives are also reduced past the truck loading bay access ramps, as trucks are not required to access these sections.

Extensive MAP3D modelling was conducted to assess the design options relative to principal and shear stress levels along the footwall drives.

Investigations are currently underway to assess the economic and design aspects of accessing the orebody directly off cross-cuts from the decline with truck loading bays located close to the decline. This would remove the requirement for footwall drives.

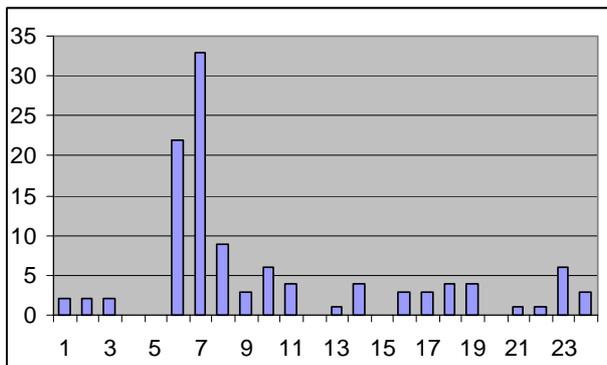
**Sequencing**

The staggering of stope faces by at least 25m was included in the stope extraction sequence to reduce the impact of stresses from one level onto the next. Development of footwall drives immediately below stoping abutments on the next two upper levels attracts higher mining induced stresses and subsequent strainbursting and back damage. Footwall drive development is currently prioritised in development sequencing. The aim is to have this development completed prior to stoping commencing on the next two upper levels.

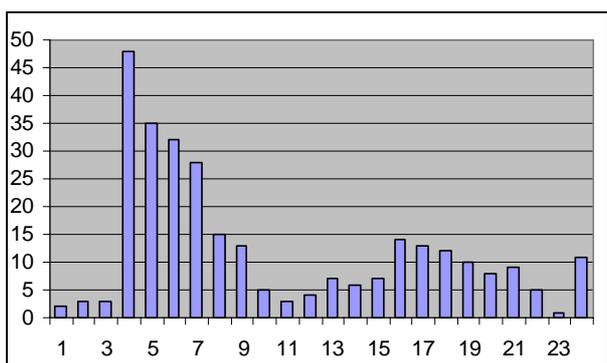
**Re-entry/exclusion zones**

The rockbursts at Big Bell have generally occurred within time periods and zones relative to stope blasting on the next level above the rockburst site. Extended re-entry periods covering these high-risk zones were implemented in mid-1999, thereby minimising the rockburst risk to mine personnel. The initial re-entry period covered 24 hours, with an exclusion zone on the level below, 50m prior to and after the blast northing. These precautionary restrictions were reduced to 12 hours and 25m in November 1999 after sufficient seismic data had been analysed to determine the lateral extent of seismic activity and following installation of rockburst resistant support. A typical graph of post blasting event decay is illustrated in Figure 10. No personnel are permitted within footwall drives during development blasting as one major rockburst was initiated by such activity (22 August 1999). A graph of activity per hour on the day of a major rockburst (Figure 11) indicates that occasionally seismic activity can occur outside blasting times and re-entry periods. On the same graph the resurgence of activity between 15:00 and 16:00 is unrelated to blasting.

**Figure 10 - Events per hour of 7 June 2000, following blast at 05:45**

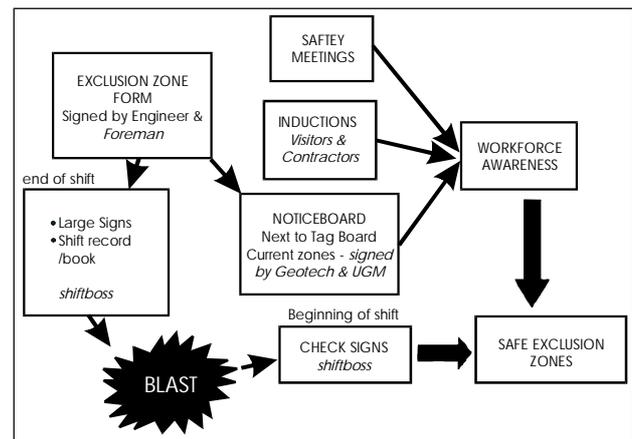


**Figure 11 - Events per hour of 17 June 2000, following rockburst at 03:27**



The nature of seismic activity and rockbursts, together with the importance of exclusion zones and re-entry periods, are discussed at weekly safety meetings with the underground workforce. The re-entry periods and exclusive zones are an integral part of managing the seismic risk and a matrix of communications routes and notices is used (Figure 12).

**Figure 12 - Exclusion zones and re-entry communications matrix**



**Conclusion**

Seismicity at Big Bell is a relatively recent phenomenon but is expected to remain with the mine as mining continues at depth. The onset of seismicity, with associated rockbursts, has required changes to stope sequencing, development designs, support and reinforcement systems. Access restrictions and seismic monitoring have also been introduced.

The seismicity at Big Bell is currently being successfully managed. Continued monitoring of performance should enable further improvements to be made to access development layouts and support systems to reduce the effects and impact of seismicity.

**Acknowledgement**

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Footnote: Big Bell experienced two  $M_L=2$  seismic events in June and July 2000, both associated with major rockbursts, and further analyses are being undertaken to assess source mechanisms and support requirements.