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Understanding Mine Seismicity—A Way to Reduce Mining Hazards at Barrick's Darlot Gold Mine

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Numerous underground Australian mines are operating in high stress ground conditions with seismicity and rockbursting becoming an increasingly common problem. The first modern microseismic system was not installed in Australia until 1994 and the formal research of mine seismicity in Australia was not started until 1999. Through research, development and technology transfer, the seismic monitoring system, a black box only a few years ago, has become a practical rock mechanics tool to aid in maintenance of underground production.

Presented in this paper are mine seismicity experiences in a Western Australian mine at a relatively early stage of a mining operation, as well as at increasing levels of extraction. Planning and sequencing of stopes has been used to manage and reduce risks associated with a burst-prone rockmass and large geological structures. Examples of effective planning and sequencing to manage the seismic risk at Darlot are outlined. Analysis tools such as MAP3D modeling and MS-RAP are used for back analysis of seismic data and identification of potential hazardous areas. The results from case studies are presented to show the effectiveness of using seismic monitoring in a day-to-day production environment.

1 INTRODUCTION

Although Australian underground mines have a long history of mine seismicity, systematic seismic research, to develop risk assessment tools, was not started until the late 1990's. The first modern seismic monitoring system was installed at Mt Charlotte, WA, in 1994 (Mikula and Poplawski, 1995), and was used to assist in the understanding of mine seismicity and to reduce the risks associated with large seismic events. Since the implementation of a seismic monitoring system at Mt Charlotte, the use of seismic systems as tools for the investigation of rockmass failure mechanisms in Australian mines has become commonplace. Seismic systems are used for investigating the caving mechanisms in block caving mines, slope stability in open cut mines, as well as failure mechanisms in underground narrow view and bulk mining operations. In addition to the use of seismic systems within the mining environment, many civil engineering projects are employing the use of a seismic system for investigative and monitoring purposes. Although the investigations significantly increased the knowledge of seismic impact on structural stability, there were few practical tools, designed for site engineers, to employ in their daily management of seismic issues.

In 1999, an industry-sponsored research project was initiated, coordinated by Australian Centre for Geomechanics (ACG). The project aimed at developing practical tools for daily use of seismic monitoring at Australian mine sites (Hudyma et al., 2002). Darlot Gold Mine was involved with the development of such practical tools and currently uses them to assess and reduce risks associated with mine seismicity.

2 DARLOT GOLD MINE

Darlot Gold Mine is located 350 km north of Kalgoorlie, WA. It is fully owned by Barrick Gold of Australia Limited, a business unit of the Barrick Group. The mine is accessed by road and charted air services. The operation is fly in fly out from Perth and Kalgoorlie.

Open cut mining at Darlot ceased in 1995 with the commissioning of underground mining. Mining is currently focused on the Centenary Deposit, discovered in 1996, and accessed from two declines. Conventional sublevel longhole open stoping is used for bulk stopes, with primary stopes filled with cemented aggregate fill and secondary stopes with waste rocks. Narrow vein orebodies are mined with up-hole benching and waste rock fill. Due to the relative shallow depth and scattered nature of the Centenary Deposit, a truck fleet is used for haulage. Mine production is scheduled at 800,000t of ore and 450,000t of backfill per annum with a projected mine life of eight years, to 2012.

3 GEOLOGY

The Centenary orebody at Darlot Gold Mine is a zone of stacked, shallow westerly dipping, gold associated quartz veins bounded between mineralized footwall and hangingwall reverse faults (45 degree dip, N-S strike). The mineralization is hosted within a magnetic dolerite unit, which is part of a 400m thick dolerite sill intruded within a moderate easterly dipping sequence of basalts and pyroclastic sediments.

Gold mineralization predominantly occurs within planar quartz veins and associated narrow alteration containing sericite, ankerite and hematite. Strongly mineralized zones are characterized by closely spaced veining, stock-work veining and brecciation.

Lamprophyre dykes intruded the dolerite and volcano-sedimentary sequences prior to gold mineralization. A regular array of large, sub-vertical, E-W striking faults cross cut the host dolerite of the Centenary orebody. The lamprophyre dykes are spatially associated with the E-W striking faults.

4 GEOTECHNICAL CONDITIONS

Rock strength is considered to be strong to very strong. From laboratory testing, the average Uniaxial Compressive Strength (UCS) of the gold bearing magnetic dolerite rock is 220 MPa. Flat dipping quartz veins are dominant structures and wedges are often formed with the presence of moderately to steeply dipping joints. Large faults dominantly control regional stability and are normally spaced at 30 – 50 m. Infill material of these faults is variable from soft sericite to hard

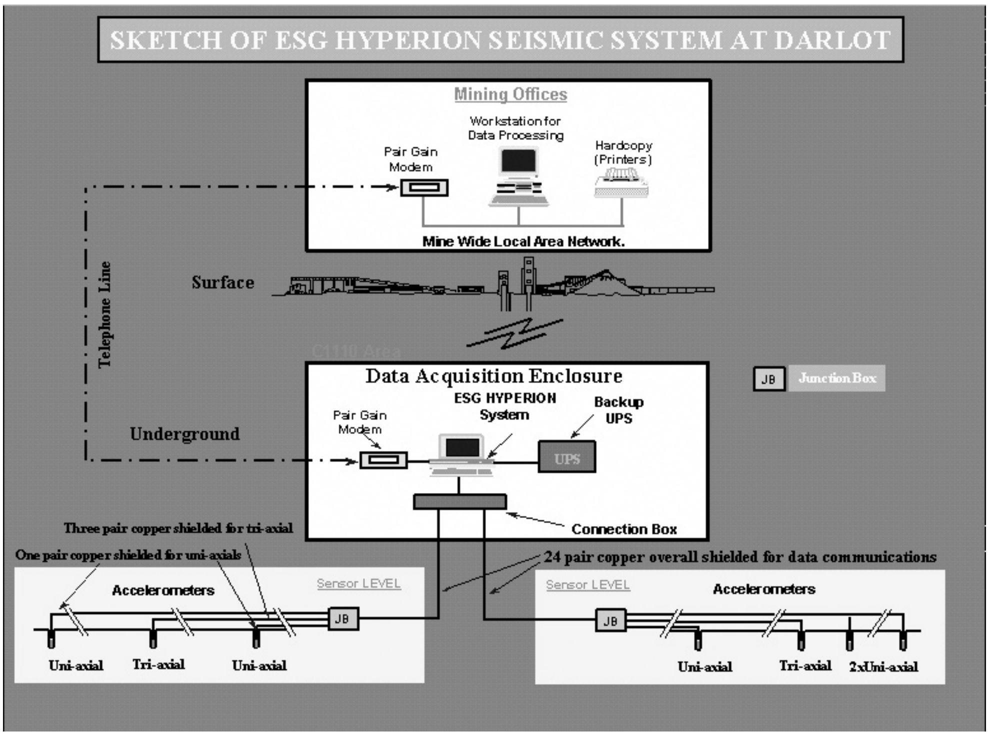

FIG. 1 Darlot Gold Mine Hyperion Seismic System

quartz. The rockmass between the faults is rated good to very good according to the RMR and NGI rockmass classification systems.

The magnitude of the stress field at the Centenary orebody is high. The major principal stress is shallow dipping on a SE – NW orientation and at 500 m depth has a magnitude of 60 MPa. Stress related strain bursting has occasionally occurred in highly silicified rocks such as quartz and felsics, and fault-slip rockburst concerns are associated with the major fault structures.

5 HYPERION SEISMIC MONITORING SYSTEM

An ESG Hyperion seismic system was installed in late 1999 to monitor mine seismicity and to investigate rockmass response to mining under the high stress conditions present. Initially the implementation of such a system was not expected due to the lower stresses encountered throughout the shallow Darlot underground mining area and with the initial mining experiences within the Centenary deposit. Mining was expected to be relatively shallow, having a depth limit of 600 m below surface. The use of conventional monitoring devices, such as extensometers, were originally proposed to monitor the relevant structures and stope backs.

After careful consideration, discussion and investigation a decision was made to install a seismic system early in the mine life. The mining of nearby deposits, such as those near Leinster, exhibited high stresses at relatively shallow depths and the possibility arose to extend mining of the Centenary orebody to depths in excess of 600 m. Due to the scattered nature of the Centenary orebody, conventional monitoring methods, such as extensometers, were deemed insufficient, as the only monitoring method to be adopted. An understanding of the overall rockmass behavior was critical for the mine planning process. The implementation of a seismic system provided the data to monitor the rockmass response to mining of the Centenary orebody.

A 24-channel ESG Hyperion Seismic Monitoring System was initially installed. There have been two subsequent expansions of the system, resulting in the present 48-channel system. A schematic of the layout of the Hyperion Seismic System is displayed in Figure 1. Due to the large distance between the mining offices and the underground development, a telephone configuration is utilized with high speed pair-gain modems to increase the data transfer rate from the underground acquisition computer to the surface processing computer. The use of the high speed pair-gain modems assists to keep the system connected with the surface at near real time. The seismic system currently consists of 8 triaxial accelerometers and 8 uniaxial accelerometers. The installation of additional sensors is completed on a regular basis as permitted by suitably located development.

6 SEISMICITY AND STOPING

Early mining within the Centenary orebody resulted in a relatively minor level of seismicity being recorded. This minor level was primarily due to the shallow depth of mining (220-320 metres depth) and to the methods of mining being employed. The mining of the Middle Walters lode (340-420 metres depth) started in mid-2002, and resulted in a significant increase in seismicity. Figure 2 is a magnitude time history chart for the event in the mine, which shows the dramatic increase in event frequency and event magnitude. The increase in seismicity was primarily due to higher stresses at greater depth and to the inclusion of rib pillars between stope panels, which concentrated stress within the stopes.

Analysis of seismic data from Middle Walters lode indicated that the seismic events recorded were generally a result of shearing of major structures or of rib pillar loading and failure. Figure 3 shows seismic events concentrating on rib pillars in the Walters zone. It was found that the rib pillars, consisting largely of brittle burst prone quartz, exhibit substantial fracturing and spalling. The spalling of the rib pillars has resulted in diminished pillar size and increased stope size, leading to significant hangingwall instability. For this reason, mine scheduling was adjusted to ensure only one panel was open at any time, with the previous panel fully backfilled before the following panel began. This has helped to reduce rib pillar deterioration and hangingwall overbreak. The panels were typically filled with development generated

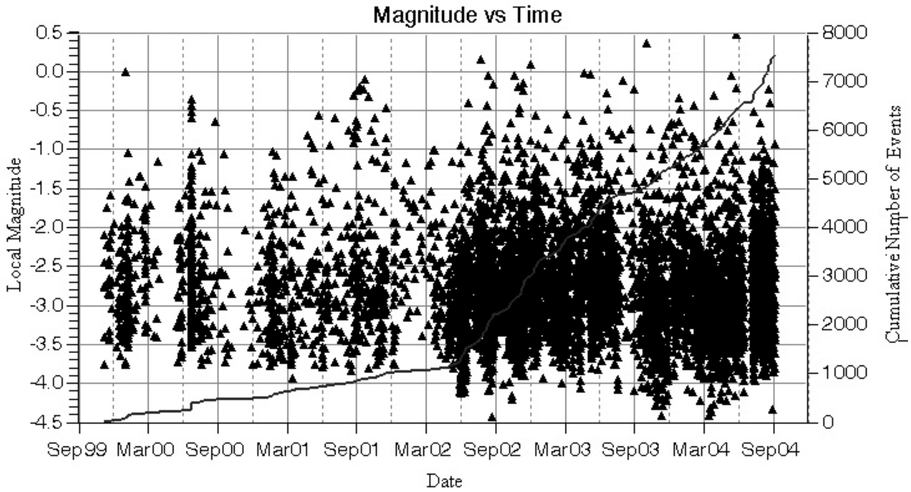

FIG. 2 A magnitude time history chart for the events at Darlot shows the increase in seismicity from 1999 to 2004. There was a dramatic increase in the number and magnitude of events starting in early 2002

rough waste, with the addition of a Cemented Aggregate Fill (CAF) layer on top. To further assist in hangingwall stability, CAF was placed tight against the hangingwall on the top drill drive.

The Lillee bulk stoping lode, presented concerns relating to the possible violent shearing of major geological structures passing through the block. Such events would have adverse consequences on mine safety and production. Sequencing the stopes within the Lillee lode to mine away from structures likely to shear has been a strategy successfully used to reduce the likelihood of a significant violent rockmass response. To reduce the exposure of the workforce to risks from stope blasting associated seismicity, a seismic event decay study was undertaken to determine an acceptable re-entry time after blasting. Figure 4 shows a typical seismic event decay chart for a blast in the Lillee lode.

A six-hour re-entry delay after stope firing was chosen, as after this period of time, 80-90% of the post-blast seismic energy had been typically released. The remaining 10-20% of energy was largely experienced as smaller seismic events unlikely to cause any significant rockmass damage. Production has continued in the Lillee stoping lode with no significant sized seismic events (local magnitude > -1) being recorded in the Lillee Stoping block outside the six-hour re-entry delay.

7 DAMAGE DUE TO LARGE SEISMIC EVENTS

In recent times, seismic events have been associated with significant rockmass damage in mine development. A Richter scale +1.6 (local magnitude +0.4) was recorded near the T1000RL intersection (460 metres depth) on 2nd November 2003. No blasting had occurred directly prior to the event, which resulted in a 20 m length of drive being damaged. Figure 5 shows the seismic system location of the event and the associated rockmass failure. The damage blocked off access along the T1000 crosscut (XC). The drive was supported with 2.4 m friction bolts and mesh, whilst 6.0 m long, twin strand cablebolts, in addition to the friction bolts and mesh, supported the intersection. The rockmass within the area was considered highly jointed with no major faults or shears immediately present.

The nearest recent mining to the location of the damage was at a distance of 30 m vertically on the T1030RL level. Mining in this level has been undertaken along the Oval Fault and other associated sheared structures. The sheared structures vary in thickness, with the most definitive sheared zone being in the hangingwall of the Oval Fault. The oval Fault sheared zone varies in thickness from 1 m to 10 m and is infilled with heavily sheared material including soft sericite and chlorite. No definite conclusion could be drawn relating to the cause of the seismic event, although it is believed the adjacent mining activities on the T1030RL level and the response of the Oval Fault to the mining are associated. The damaged area was rehabilitated with cement grouted bolts, mesh and fibrecrete. While further mining on the T1030Rl level has continued, no further damage has been experienced since rehabilitation.

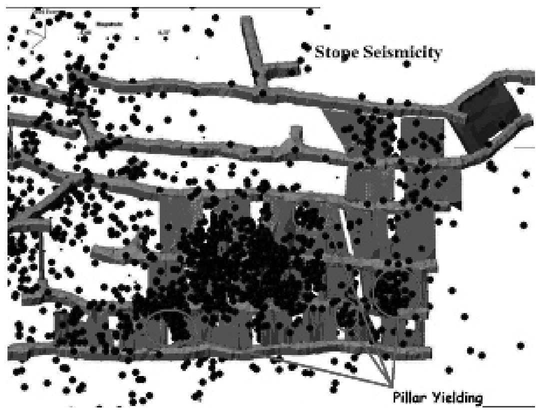

FIG. 3 Seismic events recorded in the Middle Walters stoping lode

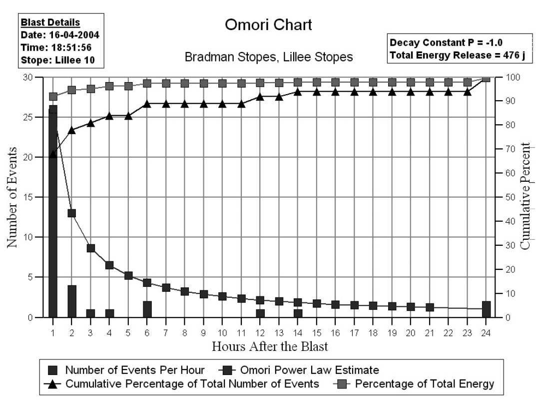

FIG. 4 Seismic event decay curve (Omori Analysis) following a stope blast in the Lillee lode

Another seismic event assessed at Richter magnitude +1.7 (local magnitude +0.5) was recorded at the W965 intersection (500 metres depth) on 23rd June 2004. A rockfall of approximately 250 tonnes occurred within the intersection, completely blocking access to the W965 level. The event occurred 14 seconds after a development blast in a drive was fired one sublevel above the intersection.

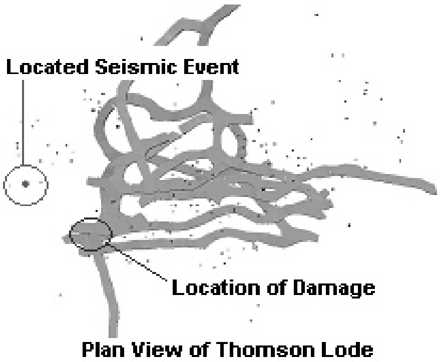

FIG. 5 Location of T1000 damage

Several faults have been mapped through and around the intersection with the area being identified as a "hot-spot" for seismicity. Development mining in this area resulted in anomalous levels of seismicity directly after firing, including several 'significantly sized' seismic events (local magnitude > -1). Due to the span of the intersection and presence of the structures within the intersection, additional twin strand cablebolts had been installed in the intersection, along with the normal regime ground support before the event.

The extensive rock fall reduced the pillar between W965 and W980 levels (960RL – 980RL) from 15 m to only 7.5 m. Substantial rehabilitation work was required to rebuild the access. Fibrecrete was used to secure the failed area before the intersection was backfilled with high strength cemented aggregate fill, through which the W965 access was re-developed. This process delayed operation on both the W965 level and W980 level and considerable labor and material was required for the rehabilitation.

In both the T1000XC and W965 level rockbursts, development mining in proximity to major faults triggered the seismic events. Stope blasting was distant and unrelated to occurrence of the events. It is believed that development mining near some mine faults may trigger the release of tectonically stored energy on the structures. In hindsight, anomalous levels of seismicity associated with development mining, identified these areas as being distinct from other development areas in the mine. This pattern has now been observed on several occasions in the mine. Vigilant analysis of seismic data on a daily basis has the potential to recognize structures prone to large triggered seismic events.

8 FAILURE MODES AND MECHANISMS

During the stoping of the Centenary orebody, the rockmass behavior is closely monitored. Pillar behaviour is recorded for back analysis and hangingwall performance is observed. MAP3D stress modelling is employed to develop models through which the failure criterion of the stope-scale pillars can be determined. Figure 6 displays modelling results and a potential failure criterion for narrow vein pillars in the Walters lode.

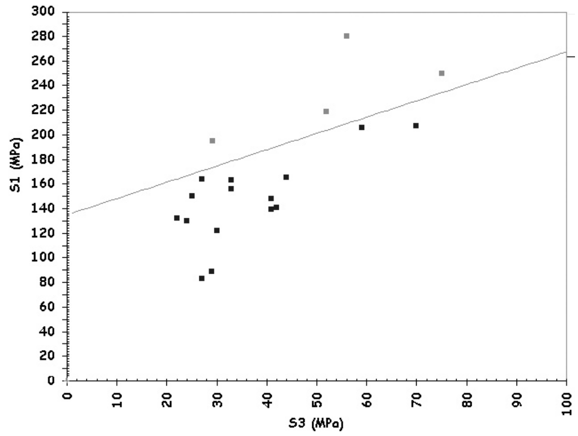

FIG. 6 Numerical modelling results and a failure criterion for rib pillars in the Walters Lode

Based on back analysis of seismic events, the seismicity within the Centenary orebody cannot be attributed to any one particular mechanism. Trifu, Shumila and Chen (2002) analysed the failure mechanisms of 78 microseismic events using a moment tensor approach. The results indicated that most of the larger seismic events are associated with stoping within the orebody. Evidence from the study also suggests some of the seismic events were associated with the Centenary orebodies major geological structures. Initial concerns were raised with the possibility of experiencing large-scale fault-induced seismicity. These concerns still remain, as the mechanisms and interactions of many of the larger recorded seismic events are still not fully understood.

9 HAZARD IDENTIFICATION AND RISK ASSESSMENT

Hazard identification and risk assessment is currently aided through the implementation of the Mine Seismicity Risk Analysis Program (MS-RAP) developed by the ACG through the Mine Seismicity and Rockburst Risk Management project. MS-RAP uses a self-similar clustering technique to create logical subsets of seismic events that can be easily analysed using a number of methods. At Darlot, the clusters defined by the program are placed into 'Groups' associated with different mining lodes in the mine. The clusters and groups of seismic events are analysed to estimate relative seismic hazard and likely seismic source mechanism.

MS-RAP is essentially a relational database with mine seismicity analysis tools. The goal of the program is to take maximum advantage of the full seismic history in a mine to better understand seismic hazard and seismic source mechanism in the mine.

Omori Analysis (Time-Decay) of the seismic response to mine blasting has been of considerable value. The initial time-decay study within the Lillee lode has been used to as an example to develop local re-entry times for each of the lode in the mine. Although used as a guide to the expected seismicity, the Omori Analysis process has also allowed other factors to be investigated, such as blast size, and stope and orebody geometry.

The identification of seismic hotspots, or areas of elevated seismic hazard, is related to several functions within the MS-RAP program. Each group of events is assigned a hazard rating according and when combined with the available functions, an understanding of the seismic hazard potential and mechanism for each mining area can be estimated.

Frequency-magnitude (b-value) analysis is widely utilized at Darlot Gold Mine to determine the potential for the largest predicted seismic event for each area of the Centenary

Orebody. Figure 7 contains a frequency-magnitude chart for a subset of events in the mine. Frequency-magnitude analysis of seismicity in each mining block in the Centenary orebody has shown that the x-axis intercept of the relation is a good estimate of the maximum event size in each mining block. Due to the violent, destructive nature of seismic "shear" failures, identifying locations of high seismic hazard is advantageous for both mine planning and for the required ground support. Combining the b-Value analysis with S-wave to P-wave energy analysis provides an insight into possible locations where future large shear events may occur. Altering stope design, firing sequence or ground support are some of the risk management techniques applied to supplement mine safety and avoid production interruption.

The use of Diurnal Charts (time of day analysis) for each of the mining areas also provides insight into the locations where the seismicity is not directly related to development or stope firings. These locations have a higher seismic risk due to the increased likelihood of a larger seismic event occurring unrelated to firing time when mine personnel may be present.

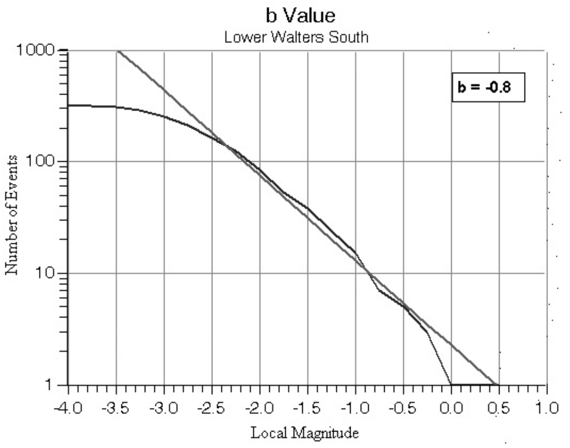

FIG. 7 **Typical b-Value analysis for a mining block at Darlot**

Magnitude time history analysis is particularly useful in understanding the seismic response to mining. The occurrence of events is plotted over time, along with a plot of the cumulative number of events. A typical magnitude time history chart is shown in Figure 8.

The magnitude time history chart contains a number of valuable pieces of information:

- It shows the seismic response to mine blasting and when the large events are occurring compared to mine blasting.
- The chart shows the largest event to occur in the dataset, which is an indicator of relative seismic hazard.
- The Cumulative Number of Events line shows how seismic event frequency of occurrence changes over time.

10 DISCUSSION

Throughout the past five years of seismic monitoring at Darlot Gold Mine, a large amount of information has been gained in understanding the seismic related failure present within the Centenary orebody. The transition from a seismically quiet mine to one exhibiting moderate levels of seismicity has occurred with the progression of mining within the deposit. Recent analysis and discussions have suggested that mine seismicity can be classified into stages. Each stage is characterised by several factors, and is often influenced by level of mine extraction and the mining method and mining practices used.

Stage I, Quiet Stage

The initial Quiet Stage can be defined as the periods where limited seismicity occurs, even during periods of active stoping. The few events that do occur are generally of lower magnitude and tend to occur directly following mine blasting, and cause minimal damage in the surrounding rockmass. The relative seismic risk at this stage is low.

Stage II, Transition Stage

During the Transition Stage, seismicity increases with stoping activity and the magnitude of events experienced is also expected to increase. Stope sequencing and orebody geometry become important planning considerations due to the likelihood of seismic related damage around active mining areas. Larger, damaging seismic events become more common, resulting in an increase in the relative seismic risk to a medium rating. Darlot Gold Mine is considered to be within the Transition stage.

Stage III, Active Stage

The Active Stage sees the number of large seismic events increase dramatically. Large seismic events are more likely to cause substantial damage to nearby structures, often resulting in a seismically influenced production schedule. Stope design

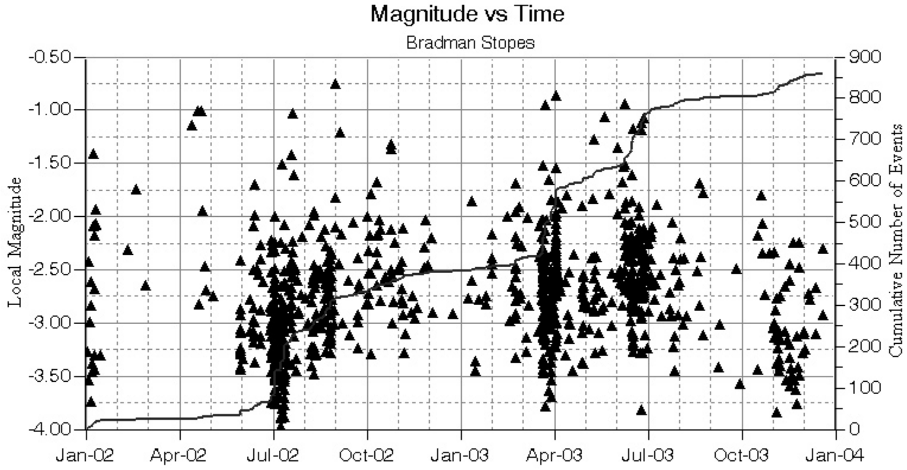

FIG. 8 **Magnitude time history chart for events in the Bradman stoping block at Darlot**

and global sequencing to manage seismic hazard becomes of utmost importance. A high seismic rating is associated with the mine and a well-developed risk management program is required. In some instances, safe mining may no longer be economically feasible.

Several indications suggest that Darlot may enter the Active Stage. High horizontal stresses have been measured at depth, sheared faulting oriented acutely to the principal stress direction is widely present, and burst prone rock types are common throughout the mine. Currently, sequencing of the remainder of the resource is being reviewed in an attempt to decrease seismic hazard in several identified high risk areas. The ground support practices are being reviewed to ensure all development, both long and short term, is being supported adequately to ensure the safest practical working environment.

11 CONCLUSIONS

One of the unique geomechanical characteristics in West Australian mines is the influence of high stresses at relatively shallow depths. Many Western Australian mining operations have had great difficulties in coping with the "sudden" deterioration of ground conditions associated with relatively small increases in mining depth and a lack of experience in dealing with high stress and seismically active conditions. This lack of experience has sometimes resulted in mine management utilizing conservative mining strategies, generally incurring high operational costs and/or capital costs.

The unexpectedly difficult ground conditions have sometimes left the mine management with no plan regarding the management of risks associated with such a change. Due to this lack of preparedness, the workforce could potentially be exposed to a hazardous burst prone environment.

A seismic monitoring system was proactively installed at Darlot in 1999. No large events or rockbursts had occurred in the mine prior to seismic monitoring. The seismic database collected since early in production mining has provided an invaluable tool to understand the dynamic rockmass response to mining. Five years of seismic monitoring and development of associated risk management tools has enabled Darlot Gold Mine to identify, manage and sometimes mitigate geotechnical risks associated with high stress and rockburst conditions.

Establishing risk management strategies is important in reducing risks in personnel injuries, equipment damage, and avoiding mine production losses. Rockbursting conditions are best managed using an experienced management, technical staff and workforce team. The installation of the seismic monitoring has been well justified by increasing the level of experience and knowledge of the problem.

Identification of hazardous areas (hot-spots) is important for the management of rockburst risks. Development intersections containing lamprophyre dykes, major continuous joints and/or faults are considered to have higher rockburst damage potential. Although the highly siliceous quartz is prone to fracturing, it is not considered highly hazardous due to its very brittle nature and low UCS. At Darlot, seismicity in a quartz dominated rockmass usually occurs with a lower energy level.

Stope sequencing is also important in reducing rockburst hazards. Retreating stopes away from seismically active faults is often used to reduce the risk of rockbursting. This practice has been well integrated into the mine planning and design routines at Darlot. Stope firings are also planned with seismic considerations to reduce the associated seismic risk. Reducing volume of explosive in each delay and reducing number of blasts for each stope assists in minimizing the seismic hazard.

MS-RAP is a useful tool for analyzing and presenting seismic data. The clustering technique is proven to be important for hazard identification thereby enabling site engineers to manage risks associated with the identified hazards. Incorporating several of the MS-RAP functions enables the source mechanisms of the numerous clusters to be investigated and appropriate actions to be taken to manage the associated hazards.

The seismic monitoring system was once an under-utilized black box for site engineers. Through exploring the potential of a seismic system, experienced management and technical staff have made it possible for such a system to become a practical daily production management tool. The understanding of the seismic system has also made it possible for seismicity and the associated risks to be handled at the front line production management level.

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