Research on the prediction of rockbursts at Western Deep Levels

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SYNOPSIS

Recent research into the prediction of mining-induced seismic events by the monitoring of small microseismic events at Western Deep Levels Gold Mine is described. Measurement and interpretation techniques and results are presented.

It was found that the occurrence of the larger events near longwall faces on the Carbon Leader reef is preceded for some hours by an increased rate of microseismic emission and spatial concentration of the microseismic events in the zone of eventual failure.

The research is currently being expanded with the aim of producing a practical rockburst early-warning system.

SAMEVATTING

Navorsing om mynbou-geïnduseerde seismiese gebeure te voorspel deur middel van die waarneming van klein mikroseismiese gebeure by die Western Deep Levels goudmyn word beskryf. Metings- en interpretasie-tegnieke sowel as resultate word aangebied.

Daar is gevind dat seismiese gebeure in die omgewing van strook-afboufronte op die Koolstofgidslaag 'n aantal ure voorafgegaan word deur 'n verhoogde frekwensie van voorkoms en konsentrasie van mikroseismiese gebeure in die gebied van uiteindelike swigting.

Die navorsing word huidiglik uitgebrei met die doelstelling om 'n praktiese vroeë-waarskustelsel teen rotsbarstings daar te stel.

Introduction

The paper describes research carried out over the past four years at Western Deep Levels (WDL) in an attempt to predict potentially hazardous rockbursts by the monitoring of very small seismic events (i.e. microseismic events) prior to the occurrence of the main seismic event. The initial results of this research work were highly favourable, and have prompted a major expansion of the research effort aimed at the development of an operational early-warning system.

WDL is a deep-level goldmine in which 45 per cent of the mining activity takes place at a depth below surface of more than 3000 m. The reef is extracted to a height of 1 m by means of drilling and blasting, and the general shape of the longwall is overhand. The longwall faces are divided on dip into panels that are 30 to 40 m long separated by 11 m leads. Nearly all the development is in the footwall following the longwall faces, which advance on strike at approximately 8 m per month. Fig. 1 is a plan view of the working area covered by the research work. Apart from a 2 m thick bar of chloritoid shale, which is known locally as Green Bar, 2 m above the reef, the country rocks are hard, dry, glassy quartzites with a uniaxial compressive strength of about 200 MPa.

Owing to the depth and extent of mining, seismic events are a common feature, with as many as 1200 being detected and located per month[1]. About 1,5 per cent of the seismic events radiate waves of sufficient intensity to cause visible damage in the workings or injury to personnel; these events are called rockbursts[2]. Rockbursts are the largest single cause of underground fatalities at WDL, being responsible for 46 per cent of all fatalities. The average rockburst fatality rate is 1,0 per thousand per annum, as against 0,19 per thousand per annum in a sample of five shallower mines. Rockbursts also interrupt production and discourage the introduction of costly mechanized equipment into stopes[2].

The prediction of seismic events to allow timely evacuation of men and equipment from the areas likely to be affected by the rockburst is one of several approaches currently being followed to ameliorate the serious rockburst problem in South African deep-level gold mines[2].

The first research on the prediction of rockbursts was instigated by the U.S. Bureau of Mines[3] in 1938. It was discovered that the instability of an excavation was preceded by a number of microseismic events generated in the surrounding rock. Neyman *et al.*[4,5] in Poland, Brady[6] and Langstaff[7] in the U.S.A., and Hallbauer[8] and McNaughton[9] at WDL noted increased microseismic activity before rockbursts without establishing a clear predicative relationship.

The results of Hallbauer and McNaughton motivated the Anglo American Corporation and the Chamber of Mines to establish the Rock Burst Project at Western Deep Levels in 1973, with the development of rockburst prediction as one of its prime tasks.

The research was aimed at a determination of whether individual seismic events could be predicted in time and space and whether a practical early-warning system could be implemented in the mining environment. The system would have to satisfy the following requirements:

(a) high effectiveness of prediction,
(b) low false-alarm rate,
(c) accuracy in space and time.,
(d) economy of installation and operation, and
(e) indication of the size of the impending event.

It was clear that the major problem of any prediction system would be the production losses suffered while men were evacuated awaiting a rockburst and the extreme

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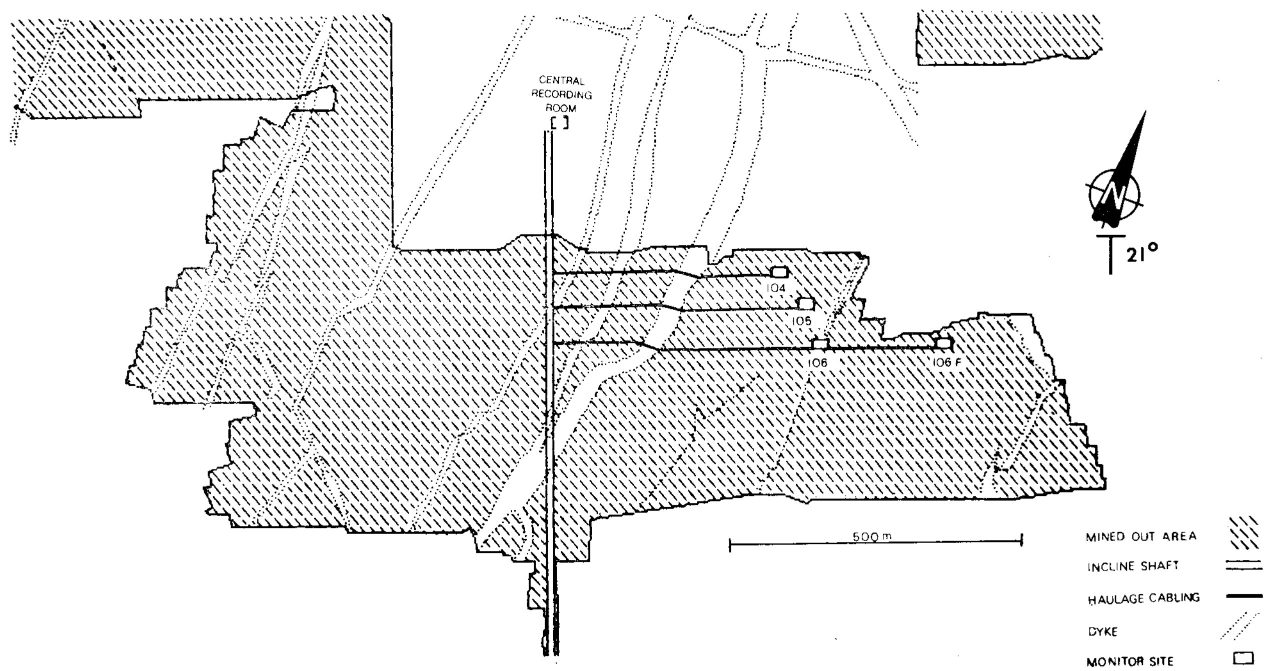

Fig. 1—Plan of the microseismic network (the central recording room is at a depth of 3000 m)

difficulty of deciding when to send men back into an evacuated area if the prediction appeared false. As these problems would be minimized by accurate predictions, it was felt that the expenditure on sophisticated equipment and thorough research was justified.

Detection of Microseismic Events

The microseismic events used in the research range in size from Richter magnitude –1,0 to smaller than Richter magnitude –3,0.

A typical microseismogram and an averaged power spectrum as recorded at 125 m from the source are shown in Fig. 2. The events have a root-mean-square (rms) acceleration of about 10^{-4} g (1 g = 9,8 m/s^2). By the use of methods described by Spottiswoode and McGarr[10] the average radius of the source region of the event was calculated to be 1 m or less.

Experience elsewhere[11] in the location of such small events with conventional geophone arrays was not encouraging. In the present work, it was decided at the outset that a major departure from conventional practice should be adopted, and single high-quality three-dimensional transducers were installed so that each event could be located from one site only, monitoring a spherical volume of rock 200 m in radius. Reliable detection and analysis of the extremely small, high-frequency microseismic signals required ultra low-noise and low-distortion instrumentation, much of which was developed locally.

Piezoelectric accelerometers are used as transducers of the microseismic signals because geophones are unsuitable in the higher-frequency range. The sensitivity of the microseismic monitoring system is critically dependent on the amount of electrical noise generated within the accelerometer. The present level, achieved by the individual selection of units from the best available makes, is equivalent to an acceleration of 5×10^{-5} g and still allows for considerable improvement, which would be highly beneficial in the resolution of the signals.

The accelerometers have a transverse sensitivity of less than 5 per cent, so that the output is almost entirely a measure of ground motion along their axes. This is essential for accurate location of the events. Their shock limit is over 5000 g to ensure survival from high accelerations in the resonant band of the accelerometer caused by nearby seismic events and blasting. Their useful lifetime is typically two years, after which time they have been left too far behind the stope faces.

The accelerometers are mounted to form an orthogonal triaxial unit, which is installed in an NX borehole drilled vertically downwards from a haulage 15 m below the reef and close behind the faces. The borehole is made at least 15 m deep to take the accelerometers out of the zone of highly fractured rock around the haulage. The unit is orientated parallel to the mine coordinate system by means of a north–south line established at the mine survey department, then permanently fixed at the bottom of the hole, and tightly coupled to the rock by expanding cement. After filtering, amplification, and frequency modulation with low-noise electronics, the accelerometer outputs are transmitted over coaxial cables to the shaft, where they are demodulated and transmitted over unscreened telephone cables to the surface[12].

To utilize the sensitivity of the microseismic transducers, very low-noise amplifiers were designed and constructed. A noise level. referred to input, of 0,7 μV for a bandwidth of 500 Hz to 10 kHz is maintained. As the gain of the amplifier is 80 dB, an output sensitivity of 2000 V/g is obtained for an accelerometer sensitivity of 200 mV/g.

The frequency modulation is obtained through an off-the-shelf voltage-to-frequency converter with a carrier frequency of between 40 and 80 kHz. The carrier frequen-

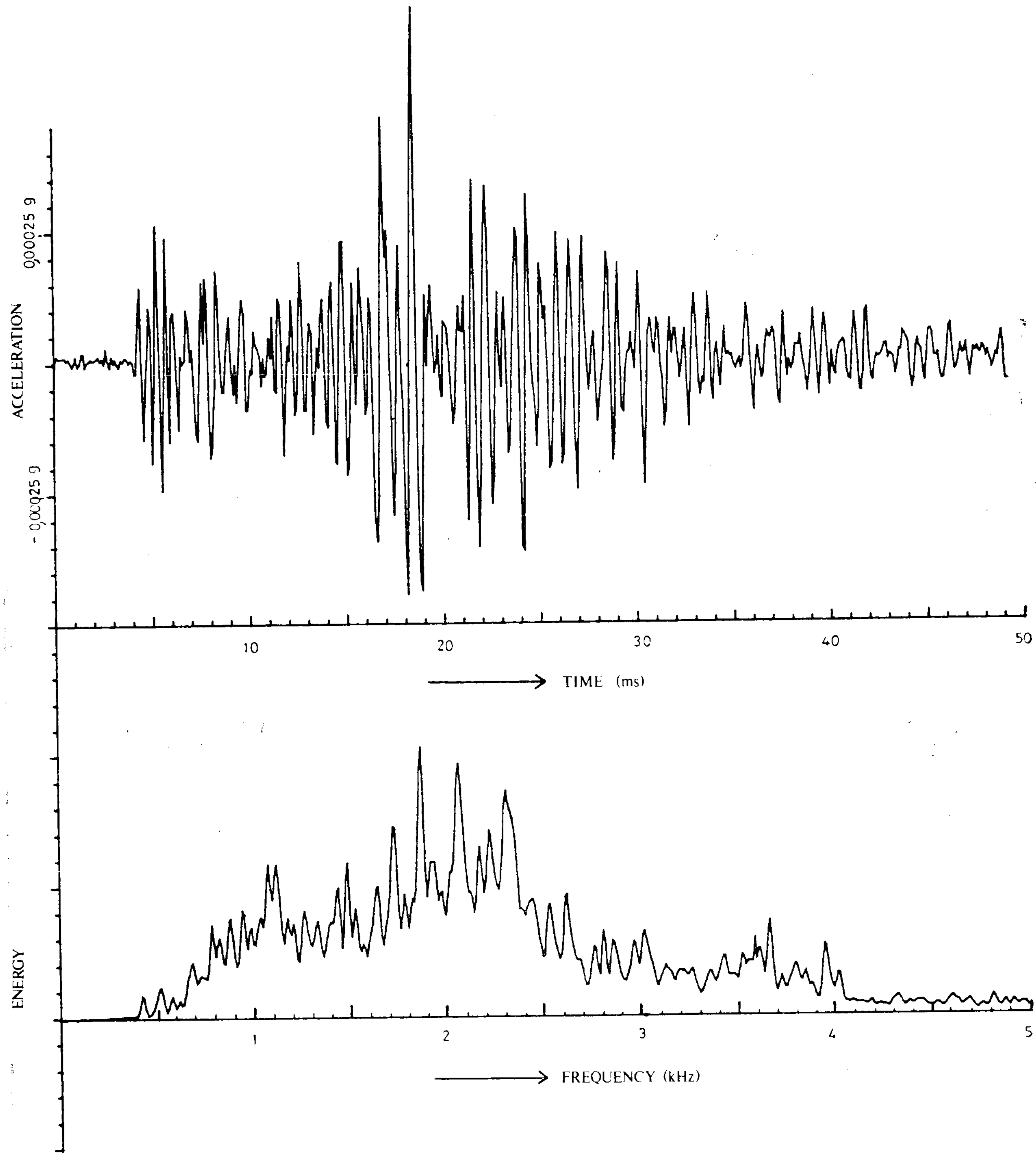

Fig. 2—A typical microseismic event and an average power spectrum

cies are selected judiciously to prevent any intermodulation products falling in the bandwidth of the wanted signal, i.e. a carrier frequency of about 5 kHz.

On the surface, the demodulated signals are received by differential amplifiers that eliminate the common-mode noise. Subsequently, the signals are bandlimited between 500 Hz and 5 kHz. For every three channels from one monitoring position, a fourth component, being the sum of the squares of the three channels, is generated and is used for the detection of events after digitization of the analogue signals.

The relative and absolute calibration of the three channels is maintained by the periodic introduction of a common signal from a laboratory-calibrated source at the outputs of the accelerometers. A comparison of the input with the signals actually obtained on the surface establishes the gain of each channel. The accelerometers are individually calibrated (in mV/g) by the manufacturer.

Recording of Events

The 41E longwall was chosen as the experimental site since it exhibits intense seismic activity. Four (later five) monitors were installed, the signals being recorded on an instrumentation tape-recorder situated at 100 Level, with the tapes subsequently being brought to the surface for playback. Since June 1979, only one monitor has been used at a time transmitting direct to the surface.

Recording started in June 1977, and continued between 20h00 and 06h00 nightly and continuously over weekends until June 1980. Blasting-induced activity, overloading by the noise from rock-drills, and the use of the necessary computer facilities for other tasks prevent operation of the present system during the rest of the day.

The processing of signals on the surface consists in event detection, event recording, and event location. The volume of data to be handled at each stage is so large (for example, the event-detection phase must scan 30 000 values per second) that programs were written to completely automate all of the signal processing and seismographic analysis. After being amplified, the analogue signal from each channel is low-pass filtered to prevent aliasing, and is then sampled and digitized by an analogue-to-digital converter. The digitized data are fed to a minicomputer for processing, the input being continuous at the rate of 10 000 samples per channel per second irrespective of whether a seismic event has occurred.

With an average duration of 50 ms for microseismic events, and a repetition rate of about 2 events per minute, the recorded data consist of microseismic events and unwanted noise in a ratio of almost 1 to 1000. Essential for further analysis is the rapid and reliable automatic extraction of seismic signals from the background noise. The criterion of event detection is a rise in the short-term (6,4 ms) over the long-term (400 ms) average amplitude[13].

A two-stage trigger is used in which all the data are rejected until a single sample from the sum-of-squares channel exceeds the trigger threshold. The average signal level over the next 64 data points is calculated and recompared with the trigger level; only if the average value is acceptable is the signal considered to contain an event. The procedure is necessary to eliminate noise spikes while at the same time giving a high throughput of data. The triggering thresholds are reset every 400 ms on the basis of ambient noise level.

The initially selected events are further edited to select only events consisting of the complete seismic signal, and are corrected to maintain accurate relative calibration. The three (X, Y, Z) components of the event, together with timing and synchronizing information, are stored on digital magnetic tape. The detection and recording of events are performed in real time, and the programme must therefore simultaneously read in new data, search for events, and output the selected information. Programming in ASSEMBLER language is necessary to attain the requisite speed. Several hundred microseismic events are recorded nightly. Since most of these events are not associated with major seismic events, it is thought that they derive from the normal extension of the fracture zone ahead of the stope faces[14]. To distinguish between these and true precursory activity requires analysis of the seismograms and location of the foci of the individual events. This is rendered possible by the excellent component resolution of the triaxial accelerometer unit (Fig. 3). The location of the foci of individual microseismic events and the study of their distribution are a novel feature of this research programme.

The focus of each event is located by the establishment, first, of the line of propagation of the seismic waves, and, then, the distance between the source and the detector. The seismic signal consists of a longitudinal p-wave travelling at 5800 m/s and a transverse s-wave travelling at 3600 m/s. The line of propagation is parallel to the ground motion set up by the p-wave. An algorithm to calculate this direction from an analysis of the motion of the p-waves detected by the three accelerometers is given in the Addendum. Only the first ten samples (1 ms in total) of the seismic signal are used in the analysis to ensure a pure p-wave. When the line of propagation has been established, the source is constrained to be along this line, and the location is completed by the determination of the source–detector distance. This distance is calculated by the standard technique of measuring the difference in arrival times of the s- and p-waves.

If

Tp = arrival time of the p-wave,
Ts = arrival time of the s-wave,
Vp = velocity of the p-wave (5800 m/s),
Vs = velocity of the s-wave (3600 m/s), and
D = source–detector distance,

then $Tp = D/Vp$ and $Ts = D/Vs$.

Therefore, $$D = (Ts - Tp)\,\frac{Vs \times Vp}{Vp - Vs}$$ or

$$D = 9{,}49\,(Ts - Tp),$$

where D is in metres and $Ts - Tp$ in milliseconds.

The onset of p-waves is taken as the start of the signal, while the onset of s-waves is marked by an increase in signal amplitude. However, a study of Fig. 2 shows that the onset of s-waves may be difficult to detect, even by an experienced human interpreter, who may use subtle changes in wave-form to assist him. Reliable automatic estimation requires mathematical rotation of the coordinate system to separate the p- and s-waves, followed by low-pass digital filtering to detect the envelope of the signal and numerical differentiation of the envelope to enhance the increase in amplitude associated with the onset of s-waves. Fuller details are given in the Addendum.

Locations can also be performed in real time, and microseismic activity in a particular area can therefore be extracted from the general activity and monitored.

The accuracy of location was tested on signals from hammer-blows struck at a surveyed point in the haulage one level above (30,6 m) and 176 m away from an accelerometer site. The results showed a 95 per cent probability[15] of locating an event within 20 m at a range of 200 m. The signal-to-noise ratio (SNR) of the hammer signals was lower than the SNR for most microseismic signals, which should give better results.

With only one accelerometer unit, there is an ambiguity in location since no transducer can distinguish between a compressional pulse from one direction and a rarefractional pulse from the diametrically opposite

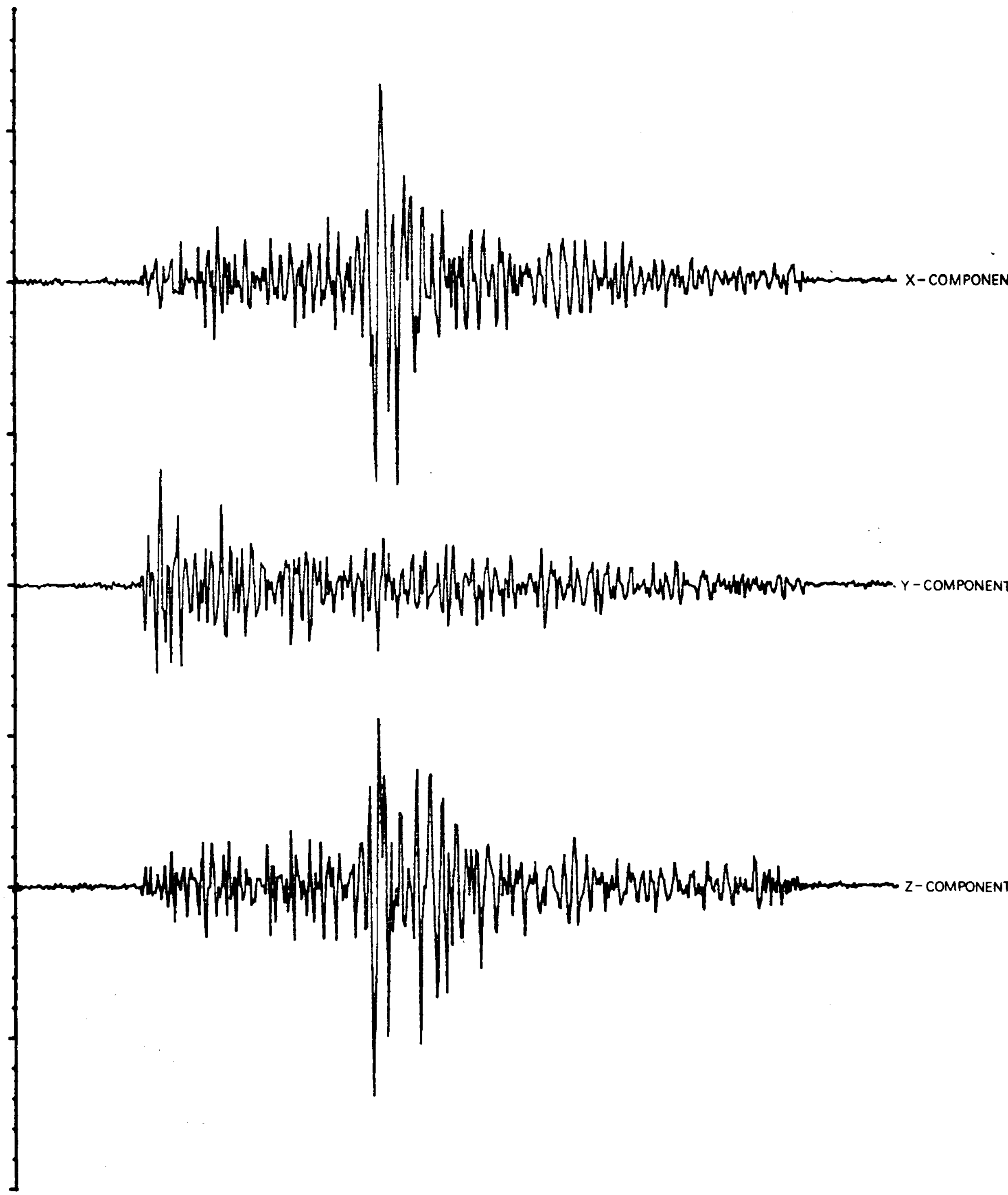

Fig. 3—A selected event (that on 18th August, 1978) to illustrate component resolution

direction; hence, two possible foci are obtained. In practice, this is not a serious difficulty because the two locations are well separated and one is usually in an improbable area for an event. The most likely and most dangerous location is that closest to the faces.

Results

Seismic events within the area monitored by the accelerometers were preceded by an increased level of microseismic activity, which concentrated in the zone of eventual failure. There was usually a short-lived marked drop in activity immediately prior to the event.

Changes in the power spectra and size distributions of events were investigated[16] without the uncovering of any predictive properties.

Some individual results are discussed below. As they were all obtained before real-time monitoring had been developed, the activity patterns could be analysed only after the occurrence of the events.

Event Recorded on 18th August, 1978

A medium-sized seismic event (Richter magnitude 1,5) was recorded at 05h18 on the 18th of August, 1978. The detailed plan of the workings at that date is shown in Fig. 4. The exact position of the Trevor Dyke was subsequently determined. The location of the event was obtained from the mine-wide seismic network. An accuracy of about 20 m in this area was achieved with the mine-wide network.

Microseismic recording started at 21h16 on the 17th of August and continued until 05h45 on the 18th. Examination of the foci showed a hyperactive volume of rock between 15 and 40 degrees in azimuth from north, between 50 and 70 degrees in elevation from vertical, and between 72 and 108 m away from the detectors (Fig. 4). The microseismic emission rate from this volume was 11,25 events per hour, i.e. 4,3 times the ambient rate observed in the area. The spatial and temporal distribution of the events and cumulative seismic energy (uncorrected for distance) are shown in Fig. 4.

Three quiet periods, each with a duration of approximately 30 minutes, occurred prior to the rockburst.

Event Recorded on 29th September, 1978

A small seismic event (Richter magnitude 0,3) was recorded at 00h24 on the 29th of September, 1978. The layout of the Lower Carbon Leader on that date and the distribution of the precursive events are shown in Fig. 5. The diagram shows that the majority of microseismic events had shifted away from the faces to the Trevor Dyke. At that time the dyke was not intersected by the faces and, at the closest point, was more than 20 m ahead.

Again, an increase of more than 5 times the average emission rate for microseismic events was recorded. A 25-minute period of low seismic energy immediately preceded the seismic event, after an earlier quiet period of 1 hour and 20 minutes before the event.

Event Recorded on 13th October, 1978

A small seismic event (Richter magnitude 0,4) occurred at 00h35 on the 13th of October, 1978. Two potential source areas are distinguishable in Fig. 6, one close to the face positions and the other on the Trevor Dyke.

No changes in the emission rate of microseismic events can be detected, although a high emission rate is present in both areas. An 11- and 15-times increase is recorded respectively in these areas.

The area associated with the face positions exhibited the usual background activity associated with the development of a fracture zone and a distinct concentration at 95 m from the detector. This area showed an irregular rate of seismic emission with a quiet period of 45 minutes immediately preceding the rockburst.

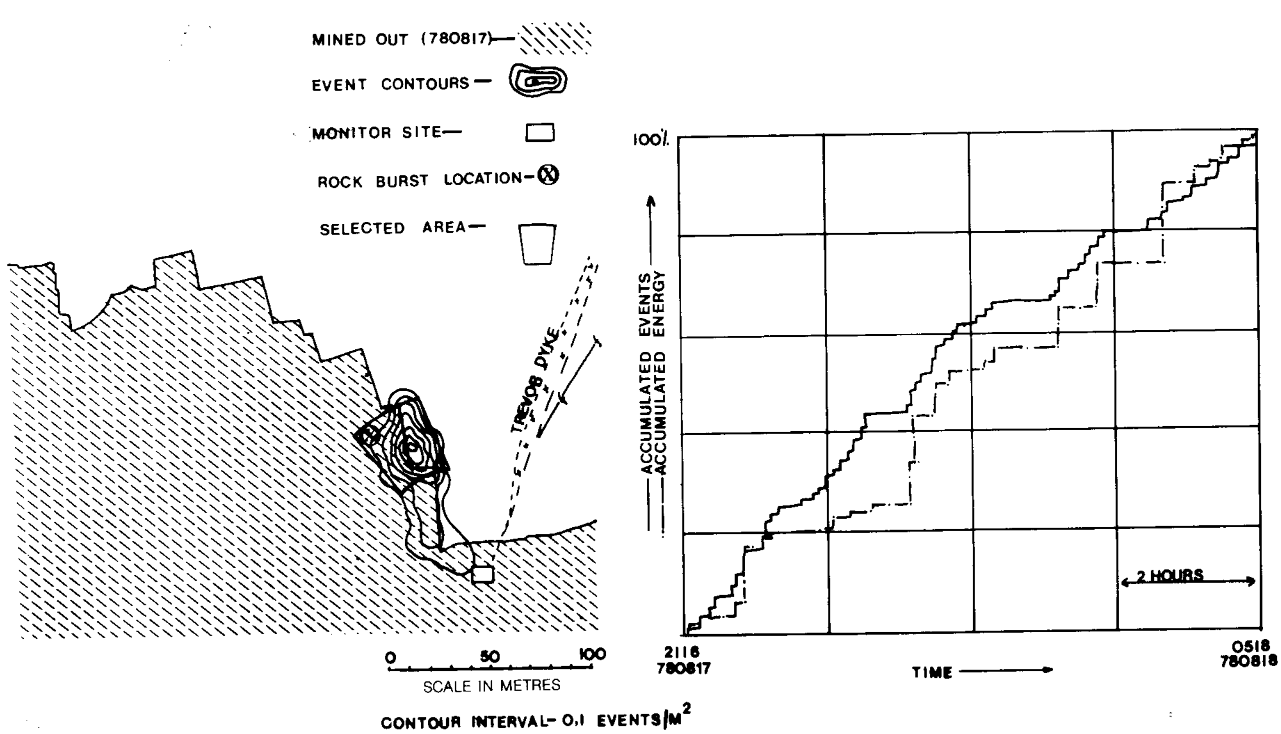

Fig. 4—Microseismic events precursive to the seismic event at 05h18 on 18th August, 1978
Left: Microseismic activity on 41 E longwall projected on reef plane
Right: Accumulated events and energy in the selected area

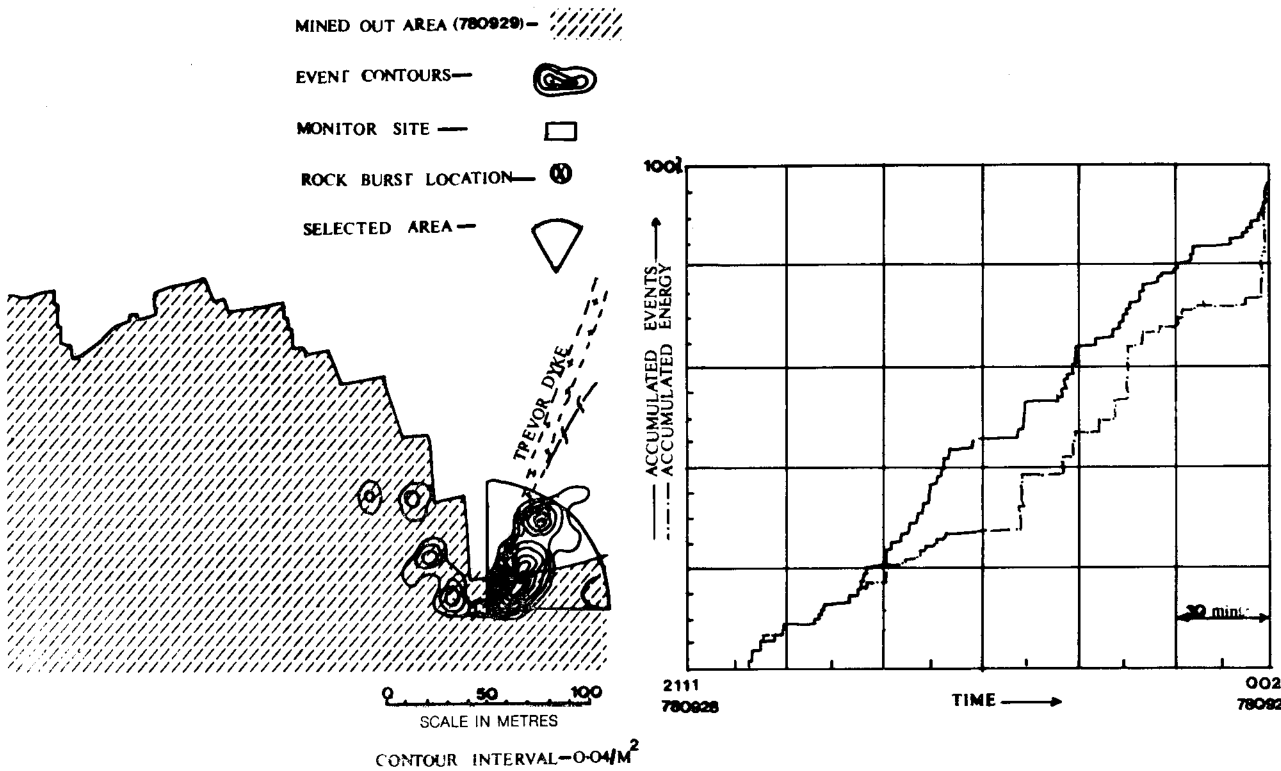

Fig. 5—Microseismic events precursive to the seismic event at 00h24 on 29th September, 1978
Left: Microseismic activity on 41 longwall E projected on reef plane
Right: Accumulated events and energy in the selected area

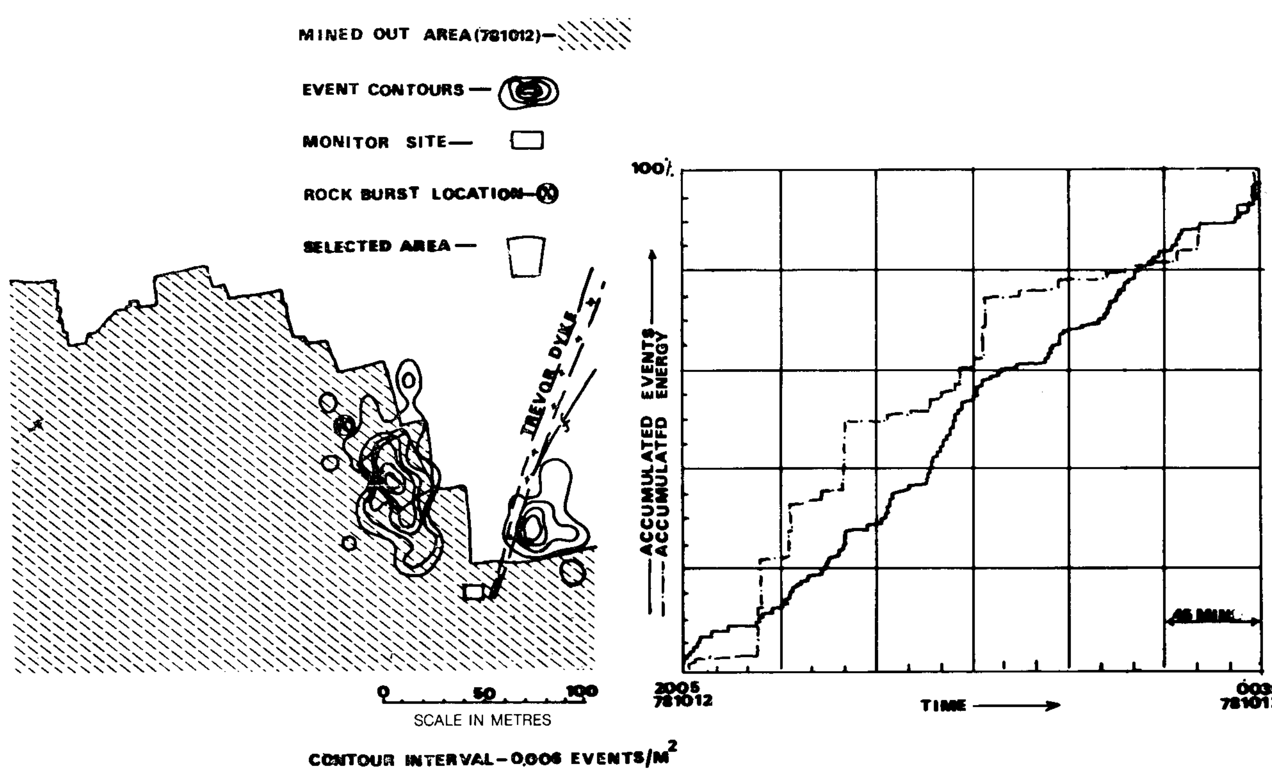

Fig. 6—Microseismic events precursive to the seismic event at 00h35 on 13th October, 1978
Left: Microseismic activity on 41 longwall E projected on reef plane
Right: Accumulated events and energy in the selected area

The activity associated with the Trevor Dyke exhibited a high but very regular emission rate. At the moment, insufficient evidence exists to positively link irregularity to precursive sequences, but Brady[6] found that precursive sequences are generally characterized by such irregularities. Additionally, a distance histogram indicated that microseismic events occurred along the dyke over a range of almost 80 m. There was thus no well-developed spatial concentration.

Event Recorded on 18th November, 1979

A rockburst (Richter magnitude 2,5) occurred at 22h39 on the 19th of November, 1979, causing a small amount of damage in the follow-behind haulage on 105 Level. The mine layout, event location, and precursive microseismic events in the vicinity of the main burst are shown in Fig. 7.

Microseismic recording commenced at 19h00 on Friday, the 16th of November, 1979, and, apart from a short break for computer maintenance between 05h00 and 11h00 on the 17th of November, 1979, continued until 07h00 on Monday, the 19th of November, 1979. The rockburst occurred on the Sunday evening – more than 50 hours after the previous blast in the area.

From 19h00 on Friday evening to 05h00 on Saturday morning, 1200 events were recorded and located, of which 123 occurred in the selected volume of rock (i.e. 12,3 events per hour). The average emission rate for the same volume of rock during the previous 30 days was 2,8 events per hour.

During the Saturday night and the whole of Sunday, a high emission rate persisted. Contrary to expectations, the rate of seismic-energy release increased through the Sunday up to a quiet period immediately before the rockburst.

Discussion

The events recorded on the 18th of August, the 29th of September, and the 13th of October, 1978, would all have been anticipated since they were preceded by anomalously high concentrations of microseismic activity in small volumes of rock. In a practical early-warning system, men might have been withdrawn from the likely-to-be affected areas but in no case would more than one shift, prior to the burst, have been lost. The necessity for the location of the foci of the microseismic events is illustrated by microseismic activity along the Trevor Dyke on the 13th of October, 1978; had simple pulse-counting been performed, the marked increase in activity in the area behind the faces would not have been detected.

The event of the 18th of November, 1979, would also have been predicted, but on this occasion the 180-degree ambiguity in location made both the forward faces on the 106–107 Levels or the rearward faces on the 104–105 Levels equally likely locations, and in practice there would have been the difficulty of deciding which faces to evacuate.

The use of state-of-the-art low-noise accelerometers allowed the recording of large numbers of extremely small microseismic events, essential for the reliable analysis of possibly precursory activity. The decision to use single-site detection was vindicated, and the efficiency of the system showed that only 40 three-dimensional sites would be necessary for overlapping coverage, providing unambiguous locations over the entire 8 km of longwall face on WDL. The only disadvantage of single-site detection is the increased power required of the computers to perform the sophisticated signal processing. At the present-day and projected future prices of computers, this disadvantage is small and decreasing.

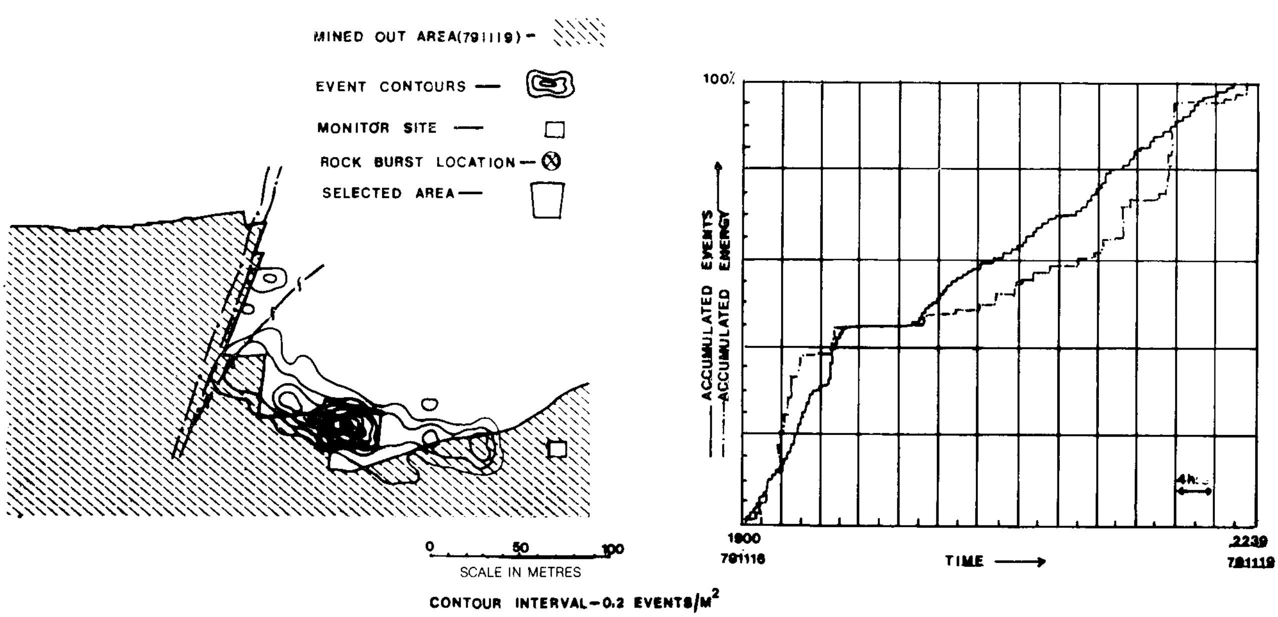

Fig. 7—Microseismic events precursive to the seismic event at 22h39 on 19th November, 1979
Left: Microseismic activity on 41 E longwall projected on reef plane
Right: Accumulated events and energy in the selected area

An analysis of the precursory activity patterns indicated that both the characteristic spatial concentration and the increased rate of emission should be present before a seismic event can be predicted confidently. At present, it is unresolved whether *all* seismic events are preceded by heightened activity and whether there will be false alarms, although during the 8000 hours of recording, no false alarms were noted. Abnormal microseismic activity appears to be a highly reliable predictor of seismic events. In the future, attempts will be made also to predict the size of an impending event from characteristics of the precursive sequence.

Two problems have been identified: it is at present not possible to monitor while rock-drills are active in the area, and large excavations (like the stopes) in the transmission path cause diffraction of the waves and seriously degrade the accuracy of the location. The drilling problem is not expected to be a serious handicap since the generally long (3 or more hours) precursory pattern will allow most drilling-shift events to be anticipated during the previous cleaning shift. Attempts are also being made to electronically filter out the signals produced by drilling. Interfering excavations can be avoided by judicious placement of the monitoring sites. As most events on WDL tend to occur ahead of the faces[17], siting in this region should give the best results. Long boreholes and pre-developed footwall drives are being investigated for this purpose.

The extraction of remnants, an operation frequently necessary in scattered-mining schemes on other mines, carries a high seismic risk. Fortunately, this seismicity is especially amenable to prediction by microseismic monitoring because the active volume is small, static, and highly accessible.

Conclusion

It has been demonstrated that, by the use of back-analysis, microseismic monitoring can be used as a short-term predictor of individual seismic events. Currently, the scale of the research is being greatly expanded to fully evaluate the accuracy, reliability, and practical implications of predictions made in a production environment over the next three years.

Acknowledgements

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Addendum: Theory of single-site seismic location

Each single-site detector consists of three mutually perpendicular accelerometers defining an orthogonal coordinate system with the origin at the detector. The locations of microseismic events are described with respect to these local coordinates.

The Line of Propagation

A p-wave incident on the detector will set up ground motion parallel to the line of propagation (owing to the longitudinal nature of the p-wave). If the ground acceleration vector is denoted by $\mathbf{P}(t)$, then the components of acceleration along each accelerometer axis are

$$\begin{aligned} P_x(t) &= lP(t) \\ P_y(t) &= mP(t) \\ P_z(t) &= nP(t), \end{aligned} \qquad (1)$$

where P_x, P_y, P_z are the component accelerations along the respective axes; l, m, n are the direction cosines of $\mathbf{P}(t)$ with respect to the X, Y, and Z axes; $p(t)$ is the magnitude of $\mathbf{P}(t)$.

In practice, what are available are the sampled accelerometer outputs over some interval; x_i, $i = 1, 2 \ldots n$, y_i, $i = 1, 2 \ldots n$, and z_i, $i = 1, 2 \ldots n$, where the i-th sample on each channel is taken at the same time and the samples are equally spaced in time. The outputs x_i, y_i, z_i are proportional to the respective axial accelerations with noise added. If it is assumed that the constant of proportionality is 1,

$$\begin{aligned} X_i &= lP_i + e_{xi} \\ Y &= mP_i + e_{yi} \\ Z &= nP_i + e_{zi}, \end{aligned} \qquad (2)$$

where e_x, e_y, and e_z are the three noise components. The noise is assumed to have zero mean.

From x_i, y_i, and z_i, $i = 1, 2 \ldots n$, it is desired to determine l, m, and n as these define the line of propagation.

Algorithm

The algorithm is based on the observation that, in the absence of noise, each component could be made identical to the other over the N samples by the application of constant scale factors. In the presence of noise, the algorithm seeks to determine constants that will give the *best fit* between components. 'Best fit' is chosen as the fit that minimizes the sum of the squared residuals, i.e. the least-squares best fit.

The constants are those that minimize the sum.

$$\sum_{i=1}^{N} (x_i - ay_i)^2 + (y_i - bz_i)^2 + (x_i - cz_i)^2 \qquad (3)$$

Hence,

$$\begin{aligned} E[x_i]|y_i &= ay_i \\ E[y_i]|z_i &= bz_i \\ E[x_i]|z_i &= c_{zi} \qquad \text{for all } i \end{aligned}$$

where, for example,

$E[x_i]|y_i$ denotes the expected value of x given y.

It follows from (2) that:

$$\begin{aligned} a &= l'/m' \\ b &= m'/n' \\ c &= l'/n', \end{aligned} \qquad (4)$$

and hence $ab = c$,

where

l', m', and n' are estimators for l, m, and n respectively.

When $ab = c$ is substituted into (3) and the equation is differentiated with respect to a and b,

$$\sum_{i=1}^{N} x_i y_i - a\sum_{i=1}^{N} y_i^2 + b\sum_{i=1}^{N} x_i z_i - ab^2\sum_{i=1}^{N} z_i^2 = 0$$

$$\sum_{i=1}^{N} y_i z_i - b\sum_{i=1}^{N} z_i^2 + a\sum_{i=1}^{N} x_i z_i - a^2 b\sum_{i=1}^{N} z_i^2 = 0.$$

This non-linear system of equations is readily solved for a and b by iteration. By the substitution of a and b into (4) and imposition of the constraint,

$$l'^2 + m'^2 + n'^2 = 1,$$

which determines l, m, n to within a sign, expressing an inherent 180° ambiguity in location. The relative signs of l, m, and n are determined from a and b.

Special (simplified) treatment is necessary for events occurring in the axial planes.

Detailed monitoring of the application of the algorithm to actual microseismic events showed that the iteration converged rapidly to unique and accurate solutions. These observations and an analysis of several alternative algorithms are given by O'Connor[13].

Determination of Range

The estimation of the source–detector distance is dependent on the determination of the onset of s-waves. This point is generally obscured by the p-wave coda as can be seen in Fig. 2, and a method was therefore devised to separate the two waves.

In a coordinate system with the X-axis along the line of propagation determined previously, the X-accelerometer will detect the longitudinal p-waves while the Y and Z accelerometers will detect the transverse s-wave but no p-wave, thus achieving separation of the two. (Fig. 3 shows a situation in which the event focus was near the Y-axis.) To enhance the accuracy of range determination, the coordinate system is rotated mathematically in each case so that the X' axis (i.e. the rotated X axis) is along the line of propagation; the signals on the Y' and Z' axes are therefore mainly s-waves. The Y' and Z' signals are then squared and summed to give the total s-wave energy at a point in time. The wave is divided into blocks of 10 samples each, and the average s-wave energy in each block is calculated, thus detecting the envelope of the signal; the s-wave onset is marked by a sudden increase in the amplitude of this envelope. To enhance the increase, the first forward-differences of the block-averaged energy values are taken, i.e. if (E_i), $i = 1, 2 \ldots N$ is the sequence of block averages, the sequence $(D_i), i = 1, 2 \ldots N$ is formed by $D_i = E_{i+1} - E_i$. The sequence of values D_i is scanned for a positive maximum $D_{\max}$, which is near the onset of the s-waves. It was found by comparison with visual determinations that the most accurate estimate of the onset of s-waves is one half of a block-width ahead of the position of the maximum difference value, $D_{\max}$.

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