Surface and borehole microseismic monitoring of longwall faces; their potential for three-dimensional fracture imaging and the geomechanical implications.

Styles P1, Bishop F1, Toon S2

ABSTRACT

To determine whether 180 felt earth tremors around Doncaster, Nottinghamshire, U.K., which also experienced severe surface fissuring, were caused by coal extraction, a surface seismometer array was established around Thorpe Colliery. Over the next year, 785 microseismic events were detected. The spatio-temporal seismicity patterns are clearly associated with the commencement, continuing extraction and closure of faces. Of particular note are events which locate at the surface and appear to be related to the active fissuring. Events occur within days of commencement of production and cease when production finishes, with good correlation between face advance and hypocentral position. Naturally occurring microseismic events have also been detected up to 1 km ahead of active longwall faces in the Midlands using triaxial geophone packages grouted into the seam together with a surface seismometer in the top of the borehole. The quality of these data were very high and guided waves can clearly be seen with the dispersive characteristics associated with seam waves. In one experiment more than 2000 events were detected in only two days of monitoring even in a relatively noisy surface environment. This paper demonstrates how very accurate locations (≤ 10 metres) can be generated using three-component digital data from only one borehole. The surface seismometer and the borehole P-wave onset can give extra precision for the height of the event relative to the seam. The event distributions give a dynamic, three-dimensional image of the developing patterns of fracturing above, below and ahead of the longwall face with important implications for roof control, subsidence prediction and gas migration.

INTRODUCTION

Microseismic activity is the occurrence of minor, generally unnoted, but with occasional felt, earthquakes, associated with the extraction of deep-mined coal by long-wall methods has been reported in coal mining areas since at least the turn of the century. The association with coal production from deep mines has often been assumed but rarely proven, Davison (1905), Davison (1919), Dollar (1951), Naismith et al. (1984). Although the Mining industry has been reluctant to accept the existence of earthquakes caused by mining it has not been generally appreciated that they provide a very clear insight into the state of stress present around the area of extraction. They can be used to monitor roof stability and the development of fractures around the extracted zone and the nature of interactions with previously extracted areas, aquifers and major faults.

A number of relationships have been postulated in order to predict the extent and nature of fracture zones around total extraction panels. The majority of these link the seam thickness to the extent of rock mass failure. Much of this work is based upon physical and numerical modelling studies that have largely not been completely validated from measurements. Currently the extent of caving and fracturing above the seam is considered to be in the region of 50 times the seam thickness for a 200m wide longwall panel, with an approximately linear decrease with decreasing panel width; a figure of 10 times seam thickness has been suggested for a 40m wide panel for example (Choi and McCain, 1982, Bieniawski, 1987, Peng and Chang, 1984, Pollington, 1988). Little information exists with respect to the fracturing around pillar extraction panels. There is no general consensus as to the
depth of fracturing in the floor, other than it is significantly less than for the roof. It is generally perceived that the seam thickness also influences this. Although seam thickness will undoubtedly influence the extent of fracturing, the complex interaction between seam thickness, depth, magnitude and direction of in-situ stresses, panel width and geomechanical properties of the strata will be the controlling factor. Although numerical models have increased in sophistication and accuracy, they are not as yet a reliable guide in this complex geomechanical environment. More measurements of the extent of fracturing are needed.

The determination of the extent of fracture zones around total extraction panels has been attempted using extensometers, Peng and Chiang (1984). However this is difficult, time consuming and expensive and as a result cannot be routinely conducted. Microseismic monitoring holds the potential of being able to determine and delineate the full extent of the fracture zone, in real time and at relatively low cost. The data provided by such a system will significantly increase our understanding of the mechanisms leading to strata failure. There are a number of conditions where a knowledge of fracturing would significantly aid design. Knowledge of the extent of fracturing above a longwall or pillar extraction panel is essential if the working seam lies in close proximity to an aquifer or surface water source, as these fractures can act as a conduit to the workings. Likewise gas can migrate from below longwalls if fracture extends to other seams. Where multi seam mining is practised or planned, the extent of fracturing of seams above and below total extraction panels could influence the way in which they are to be mined. The extent and timing of caving where seams are extracted under strong roofs influences the mining process, as periodic weightings and air blasts can occur. All of these conditions represent problems currently faced by the Australian underground mining industry.

**SURFACE MICROSEISMIC MONITORING**

The coalfields can clearly be seen on a map of the British earthquakes (Figure 1) as concentrations of activity along with the normal background of tectonic seismicity such as the Carlisle (1979) and Llwyn (1984) earthquakes and aftershocks and events from Kintail and the Ochil Hills in Scotland. The coalfields of Midlothian, Staffordshire, Nottinghamshire and South Wales are clearly shown but Northumberland, Fife, Yorkshire have fewer events. The British Geological Survey report that about 26 per cent of small to moderate earthquakes (less than $M_s = 3$) recorded by the UK regional seismometer network occur in the coalfields (Redmayne, 1986).

Following public concern over mining induced seismicity in the Midlands, the British
Geological Survey installed 6 seismometers (Browitt 1979), augmented by mobile network that could be used to examine small areas in greater detail. After a damaging earthquake in the Stoke-on-Trent area (body wave magnitude, $m_b=3.4$, modified Mercalli scale, MM=VI) and several smaller tremors on the 15th of July, 1975, a network of seismometers (aperture of about 10 km) was deployed to monitor the spatial and temporal pattern of activity which continued over the next five years. Westbrook et al. (1980) concluded that the earth tremors were caused by longwall coal mining at a depth of 1000 metres, that the event rate correlated with coal production in both space and time and that previous mining played an important part in the size of the tremors.

Using a small aperture array (1.5 km) to concentrate on two adjacent working panels, Kuszniir et al. (1984) identified two separate mechanisms responsible for generating the seismicity. The smaller events ($M_b<2.5$) with an implosional source mechanism were thought to be generated by waste collapse. The larger events ($M_b>2.5$), with shear source mechanisms, occurred in pillars of old workings in adjacent seams and are caused by the superposition of the pillar stress-field and the front abutment pressure of the advancing face, when the face passes above or below the pillar.

Cynheidre Colliery in South Wales, United Kingdom was monitored microseismically from a surface network of 8 seismometers for 7 years from 1982 to 1989. One of the principal objectives was to study the activity associated with active longwall mining in a situation where there was no interaction with other mine workings. Styles (1988) distinguished two types of microseismic activity. The first type showed clear correlations between underground working practices and microseismic activity with as many as 800 (unfelt) microseismic events detected during an eight-hour shift. He concluded that the activity was localised in front of the advancing face and suggested that it was generated by the brittle failure of the sandstone roof and floor and was directly correlated with the rate of extraction of coal. Kuszniir et al. (1985), found seismicity clustering around the active faces with magnitudes in the range $M_b = 1$ to $-1$.

The second type of activity was associated with dilatant microfracturing in the coal associated with the disintegration of the coal structure and the imminent onset of coal and gas outbursts and using these an on-line warning system was implemented. Styles et al. (1986), Styles et al. (1991).

---

**Figure 2** Seismicity plots in a stationary frame of reference.

**Figure 3** Seismicity plots in a moving frame of reference.
The event locations (Hypocentres) can be calculated from observations of the relative arrival times of the events at several seismometers and plots of these can show the distribution of events in space and time both in normal geographic coordinate frames for comparison with pre-existing faults and also in a moving frame related to the position of working faces, enabling the development of new fractures associated with waste collapse and the subsequent upward propagation of fractures to be identified. Figures 2 and 3 show some seismicity plots from Staffordshire (Kussnier et al., 1985) illustrating the complementary merits of both of these displays. They clearly show that the principal activity lies slightly in advance of the face position and extends from just below seam level to a considerable distance above the seam. Analysis of the mechanisms of the events shows that they fall into two types with the predominance of the activity associated with 'collapse-type' mechanisms caused by roof caving and the subsequent higher-level fracturing, i.e., the ground is moving downwards towards the zone of extraction. Events also occur in the floor beneath the seam.

Investigations by Isaac and Pollington (1988) during mining of the H66 seam at Cotgrave Colliery, Nottinghamshire, have shown that high loading levels on the powered supports were caused by failure of the Deep Soft Seam and the roof immediately above the Deep Hard Seam which was being mined. These beds were unable to transmit support resistance to the bridging siltstones above, which resulted in the generation of brittle failures which propagated into the overlying strata. This type of roof failure will certainly give rise to energetic microseismic activity which will be detected at considerable distances and will couple strongly into the seam as guided waves. Floor failures also generate microseismic activity which is detectable in the same way.

The fewer remaining, generally larger events were shown to be associated with pillar failure in workings above or below the active seam caused by the superposition of the pillar stress field and the front abutment pressure. This type of event is also likely to be generated when faults are re-activated by mining activity. It is apparent that the microseismic activity associated with the development of fractures associated with caving of the roof can be monitored using surface seismic networks although with limited precision in the final position.

MICROSEISMIC MONITORING OF THORESBY COLLIERY

Between July 1989 and August 1990, over 130 separate earth tremors were reported to the Thoresby Estate Offices, Thoresby Park, Nottinghamshire. Occasionally, items of furniture or other fittings were reported as having shaken or moved; this corresponds to a MM intensity of IV. Following the increasing concern from the general public in the Thoresby/Edwinstowe area of Nottinghamshire and in order to determine whether the tremors were caused by mining activity, British Coal commissioned the University of Liverpool to deploy a network of surface seismometers around the take of Thoresby Colliery, whose workings lie beneath Thoresby Park and Edwinstowe. This provided an opportunity to carry out a detailed study of the temporal and spatial changes in seismicity for an area where large amounts of energy are being released seismically.

Around Thoresby Colliery, the surface rocks are composed entirely of Permo-Trias rocks, notably the Bunter Sandstone (Sherwood

![Figure 4 Location of the seismometer network deployed in the Thoresby area.](image)
Seismometer and Amplifiers/Modulators are housed in a 6" diameter plastic tube, the base of which is filled with concrete, set into the earth to a depth of approximately 1 metre.

Eight channels of digital data were transmitted back to the Control Room at Thoresby Colliery using UHF digital telemetry, decoded and recorded on digital cassettes on an EARTHDATA EDR8000 with a bandwidth of 52 Hz, on 12 hour cassettes, together with the MSP time signal, broadcast from Rugby.

Analysis and event location
Tapes are replayed to a Gould 831000 system for hardcopy and visual examination of the data and locatable events were digitized by Laboratory Work Bench (LWB) software and stored on a Masscomp 5450 Unix workstation and located using HYPOCENTER (Lienert et al. 1985). The velocity structure for the Edwinshawe area was deduced from a variety of data sources and is shown in Table 1.

<table>
<thead>
<tr>
<th>Thickness (m)</th>
<th>Vp (km/s)</th>
<th>Vs (km/s)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.050</td>
<td>1.9</td>
<td>1.28</td>
<td>Weathered Basalt</td>
</tr>
<tr>
<td>0.075</td>
<td>2.76</td>
<td>1.64</td>
<td>Unweathered Basalt</td>
</tr>
<tr>
<td>0.130</td>
<td>3.1</td>
<td>1.74</td>
<td>Permian</td>
</tr>
<tr>
<td>0.744</td>
<td>3.5</td>
<td>1.67</td>
<td>Coal Measures</td>
</tr>
<tr>
<td>0.592</td>
<td>4.2</td>
<td>2.06</td>
<td>Millstone Grit</td>
</tr>
<tr>
<td>1.40</td>
<td>5.2</td>
<td>2.02</td>
<td>Carboniferous Limestone</td>
</tr>
<tr>
<td>35.0</td>
<td>8.0</td>
<td>3.27</td>
<td>Pre-Cambrian</td>
</tr>
</tbody>
</table>

Table 1. Seismic Velocity Structure for the Thoresby area.

Spatial distribution of seismicity with respect to working panels
It was found that mining-induced events had hypocentres which were located between the surface and depths up to about 1 kilometre and located in the times of either Thoresby Colliery or one of the adjacent working collieries in Mansfield (South Yorkshire Area), Bevercotes, Offerton, Bilsthorpe, Clipstone and Welbeck.

From the 22nd of August 1990 to the end of July 1991, some 785 mining-induced events were detected on two or more
seismometers of the network, with estimated magnitudes from -2 to approximately 2.4. As the felt events invariably saturate the high gain system, magnitudes based on the duration of the seismic event were used. The estimated magnitude is calculated from the event duration using the formula (Tsunomura, 1967):

$$M_{DUR} = 2.85 \log(Dur.) - 2.53 + 0.0014(Dur.)$$  \hspace{1cm} (1)

Those magnitudes are in reasonable agreement for regional events which have been detected both by this array and by the British Geological Survey regional network.

Figure 5 shows a Gutenberg-Richter plot (Gutenberg and Richter, 1949) of the number of events exceeding any particular magnitude, plotted against magnitude, from one year's records. The frequency-magnitude relationship follows the general relation:

$$\log N = a - bM_M$$  \hspace{1cm} (2)

where $N$ is number exceeding a certain magnitude, $M_M$ is the magnitude and $a$ and $b$ are constants. It has been shown that for

![Frequency magnitude plot for Earthquakes from the Thoresby area.](image)

**Figure 5** Frequency magnitude plot for Earthquakes from the Thoresby area.

**Figure 6** Distribution of Felt events from the Edwinstowe Region

earthquakes over a very large range of magnitudes that there is an empirical relationship between these variables. If the events all belong to a single population they should plot on a single straight line. The slope of the large magnitude events does indicate however that an upper limit of about magnitude 2.5 seems likely with present data. The $b$ value of 0.8 is consistent with values obtained by Kusznia et al. (1984) for mining-induced seismicity from the North Staffordshire Coalfield.

Of this data set 23 events have been felt and reported from the Edwinstowe region. Only one of these events was felt within the colliery. The epicentral locations for all the felt events are shown in figure 6, together with the working faces from some of the surrounding collieries. Of the 23 events, 14 originate from within the Thoresby take.

**Spatial Variation of Seismicity from Thoresby Colliery**

At the beginning of the period, panels PG114 and PG115 in the north eastern area and PG141 in the south western area were in full production. These faces were replaced by PG119 and PG145. At the end of the monitoring period (July 1st 1991) PG145 had finished leaving PG119 nearing the end of its production life.
Figure 7 The microseismicity in the Edwinstowe area for the period 22/05/90 to 04/02/91.

Figures 7 and 8 show the epicentres of the seismicity from just the Thoresby mine. The figures cover two periods (Figure 7) from August the 22nd 1990 to February the 4th, 1991 and (Figure 8) from February the 5th to June the 30th 1991.

The principal observations are:

i) events cluster around the northern end of PG115 which finished production in November at that end of the panel. There is still some seismicity from PG115, even after production from the face ceased in November 1990. This is probably due to the proximity of PG119, which is altering the local stress field and the presence of a pillar of coal, left behind in the Top Hard seam which runs roughly down the centre of PG115 at a depth of approximately 530 metres below datum. There is a range of depths for these events, from ground level down to 1020 metres below datum. Figure 9 is an example of a series of burst of felt events, located at or near the surface. Within a few minutes, this burst was followed by another earthquake swarm whose epicentres all appear to lie along a NW/SE line which can be seen in Figure 8, just to the west of Perlethorpe.

Figure 8 The microseismicity for the Edwinstowe area for the period 04/02/91 to 31/08/91.

ii) events cluster around the northern end of PG119 which started production in late October from the northern end of

Figure 9 Felt event (M_w=1.7), one of a burst of events which locates at the surface and appear to be associated with the fissuring seen near Perlethorpe.
the panel. Most of the seismicity from the Therebey take has originated from this region.

ii) events cluster around the northern end of PG114, production from which finished at the end of December with the last locatable event on the 28th of November 1990.

iv) events cluster around the southern end of PG141, which finished production on the 4th February 1991. The events although few in number, are located at depths from near the surface to 1000 metres below datum. Other similar events have been recorded that appear to belong to this group of family of events but were too poor to be located. The largest event recorded during this experiment, with a magnitude of 2.25 and a depth of 610 metres, came from this area and was reported from Thoresby Colliery and the village of Butley (Figure 4). The last recorded event from PG141 was on the 22nd of January 1991 and production stopped a week later.

Figure 8 shows the seismicity from the 5th of February, 1991:

i) a few events cluster around the northern end of PG115, which finished production in November 1990.

ii) events cluster around the northern end of PG119 with the epicentres migrating down the panel towards the southern end as production continues.

iii) Events originate from PG145, which commenced production at the southern end on the 4th of February and finished at the northern end on July 3rd 1991. Four felt events locate around the southern end of PG145 where production started. The first occurred only three days after production started and was located 190 metres to the south of the edge of the panel at a depth of 680 metres. The event lies about 60 metres away from a pillar in the Top Hard seam (depth 470 metres) which was left because the coal was faulted. Two of these events on the 13th of February, 1991 nine days after production commenced, locate above the southern edge of the panel (depth 460 and 10 metres). Figure 9 is an enlargement of this part of the Thoresby take. The last few located events occur about 280 metres along the face. The face had retreated 330 metres at this time and it appears that the seismicity is following the retreat of the face. The last locatable event on the 22nd of May also follows this trend.

Overall, the data appear to show a clear spatial relationship between the seismicity and production status of a panel indicating that the seismicity is generated and controlled by the extraction of coal.
Hypocentral depths for events within the take of Thoresby Colliery

Figure 11 is a histogram showing the variation in hypocentral depths for events located within the Thoresby take, placed in 100 metre bins from 0.0 metres to 1200 metres. Most of the hypocentres fall into two regions, one at or near the surface, the other at depths of between 400 and 900 metres. In this area, the Parkgate seam is approximately 700 to 800 metres below datum. The Top Hard seam at 600 metres has also been completely extracted in this area with the exception of some remnant pillars. The depth distribution of the hypocentres implies a causal relationship between the seismic activity and active retreat mining and its associated roof collapse for the Parkgate seam and the older workings above.

A simplified well log of the geology is shown in Figure 12. If the distribution of the hypocentres is compared with the log, it shows that the brittle failure appears to be associated with two parts of the stratigraphic section:

(i) the Bunter sandstone and that it is presumably associated with the fissuring seen at the surface in the village of Perliethorpe. Figure 13 shows an example of this fissuring exposed during remedial works carried out during September 1990. Small cracks were observed and later repaired in the tarmac of the B6034, which runs north out of Edwinstowe and directly over PG145. Older examples of fissuring are found on the spoil heap site plan for Thoresby Colliery where an area of fissuring has been delineated. It lies over a worked out panel, PG147.

(ii) at depths greater than 400 metres and less than 1000 metres, which is in the productive or Middle Coal Measures, with a peak at the level of the Parkgate workings which lies almost completely within the 700 metre bin (i.e. 700 to 800 metres).

Temporal variations of seismicity in the Edwinstowe area

Figure 14 shows a histogram for November 1990 of all microseismic events recorded by the array. The seismicity peaks in

---

Figure 11: Histogram showing the variation in hypocentre depths for events located within the Thoresby take. All the Parkgate workings lie within the 700 metre bin.

Figure 12: Simplified well log for the Thoresby area.
events per day. The rate dies away at weekends to a rate of 0 to 2 per day, with a minimum on Sundays. This pattern together with the decrease in activity at weekends and over Christmas and other breaks, indicates a strong temporal relationship between coal-winning and the local microseismicity. Production on a week-day is about 1800 to 1900 metres of coal cut per day and this rate falls to about half at the weekend. There is a general decrease from February to May, this may in part be because only two faces instead of the normal three were being worked during this period in the Thoresby take. Figure 15 shows the cumulative daily event rates for those events known to be from within the Thoresby take indicating that there is

Figure 13 Fissuring exposed near the village of Ferlethorpe. The strike = NWSE. Scale provided by the foot marks on the top and the excavator on the bottom.

the middle of the week with between 6 and 13

Figure 14 Histogram of the seismic activity for November 1990.

Figure 15 Cumulative daily event totals for all events recorded by the Thoresby array and production rate.
more seismicity and also more of the large magnitude events in the middle of the week. The event rate then decays, reaching a minimum on Sunday. Also shown in Figure 15 are the total number of hours worked each day over this time period. This demonstrates that there is good correlation between event rate and production.

**Borehole In- Seam Microseismology**

An enormous increase in precision in the location of events can be achieved by the incorporation into the network of detectors located in boreholes. One example of the advantages gained from borehole detectors is demonstrated by the Hot Dry Rock project operated at Rosemanowes Quarry, Cornwall by Camborne School of Mines where, using hydrophones in shallow boreholes (200 Metres) they have obtained location accuracies of ±20 Metres (Baria et al. 1986) for fractures generated by hydraulic stimulation of granite down to depths of ±2.5 km.

A further significant increase in the accuracy of hypocentral position determination is made possible because of the particular seismic attributes of the floor-coal-roof 'rock sandwich', Toon (1980) and Toon and Styles (1992). The low seismic velocity and low density of coal means that the acoustic impedance contrast between coal and the roof and floor is often a factor of four. This physical situation means that the coal acts as a very efficient waveguide with waves trapped in the seam propagating for very large distances with little attenuation.

**Experimental Setup**

The downhole sondes consist of six geophones which are arranged so that two are vertical and four are horizontal. The horizontal geophones are spaced at forty-five degree intervals, giving two independent orthogonal sets. The arrangement is shown in Figure 15. The sonde is cemented down the borehole at the level of the centre of the coal-seam and is orientated using a digital compass in the sonde, accurate to ±5°, but the orientations have been more accurately determined by British Coal during an in-seam seismic transmission survey. The signals were amplified by 80 dB and then recorded using an Earth Data EDS8000 digital tape recorder.

**Figure 16** Experimental set-up for borehole microseismic monitoring.

**Littleton Experiment**

For this experiment three boreholes, Sycamore 1, 2 and 3 (SYC1, 2 and 3), were used. Six hours of data were recorded over two days (25th-26th August 1988). The quality of these data were very high and clear guided waves (Figure 17) can clearly be seen with the dispersive characteristic's clearly associated with seam waves. The azimuth of the event is determined from P-wave hodograms, assuming the low frequency compressional arrival is polarised along the source-detector axis.

**Figure 17** Typical microseismic event detected at Sycamore 1 borehole showing the guided phases associated with channel-wave propagation.
The distance to the event is determined from the time difference between P-wave and S-wave arrivals, using the velocities \( V_p = 3.5 \text{ km/s} \) and \( V_s = 2.0 \text{ km/s} \). An Airy Phase (a late-arriving, high frequency mode which travels with the lowest velocity) was not detected for events arriving at Syc2, whereas it was always detected at Syc1. It appears that there is some discontinuity in the seam preventing high frequency energy reaching Syc2. Naturally occurring microseismic events have been successfully detected in Syc3 which is more than 1 km away from the active longwall face at Littleton Colliery and it has proved possible to obtain satisfactory locations using these data.

Coventry Experiment

For this experiment a single vertical component seismometer was deployed at the surface in addition to the multi-component downhole sonde in order to see if any of the events could be detected at the surface. Fifteen hours of data were recorded over a period of three days (24-26 September 1991). In this experiment, cables carrying the signal from the geophones to the surface picked up 50 Hz mains noise which was then amplified by 80 Db. This has been removed by filtering. Noise adaptive filtering (Anderson and McMahon 1988) was attempted but it was found that a simple notch filter at 50 Hz was more effective. In the Coventry experiment more than 20000 events were detected in only two days of monitoring even in a relatively noisy surface environment (c 1 km from the Jaguar Motor Works as compared to c 0.8 km to the seam). The source direction was determined using the spectral matrix method. This method was first used by Samson (1979) in the analysis of ultra-low frequency magnetic fields. It has since been successfully used in the analysis of local network seismic data and Acoustic Emission data. The spectral matrix is defined as:

\[
[S_{ij}(\theta)] = \begin{bmatrix}
S_{xx}(\theta) & S_{xy}(\theta) & S_{xz}(\theta) \\
S_{yx}(\theta) & S_{yy}(\theta) & S_{yz}(\theta) \\
S_{zx}(\theta) & S_{zy}(\theta) & S_{zz}(\theta)
\end{bmatrix}
\]

where \( S_{ij}(\theta) \) are the cross-spectra between the components of the signal and \( S_{ij}(\theta) \) are the auto-spectra of each component of the signal and

\[
\lambda_i(\theta) = \lambda_i(\theta) \quad (i=1,2,3)
\]

the degree of linear polarization is given by (Batalie and Chiu 1991):

\[
P_i = \frac{(\lambda_1-\lambda_2)^2 + (\lambda_1-\lambda_3)^2 + (\lambda_2-\lambda_3)^2}{2(\lambda_1+\lambda_2+\lambda_3)^2}
\]

The principal direction of the polarization at a frequency \( f \) is obtained from the pointing direction of the eigenvector \( u(f) \) corresponding to the maximum eigenvalue \( \lambda_1(\theta) \). The most linearly polarized frequency was used to calculate the source direction. The distance to the event is determined from the time difference between P-wave and Airy phase (guided-wave) arrivals, using the velocities \( V_p = 3.6 \text{ km/s} \) and \( V_s = 0.8 \text{ km/s} \).

Examples of the distribution of the events relative to the face for Coventry are shown in Figure 18. The bulk of the events lie within 50 metres above and below the seam but there is activity up to 2-300 metres above the seam presumably associated with bit separation. In section the events appear to delineate inclined surfaces lying away from the long-wall corners in accord with numerical predictions of the mode of failure for this type of mine opening. The events are generated above and below seam-level but because of the spatial spread of the Green’s function (the displacement response of the ground to a point impulse situated at the event location) seam waves will be stimulated even when the source is some considerable distance above the seam itself with the decay of the amplitudes of the Airy phase in particular being very sensitive to vertical distance above the seam. It may be possible to use the ratio of the amplitudes of the various phases to establish the
Figure 18. Event locations for Coventry Colliery, (a) Plan view, (b) Section looking along face advance direction, (c) section looking perpendicular to face advance direction, (d) Histogram showing depth distribution of events relative to seam.
vertical location of events occurring above the seam as collapse progresses with considerable precision, probably to better than 5 metres, particularly for those events within 50 metres or so of the seam. Additionally, naturally occurring events are found to be much more efficient stimulators of guided waves than are explosive shots in the seam probably because of the inherent asymmetry of natural events and the broad spectrum of frequencies they generate.

CONCLUSIONS

Felt events experienced in the Edwinstowe area of Nottingham have been caused by longwall mining in the surrounding collieries and the majority of the other events detected appear to be mining-induced for the following reasons:

1) The daily event rates show excellent correlation with current mining production.

2) The epicentres fall on the active longwalls in the Parkgate seam between 700 and 600 metres depth.

3) Activity closely follows production with little or no seismicity from the region of a longwall before or after extraction. The seismicity starts from the same end of the longwall as production and follows the face retreat.

4) Hypocentres are shallow (less than 1 km) and concentrate in two areas:

i) peaking around the Parkgate workings (700 to 800 metres) and also including the worked out Top Hard seam (600 metres).

ii) in the Bunter sandstone, from the surface down to about 200 metres. The surface expression of the shallower events must be related to the mechanism causing the extensive, near-vertical fissuring seen around the village of Perlethorpe where cracks over a metre wide, several hundred metres long and of unknown depth were observed.

Borehole microseismic monitoring provides substantially increased resolution of the hypocentral positions and permits delineation of the spatial and temporal development of the fractures around the active longwall. Ideally, detectors in boreholes would be deployed around a colliery with multi-component geophones grouted at 100 intervals from seam level to the surface and recorded for subsequent off-line discrimination and analysis, with eventual progression to real-time monitoring. The combination of multi-component detectors in-seam and throughout the overlying rock mass would permit high precision hypocentral locations (+/- 5 metres) and the determination of the fracture characteristics including approximate dimensions, orientations and stress drop. This could be carried out in existing exploration boreholes currently being drilled or in piezometric boreholes drilled for hydro-geological investigations.

Three-dimensional imaging of the dynamic development of fracturing may eventually lead to the demarcation of the intersection of propagating fractures and sub-level caving with equifocal and mapping of floor fractures controlling excess gas migration from underlying seams. It may allow modification of the mining parameters to enhance strata control and provide 'ground-truth' input to Finite and Distinct-Element simulations of the behaviour of the mine excavation to improve numerical modelling techniques.

ACKNOWLEDGEMENTS

We are grateful for the co-operation afforded us by Mr. K.G. Fuller, the manager of Thoresby Colliery and for the co-operation and assistance of the residents and land-owners of the area around Thoresby Colliery who provided information and allowed us to site equipment on their property. This work was carried out under the British Coal Research Contract No. YCE 50/20784: Microseismic monitoring of the Edwinstowe
mining district, Nottinghamshire and is published by permission of British Coal although the views presented in this paper are solely those of the authors.
S. Toon acknowledges the support of a SERC CASE studentship (with British Coal).

References


11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1992.


Tyen, S., (1990), The location of faults in coal seams using microseismic activity, B. Sc. Dissertation (Unpublished), University of Liverpool.

