STEVE HEARN AND NATASHA HENDRICK

DEMYSTIFYING COAL-SEISMIC RESOLUTION: A MODELLING APPROACH

Seismic reflection is now accepted as being a prime geophysical tool for coal-mine planning and development. However, there is some conjecture as to the true resolving power of the method. Numerical modelling is a cost-effective indicator of the resolution to be expected for particular recording parameters and in particular geological situations. The fundamental control on seismic resolution relates to the frequency bandwidth of the recorded signal. It is important that high frequencies be accurately recorded, up to the limits imposed by earth scattering effects. Conversely, low-end frequencies appear to be less critical to good resolution, and this has implications for coal-seismic instrumentation. Numerical modelling provides insight into the scale of geological features which can be observed on seismic images. More subtle features can be detected if auxiliary seismic attributes are also examined. Multicomponent modelling suggests that conventional vertical-component seismic images may be prone to contamination from converted S-waves. Multicomponent recording has the potential to provide higher quality and higher resolution imagery of coal structures.

INTRODUCTION

Of the available geophysical techniques, the seismic reflection method is arguably the most reliable and cost-effective way to obtain stuctural information suitable for coal-mine planning and development. However, the true resolving ability of the technique has been the subject of some conjecture. Ultimately, the best understanding of the capabilities of the method will be based on comparing real seismic results with geological information obtained from drilling or mining. As a cost effective precursor, numerical seismic modelling is a valuable tool for developing an understanding of practical resolution issues in the coal-mine environment. The purpose of this paper is to provide a number of examples of this approach.

NUMERICAL-MODELLING OVERVIEW

Seismic-reflection modelling can be carried out using various techniques, which involve different compromises between cost and realism. The simplest modelling method used here is referred to as zero-offset modelling. The underlying assumption is that all ray paths are vertical, resulting in an image which is geometrically equivalent to a stacked seismic section. The numerical algorithm used here to compute the zero-offset sections is the scattering-matrix method (Robinson & Treitel, 1980), which can provide primary reflections and, if desired, all possible multiples. This approach is extremely useful for rapid investigation of frequency bandwidth issues and, with some restrictions, vertical resolution issues. However, it ignores the smearing effects of common-midpoint (CMP) stacking.

Where lateral and vertical resolution issues are of particular interest, it is more appropriate touse finite-offset modelling which allows the geophone to be at an arbitrary distance from the source. That is, non-vertical ray paths are accommodated. In this case, a series of synthetic shot records are generated across some geological model. These data can then be subjected to conventional CMP-style processing. Consequently, the final output seismic section is more indicative of real seismic results.

In the course of the modelling work carried out here, we have used two forms of finite-offset modelling. The reflectivity approach (Kennett, 1979) produces full elastic seismograms (which include both compressional (P) and shear (S) waves), and is appropriate to horizontally layered media. Where horizontal layering can not be assumed (e.g. faulted coal seams), the finite-difference technique (Kelly & others, 1975) is more appropriate. This approach can handle models of arbitrary complexity, but is computationally expensive.

SEISMIC FREQUENCY CONTENT AND RESOLUTION

Perhaps the most fundamental requirement for optimum seismic resolution relates to the frequency content of the propagating seismic pulse. Firstly, we require a broad frequency bandwidth to provide a stable, non-ringy pulse. Additionally, resolving ability is related to the dominant frequency of the pulse (i.e. the apparent pulse frequency as measured from one cycle on the recording). An increase in dominant frequency corresponds to a decrease in the wavelength of the seismic pulse. Intuitively, this would be expected to yield improved definition of smaller structures.

Practical seismic sources can be designed to generate an extremely broad frequency bandwidth. The primary physical limitation to seismic bandwidth relates to the ability of high-frequency waves to successfully propagate through the earth. The earth's normal heterogeneities become increasingly more apparent to higher frequency waves, resulting in scattering rather than coherent propagation. Practical coal-seismic experience suggests that it is possible to record waves from 0Hz up to approximately 250–300Hz.

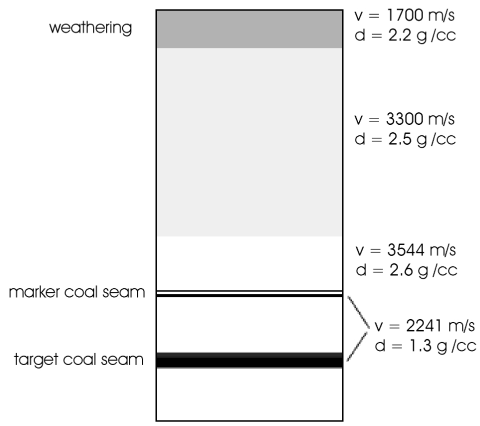

Figure 1. Simplified geological model used as basis for numerical modelling. The total vertical scale of the model is 150m. The seismic velocities (v) and densities (d) of different components are indicated at the right of the figure.

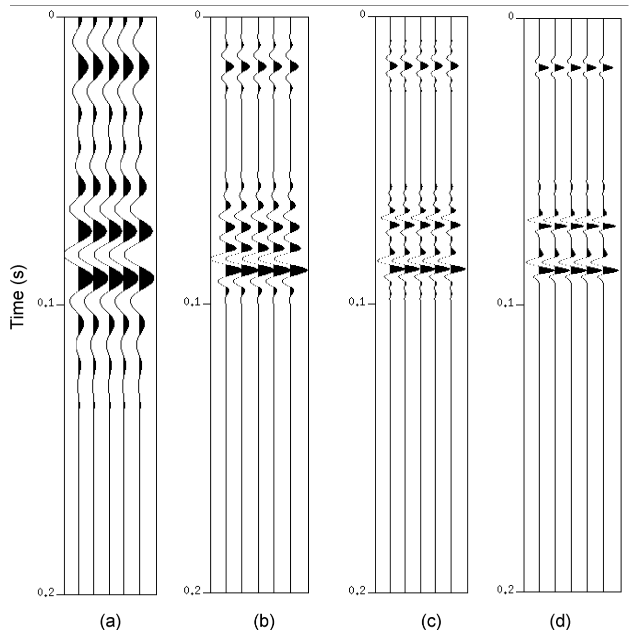

Figure 2. Effect of frequency bandwidth on seismic resolution for the model in Figure 1. The three main reflectors expected are base of weathering, marker seam and target seam. The low end of the frequency band is fixed at 30Hz. The high-end frequency is varied between (a) 60Hz (b) 120Hz (c) 240Hz and (d) 480Hz. The dominant pulse frequencies, as measured from the images, are (a) 60Hz (b) 110Hz (c) 180Hz and (d) 220Hz.

Simple, zero-offset modelling provides an effective means of assessing the changes caused in a seismic image as the frequency bandwidth is changed. It is of interest to consider independently the effects of high-frequency and low-frequency information.

Figure 1 shows a simplified geological model representative of coal-seam features expected in parts of the Bowen Basin. Velocity and density information is shown. For the modelling exercises undertaken here, various structural features have been superimposed on this background geology.

Figure 2 illustrates that layer resolution is significantly improved as the high end of the signal bandwidth is increased from 60Hz through 120Hz to 240Hz. A further increase in high-cut frequency to 480Hz provides a more subtle, though visible, resolution improvement. Such observations suggest that in practice, it is important to retain all high frequencies up to the limit imposed by the earth's scattering effects.

In contrast, the resolving ability of seismic data appears somewhat less sensitive to changes at the low-frequency end of the signal bandwidth. Figure 3 demonstrates that if the high-frequency limit is fixed at 240Hz, (appropriate to coal exploration) there is little change in dominant frequency, and hence resolving ability, as the low-cut frequency is increased from 10Hz up to 60Hz. In this example, even a bandwidth of 120–240Hz provides reasonable resolution. Eventually of course, if the bandwidth becomes unreasonably narrow (180–240Hz), the seismic pulse becomes unstable, and accurate imaging is not possible. These results indicate that, where sufficient high-frequency information is available, the

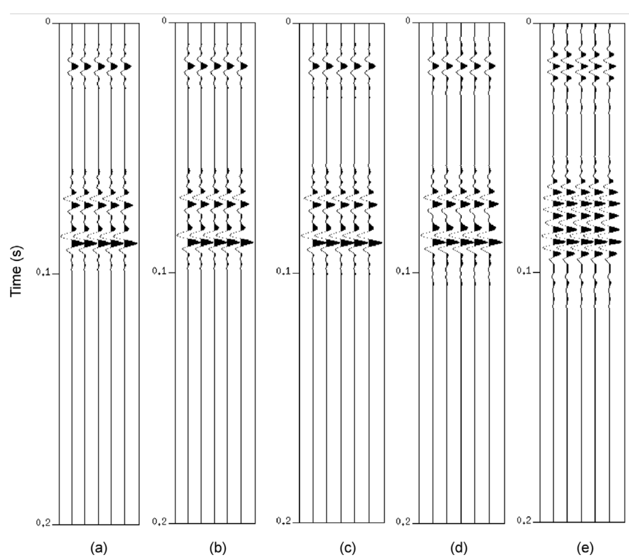

Figure 3. Effect of frequency bandwidth on seismic resolution for the model in Figure 1. The high end of the frequency band is fixed at 240Hz. The low-end frequency is varied between (a) 10Hz (b) 30Hz (c) 60Hz (d) 120Hz and (e) 180Hz. The dominant frequency is much less sensitive than in Figure 2, varying from approximately 185Hz (a) to 195 Hz (e).

lower frequencies contribute much less significantly to the seismic image. This has implications for field instrumentation used in high-resolution coal seismic surveying.

Firstly, it is well known that geophones are prone to an undesirable parasitic resonance phenomenon caused by transverse compliance in the suspension spring (e.g. Ziolkowski & Lerwill, 1979). It is generally considered that a geophone of natural frequency f_n should be free of such spurious effects up to about $10 f_n$. (Knapp & Steeples, 1986). This suggests that standard petroleum-style geophones (f_n = 10–15Hz) may not be capable of accurately recording the highest frequencies utilised in coal seismic. Secondly, near-surface sources including dynamite and vibroseis often generate strong ground-roll (Rayleigh wave) noise at lower frequencies. This noise can be attenuated if the geophone natural frequency is increased to 30-40Hz.

Given the modelling result that loss of low frequencies does little to degrade the seismic response, these considerations suggest that for coal seismics, geophone natural frequencies should be somewhat higher than for conventional petroleum seismic.

SPATIAL RESOLUTION OF COAL-SEAM STRUCTURES

Spatial resolution refers to the ability of the seismic method to detect gelogical features in the vertical or horizontal dimension. In the context of coal seismics, this includes the ability to detect thin seams, the ability to distinguish closely-spaced interfaces, and the ability to detect structural features such as normal and reverse faults.

A number of classical rules-of-thumb have been quoted for estimating vertical resolution in 2D seismic images. For example, the *detectable limit* (Sheriff, 1991) is defined as the minimum layer thickness required to give a detectable seismic reflection. This is generally taken to be of order $\lambda/30$, where λ is the dominant wavelength, related to dominant frequency (f) and seismic velocity (v) via $\lambda = v/f$. Similarly, the *Rayleigh resolution limit* (Sheriff,1991), defined as the minimum separation needed for individual interfaces to yield distinct reflections, is $\lambda/4$. These simple rules would suggest, for example, that the detectable limit of a thin coal seam might be of the order of 0.5m, whilst the top and bottom of a seam of thickness 4m should be independently distinguishable. (These computations assume a dominant frequency of 150Hz and a seismic velocity of 2500 m/s.)

Whilst such rules-of-thumb provide a useful starting point for assessing vertical resolution, they are approximate, and are essentially intended only for resolution issues relating to layer thicknesses. A more pragmatic feel for both the vertical and horizontal resolvability of features of greater structural complexity can be obtained by direct visual examination of synthetic seismograms.

As one simple example of this approach, Figure 4 illustrates the use of zero-offset modelling to demonstrate how the detectability of a normal fault can be expected to degrade as vertical displacement decreases from 4m to 1m. Note that the simple zero-offset modelling used in Figure 4 presents an overly optimistic view. Figure 5 gives some idea of how more realistic modelling can better indicate real seismic resolution, for the case of a 3m fault. Figure 5(a) repeats the simple zero-offset synthetic. Figure 5(b) still utilises zero-offset modelling, but now incorporates noise from multiples. For Figure 5(c) a number of individual shot records have been constructed using finite-difference modelling, and the section shown has been generated via the more realistic CMP stacking process. As an aside, note that the absence of the primary weathering reflector, and the slight time shift of the coal reflectors, is due to the

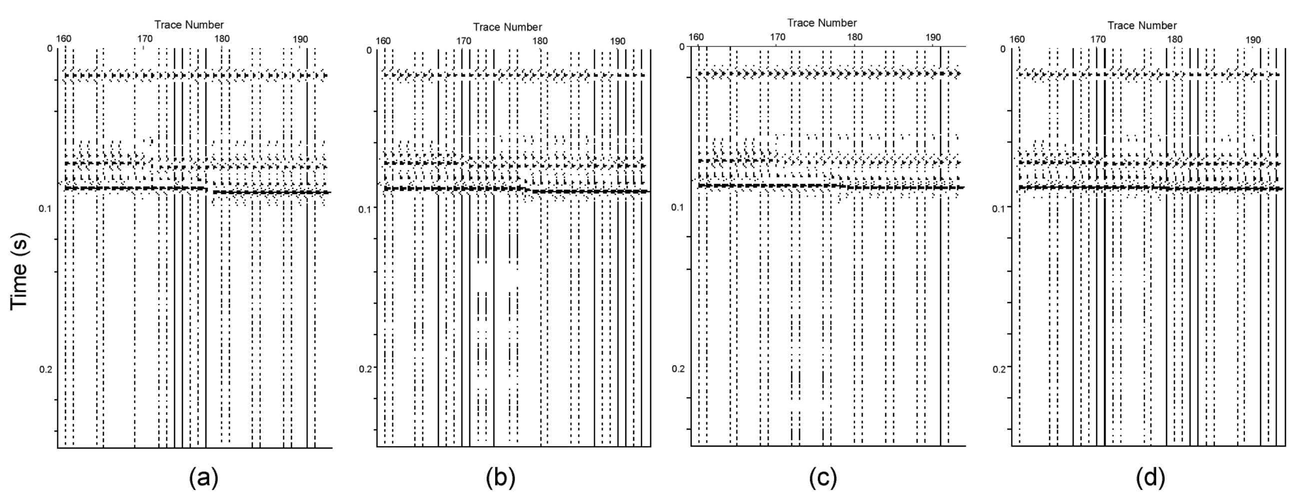

Figure 4. Change in detectability of fault as throw is reduced: (a) 4m, (b) 3m, (c) 2m, (d) 1m. The model is based on Figure 1. The horizontal extent of the section is 85m. The normal fault occurs in the marker seam around Trace 170 and in the target seam around Trace 178. The frequency bandwidth is constant at 30-250 Hz.

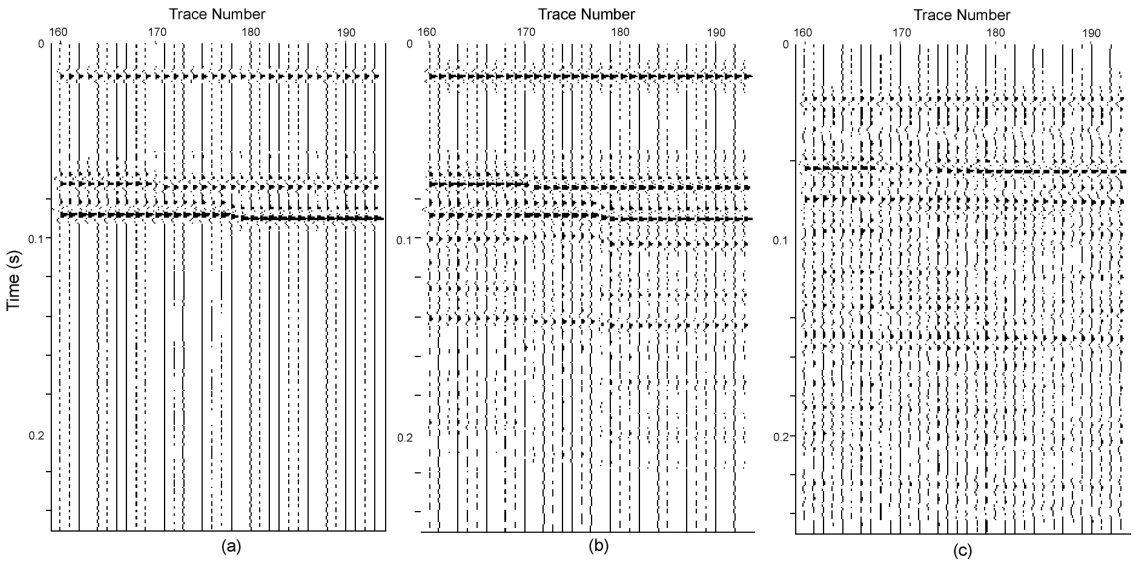

Figure 5. Seismic images of fault (3m throw) for different degrees of modelling realism. (a) zero-offset modelling (b) zero-offset modelling with multiples (c) finite-difference generation of shot records followed by CMP processing. The frequency bandwidth is constant at 30-250 Hz and the fault is positioned as in Figure 4.

incorporation of buried shots. Of main interest here, however, is the fact that the fault is considerably less obvious, due to the smearing effects of stacking.

Studies such as these suggest that interpretation based on visual examination of 2D seismic images would have difficulty detecting faults with vertical displacements less than 2–3m. Fortunately, more subtle features can be detected if visual examination is augmented by display of various secondary attributes computed from the seismic data (eg. horizon time and amplitude, horizon time and amplitude gradients). While the 3m fault is only marginally detectible on the 2D finite-offset image of Figure 5(c), it can be more reliably inferred when corresponding attributes are examined (Figure 6). Real data experience suggests that detectability of quite subtle features can often be significantly enhanced when such attributes are mapped in a 3-D sense across the survey area.

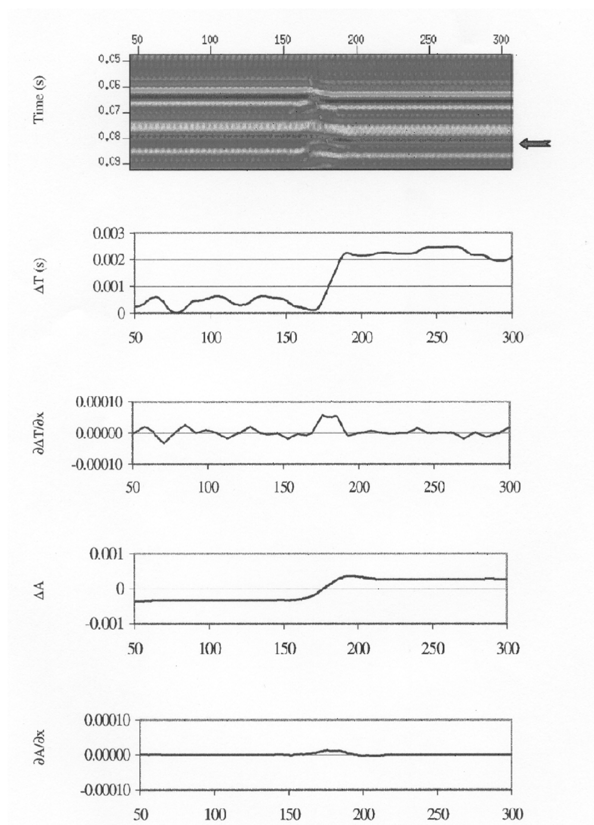

Figure 6. Seismic attributes computed for the complete finite-difference section from which Figure 5(c) is taken. Horizontal coordinates correspond to the trace numbers in Figures 4 and 5. For reference, a small time slice of the seismic section is shown at the top of the figure. The four attributes plotted apply to the target horizon (arrowed), and are (top to bottom) relative horizon time, horizon-time gradient, relative horizon amplitude, horizon-amplitude gradient.

MULTICOMPONENT MODELLING

In the example given above, the seismic stacks generated using the more realistic finite-offset approach tend to exhibit considerably lower resolution than those obtained via simple zero-offset modelling. This is due to the CMP stack process introducing spatial smearing. A further complicating factor for real data is the possibility of mode conversion (P to S-wave energy and vice versa) which can occur at any discontinuity in the earth. We have investigated this issue using the reflectivity approach to finite-offset modelling. The modelling results which follow are again based on the model in Figure 1, and incorporate realistic assumptions as to P/S velocity ratio (γ), and seismic quality factor (Q).

Typically, coal seismic data is acquired using a P-wave source (e.g. dynamite, vibroseis) with only the vertical

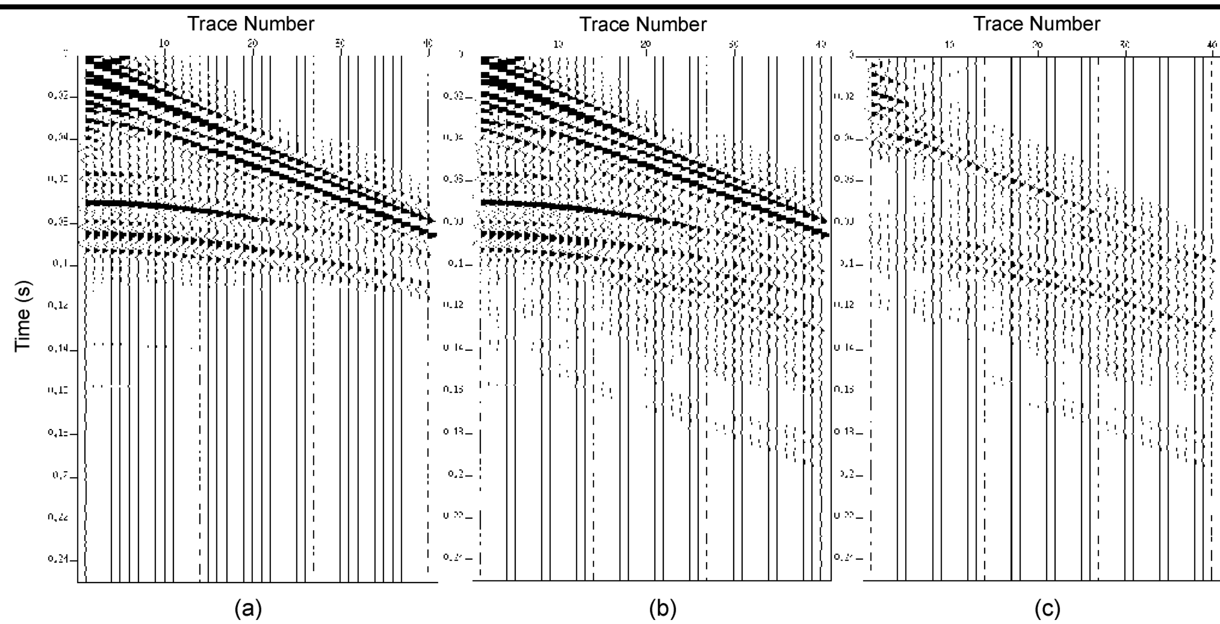

Figure 7. Multicomponent modelling: Vertical-component shot records for the model in Figure 1, generated using the reflectivity method. The geophone spacing is 5m, such that the maximum offset is 200m. (a) No P-S conversion. (b) P-S conversion allowed. (c) Difference, representing converted S-wave energy on the vertical component.

component of ground motion being recorded. Current processing practice is to assume that everything recorded on the vertical geophone is P-wave energy. Figure 7(a) shows a finite-offset shot record computed in accordance with this assumption. That is, no P-S conversion is permitted and hence the record contains only P-wave energy. Figure 7(b) shows the same record but with the physically realistic assumption that P-S conversions occur. Figure 7(c) shows the difference between these two. The reflection energy occurring at times in excess of 0.07s represents mode-converted S-wave energy. This suggests that conventional vertical-component recording practice may be prone to significant contamination from P-S conversions. This will necessarily degrade the resolution of the resulting seismic section.

It is of interest to consider the implications of recording not only the vertical component of ground motion, but also the horizontal components. Figure 8 shows the horizontal in-line recordings corresponding to the vertical records in Figure 7. Figure 8(a) is the horizontal recording from an explosive source when no P-S conversion is allowed. This represents the pure P-wave energy expected on the horizontal component. Figure 8(b) shows the total horizontal component recorded under the more realistic assumption that P-S conversions occur. Figure 8(c) shows the difference between these two (i.e. the S-wave energy on the horizontal component).

These observations suggest that there may be practical value in recording horizontal ground motion as well as vertical. Firstly, Figure 8 indicates that the horizontal component contains dominantly S-wave reflection energy, with little P-wave contamination. This suggests that a seismic image based on converted S-waves, derived from the horizontal component, may be less prone to cross-mode contamination than a conventional P-wave image. Further, Nobuaoka & others (1999) and Garotta (1999) note that, particularly for shallow targets, S-wave reflections may provide higher resolution than P-waves, due to wavelength reductions.

In addition, recording of the full vector wavefield presents the possibility of vector separation of the P and S wavefields (e.g. Hendrick & Hearn, 2000). This has the potential to provide a substantially cleaner P-wave image than is achievable with current practice.

CONCLUSIONS

Numerical modelling provides a cost effective indication of the resolution to be anticipated with particular recording parameters and in particular geological situations. An analysis of the influence of frequency content suggests that it is important to record high frequencies up to the limit imposed by earth scattering. Conversely, frequencies at the low end of the spectrum are less critical to a high-resolution seismic pulse. This has implications to coal seismic instrumentation.

Numerical modelling can provide insight into the scale of geological features, such as faults, which can be observed on seismic images. Detection of such features can be enhanced if visual examination of seismic image is augmented by computation of seismic attributes.

Multicomponent modelling based on Bowen-Basin geology indicates that coal seams are good generators of mode-converted seismic waves. This suggests that the assumptions of conventional vertical-component reflection are being violated, and that current images may be prone to contamination from converted S-waves. There is scope for

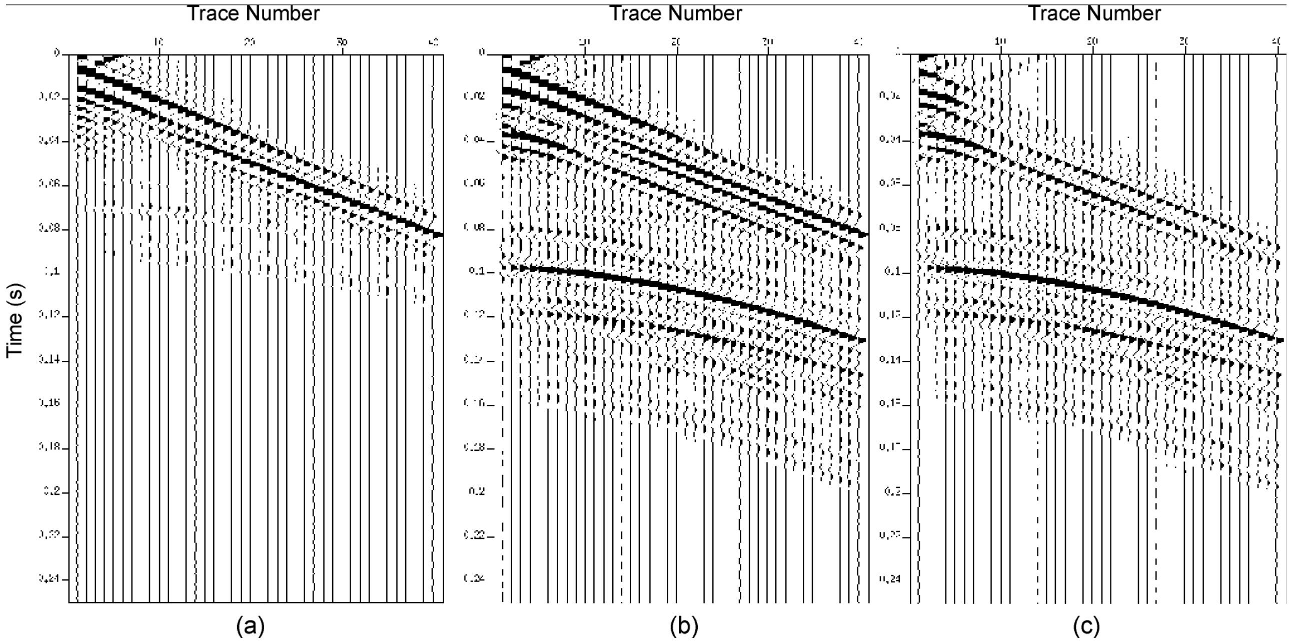

Figure 8. Multicomponent modelling: Horizontal-component shot records for the model in Figure 1, generated using the reflectivity method. The geophone spacing is 5m, such that the maximum offset is 200m. (a) No P-S conversion. (b) P-S conversion allowed. (c) Difference, representing converted S-wave energy on the horizontal component.

recording both vertical and horizontal components. This has the potential to provide an alternative, perhaps more highly resolved, image based on S-waves. Additionally, vector separation methods have the potential to provide a cleaner P-wave image.

ACKNOWLEDGEMENTS

Some of the work described here was carried out with support from the Newlands Coal Underground Project, and we acknowledge the interest of Gary Fallon and Paul Harrington. Parts of the analysis used the Seismic Unix system, which was implemented at University of Queensland with support from the Centre for Wave Phenomena at Colorado School of Mines. Natasha Hendrick's Ph.D. Project is supported by an Australian Post Graduate (Industry) Scholarship. The industry partner is Veritas DGC (Australia) Pty. Ltd.

REFERENCES

GAROTTA, R., 1999: Shear waves from acquisition to interpretation. *Distinguished Instructor Series*, **No. 3**, Society of Exploration Geophysicists, Okalahoma.

HENDRICK, N. & HEARN, S., 2000: A comparison of two multi-trace, multi-component wavefield separation techniques. Presented at 14th ASEG International Geophysics Conference and Exhibition, Perth.

KELLY, K.R., WARD, R.W., TREITEL, S. & ALFORD, R.M., 1975: Synthetic seismograms: a finite-difference approach. *Geophysics*, **41**, 2–27.

KENNETT, B.L.N., 1979: Theoretical reflection seismograms for elastic media. *Geophyiscal Prospecting*, **27**, 301–321.

KNAPP, R.W. & STEEPLES, D.W., 1986: High-resolution common-depth-point seismic reflection profiling: Instrumentation. *Geophysics*, **51**, 276–282.

NOBUAOKA, D., KAIDA, Y., BROUWER, J. & NIJHOF, V., 1999: High-resolution shallow seismic reflecting using a portable S-wave vibrator. *Extended Abstracts V1, EAGE 61st Conference and Technical Exhibition*, Helsinki, 4–43.

ROBINSON, E.A. & TREITEL, S., 1980: *Geophysical Signal Analysis*. Prentice-Hall Inc., New Jersey.

SHERIFF, R.E., 1991: *Encyclopedic Dictionary of Exploration Geophysics*. Society of Exploration Geophysicists, Okalahoma.

ZIOLKOWSKI, A. & LERWILL, W.E., 1979: A simple approach to high resolution seismic profiling for coal. *Geophysical Prospecting*, **27**, 360–393.

Steve Hearn
Velseis Pty Ltd, PO Box 118, Sumner Park, Qld. 4074 (steveh@velseis.com.au)
Natasha Hendrick
Exploration Geophysics Laboratory, Department of Earth Sciences, University of Queensland, 4072