The Crosshole Seismic Reflection Method in Opencast Coal Exploration

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The crosshole seismic reflection method in opencast coal exploration[1]

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Introduction

In opencast coal exploration in the UK, a dense grid of boreholes is drilled to provide the necessary information on the quantity and quality of coal reserves and on the geological structure. Typically, borehole spacing is 40–60 m, but it may be reduced around faults or where there are old room-and-pillar mineworkings. Even with this density of boreholes, it is not possible to detect faults with throws less than 2–3 m, and these can pose a hazard to stability during excavation which may be particularly critical at site boundaries. Also, estimates of the quantity of coal reserves could be improved if old mineworkings were located more accurately.

The potential of borehole seismic surveys in this application was discussed in more detail in an earlier paper (Kragh *et al.* 1991). Here we report on the development of the crosshole reflection method, making use of opencast exploration boreholes, to provide seismic cross-sections between boreholes. Small explosive charges are used as sources with hydrophones as receivers. The use of downhole sources and receivers leads to excellent resolution compared with surface seismic and VSP surveys; signal bandwidth is typically 200–500 Hz.

Readers interested in the application of cross-well surveys to the definition of hydrocarbon reservoirs will note that the environmental conditions for our surveys were relatively undemanding: low temperatures and hydrostatic pressures in uncased boreholes at relatively close separations. Nevertheless, the results indicate the potential of the method for deeper, larger scale surveys in sedimentary rocks, where even higher frequencies can be successfully transmitted (e.g. Harris 1988).

Data acquisition

A string of 12 hydrophone receivers at 2 m spacing is placed in one borehole (Fig. 1). Small explosive charges

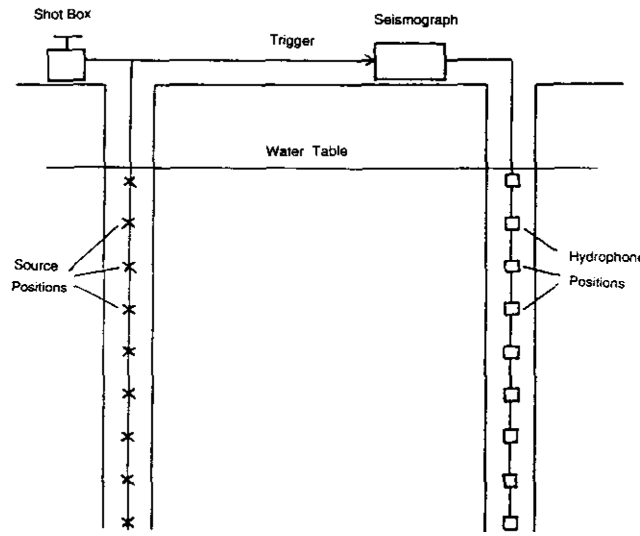

Fig. 1. Schematic diagram of field set-up for data acquisition. Borehole separations are typically 30—60 m and source and receiver spacings are 2 m over a depth range of 40 m or more.

(either a single electric detonator on its own, or with 15 g of chemical explosive) are fired successively in a neighbouring borehole at 2 m intervals. Coverage is then extended by repositioning the hydrophone string in the receiver borehole and repeating the shot sequence. The triggering signal for the seismograph is obtained by wrapping a wire around the end of the detonator. This blows open-circuit when the shot is fired, providing an accurate time-break. It is necessary that all shot and receiver positions are below the water table in order to provide good acoustic coupling to the rock. A typical common-shot gather is displayed in Fig. 2a.

The deviation of the boreholes from the vertical is measured using a pendulum-type inclinometer. This tool is run in the borehole inside its own purpose-designed casing, which has grooves so that inclinations may be measured in two perpendicular azimuths. Deviation from the vertical in these shallow boreholes has generally been slight (no more than 3 m at the deepest source or receiver position), and neighbouring boreholes tend to deviate by similar amounts in the same direction.

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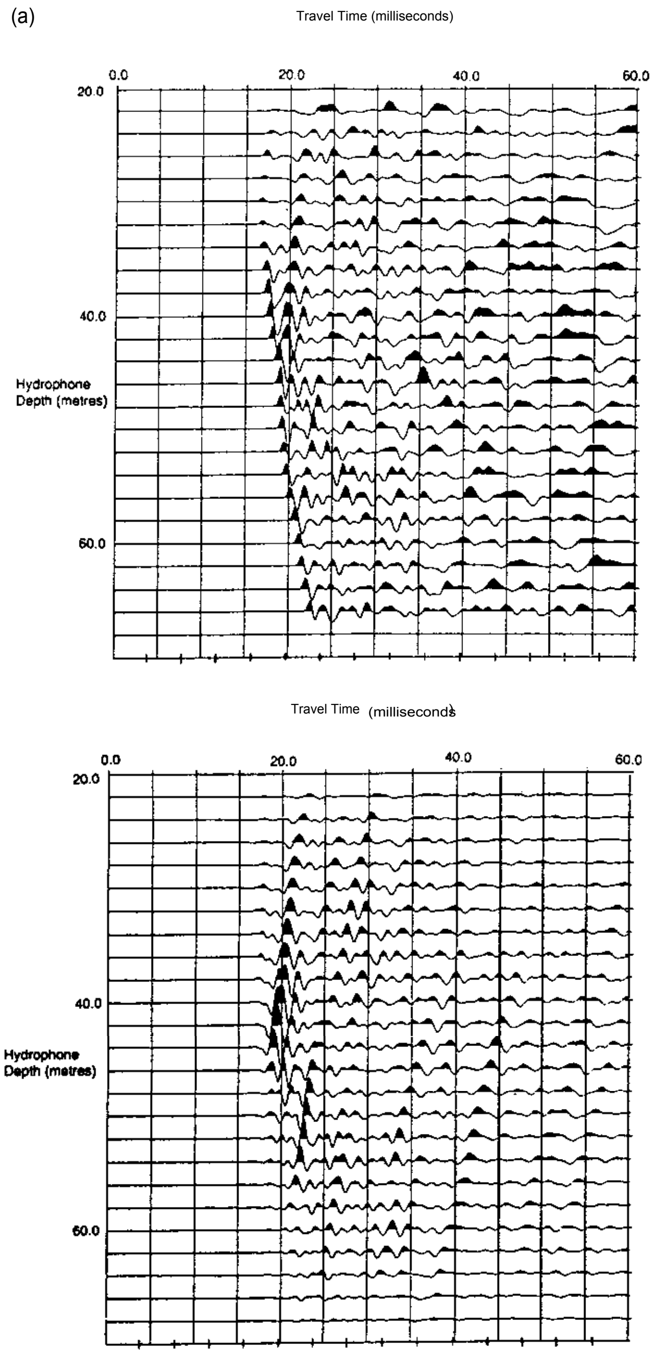

Fig. 2. Common-shot gather from a detonator at 30 m depth with hydrophones over the depth range 22–66 m: (a) raw data with gain ramp applied proportional to traveltime squared; (b) showing only the upgoing wavefield at the receivers after wavefield separation in the f–k domain.

In order to illustrate the sub-surface coverage which may be obtained in such surveys, the reflection point loci for alternate source and receiver positions in a pair of vertical boreholes 50 m apart are plotted in Fig. 3.

These loci were calculated for a constant velocity field assuming horizontal interfaces. They indicate where reflections would occur for rays which leave the source positions in a downward direction and are incident on

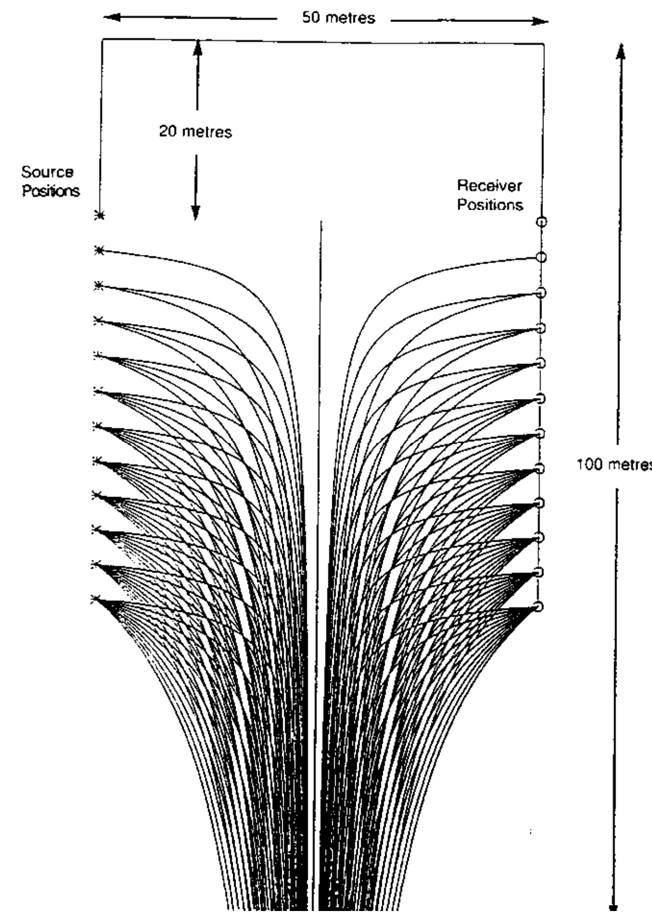

Fig. 3. Reflection point loci for upgoing primary reflections in a crosshole survey of typical dimensions. Only alternate source and receiver positions, at 4 m spacing, are shown for clarity.

the receivers in an upward direction (i.e. primary reflections in the upgoing wavefield). The diagram could be inverted to show the sub-surface coverage of the downgoing wavefield, including primary reflections from interfaces above source and receiver positions. Thus subsurface coverage extends above the water table and below the deepest locations of sources and receivers, albeit with reducing width.

Data processing

An outline of the processing sequence is sketched in Fig. 4. First, upgoing and downgoing wavefields at the receivers are separated by filtering common-shot gathers in the frequency–wavenumber (f–k) domain. The upgoing wavefield from the common-shot gather in Fig. 2a is shown in Fig. 2b. The direct wave arrivals may be muted out, either before or after wavefield separation. Inclusion of the direct arrivals in the wavefield separation process can lead to ringing problems in the filtered data, but on traces where the direct arrivals are, say, downgoing and the reflections of interest are upgoing, it is preferable to mute after wavefield separation in order to preserve as much of the reflected energy as possible.

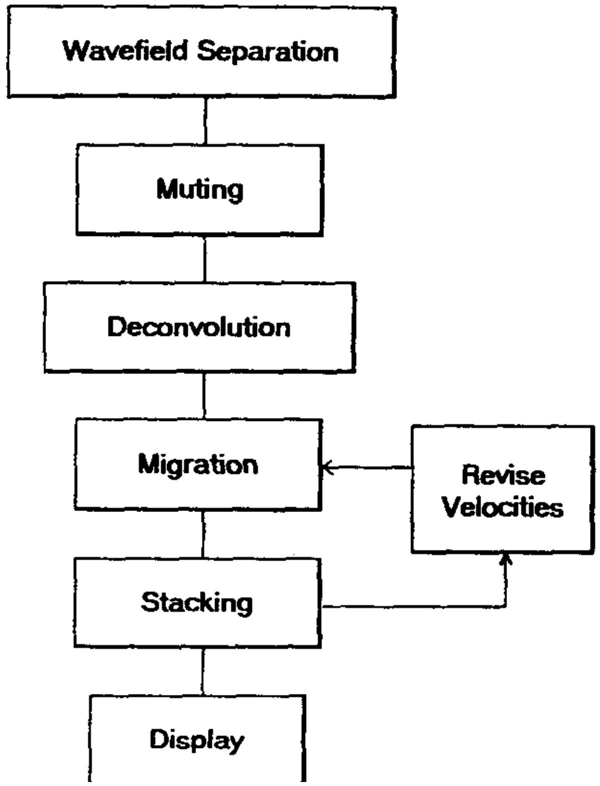

Fig. 4. Outline processing sequence for crosshole seismic reflection data.

Receiver spacing needs to be less than half the apparent vertical wavelength in order to avoid spatial aliasing. The spacing of 2 m is small enough for the signal bandwidth and velocity fields in these shallow surveys.

A common problem with borehole receivers is the presence of tube waves in the data. We have observed them in some of our crosshole datasets, where they characteristically have lower bandwidth than the body waves. They sometimes emanate from the top (or water table) and bottom of the receiver borehole, and frequently from the depth levels of coal seams. These events are apparently generated by the interaction of the direct body waves with discontinuities in the receiver borehole. In our datasets, where tube waves have been observed, they have readily been suppressed by f–k filtering.

Before imaging the data, it is advantageous to shape the effective wavelet into a zero-phase wavelet with a flat amplitude spectrum over the useful signal bandwidth. The effective wavelets in the upgoing and downgoing wavefields are estimated separately because of differences in short-period multiple content. The wavelet in each case is assumed to be minimum-phase and is calculated from the averaged autocorrelation functions of all the traces in the (wavefield-separated) common-shot gather.

The VSP–CDP transform (see Dillon and Thomson 1984) was used to image the data by reflection point mapping in the first survey of this type which we processed (Goulty a *al.* 1990). Subsequently, we used the same technique to refine the velocity field prior to migration. However, more recently we have discarded it. An initial estimate of the velocity field is obtained by measuring uphole times in each borehole at 2 m intervals, and from a traveltime tomogram obtained by inverting the direct wave arrival times by the simultaneous iterative reconstruction technique (SIRT).

The separated wavefields in each common-shot gather are migrated using the generalized Kirchhoff integral of Dillon (1990), which is valid in the far-field approximation. A gain ramp proportional to the square root of the traveltime is applied to each trace, followed by spectral correction factors appropriate for the assumption of 2D structure. Rays are traced from each grid point on the section to be imaged to each source and receiver position, and corresponding traveltimes calculated. Amplitude values are summed for each `diffraction point' over an aperture which includes dips of ±22.5°.

The migrated wavefields are stacked to yield one section for upgoing reflections and another for downgoing reflections. The polarity of the downgoing reflection section has to be reversed as reflection coefficients change sign when the wave is incident from the opposite side of the interface. Any mismatch in stacking indicates errors in the velocity field, which has to be modified and the migration step repeated. The migrated up- and downgoing wavefields are then combined in a final section.

Results

The results from two surveys at an exploration site in Yorkshire, England are presented here. One is across undisturbed ground and the other across a normal fault zone with approximately 25 m of vertical throw.

In the first survey, the boreholes were 41 m apart. Detonators and hydrophones were positioned at 2 m intervals in the respective boreholes over the approximate depth range 10–60 m. The stacked, migrated down- and upgoing wavefields are shown in Figs 5a and b. Normal SEG polarity is adopted, so the reflection from the top of a coal seam is black.

It is very difficult to adjust the velocity field for migration such that the overlapping part of the up- and downgoing sections matches. Consequently, it is expedient to combine the two sections using complementary cosine tapers over a zone of low reflectivity to produce the complete section of Fig. 5c.

The coal seams give rise to the strongest reflections in the section, although there is also a strong reflection at the water table. Slight mis-matches in depth between black peaks and the tops of coal seams indicate that the velocity field was not estimated perfectly.

The presence of a small fault between 70 and 80 m depth in the borehole on the left is readily apparent from the missing section between the sandstone bed and the next coal seam below it. Unfortunately, the fault cannot

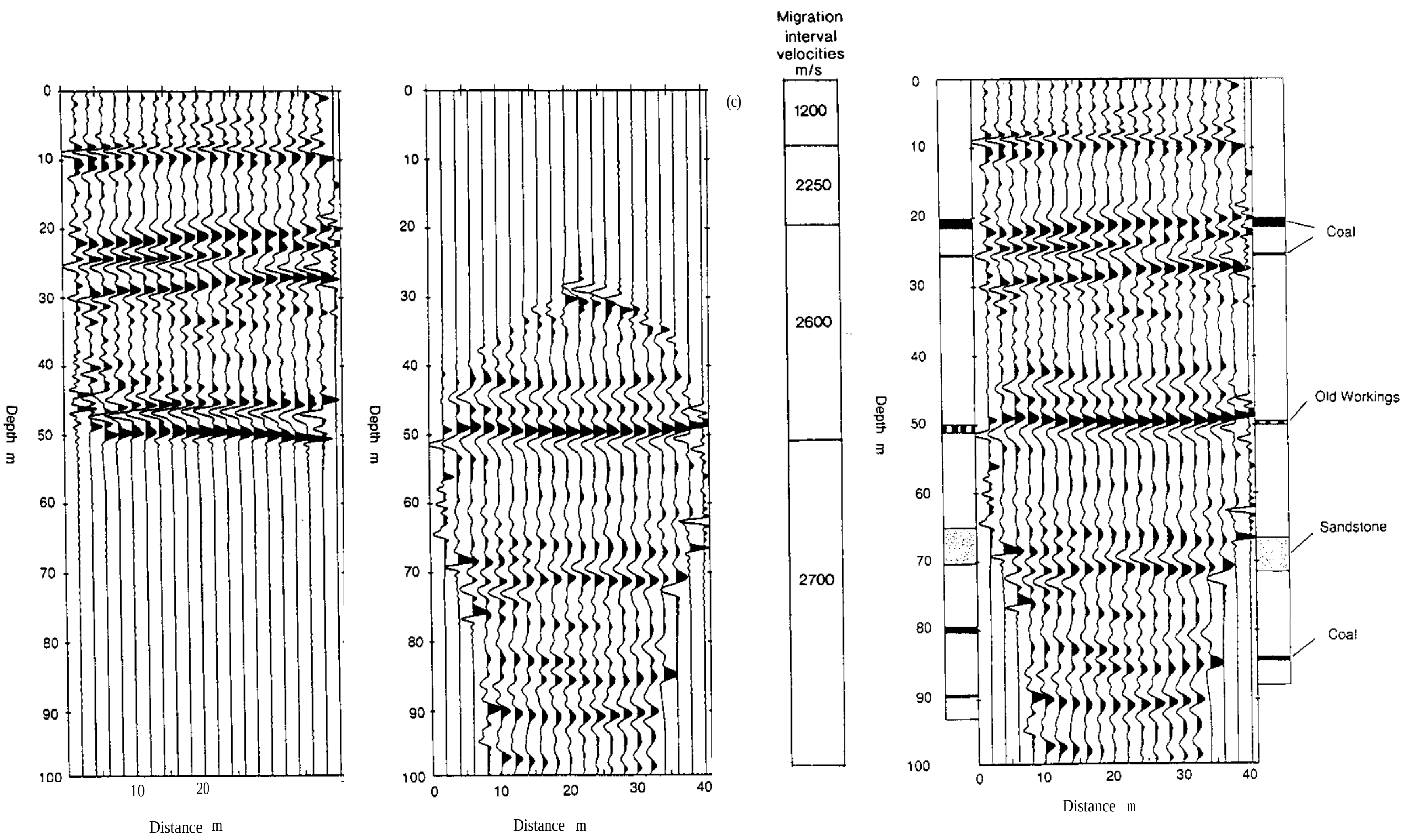

Fig. 5. Stacked sections with prestack depth migration from an example *survey:* (a) downgoing wavefield; (b) upgoing wavefield; (c) combined up- and downgoing wavefields. The velocity field used for migration is displayed to the side.

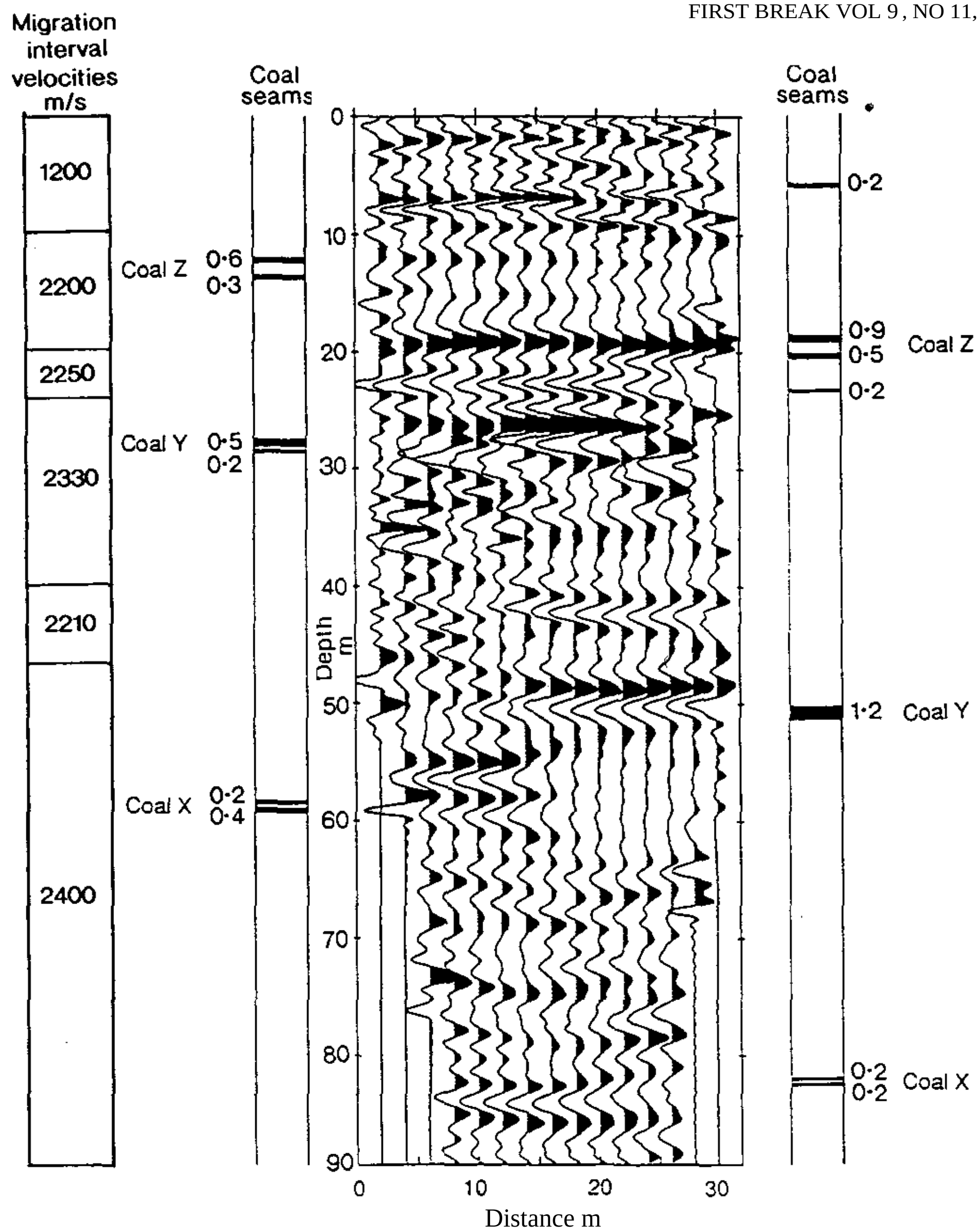

Fig. 6. Final section with prestack depth migration from a survey across a normal fault zone. The velocity field used for migration is displayed to the side.

be picked on the seismic section, either because it is too close to the borehole, or because of lack of penetration of signal through the worked seam at 50 m depth. The use of larger charges might have overcome the latter problem.

In the second survey, the boreholes were just over 30 m apart. Detonators and hydrophones were spaced at 2 m intervals over the approximate depth range 10–50 m. The migrated depth section, with up- and downgoing reflections combined, images the fault zone quite clearly (Fig. 6). The reflection from coal seam Z is continuous across the section from the borehole on the right, so there must be a fault with 7 m vertical throw at this horizon very close to the borehole on the left. A larger fault, of some 15 m vertical throw, cuts the borehole on the left between coal seams Z and Y. The truncations of reflections from coal seam Y to the right, and from coal seam X to the left at the fault zone are clearly imaged in the body of the data.

Discussion and conclusions

The most demanding step in processing has been to estimate the velocity field correctly for the prestack depth migration. Adjustment of the velocity in one interval to reposition one reflector generally requires adjustment of the rest of the velocity field too. The velocity field in coal measures is anisotropic, and no doubt it would be necessary to introduce anisotropy to achieve the best possible result. We have experimented with an overall anisotropy of 15%, velocities being faster in the horizontal direction than in the vertical, as this was indicated by the uphole and crosshole direct-wave traveltime data. However, the results were no better.

We have been able to suppress any tube waves in our datasets quite readily by filtering in the f–k domain, but they may be much more dominant, and therefore much more of a problem, in other crosshole datasets. For example, Albright and Johnson (1990) observed tube waves in the receiver borehole generated by tube waves in the source borehole and transmitted between boreholes as a channel wave in a coal seam. However, our experience in northern England shows that it is not usually possible to generate channel waves in coal seams shallower than 100 m depth (Goulty *et at.* 1990), even when one wishes to do so to check for cross-hole continuity of the coal seam!

The results show that high-resolution images of coal measures strata can be obtained using the crosshole seismic reflection method. Strong reflections are visible from coal seams only a few tens of centimetres thick, and the wavelengths present in the section suggest that isolated small faults with throws as small as 1 m might be detectable. The lack of coverage very close to, and directly below, the boreholes is a restriction in the method; however, this zone may be filled in using the hole-to-surface seismic reflection method (Kragh *et al*. 1991).

In conjunction with hole-to-surface seismic profiles, the crosshole reflection method should be useful in opencast coal exploration for locating small faults at site boundaries which can pose a hazard during excavation. It could also be used to detect the boundaries of old mineworkings between boreholes. This would help to improve estimates of site reserves in an exploration context, but might be more useful in site investigation for civil engineering construction. Crosshole seismic profiles might also be acquired beneath obstacles such as buildings or water courses where drilling and planting surface geophones are impractical.

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References

ALBRIGHT, J.N. and JOHNSON, P.A. 1990. Cross-borehole observation of mode conversion from borehole Stoneley waves to channel waves at a coal layer. *Geophysical Prospecting* **38**, 607-620.

DILLON, P.B. 1990. A comparison between Kirchhoff and GRT migration on VSP data. *Geophysical Prospecting* **38**, 757-777.

DILLON, P.B. and THOMSON, R.C. 1984. Offset source VSP surveys and their image reconstruction. *Geophysical Prospecting* 32, 790-811.

GGULTY, N.R., THATCHER, J.S., FINDLAY, M.J., KRAGH, J.E. and JACKSON, P.D. 1990. Experimental investigation of crosshole seismic techniques for shallow coal exploration. *Quarterly Journal of Engineering Geology* 23, 217-228.

ARRIS, J.M. 1988. Cross-well seismic measurements in sedimentary rocks. 58th Meeting. Society of Exploration Geophysicists, Expanded Abstracts, 147-150.

KRAGH, J.E., GOULTY, N.R. and FINDLAY, M.J., 1991. Hole-to-surface *seismic* reflection *surveys for* shallow coal exploration. *First Break* 9,335–344.