Imaging coals with seismic reflection data for improved detection of sandstone bodies

From Earthwise

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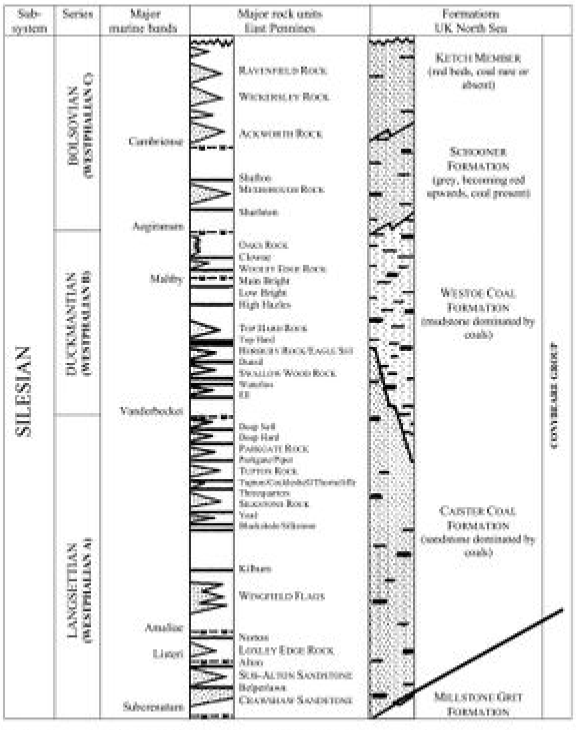

Figure 1 The stratigraphy of the Silesian of the East Pennine Basin and the Southern North Sea. In the southern North Sea sandstone dominates the Namurian and the Caister Coal Formation is also generally sandstone rich. The middle and upper Westphalian B successions are notably sandstone free, where proved, and are similar to successions in the East Pennines. (Modified from Guion et al, 1995)

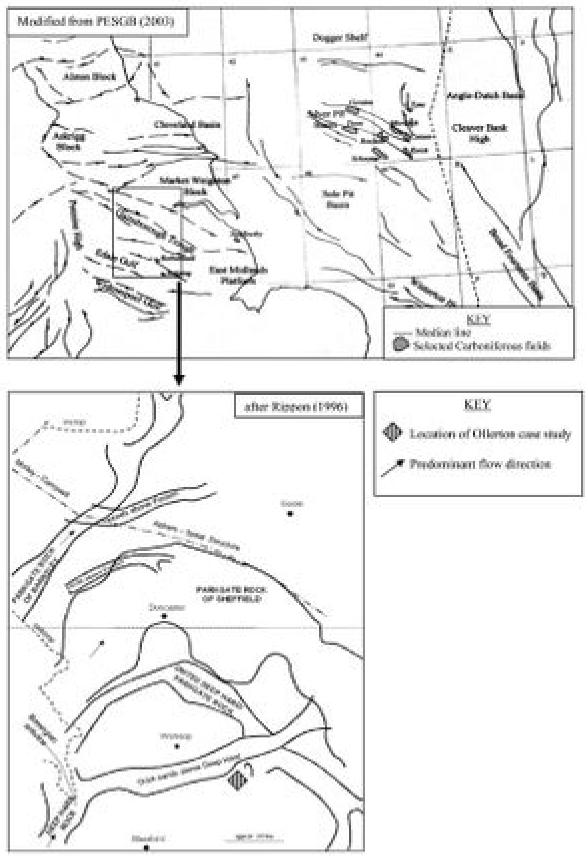

Figure 2 Location maps showing main structural units, some onshore and SNS Carboniferous reservoirs and the location of the Ollerton case study. Large sandstone bodies are well known across the East Pennine Basin. Although some show a correlation with the underlying structure, such as the Parkgate Rock (Sandstone), which swings round into the Gainsborough Trough, others, such as the sandstones above the Deep Hard, cut across the Dinantian basement.

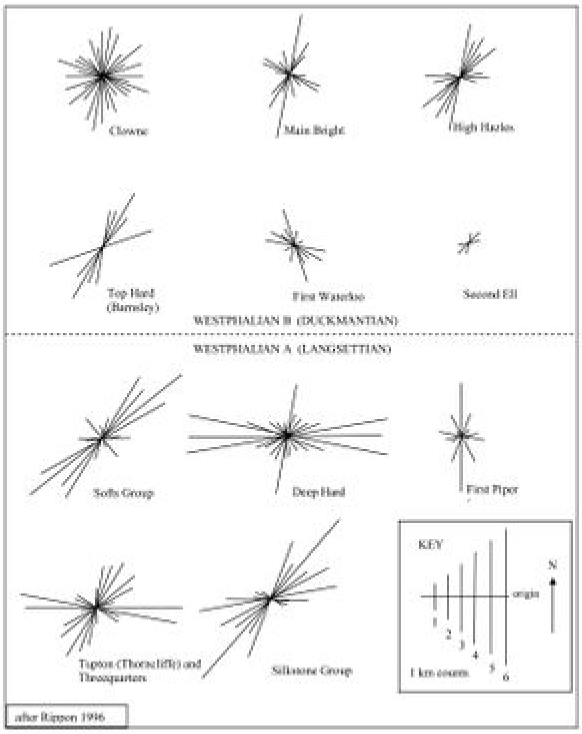

Figure 3 Palaeoflow trends in the Westphalian A/B of north Nottinghamshire and northeast Derbyshire. The rose diagrams incorporate data from well constrained channel mapping undertaken for mining purposes. The length of the radial lines indicates the number of kilometres along which the particular orientations have been mapped. For stratigraphical position of the coal seams, refer to Figure 1.

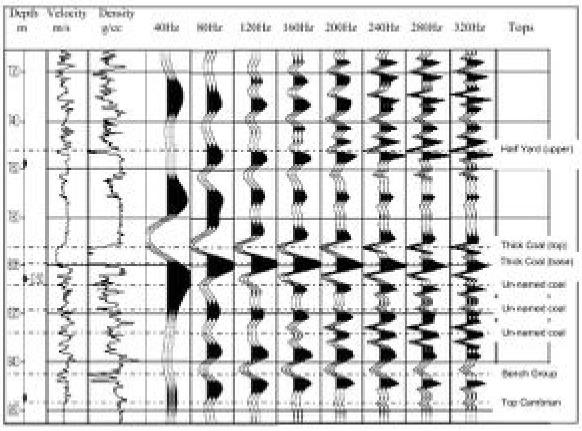

Figure 4 Synthetic seismograms convolved with increasing-frequency Ricker wavelets. The Thick Coal is a composite seam, 3–6m thick, in the Warwickshire coalfield. Note how the top and bottom of the seam are defined by a single wavelet up to 200Hz. Above 240Hz separate reflections are generated from the top and bottom of the seam and the bed is no longer regarded as a thin bed. Although seams such as the Half

Yard and the Bench group would be interpretable at 80Hz, the un-named seams below the Thick Coal are interpretable only at higher frequencies. At 40Hz the Thick Coal and the Bench Group would be correlatable. The composite trough associated with Half Yard would be difficult to follow on a seismic section.

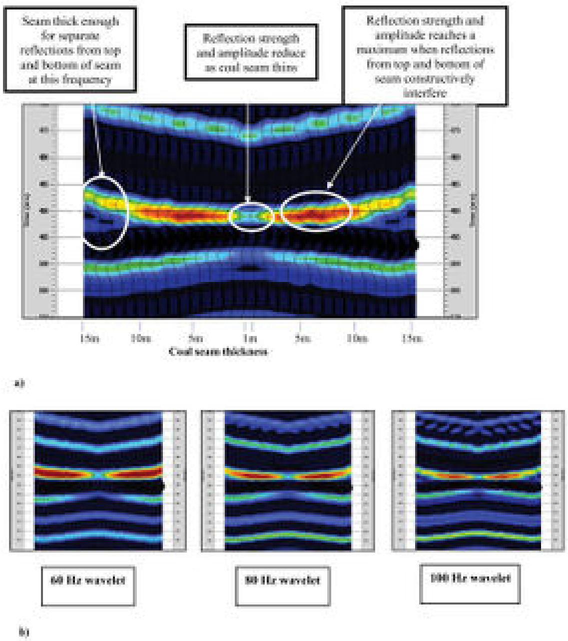

Figure 5 Synthetic models of coal seam thicknesses. (a) Synthetic model showing the relationship between reflection strength, amplitude and seam thickness. The density model has been convolved with a 100Hz Ricker wavelet. (b) The same model as part (a), recalculated with 60Hz, 80Hz and 100Hz wavelet. Note how the area of maximum amplitude is broader on the lower frequency plots. The lateral resolution as well as the vertical resolution therefore reduces as the frequency is lowered.

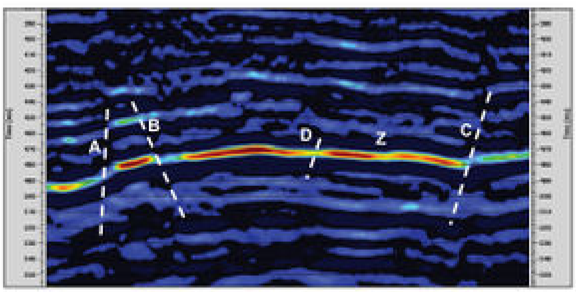

Figure 6 Small-scale faulting in UK Coal Measures. Faults at A, B, and C are clearly visible on a reflection strength plot. Faults A and B have throws of 7m to 10m and have been proved in adjacent mine workings, and Fault C has a throw of approximately 15m.

Fault D shows no displacement of the reflector but has been intersected by a mine roadway and is known to have a throw of 2.9m. The low-amplitude zone marked Z is on the alignment of a channel, which cuts into top of the seam farther south.

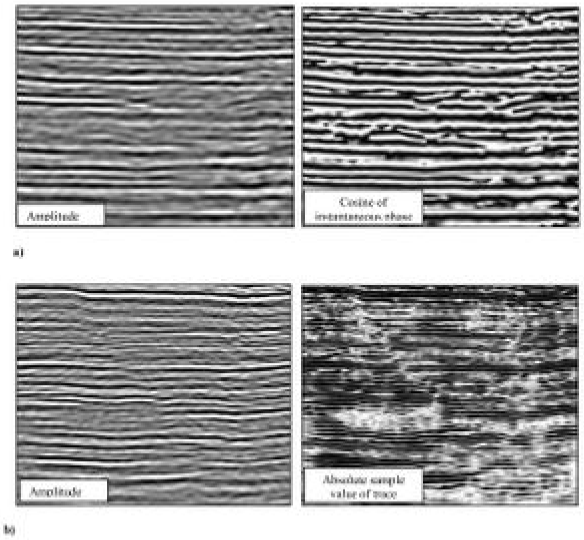

Figure 7 Sedimentary variations in coal seam lithologies within the Ollerton case study depicted using differing seismic displays. (a) sedimentary variations associated with fluvial structures are highlighted using the cosine of the instantaneous phase (timing lines every 50ms), (b) the absolute sample value of the trace reveals low amplitude zones associated with small faults (timing lines every 50 ms).

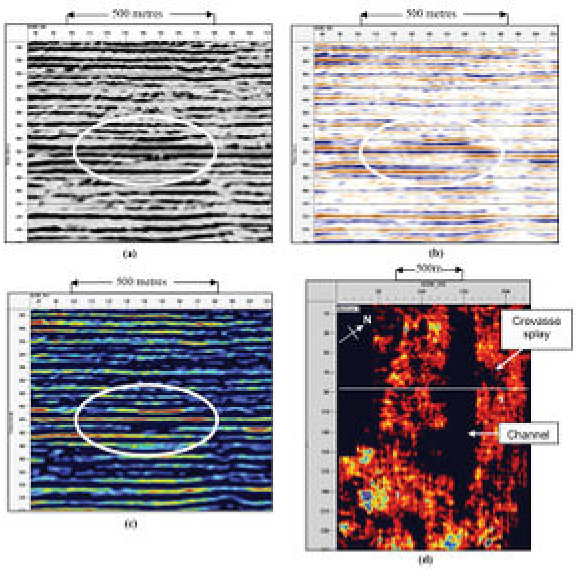

Figure 8 The use of varying seismic attribute displays to recognize channel features in the roof of the Top Hard Seam in the Ollerton 3-D seismic case study. (a) Conventional wiggle trace plot. Coal seams

tops have a negative reflection coefficient and are therefore shown as troughs. (b) Amplitude plot; negative amplitudes (e.g. coal seam tops) in blue. (c) Reflection strength plot; high reflection strength (e.g. coal seams) in "hot" colours. Note variations in seam thickness evident in colour variations, (d) Time slice showing northwest–southeast-trending channel feature, possibly with crevasse splays. (The position of the in-line in (a–c) is indicated by the white line.)

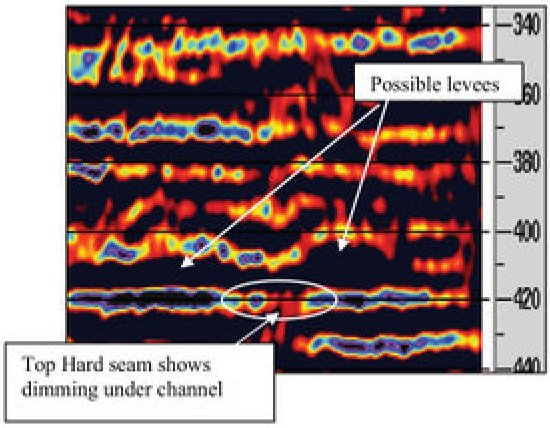

Figure 9 Channel feature above the Top Hard seam. The Top Hard seam, at 420ms TWT, shows a dimming in reflection strength, indicating a possible thinning of the seam. The cross section of the channel feature appears to have banks or levees.

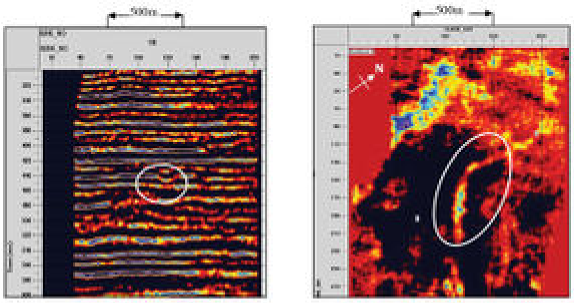

Figure 10 Feature visible at Dunsil Seam horizon in the Ollerton study area. Seam disturbance apparent on in-lines appears as a strong linear event on the flattened time slice. This structure is approximately 120m wide. Its arcuate shape and narrow width are typical of channel bank collapse structures seen in mine workings.

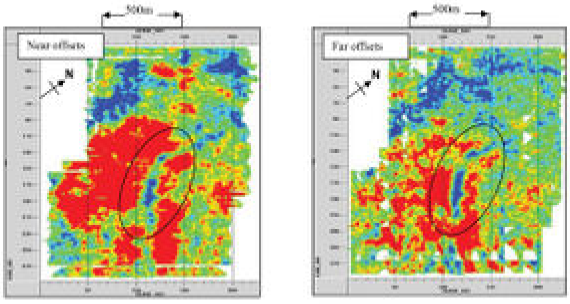

Figure 11 Evidence of brightening of negative amplitude on the far offsets in the middle of the channel feature at the Dunsil Seam horizon. However, the angle gathers show the acquisition geometry makes AVO analysis unreliable.

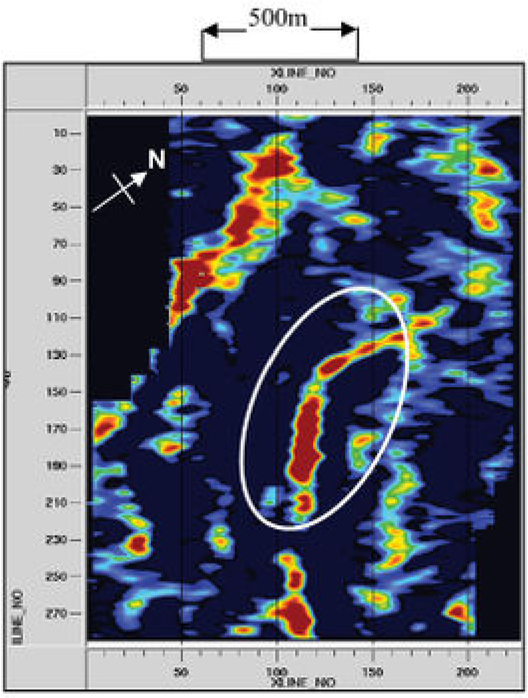

Figure 12 Channel feature shown in [Figure 10](#) with a 50Hz high-cut filter applied pre-stack. This suggests that, at the sort of frequencies recorded in the SNS, a sandbody of this size may be interpretable.

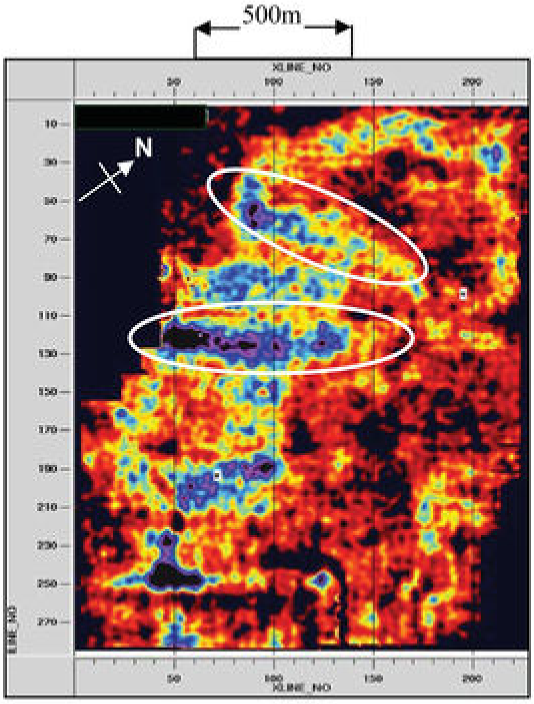

Figure 13 A large erosional channel system above the Parkgate Seam, with a southwest to northeast flow direction, is known from mine workings at Ollerton. The width of the channel system is about the same as the dataset so the features indicated above may represent preferred abandonment channels.

Table 1 Acquisition parameters.

Energy source	Explosive
Source pattern	Single hole
Charge size	1 lb (454 g)
Charge depth	40 ft (12.2 m)
Station interval	12 m
SP interval	12 m
Spread	Split spread
Near offset	6 m
Maximum offset	726 m
No. of channels	144
Nominal fold	6
Low-cut filter	25 Hz
High-cut filter	250 Hz
Geophone array	2 strings of 6 × 2.0 m, in parallel
Geophone frequency	30 Hz
Record length	2 s
Sample rate	1 ms

Table 1 Acquisition parameters.

Table 2 Processing sequence.

Demultiplex
Geometry application and QC
Trace editing
Spherical divergence correction
Surface consistent amplitude correction
First break picking
Tomographic refraction static calculation
Surface consistent deconvolution
Spectral balancing
Surface consistent residual statics calculation
Normal moveout correction
Post NMO mute
3D Stack
Bandpass filter
FXY deconvolution
3D phase shift migration
Zero phase

Table 2 Processing sequence.

Table 3 Sand bodies, mapped from borehole and mining records, across or adjacent to 3D study area (in descending stratigraphical order).

Sand Body	Description	Maximum width (km)	Maximum thickness (m)	Key borehole
Above Top Hard Seam	2.5 km north of study area. Sandstone with conglomerates and breccias	2.5	35 Multi-storey	Gravel Pit Lane E [illegible] N [illegible]
Above Dunsil Seam	Crosses study area from NW to SE.	4	15 Single storey	Mill Mount E [illegible] N [illegible]
Above Vanderbeckei Marine Band	Just SE of study area. At same horizon as Friend Rock of East Midlands oil-field.	3	20	Gracefield Lane E [illegible] N [illegible]
Above Deep Hard Seam	4km NW of study area	4.5	30 Multi-storey	Poulter E [illegible] N [illegible]
Above Parkgate Seam	Crosses study area from WSW to ENE	1.5	15	[illegible] E [illegible] N [illegible]
Above Tupton Seam	Just south of study area. A series of minor channel belts. Poorly known because below level of mining and boreholes.	Unknown	Unknown	

Table 3 Sand bodies, mapped from borehole and mining records, across or adjacent to 3D study area (in descending stratigraphical order).

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Imaging coals with seismic reflection data for improved detection of sandstone bodies

By B. A. McGlen and J. H. Rippon From: Pages 119–134 of *Carboniferous hydrocarbon geology: the southern North Sea and surrounding onshore areas*, edited by J. D. Collinson, D. J. Evans, D. W. Holliday, N. S. Jones. Published as volume 7 in the Occasional Publications series of the Yorkshire Geological Society, © Yorkshire Geological Society 2005.

Summary

Significant gas reserves in Quadrant 44 of the southern North Sea have been proved in channel sandstones within the Westphalian A/B Coal Measures of the Upper Carboniferous. The net-to-gross can be relatively high but the seismic response is dominated by the highly reflective cyclical coal sequences. The sandstones are, therefore, difficult to identify and map using seismic reflection data. A 3-D seismic analogue was studied in the East Pennine Basin coalfield to identify attributes, which may indicate the presence of channel sandstones within the Coal Measures. The study area lies between the onshore oilfields of the Eakring, Egmanton and Bothamsall anticlines. Modelling of variations in the sedimentology of coal-seam sequences has demonstrated the expected response on the seismic signal. Some of these variations have been located in a 3-D seismic volume, particularly those relating to channel sandstone bodies. The correlation between the identification and orientation of channel features on the seismic reflection data, and that obtained from the borehole and mining data, is good, with both the size and the geometry of the seismic features matching that expected from the geological data. By combining mining and borehole data with the 3-D seismic reflection data, there has been a significant reduction in interpretation uncertainty.

Introduction

Carboniferous formations have an extensive subcrop beneath the North Sea. The sequence is up to 9000 m thick, with rapidly changing facies and pronounced local changes in thickness (Besly 1998). It is economically important for two main reasons:* The coals and carbonaceous shales are source rocks, particularly for gas, in the overlying Permian and Triassic reservoirs of the southern North Sea (SNS).

- The Carboniferous sequence itself contains important sandstone bodies that act as gas reservoirs, notably within the Westphalian of the northern part of the SNS.

Between 1983 and 1993 some 20 gas discoveries were made within the Carboniferous of this region, including several major finds, and commercial development of the Murdoch, Caister and Ketch fields began. However, the Westphalian reservoirs are difficult to locate, because, although the ratio of net reservoir sandstones to gross interval (net-to-gross) can be relatively high, the seismic resolution is low. Westphalian strata lie beneath up to 4000 m of overburden, including Zechstein salts, which rapidly attenuates the seismic signal. Within the Westphalian itself, the highly reflective coals dominate the seismic response. The sandstone bodies forming the gas reservoirs are the coarse-grained fluvial channel features, which are inherently complex in both their geometry and internal architecture. They are generally less than 100 m thick and close to or below seismic resolution. Additionally, late Carboniferous uplift and erosion has reduced the area within which the Carboniferous strata are preserved, and subsequent tectonic activity has broken them into a series of northwest-trending fold and fault blocks, all of which makes their identification and correlation on seismic data particularly difficult.

Evans et al. (1992) observed two distinct “facies” on seismic reflection data imaging the Carboniferous of the SNS. The first they described as the “reverberative or resonant” package, which is dominated by moderate to high-amplitude continuous reflectors and clearly equates to the tilted fault blocks of the coal-rich Westphalian A/B. The second seismic facies is the “transparent or opaque” package that is characterized by low amplitude chaotic reflectors with little lateral continuity. This corresponds to the Westphalian C/D clastic-rich sequence known as the Red-beds or Barren Redbed Measures.

Also recognized by Evans et al. (1992) were some detailed features within the highly reflective Coal Measures zone. These are seismically quieter zones up to 3.5km wide, which interrupt the continuous reflectors and have been interpreted as stacked channel complexes similar to the multi-storey channel sandstones in the East Pennine coalfield described by Guion et al. (1995).

Aitken et al. (1999) examined an extensive borehole and 2-D seismic reflection dataset from the East Pennine coalfield and the East Midlands oilfield. They correlated and mapped the major Westphalian A–C sandstones, concluding that the architecture, variability and 3-D geometry of the onshore sandbodies can be used as an analogue for SNS reservoirs. This paper describes the analysis of a simple 3-D seismic analogue from the East Pennine Basin, which was studied to establish those attributes giving a better image of sandstone bodies. A comparison of the Silesian stratigraphy of the East Pennine Basin and the southern North Sea is shown in Figure 1.

1. The East Pennine Basin

Westphalian strata crop out on the eastern margin of the Pennines and then dip gently eastwards under an increasing thickness of Permian and Mesozoic overburden. Late Devonian rifting in northern England initiated a series of linked, strongly asymmetric half grabens, which were the precursors of the northwest–southeast trending Gainsborough and Edale troughs in the East Pennine Basin. Subsidence during the Namurian and Westphalian was broadly regional, although some fault reactivation is thought to have occurred in early Namurian times along the Askern–Spital fault on the northern edge of the Gainsborough Trough (Fraser & Gawthorpe 1990). Post-depositional extension has left a rhomboidal system of northeast- and northwest-striking faults and there is some gentle folding; otherwise the area has undergone little post-Palaeozoic deformation. Details of post-Palaeozoic deformation in the concealed part of the coalfield are provided in the various relevant maps and memoirs of the British Geological Survey, for example Gaunt (1994).

1.1 The East Pennine Basin coalfield

In the outcrop areas in the west of the East Pennine Basin coalfield, the existence of large sandstone bodies (Figure 2) has been well known since the late nineteenth century, and some of the earliest descriptions of washouts (penecontemporaneous erosions of peat) and other channel-related features are from this coalfield. The coalfields in Yorkshire and Nottinghamshire proved ideal for the development of a sedimentological understanding of the coal-bearing Westphalian strata because of the economic imperative, good underground exposures and an excellent borehole dataset. It was assumed that flow directions into the Pennine Basin were mainly southerly from Fennoscandia, with minor flows from the east and south. Developing a system of lithofacies interpretation based on sedimentological modelling, partly using the Mississippi Delta as an analogue for the clastic facies, Elliott (1970) illustrated that the dominant flow direction was from southwest to northeast. Guion (1987) investigated a variety of Westphalian channel systems and found minor channel directions from the west and northwest above the Threequarters Coal (Westphalian A), and from the southwest above the High Hazles Coal (Westphalian B). Subsequent work on the major Silkstone Rock (Westphalian A) sandstone of south Yorkshire (Guion et al. 1995) showed that the overall flow direction was from the west. It has been shown that the main channel flow across a large part of England and Wales during the Duckmantian and most of the Langsettian was from the west, although occasional sand bodies in the East Pennine Basin appear to derive from the east (Rippon 1996, Aitken et al. 1999). Indeed, Rippon (1996) considered most of the mid-Langsettian to midBolsovian inflows in the entire (West and East) Pennine Basin to be from the west and northwest.

The depositional environment of the Coal Measures of the East Pennine Basin was, therefore, a generally easterly flowing freshwater fluvial delta top or alluvial plain, generally hundreds of kilometres from the contemporary coastline. Widespread and correlatable marine bands represent transient marine incursions (Rippon 1996, O'Mara & Turner 1997). In northeastern England and eastern Scotland the main flow direction was from Fennoscandia in the northeast, much as it was in the Silverpit Basin in the SNS (Fielding 1984, Cowan 1989, Rippon 1996).

The large sandstone bodies show little correlation between their orientation and the underlying structure. The half grabens created in Dinantian times were mainly infilled with Namurian and early Westphalian A strata, so that by the time the Coal Measures mires were being formed, with their associated river systems, the region was probably a low-lying plain with little relief. Rose diagrams of palaeochannel directions constructed from mining data in northeast Derbyshire and north Nottinghamshire (Figure 3) show a dominant flow direction controlled by the overall palaeoslope but with a wide spread of current directions, as would be expected in a low-energy river system (Rippon 1996). These channels tend to be smaller features rather than major channel belts. Upscaling to major channel belts is not straightforward, because some of the latter are known to have been very long lived, probably outlasting several generations of smaller drainage systems. However, by mid-Langsettian times a general flow direction from the west or southwest was well established. By the Duckmantian and lower Bolsovian the southwest trend had become dominant at many horizons (Rippon 1996). In general, the depositional system of the East Pennine Basin was very remote from marine influence, and the dominant depositional controls were basin subsidence and upstream sediment supply (Rippon 1999). Channel systems crossed the depocentre and some major channel belts, such as the Parkgate Rock that swings round into the Gainsborough Trough, flowed out across the eastern side of the basin, where large lacustrine deltas were developed. Some sandstones above the Deep Hard Seam cut across the Edale Trough and appear to have flowed across both the underlying Dinantian structure and the Westphalian depocentre. Similar sandbodies farther south cross the Widmerpool Gulf obliquely.

Although the underlying structure has had only a minor effect on palaeoflow direction, it does have an effect on the thickness and vertical connectivity of the sandstones. Over the structural lows, subsidence continued at a rate that maximized net deposition. Consequently, individual sandstones and coals thicken towards the basin depocentre and, in the preserved rock succession, the sandstones are separated by mudstones and coals. However, over the structural highs subsidence was lower, the individual peat mires were thinner and the section condensed, with a channel much more likely to erode into the peat mire in this elevated setting. Although the sand would be buried beneath later peat mires once the channel was abandoned, a subsequent channel would have been more likely to cut down and therefore "connect" with a previous sandbody.

1.2 East Midlands oil province

The East Midlands is a major onshore oil and gas province, comprising many oilfields generally formed by Variscan anticlines and discovered since 1939. A case study from north Nottinghamshire is presented in Section 3 of this paper, between the onshore oilfields of Bothamsall, Eakring–Dukes Wood and Egmanton (Figure 2). Discovered in 1958, the Bothamsall oilfield lies just to the north of the study area. The oil-bearing sandstone reservoirs are found in distributary channels and barrier bar facies at the base of the Westphalian A succession at depths of 975–1100 m. Lithofacies have been identified that are considered to correlate with the Crawshaw and Sub-Alton sandstones in the early Langsettian and which Hawkins (1978) thought represented deposition by westward-flowing distributary streams across a delta plain during the constructive phase of delta development. Porosity is greatest in the coarse-grained sandstones found in the axial regions of the distributary channels, and is least well preserved in the fine-grained sandstones where quartz cementation is widespread. The Eakring–Dukes Wood oilfield, discovered in 1939, occurs in a series of “en echelon” anticlines adjacent to the north-northwest–south-southeast trending Eakring–Foston Fault, to the south of the study area. The reservoirs occur in a stacked series of delta-top channel and mouth bar sandstones of Namurian to early Westphalian age (Fraser & Gawthorpe 1990). The Egmanton field was discovered in 1955 and occurs in a northwest–southeast-trending anticline to the east of the study area.

2. Coal-seam imaging

Since the 1970s, there has been extensive acquisition of 2-D seismic reflection data throughout the East Pennine Basin, mainly for coal exploration but also in the search for oil and gas. Typically, these data from the region show frequencies of up to 120Hz at depths of up to 900 m in the Coal Measures. Individual thicker coal seams are identifiable and seismically correlatable, even on 2-D seismic reflection lines.

2.1 Previous work

The encoding of variations in seam thickness within the amplitude of the reflection follows the Widess (1973) “thin bed” theory. Widess considered a layer embedded in an infinite homogeneous medium and defined a thin bed as one that produces a composite reflection because of the interference of the reflections from the top and bottom of the layer. The point at which the composite reflection no longer changed with the dimensions of the bed was the maximum thickness of the “thin bed”. In practical terms he concluded that a bed is defined as seismically thin where the layer thickness is less than one eighth of the dominant wavelength. He also demonstrated that the amplitude of the thin-bed reflection is approximately proportional to the thickness of the bed and inversely proportional to the dominant wavelength. Widess assumed that the wavelet complex reflected by the layer is obtained by addition of the wavelet reflected from the top of the layer and the one reflected from the bottom, the latter being phase inverted and time shifted relative to the former. The tuning thickness is the bed thickness at which constructive interference from the top and bottom of the bed produces the strongest reflection. Tuning occurs at a thickness of one quarter of the wavelength and is therefore a function of the dominant temporal frequency and interval velocity. Widess’s theory assumes transmission loss and internal multiple reflections to be negligible; both are untrue in cyclic coal sequences.

An important factor in a multi-seam environment is that not only do the large reflection coefficients cause high amplitude primary reflections, but strong surface multiples and interbed multiples are also set up within and between seams (Greenhalgh et al. 1986). The generation of a train of short-path multiples broadens the transmitted seismic pulse with a consequent lowering of its frequency content. Ri ter & Schepers (1978) calculated synthetic seismograms from the Coal Measures of the Ruhr and concluded that a single seam can give a distinct reflection even at a thickness of one fiftieth of the wavelength. However, in a sequence of layers containing many coal seams, they noted that individual reflections may become obscured by constructive interference from short-lag multiples.

A reverberatory sequence generating multiples can be set up between any two acoustic interfaces. Coal seams are particularly likely to generate intrabed multiples because of the contrast in acoustic impedance between coal and surrounding strata, and significant multiple energy is likely to be encountered. In cyclic coal sequences, reflection coefficients of the order of 0.4 are common. At the rock/coal interface the reflection coefficient is – 0.4 and hence typical transmission coefficients (where the transmission coefficient equals 1 + reflection coefficient) of 0.6. At the bottom of a coal seam the reflection coefficient remains the same, although opposite sign, and the transmission coefficient is 1.4. Thus, a one-way transmission through the two interfaces of a coal seam theoretically reduces the amplitude by a factor of 0.84 and the two-way transmission by a factor of 0.7056 (N. R. Goulty, personal communication). Hughes & Kennett (1983) showed that internal multiple activity generated by the non-coal layers in cyclic coal sequences is negligible, whereas internal multiple paths within the coal seams generate significant amplitude variations to a synthetic seismogram. These sequences can therefore be considered as a bi-lithological model (i.e. coal seams and country rocks only). In a sequence containing many coal seams, Rüter & Schepers (1978, 1985) showed that, by the fifth seam in a coal cyclic sequence, the amplitude of the primary reflection pulse is 20dB below the initial pulse amplitude, and short-path multiples become the dominant energy- transport mechanism through the sequence. Also, as the number of seams traversed increases, the transmitted wave becomes more delayed in time. The short-path multiples are of the same polarity as the direct pulse and consequently interfere with it. Therefore, short-path multiples increase the amplitude of the transmitted waveform at low frequencies, and interfaces deep within the sequence are imaged primarily by peg-leg multiples, rather than direct pulses. As a result of the time lag caused by intrabed multiples, correlation of zero-phase seismic data with synthetic seismograms calculated from wireline logs frequently requires a certain amount of stretching of the synthetic. A good match can usually be made though in the East Pennine coalfield, even with a “primaries only” algorithm.

Fairbairn & Ward (1984) looked at improving the imaging of small faults in coal-mining regions and found that progressively removing the lower frequencies in a series of bandpass filter panels could confirm or even reveal the presence of faults with throws of less than 5 m. They concluded that destructive interference occurs between the reflections from the upthrown and downthrown sides of the fault at a wavelength corresponding to four times the throw of the fault. Where the throw of the fault is less than 5 m, this destructive interference occurs at frequencies above 100Hz. Consequently, removing the lower frequencies from the recorded spectrum will highlight this effect. Ward et al. (1988) developed this idea by assigning colours to amplitudes after applying a technique of shaped histogram equalization. Koefoed & de Voogd (1980) considered the thickness of coal seams in relation to their response to a seismic signal rather than to their resolution, and they showed that the amplitude response for thin beds such as these decays in a quasi-linear manner. Lawton (1985) discussed the possibility of using changes in the reflection amplitude from coal seams to deduce their thickness, and Gang & Goulty (1997) attempted to take this further by using a generalized linear inversion technique to invert seismic data from the Coal Measures of the East Midlands to see if accurate values for seam thickness could be obtained. They found that their results were unstable, and concluded that a combination of multiple activity, noise, too narrow a frequency bandwidth and acquisition problems were probably all responsible to a greater or lesser extent in the failure of the technique. Kelk (1990) studied the effects of seam splits, washouts and small faults on the seismic response and compared the results of synthetic modelling of 2-D seismic reflection data with mining data in the East Midlands. In particular he looked at the behaviour of seismic trace attributes of amplitude, instantaneous phase and instantaneous frequency and concluded that an empirical relationship exists between the amplitude-versus-thickness response of coal seams less than 4 m thick, which can be used to identify channels that wash out the seam. The case study in Section 3 of this paper develops these ideas into the 3-D domain.

2.2 Synthetic seismic modelling

Modelling of the effects of coal-seam thickness on the seismic response was carried out for this study on data from a borehole in the Warwickshire coalfield drilled by the British Coal in 1992. No checkshots were available for this borehole, so time–depth relationships were calculated by integrating the long-spaced sonic log with interval velocities obtained from the stacking velocities of an adjacent seismic line using Dix's formula. A reflection coefficient series was calculated from the long-spaced sonic and density logs, and convolved with an 80Hz Ricker wavelet to form a synthetic seismogram. The synthetic seismogram was then visually compared with the extracted trace from the seismic reflection data and stretched to best match the closest seismic line to the borehole. Once a match was achieved, a deterministic extraction of the embedded seismic wavelet was performed. This extracted wavelet was then convolved with the reflection coefficient series to re-calculate the seismogram. A series of synthetic seismograms were produced by convolving with Ricker wavelets from 40Hz to 320 Hz to demonstrate the resolution of individual coal seams at different frequencies (Figure 4). It is apparent that at 80Hz the named coals (i.e. the Half-Yard, the Thick Coal and the Bench Group) all have corresponding reflections. These are all composite seams with 1.4 m, 6.2 m and 2.1 m of coal respectively. The un-named coals, which are generally less than 0.5 m thick, show clear reflections only at higher frequencies. In the East Pennine Basin the expected frequency range on seismic reflection data at the target horizons is 50–100Hz. In the SNS the dominant frequency is about 40Hz at the depth of the Coal Measures and, using this example, the Thick Coal (along with the group of thin coals below) would be correlatable, whereas the Half Yard and Bench Group would be more challenging. Coal seams up to 2 m thick are found in the Caister–Murdoch region of Quadrant 44 (O'Mara & Turner 1999); however, coal seams greater than 1 m thick are rare in the SNS (D. Quirk, personal communication) and the higher interval velocities associated with their greater depth would make correlation of individual seams difficult.

The density and sonic logs were adjusted to simulate varying thicknesses of coal and the synthetics re-calculated. Figure 5a shows the effect of varying the thickness of the seam from 1 m to 15 m at 100Hz. Figure 5b shows the same model convolved with 60Hz, 80Hz and 100Hz wavelets, and demonstrates the relationship between amplitude and the frequency content of the signal. According to Widess (1973), the maximum amplitude of zero-phase data is reached where the thickness equals approximately one quarter of the dominant period of the wavelet; that is, at approximately 6 m if a velocity of 2350 ms–1 and a dominant frequency of 100Hz are assumed. The minimum amplitude is reached at approximately half the wavelength (i.e. 12 m); beyond this thickness separate reflections from the top and bottom of the seam are discernible. At 80Hz these maximum and minimum amplitude points are 7.5 m and 15 m respectively. These values correspond well with the modelling shown in Figure 5a. Widess also predicted that where the bed thickness is below one eighth of the wavelength the shape of the wavelet will not alter; therefore, useful information about bed thickness can be gleaned only from the amplitude information. The modelling results in Figure 5b confirm his prediction. For a 60Hz wavelet and a velocity of 2350 ms–1 the wavelength is 39 m and no variation in wavelet shape would be expected when the seam was less than 4.8 m thick. However, Figure 5b shows amplitude variations clearly exist well below this thickness. This observation has been borne out in the following example.

In Figure 6 a 2-D seismic line, acquired in 1994 and reprocessed during the course of this study, shows a composite seam with an overall thickness of 6 m. An additional feature (Z) shows as a drop in reflection strength. From the modelling above and assuming a dominant frequency of 70Hz, it appears that the decrease in reflection strength at this point corresponds to a decrease in the seam thickness from 6 m to approximately 4 m. This feature is on the alignment of a sandstone channel system that is known to remove the top 3 m of the seam farther south. In addition, small faults are visible either where they cause a break in the reflectors or in the case of "sub-resolution faults", where amplitude anomalies have been shown to correspond with faults found during mining. Faults A, B and C, with throws known to be 7–15 m, are clearly visible as displacements in the reflector with an associated loss of amplitude. However, fault D has been proved in the roadway cut for a retreat mining panel and has a throw of 2.9 m (i.e. less than half seam thickness). Very little displacement of the reflector is seen, but there is a significant loss in reflection strength. The dominant frequency at this horizon is 70Hz and the interval velocity is approximately 2400 ms^{-1}. This means that the wavelength is 34.3 m and the fault throw is only one-twelfth of the wavelength.

Thus, even on 2-D seismic lines, faults of less than seam thickness are visible, and variations in seam thickness can be seen on good data. However, the identification of fluvio-deltaic structures and their architecture is difficult with 2-D lines, and the following case study looks at a 3-D seismic dataset.

3. Ollerton case study

This study was undertaken in two parts: the first involved the re-processing and interpretation of a 3-D seismic dataset, with the aim of identifying channel-like features within the seismic data; the second part involved the analysis of mining records and borehole data from the region and the mapping of channel sandstones. The two parts were then compared to see if any features identified in the seismic volume corresponded with the expected orientation and dimensions of the mapped channel sandstones.

3.1 Seismic interpretation

There has been extensive 2-D seismic exploration throughout the East Pennine Basin since the 1970s, but the number of 3-D surveys is limited. A 2km^2 3-D seismic survey was acquired by British Coal in 1991 near Ollerton in Nottinghamshire. The original purpose of the survey was to identify structures in an area of ground to the north of the existing workings at Ollerton Colliery, so that the layout of the proposed extension of the mine, in the Parkgate Seam, could be properly planned. The southwestern edge of the survey was determined as the limit of old workings in the Top Hard Seam, which is approximately 1.2 m thick at depths of 650–720 m and has been extensively worked in north Nottinghamshire in the past. The main target for the seismic survey was the Parkgate Seam, which is 2 m thick at a depth of 817 m in Kirton borehole and 868 m in Nickerbush borehole. The Parkgate 3 face from Ollerton Colliery was being mined when the 3-D survey was acquired and it had already advanced part way through the southernmost corner of the survey. This face continued for another 300 m, providing accurate depth and structural information. However, the colliery was closed before any other panels were worked in this area. The area is currently being re-examined for possible development from nearby Thoresby Colliery.

UK Coal has kindly provided the dataset, along with mine plans from the colliery, and it has been re-processed and studied specifically to identify attributes that may indicate the presence of sandstone channels within the Coal Measures. Erosive sandstones are known to exist on the Parkgate Seam in nearby mine panels and it was thought that channel sandstones at other horizons are likely to be present.

Ollerton sits between the Edale and Gainsborough troughs (Figure 2), away from the main depocentre of the East Pennine Basin but also away from the margins. In other words, it lies in a "typical" part of the basin. In this setting, there was enough accommodation space being created by subsidence for the sand bodies, as preserved, to be vertically unconnected, and with relatively little erosion of the coal seams beneath them. To the east, there are thought to be more common "washouts" (contemporary erosions) in a relatively condensed succession where subsidence was less. The area lies between northwest–southeast structural highs, but these are thought to have had only marginal influence on the course of the main channel belts.

The geological succession in the study area consists of Triassic mudstones with dolomitic sandstones and waterstones and irregular sandstone beds, overlying a Permian sequence of marls and limestones. The Upper Magnesian and the Lower Magnesian Limestones are important reflectors, generating distinctive seismic reflections in the upper part of the seismic data. The Basal Permian Sand is difficult to distinguish on seismic sections, but in this area lies just below the Lower Magnesian Limestone. The base of Permian overlies the Westphalian C strata with a slight angular unconformity. The Cambriense Marine Band (Bolsovian–Westphalian C) lies near the top of the Westphalian succession and there are approximately 145 m of Bolsovian strata consisting of a sequence of mudstones with frequent seat earths and thin coal seams, and occasional sandstones. The main coal development lies in approximately 240 m of Duckmantian strata with the Main Bright, Kent’s Thick, Top Hard and Dunsil seams being the thickest of many coal seams. Below the Vanderbeckei Marine Band, the top part of the Westphalian A (Langsettian) succession is similar to the Duckmantian, with the Deep Soft, Parkgate and Blackshale coal seams forming significant reflectors above increasingly sand-rich lower Westphalian A and Namurian sequences. The top Dinantian limestone forms the next widespread and correlatable reflector. The Westphalian strata lie in a shallow syncline plunging gently to the northwest. The surface elevations range from 29 m to 90 m above ordnance datum.

The 3-D seismic dataset was acquired using 1lb (454g) dynamite charges in 40ft (12.2 m) shot-holes. The receiver group interval was 12 m and the receiver lines were placed 120 m apart. The shot lines were approximately 168 m apart and were at right angles to the receiver lines. The shot interval was 12 m. Each 40 ft shot hole was drilled twice and shot into a 144-channel patch. The total area of common mid-point coverage was 1.9km^2 and the nominal fold of cover was 6. The common mid-point (CMP) bins were 6x6 m. The acquisition parameters are summarized in Table 1.

Table 1 Acquisition parameters

Energy source	Explosive
Source pattern	Single hole
Charge size	1lb (454g)
Charge depth	40ft (12.2 m)
Station interval	12 m
SP interval	12 m
Spread	Split spread
Near offset	6 m
Maximum offset	726 m
No. of channels	144
Nominal fold	6
Low-cut filter	25Hz
High-cut filter	250Hz
Geophone array	2 strings of 6x2.0 m, in parallel
Geophone frequency	30Hz
Record length	2s
Sample rate	1 ms

The main concerns when re-processing this dataset were to preserve surface-consistent amplitude variations and to maintain as broad a bandwidth in the signal as possible. The data were reprocessed by the author (BM) using ProMAX and Hampson-Russell software, with these specific aims in mind. The data-processing flow is shown in Table 2.

This dataset has many advantages in providing information relevant to hydrocarbon exploration:* The data quality is high with a good signal-to-noise ratio.

- The Westphalian strata are shallow and reasonably undisturbed
- The Westphalian sequence is similar to that seen in some SNS Carboniferous reservoirs.
- Two cored boreholes are sited within the study area.
- The nearby mining provides considerable geological information, albeit at one horizon.
- The dataset is small enough to allow almost unlimited testing of parameters.
  The main disadvantages are:
- The dataset is too small for mapping large channel systems.
- There are no wireline logs available.
- The short offsets limit the usefulness of some seismic attributes such as AVO.

A suite of seismic attributes was calculated on the 3-D volume. Of these, the most useful were expected to be reflection strength or amplitude envelope, instantaneous phase and instantaneous frequency. Reflection strength highlights changes in acoustic impedance and is used to identify anomalous impedance horizons such as gas-charged sandstones. As coal seams have a very low impedance compared with the surrounding strata, the reflection-strength plots will show detail in the coal seam that can lead to the recognition of small faults and variations in seam thickness . Instantaneous phase emphasizes the linearity of events and thus highlights breaks such as pinch-outs at unconformities and faults; it is not a useful attribute for detecting variations in seam thickness. The cosine of the instantaneous phase is particularly useful for enhancing sedimentary features (Figure 7a). Instantaneous frequency measures the temporal change in instantaneous phase and can be used to identify features that alter the frequency content of the data, such as gas accumulations that attenuate the high frequencies. Theoretically, instantaneous frequency can be used to detect variations in seam thickness, but it is susceptible to noise contamination and can therefore be of limited use when the anomalies are very small. It was not found to be very useful in this study. The absolute trace amplitude plot requires careful processing, but makes the identification of small faults and other low-amplitude zones easier (Figure 7b).

Table 2 Processing sequence

Demultiplex
Geometry application and QC
Trace editing
Spherical divergence correction
Surface consistent amplitude correction
First break picking
Tomographic refraction static calculation
Surface consistent deconvolution
Spectral balancing
Surface consistent residual statics calculation
Normal moveout correction
Post NMO mute
3D Stack
Bandpass filter

FXY deconvolution
3D phase shift migration
Zero phase

Four horizons were then picked in the Langsettian–Duckmantian part of the succession and the volume was flattened on each of these in turn. By analyzing time slices on the flattened volume, structurally conformable horizon slices parallel to the interpreted event can be extracted and variations in the sedimentary environment can be revealed. Comparison of the different seismic attributes can add further detail.

A comparison of a single in-line from the seismic volume is shown in Figure 8a–c, demonstrating the use of amplitude and reflection-strength plots to highlight particular features. A conventional "wiggle" trace seismic section is shown in Figure 8a. The upper surfaces of coal seams have a negative reflection coefficient and are here displayed as troughs. Note the high amplitude of the coal compared with the surrounding strata, a small fault and the high-amplitude event (circled) above the Top Hard Seam. Figure 8b shows a colour-coded amplitude plot of the same line. The negative reflection coefficients are now shown in blue, and variations in the amplitude of the Top Hard can be seen in the intensity of the blue. The bright event above is now clearly evident. "Washout" features are well documented in the Top Hard seam from mining records (e.g. Guion 1987, Kelk 1990) and the two boreholes within this study area show cannel coals around this horizon. Cannel coals are sapropelic coals thought to have formed in pools of stagnant water or sluggish backwaters. They are generally thin, have a high hydrogen content and typically produce "bright" reflections. A reflection strength plot (Figure 8c) shows how the Top Hard has a lower reflection strength in the highlighted area, which is interpreted to correspond to thinning of the seam. The reflection strength of the event above indicates that this is probably a cannel coal, and its shape suggests that it is the abandonment fill of a sluggish watercourse. Figure 8d illustrates a time slice at this horizon from the reflection-strength volume and the shape of what is probably an abandonment channel is revealed. The orientation of this feature is northwest–southeast and the termination at the southern end suggests that the local palaeoflow was from the northwest. In-line 40 to the north shows the same feature, but the high-amplitude infill is absent indicating that the abandonment channel is filled with coals and cannel coals in some places, but shales and mudstones in others. This in-line also shows what might be interpreted as banks or levees either side of the channel (Figure 9). The height of the banks in two-way time is 4–7 ms, which at a velocity of 2350 ms–1, is equivalent to 4.7–8.2 m. This corresponds very well to the palaeo-levee height of 20–25 ft (approx. 6–7.5 m) observed by Elliott (1969, 1985) in this coalfield.

Immediately above the Dunsil Seam a channel-like feature is evident on a time slice 27 ms below the flattened Top Hard horizon (Figure 10). This lies on a northwest–southeast trend before swinging round to a more north–south alignment. The feature is 120 m wide at the widest point. The arcuate shape and the narrowness of the feature are typical of channel-bank collapse structures seen in coal mines in this region. The in-line suggests that this channel is probably cutting down into the Dunsil Seam and completely removing it at this location. The Nicker-bush borehole lies on the course of this channel, albeit at a point where the feature is less clearly defined, and the borehole log describes a sand-prone interval with shale partings approximately 5 m thick. Dividing the seismic volume into near and far offsets reveals some increase in amplitude in the middle of the channel feature on the longer offsets (Figure 11). However, splitting the volume into near and far angles reveals that the far-angle volume (>12°) is poorly populated at the target horizons because of the acquisition geometry. This fact, and the absence of well-log data, meant that an analysis of amplitude versus offset effects was considered unreliable on this dataset.

Since the palaeochannel described above is clearly defined, some testing was performed to see if it could still be recognized at the sort of frequencies recorded in the SNS seismic volumes. In the SNS the depth of the Carboniferous strata and the overlying Zechstein salt severely reduce the bandwidth, so that the dominant frequency is only 30–40Hz. Unfortunately, the Ollerton dataset was recorded with a 25Hz lowcut filter applied in the field, so the high frequencies could be cut to only 50Hz before the data became too “ringy” to be interpretable. However, Figure 12 shows the same time slice as Figure 10 but with a 50Hz high-cut filter applied pre-stack. The channel sand is still clearly distinguishable; however, higher *P*-wave velocities, attributable to deeper burial in the Coal Measures of the SNS, compound the problem of poor vertical resolution.

The Deep Soft and Deep Hard coal seams lie within about 15 m of each other. The Deep Hard Seam is known to be an inconsistent reflector in this region and, at this horizon, a series of features with a west-southwest–east-northeast trend is seen in the seismic volume (Figure 13). A large channel sandstone is known to replace the top of the Parkgate horizon in nearby mine workings. The changes in reflection strength may represent small faults. In other coalfields in the UK, clusters of small faults have been observed along the margins of channel sandstones, which have been explained as consolidation faults because of differential compaction across the channel margin (A. R. Westerman, personal communication). The trend of such faults is controlled by the margins of the channel and may, therefore, be inconsistent with tectonic faults proven in this area. However, consolidation faults associated with channel margins have not been observed in this area and it is thought more likely that these features represent thickening and thinning of the coal associated with the final geometries of abandonment channels. The close spacing indicates that they may be part of a larger channel system, the edges of which cannot be seen because of the small size of the dataset.

3.2 Borehole and mining records study

This section briefly reviews the potential for mapping sand-bodies in the area, without recourse to seismic-reflection data.

3.2.1 Background

The Ollerton 3-D area lies just east and southeast of significantly mined areas, and detailed spatial data on channel belt loci and internal architecture of channels may be readily extrapolated from underground-mapping details. There is a reasonable to good coverage by boreholes drilled from the surface and from underground, both with extensive coring and most of the surface boreholes have down-hole logs (typically gamma ray, density, caliper, and locally others, including neutron and dipmeter logs).

The mining and borehole data across the wider coalfield are easily adequate for the mapping of major channel belts, and also for more minor channel belts at mined horizons. The data are not adequate for the unambiguous mapping of minor channel belts at other horizons. Channel mapping undertaken for mining purposes is well constrained by closely spaced boreholes and mining records. Rose diagrams of channel directions from the Westphalian A/B of north Nottinghamshire and northeast Derbyshire show the dominant southwest–northeast or west– east orientation of the larger channel belts, and the less predictable alignments of the smaller features (Figure 3).

Only two boreholes, Kirton and Nickerbush, lie within the 3-D area itself. Kirton was drilled in 1958, and does not benefit from modern down-hole logs. However, the hole was cored from the Permian through to the Silkstone coals (Westphalian A), and the core descriptions are suitably detailed. Nickerbush was drilled in 1970, and it was cored from early Westphalian C strata down to the Parkgate Seam (late Westphalian A). No down-hole logs have been found for this borehole either.

An analysis of borehole logs within and surrounding the 3-D area was carried out to identify sandstones within the Coal Measures sequence. These were compared with mining records to give an indication of flow direction. Within the overall channel margins, channel fill, or channel proximal (levee) sediments are preserved within the characteristic linear belt (with associated bifurcations). The margins, as mapped, exclude minor crevasse splays, which require more detailed differentiation and a greater data density. The sandstone bodies are typically fine-grained, locally medium- to coarse-grained, orthoquartzites with subordinate siltstones and breccio-conglomerates, and are usually well cemented.

Table 3 lists (in descending stratigraphical order) sandstone bodies that lie across the 3-D area or close to it and are mappable using non-seismic data (see above). It is considered that the sand bodies described in Section 3.2.2 and Section 3.2.3 were derived mainly from the west and southwest, although some (mainly in Westphalian C, and not described here) are thought to have derived from channel belts flowing into the area from the east. Some of the sandbodies represent long-lived multi-storey belts, contemporaneous with regional coal (peat) formation. Others are "single event" features of short duration, often lying within the intervals represented by regionally important splits in the major coal seams. Note that the sluggish-system features, interpreted for the Top Hard horizon in Section 3.1, are not covered here.

3.2.2 Selected sandbodies: sandbody above the Dunsil Seam

A significant sandbody is known to lie between the Dunsil and Top Hard seams (mid-Westphalian B), these seams forming the effective lower and upper limits, respectively, of the overall channel system containing the sandbody. The sandbody is up to 4km wide, possibly including more than one contemporary channel belt, and crosses the study area from northwest to southeast. The maximum sandstone thickness is probably about 15 m, the overall feature being essentially single storey. The Top Hard is typically a multi-coalbed seam up to 2 m thick, and is locally eroded in the wider area (the result of later Coal Measures fluvial systems). The Dunsil Seam is typically less than 1 m thick itself, but is locally united with the underlying First Waterloo Seam, to give a composite seam of more than 2 m (as at Nickerbush). The Dunsil Seam is locally eroded within the channel belt area.

Table 3 Sand bodies, mapped from borehole and mining records, across or adjacent to 3D study area (in descending stratigraphical order)

Sandbody	Description	Maximum width (km)	Maximum thickness (m)	Key borehole
Above Top Hard Seam	2.5 km north of study area. Sandstone with conglomerates and breccias	2.5	35 Multi-storey	Gravel Pit Lane E 470500 N 373896
Above Dunsil Seam	Crosses study area from NW to SE.	4	15 Single storey	Mill Mount E 473032 N 371967
Above Vanderbeckei Marine Band	Just SE of study area. At same horizon as Priest Rock of East Midlands oil- field.	2	20	Gracefield Lane E 479550 N 369600
Above Deep Hard Seam	4km NW of study area.	4.5	30 Multi-storey	Poulter E 464887 N 375878
Above Parkgate Seam	Crosses study area from WSW to ENE	1.5	15	Nickerbush E 469840 N 370067

Above Tupton Seam	Just south of study area. A series of minor channel belts. Poorly known because below level of mining and boreholes.	Unknown	Unknown

3.2.3 Selected sandbodies: above the Parkgate Seam

A sandbody crosses the 3-D area from west-southwest to east-northeast, between the Parkgate and Deep Hard seams (lower and upper limits of the system, respectively), in the later Westphalian A succession. The overall sandbody width is some 1.5km, reaching a maximum thickness of up to 15 m of sandstones, with subordinate siltstones. The Parkgate Seam is typically a 2 m-thick coal, but is locally eroded (and locally displaced by channel-marginal rotational slips and related features). The Deep Hard is split into thin coalbeds, the thickest

being less than 0.5 m.

3.2.4 Other sand bodies

integration of all data sources. However, two sandbodies, those In addition to those described above, the following sandstones are known at Kirton or Nickerbush boreholes, or both, but are not mappable using non-seismic reflection data:* *Kirton* A sandstone, about 8 m thick, overlies the Kents Thick Seam (Westphalian B), the base in the borehole being at a depth of *c.* 605 m.

- *Nickerbush* A sandstone (with overlying sandstone/siltstone sequences) about 5 m thick overlies the Main Smut Seam (Westphalian B) at a borehole depth of *c.* 680 m.

A further sandstone, about 6 m thick, lies in the late Westphalian A interval between the Roof Soft and Top Soft seams, the base being at a borehole depth *c.* 835 m.

3.2.5 Integration of seismic reflection and non-seismic data

This brief review of the main sandstones that are mappable, within and around the 3-D area using non-seismic data, shows that the ideal – for onshore mapping purposes – necessitates the above the Parkgate and Dunsil seams, can be identified using the seismic reflection data alone, and these are also verified by the non-seismic data.

4. Conclusions

Three channel-system features have been identified on the Ollerton seismic volume: at the Top Hard, Dunsil and Deep Hard horizons. The feature above the Top Hard represents a sluggish watercourse abandonment and is not sand rich. The orientations of the sandbodies correspond to those that can be derived using the borehole and mining data alone. However, some larger channel belts in the neighbourhood have not been identified because of the small areal extent of the seismic dataset. This highlights the fact that it is differences at the edges that are the main criteria for identifying sedimentological variations on seismic data: if the edges cannot be seen, then the channel system is hard to recognize.

In summary, modelling of variations in the sedimentology of coal-seam sequences has demonstrated the expected response on the seismic signal. Some of these variations have been located in a 3-D seismic volume, particularly those relating to channel sandstone bodies. The correlations between the identification and orientation of channel features on the seismic reflection data and that obtained from the borehole and mining data are good. Both the size and the geometry of the seismic features match that expected from the geological data. This demonstrates that careful processing and interpretation of seismic data in highly reflective coal-seam sequences can reveal sedimentological variations, which is important in both a mining context and reservoir characterization of hydrocarbon deposits. By combining mining and borehole data with the 3-D seismic there has been a significant reduction in uncertainty. This could then be extrapolated into the assumptions made in reservoir modelling in an environment such as the southern North Sea, where there is much less geological control.

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