# AZIMUTHAL IMAGING CHALLENGES IN COAL-SCALE 3D MULTI-COMPONENT SEISMIC REFLECTION

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## INTRODUCTION

In certain geological situations, improved characterisation of the subsurface can be achieved through the integration of conventional P-wave seismic reflection and PS-wave (converted, or C-wave) reflection. Initial noteworthy successes for this technology related to offshore petroleum targets, which were difficult to image with standard P-wave methods (e.g. Barkved et al., 1999; Hanson et al., 1999). More recently, integrated interpretation of P and PS imagery has been shown to yield improved geological interpretation of coal targets, including detection of new fault structures, improved determination of fault geometries, and superior imaging of top-of-coal for shallow open-cut targets (e.g. Hearn, 2004; Velseis, 2003, 2007). Application of PS-wave techniques is arguably more challenging in the onshore situation, due partly to severe S-wave receiver statics. These statics are more problematic with shallow high-resolution data, where maintenance of high frequencies is critical.

In the P-wave arena, there is an increasing trend toward 3D surveys since these produce a better spatial interpretation. It would be reasonable to assume that 3D PS-wave surveys would also lead to an improved geological interpretation. However, 2D PS-wave surveys have identified a number of issues that will make 3D PS exploration more challenging than the conventional case. For example, different geological interpretations may result from images created with positive (forward shooting) or negative (back shooting) offsets. Additionally, the asymmetry of PS-wave paths means that it is more difficult to achieve regular azimuthal and offset distributions when designing 3D grids. Associated with this is the fact that PS offsets may be more restricted due to phase effects. PS path asymmetry is generally more pronounced at the shallower depths appropriate to coal exploration (50-500m). There is also a greater tendency to use rays having higher incidence angles. Hence we believe that the problems noted here are likely to be more severe at coal depths than at petroleum depths.

In this paper, the discussion of these issues is largely based on prior 2D experience, and numerical modelling of 3D effects. It represents the design phase of a 3D converted-wave field experiment to be carried out in late 2008 (ACARP, 2008). Although we emphasise the peculiarities of the shallow coal exploration environment, the discussion is of more general relevance.

## DIODIC ILLUMINATION

A conventional P reflection is symmetric, while a PS reflection is asymmetric, with the reflection point displaced towards the receiver (Figure 1(a)). This displacement is more pronounced for shallower targets. Even in a homogenous earth, this asymmetry complicates the process of attributing a particular reflection to a specific subsurface location. PS-wave binning algorithms are now well developed, although they depend on knowledge of P and S wave velocities above the reflector. Furthermore, when lateral inhomogeneities exist, as in Figure 1(b), this asymmetry can lead to directional differences in amplitude and timing. This effect was originally identified in the petroleum industry (e.g. Thompson, 1999; Li et al., 2001), where the term 'diodic illumination' has been used (drawing on the analogous directional behaviour of the diode in electronics).

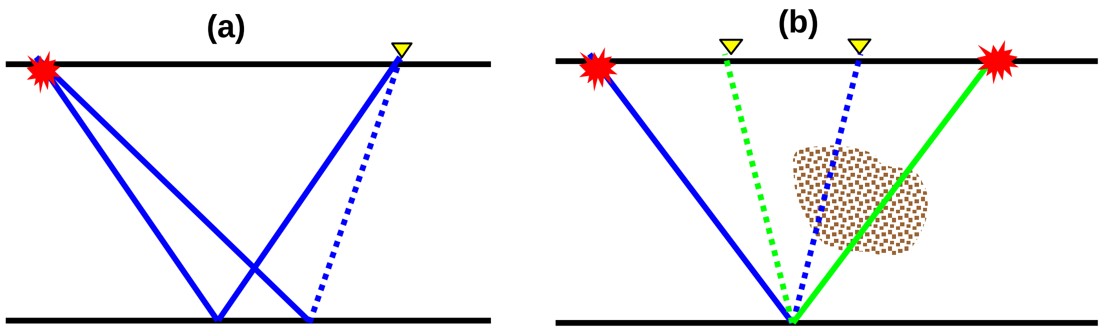


*Figure 1. (a) Geometry of P-wave and PS-wave reflection. The P-wave segments are shown as solid, while the S-wave segments are dashed. The P-wave reflection is symmetric relative to source (red) and receiver (yellow). The PS-wave reflection is asymmetric, with the reflection point displaced towards the receiver.*
*(b) Example of diodic (directional) illumination. A localised body (hatched) has anomalous S-wave properties, affecting the travel time, and possibly the amplitude, of the positive-offset ray (blue) but not the negative offset ray (green).*

We have observed this directional effect in a number of research and commercial 2D PS-wave coal-scale surveys. Figure 2 gives a typical example. The top two images (Figures 2(a) and (b)) have been stacked to include only positive offset and negative offset traces respectively, with the target coal seam annotated in red and green respectively. There are clearly differences in the implied structures (e.g. faults near the centre of the section; orientation of the target seam towards the right hand end of the image). An image constructed using all available traces (Figure 2(c)) is badly smeared, with the target seam (blue) completely losing continuity in places. These smearing effects can be easily understood when the different horizons are overlaid (Figure 2(d)) illustrating significant relative time shifts. We believe that effects such as those demonstrated here are due to imperfect binning (inaccurate velocity models) and also diodic illumination relating to geological heterogeneity.

It is clear that such directional imaging problems will be more difficult to handle in the 3D context, where rays sample the full range of azimuths. The 2D approach of interpreting positive or negative offset images can logically be extended to analysis of restricted-azimuth stacks. The validity of producing a composite, all-azimuth image is perhaps questionable. One pragmatic approach has been presented by Johns (2007), whereby relative time adjustments between restricted-azimuth image traces are estimated statistically. These relative shifts are then corrected for during construction of a composite image. This can provide a more focussed composite image, although structural positioning may be somewhat arbitrary. Our forthcoming field experiment is designed to examine these complex azimuthal issues in the context of 3D onshore coal-scale PS-wave exploration.

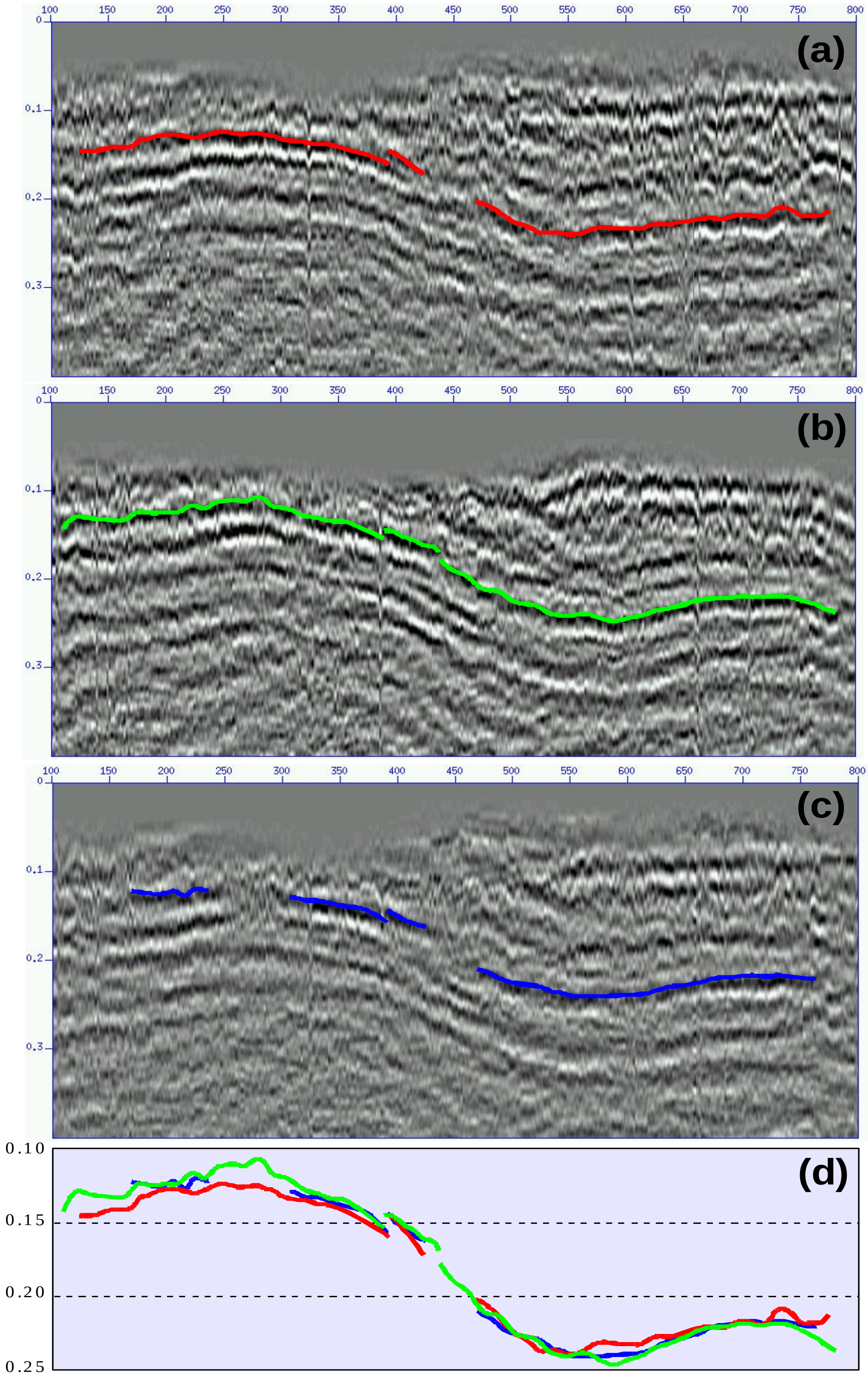


*Figure 2. Example of diodic illumination in 2D coal-scale PS imaging. On the three seismic images, the horizontal extent is 1.75 km, and the time extent is 0.4s. (a) Image constructed using only positive-offset traces; (b) Image constructed using only negative-offset traces; (c) Image constructed using all traces; (d) Relative time positioning of the target coal seam horizon, as picked on the three images (time scale in seconds).*

## 3D PS-WAVE SURVEY DESIGN: AZIMUTH / OFFSET COVERAGE

In any seismic survey it is important to ensure that all bins have sufficient fold at the target horizons. Equally in 3D surveying it is desirable that there is an even distribution of azimuths and offsets within any bin. A poor distribution can result in acquisition footprints or noise artefacts, and can lead to misinterpretation. This can be particularly problematic in regions where there is real azimuthal anisotropy. Many papers have been written with regard to P- wave 3D seismic design (e.g. Liner and Underwood, 1999; Cooper, 2004). Often, model-based methods are used to design a seismic survey with optimal parameters.

Broadly, PS surveys are approached the same way. However, PS surveys are typically performed in conjunction with a primary P-wave survey. Therefore it is usually necessary to optimise the P-wave parameters first (Thomas and Neff, 2004). For the design phase of our current 3D-PS acquisition trial we have followed a similar approach. Figure 3 shows the P and PS 'spider plots' for a typical full fold CCP bin. These plots indicate the azimuth and offset of traces contributing to the bin, for three of the tested survey designs.

Figure 3(a) shows the case where there is 90 degrees between the source and receiver lines. This design is simplest to acquire but tends to produce a stronger acquisition footprint. A common technique for improving the distribution is to change the angle between the source and receiver lines. In Figure 3(b) the angle between the source and receiver lines has been reduced to 75 degrees, which has improved the azimuth-offset distribution. We can further improve this distribution by staggering the source lines by half the source interval (Figure 3 (c)).

In general, the PS spider plots exhibit poorer coverage than for P, with bands of unpopulated azimuth-offset combinations. It is of interest that the bands remain in approximately the same location no matter what the source locations are. To confirm this, we increased the number of source points by a factor of 10 and in a randomly distributed pattern (Figure 4). Despite the significant fold increase, and the randomness of the source locations, the unpopulated zones persist. This and the relatively even distribution of the P-wave data, suggest that the unpopulated zones are a function of the asymmetric PS ray path and the bin size. Further research is currently being conducted to determine whether a flexible binning method may improve the PS azimuth-offset distribution.

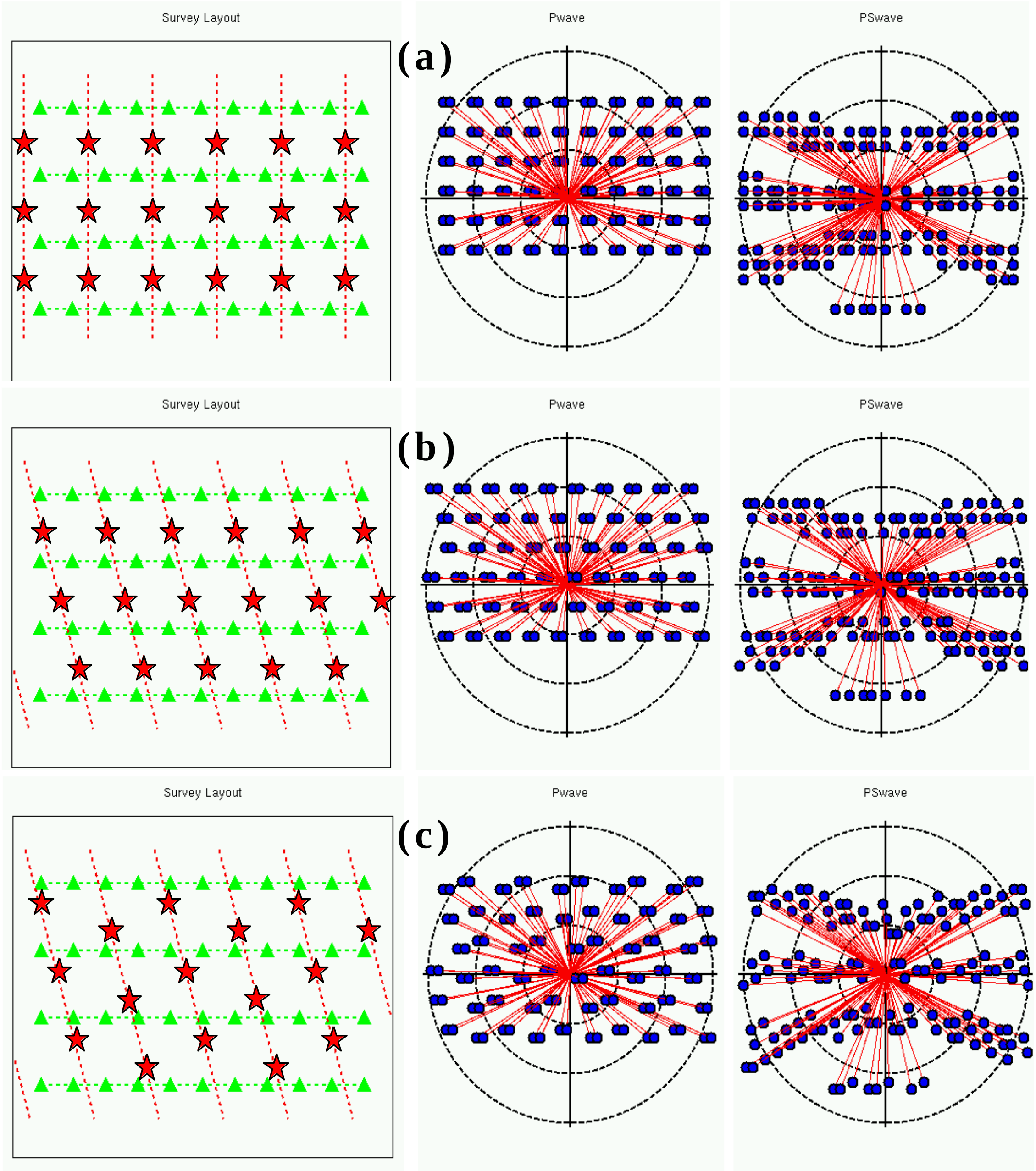


*Figure 3: P and PS spider plots for representative CCP 840. Figures on the left indicate the source (red) and receiver (green) layout. Receiver spacing is 15m; receiver line spacing is 30m; the live receiver template is 300m x 150m. Designs are: (top) source/receiver angle 90 degrees; (middle) source/receiver angle 75 degrees; and (bottom) source/receiver angle 75 degrees, staggered shots. On the spider plots each circle represents an offset increment of 100m.*

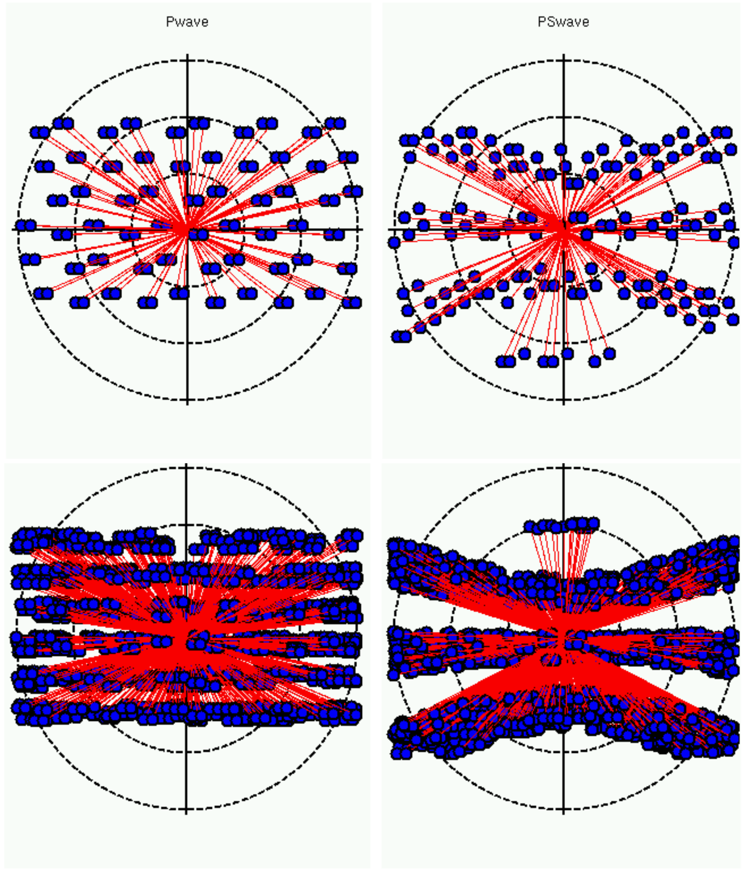


*Figure 4: A comparison of the 75 degree staggered (top) and random acquisition (bottom) designs. The unpopulated zones are essentially unchanged.*

**PHASE vs. OFFSET EFFECTS**

In the preceding fold analysis, we have included all available offsets produced from the live recording template. It is important, however, to consider how the seismic response may vary with offset. Of particular interest to this investigation is whether the phase of P or PS events changes significantly with offset. To demonstrate the possibility of such phase variation, we have considered a coal-seam model whose parameters are defined in Figure 5. We will consider two variations: a coal seam of typical thickness (5m) and a thicker seam (20m). The thicker coal seam model will allow us to independently examine the phase effects at the upper and lower interfaces.

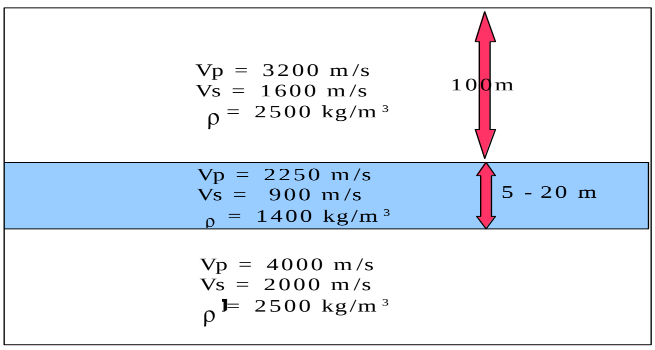


*Figure 5: Schematic showing parameters (P and S-wave velocities, density) used in coal-seam phase modelling. The seam is 100m below surface. Seams of thickness 5m and 20m are considered.*

Firstly, we will consider the general phase effects at the top and bottom of the seam, irrespective of seam thickness. Figure 6 shows the magnitude and phase responses as a function of incidence angle for our model. The phase response for the top of coal (Figure 6, left) is constant (P-wave: 0 degrees, PS-wave: 180 degrees) for all incidence angles. However, for the base of coal (Figure 6, right) the phase is only constant up until the critical angle. After the critical angle the phase varies with incidence angle for both the P and PS events. At the critical angle we also see that the PS event changes polarity.

Note that strong P-wave reflections are available at low angles of incidence, where the phase is well behaved. However, PS events tend to have their strongest energy at greater incidence angles. The temptation is to include far offset traces to take advantage of this effect. The phase examination in Figure 6 suggests that incidence angles should, ideally, not be allowed to exceed the critical angle. If the critical angle is exceeded, then data processing should, in theory, incorporate phase adjustment at far offsets.

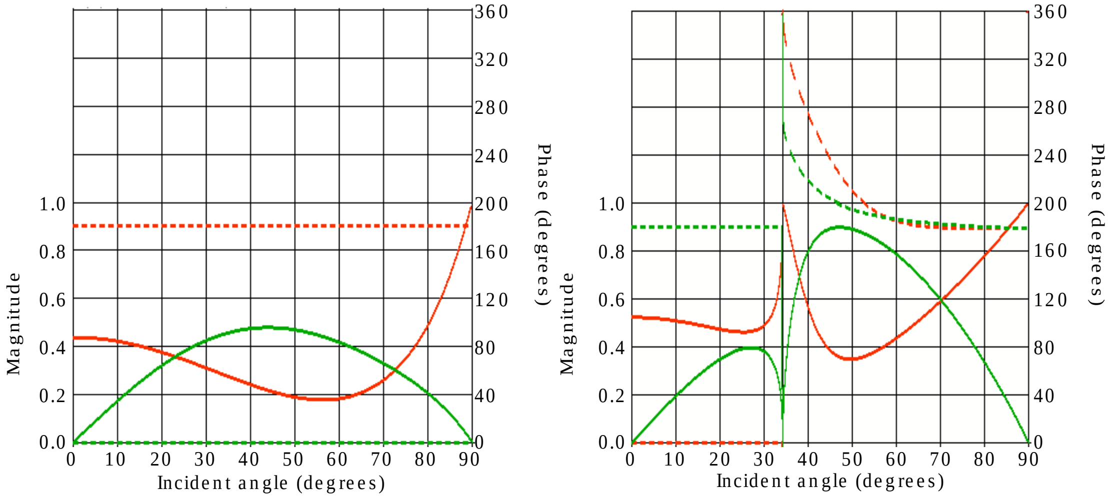


*Figure 6: Magnitude (solid) and phase (dashed) of P (red) and PS (green) reflections, for the top (left) and base (right) of the coal seam defined in Figure 5. In each figure the incident wave is a P wave and has a magnitude of 1.0. The base of coal interface has a critical angle of 34.23 degrees within the coal and corresponds to a P-wave incident angle of 53.13 degrees at the top-of-coal interface. The figures were generated with the assistance of the CREWES Zoeppritz Explorer 2.2,* www.crewes.org.

Up until now we have been discussing the effect of phase with regard to incidence angle. When designing a seismic survey it is more appropriate to think in terms of offset. Table 1 gives the absolute offset corresponding to a base-of-coal reflection at the critical angle for each wave type and for the models of different thicknesses. This table indicates that for a typical 5m seam, the P event would exhibit phase distortion for offsets greater than 270m. The effect is more serious for the PS event, which is distorted beyond 179m. If we re-examine the spider plots in Figure 3, these results suggests that most of the P-wave points suffer no phase distortion. However, the PS-wave points in the outermost ring will be phase distorted. Potentially this could reduce available fold by about 30%.

*Table 1: Absolute shot/receiver offset corresponding to a reflection from the base of the coal at the critical angle (34.23 degrees) for the model in Figure 5. Unlike the incident angle, the offset is also dependent on geometric factors such as depth and thickness of the coal seam.*

| Wave Type | Seam Thickness | Offset |
|---|---|---|
| P | 5 | 270 |
| PS | 5 | 179 |
| P | 20 | 290 |
| PS | 20 | 193 |

We have identified that offsets, which are greater than those corresponding to the critical angle introduce significant phase variations. However, it is important to understand how much these phase changes affect a seismic record. To determine this we have used finite-difference visco-elastic modelling to generate shot records (Figure 7) for our 5m and 20m thick coal seams. The P-wave records (Figure 7, left) show minimal phase distortion. For the 20m seam (top), there is a small variation in phase between the near and far offsets at the base of the coal (green line intercepts at a different point on the wavelet). For the 5m seam (bottom), this variation is even smaller and almost impossible to see.

The PS images (Figure 7, right) are, however, more strongly affected. For the 20m seam (top right), it is difficult to identify the polarity reversal on the lower event due to lower amplitude and coherent noise, but if we consider all offsets we can see that the dominant peak tends to shift, with offset, relative to the green reference line. On the 5m PS image (bottom right) the combined top and base of coal reflection has two peaks for offsets greater than 200m. In part this is due to the difference in moveout velocity between the 2 events. However, between 200 and 300m this effect is enhanced by the phase variation.

The effect of phase variation may not be critical to some applications, where broad structural mapping is the main objective. However, for high-resolution interpretation or attribute analysis (e.g. AVO) it is preferable to work within the critical angle, or to incorporate phase correction if that is practically feasible.

## CONCLUSION

Integrated 2D P-wave / PS-wave imaging can provide improved characterisation in certain geological situations, at both the petroleum and coal scales. It is logical that the idea should be extended to 3D. This extension is more challenging than for P-wave imaging, particularly in the case of onshore coal-scale exploration.

Diodic (directional) imaging problems are commonly seen in 2D PS reflection. The asymmetric nature of ray paths can cause inaccuracy in binning unless velocities are accurately known. Localised geological anomalies can result in amplitude and timing differences in images, depending on which wave types traverse anomalous bodies. Viable 2D imagery is achieved using unidirectional stacks. The logical extension to 3D is to interpret restricted-azimuth images, although the best approach to forming a composite-azimuth image requires further research.

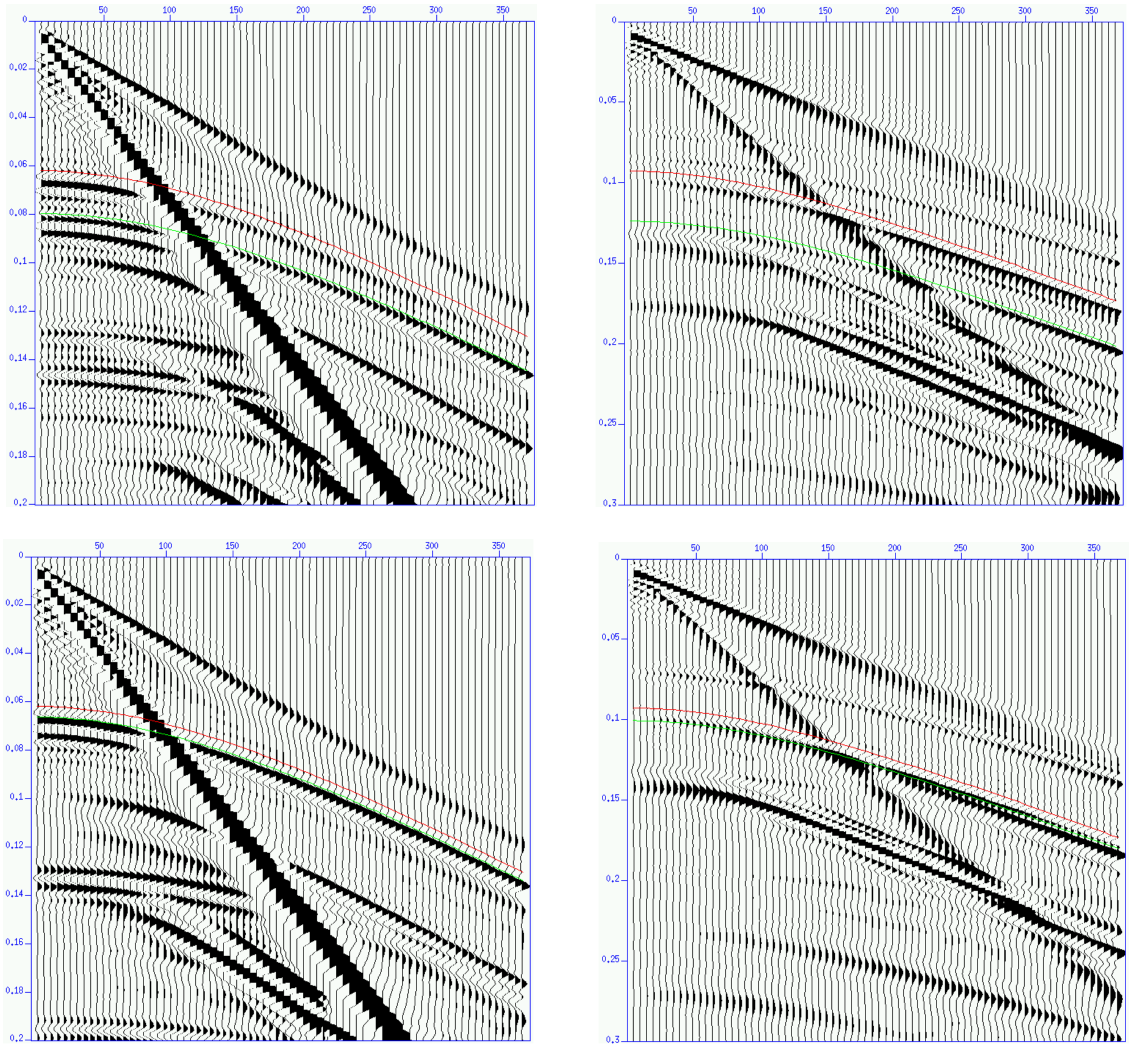

*Figure7: P-wave (left) and PS-wave (right) records for a model with a 20m thick coal seam (top) and another with a 5m thick coal seam (bottom). Theoretical arrival times for reflections from top and base of coal are indicated by the red and green lines respectively. The far offset is 375m. The maximum time is 0.2s.*

Survey modelling, whereby the distributions of fold, azimuth and offset are examined, is a valuable tool for optimising acquisition geometries. It is much harder to achieve smooth azimuth/offset coverage for PS-waves than for P-waves. This relates largely to the asymmetric nature of the PS reflection. The availability of traces may be further restricted due to the effects of phase distortion. For example, in the case of coal seams at typical depth and thickness, the usable offsets for PS reflections may be reduced by some 30% compared to P reflections.

This paper represents the design phase of an ACARP project to explore azimuthal imaging issues in 3D PS-wave coal exploration. The ideas presented here will be explored in a field trial in late 2008.

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