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A preliminary evaluation of integrated P/PS seismic interpretation for improved geological characterisation of coal environments

A preliminary investigation into the potential of integrated P/PS seismic interpretation to help characterise geological properties of the sub-surface ahead of longwall mining has been conducted. This interpretation methodology requires seismic data to be acquired using multi-component (3C) geophones, such that both compressional (P) and shear (S) seismic waves are recorded at the surface. Synthetic and real seismic data have been used to conduct this initial evaluation. Interval *Vp/Vs* analysis (where *Vp* is the interval P-wave velocity and *Vs* is the interval S-wave velocity) has been performed to map lateral changes in lithology and rock properties. This involves computing the time difference between the P and PS reflection events at the top and bottom of a selected interval in the conventional and converted-wave seismic sections, respectively, to determine the P-wave to S-wave velocity ratio.

Synthetic trials highlight that conventional seismic resolution limits govern the ability of *Vp/Vs* analysis to detect lithological anomalies. It is also demonstrated that absolute *Vp/Vs* values can be recovered for thick geological intervals. However, for thin geological intervals (thickness less than seismic wavelength), only relative *Vp/Vs* values can be recovered. Nevertheless, relative *Vp/Vs* estimates are shown to reveal more information about the geological characteristics of the sub-surface than using conventional P-wave seismic data alone. Results from a Bowen Basin trial illustrate that *Vp/Vs* analysis has the potential to discriminate between shale-rich and sand-rich material, as well as potentially highlight zones of intense fracturing about small faults.

INTRODUCTION

Seismic reflection is widely recognised as a significant geophysical tool for the remote imaging of coal seams ahead of longwall mining. Conventional seismic reflection, which records compressional (P) seismic waves, is routinely used to detect faults and highlight stratigraphic anomalies to help establish the viability of mining projects and determine mine layouts. However, geological data such as roof/floor lithology and rock strength, which are also beneficial to the early mine-planning process, are not easily recovered from conventional seismic interpretation. Converted-wave seismology is an alternative geophysical tool that can potentially yield this type of geological detail. The converted-wave seismic method takes advantage of both P and shear (S) seismic waves arriving at the surface during a seismic survey. The latter generally originate from P-to-S mode conversion occurring at the coal seam, and are commonly referred to as PS or converted waves. With the support of ACARP, Velseis Pty Ltd has recently demonstrated the viability of implementing converted-wave seismic technology in the coal environment (Velseis, 2003; Hendrick, 2004).

Our current research is directed towards evaluating the quality and quantity of additional geological information that can be extracted using converted-wave seismic surveys. This paper reviews the basic concepts of conventional and converted-wave seismic, and presents results from a preliminary evaluation of integrated P/PS seismic interpretation. A number of coal-scale synthetic seismic data trials have been conducted to examine the resolution and accuracy of geological information recoverable via integrated P/PS interpretation. In addition, a preliminary attempt to map sub-surface lithology using real P and PS coal-seismic data from the Bowen Basin is given. These early results suggest that, whilst absolute rock strength and lithology is unlikely to be recovered via integrated P/PS interpretation, useful information about relative lateral changes in rock strength and lithology can be extracted.

P-WAVE AND PS-WAVE SEISMIC

Conventional P-Wave Seismic

Conventional coal-seismic assumes that only compressional (P) waves will arrive at the surface during a seismic survey. P waves are longitudinal sound waves that have particle motion in the direction of travel. Hence a P wave travelling upwards from a geological boundary will have particle motion with a strong vertical component. Conventional seismic surveys will record only the vertical component of seismic energy arriving at the receiver (Figure 1a). This type of seismic recording can also be referred to as single-component (1C) recording.

Converted-Wave (PS-Wave) Seismic

In reality, both reflected P and shear (S) waves typically arrive at the surface during a seismic survey. S waves are transverse sound waves that have particle motion perpendicular to the direction of travel. Note that most of the S energy arriving at the surface will be mode-converted PS energy — that is, energy from a wave that travels down to a

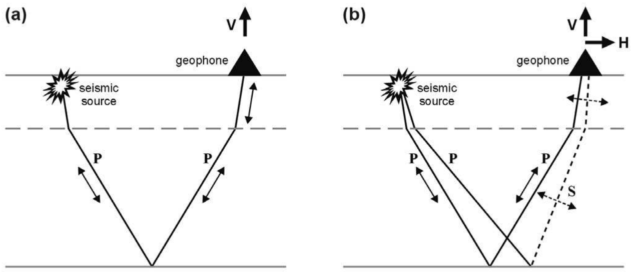

Figure 1: (a) Conventional seismic reflection assumes that only P waves arrive at the surface. Since the particle motion of an upward travelling P wave is largely vertical (indicated by the solid arrows), a vertically-oriented geophone is used for acquisition. (b) Multi-component seismic recording recognises that both P and mode-converted PS waves will arrive at the surface. The particle motion of an upward travelling S wave is largely horizontal (indicated by the dashed arrows). Thus both the vertical (V) and horizontal (H) components of ground motion must be recorded to take advantage of both wave types.

geological boundary as a P wave, gets partially converted to S energy at the boundary, and then travels back to the surface as an S wave. Any PS-wave energy travelling upwards to the surface will have a dominantly horizontal component of particle motion. To enable exploitation of both the P and PS energy arriving at the surface, converted-wave seismic surveys use multi-component receivers that measure both the vertical and horizontal components of ground motion (Figure 1b). Note that multi-component recording may also be referred to as three-component (3C) recording since the vertical and two orthogonal horizontal components (inline and crossline components) of ground motion are generally recorded.

The viability of implementing converted-wave seismic technology in the coal environment has been demonstrated by Velseis Pty Ltd over the past few years (Velseis, 2003; Hendrick, 2004). Standard seismic sources can be used (small dynamite explosions; mini-SOSIE). However, a purpose built high-resolution, high-output 3C geophone replaces the array of vertical geophones used for conventional acquisition at each receiver station. Data recorded on the vertical component of the 3C geophone is subjected to standard seismic-processing algorithms (Yilmaz, 1987) to produce a conventional P-wave seismic section. Our field experiments indicate that single-geophone acquisition does not compromise the quality of the conventional P-wave stack (Velseis, 2003).

The PS stack is generated via processing of the data acquired on the horizontal components of the 3C geophone. This is typically challenging and requires considerable geological input. Furthermore, specialised approaches to S-wave receiver statics, PS normal moveout (NMO) correction and common-conversion point (CCP) binning (Cary & Eaton, 1993; Zhang, 1996) are necessary. Nevertheless, viable PS images have been achieved for the four 2D converted-wave coal-seismic trials conducted in the Bowen Basin to date.

Physical characteristics of P and PS waves

The subsequent integrated interpretation of the P and PS sections takes advantage of the fact that P and S waves travel at different speeds through the earth, and respond differently to various geological situations. For example, S waves typically travel at about half the speed of P waves and, in contrast to P waves, S waves will only travel in solid materials. Hence, while P waves are influenced by pore space and/or fluid and gas saturation, S waves are not. In recent years these differences have been exploited in the petroleum industry, where integrated P/PS interpretation has permitted imagery through gas-filled sediments (e.g. Granli & others, 1999), improved lithology/fluid classification (Engelmark, 2001) and detected reservoir fracture systems (Potters & others, 1999). By analogy, these applications suggest interesting possibilities for the coal environment, such as gas detection, mapping of sandstone lenses or channels, and detection of fracture swarms associated with very small faults or flexures.

INTEGRATED P/PS INTERPRETATION

The fundamental approach to integrated P/PS interpretation is interval *Vp/Vs* analysis (where *Vp* is the interval P-wave velocity and *Vs* is the interval S-wave velocity). The ratio of P-wave to S-wave velocity (*Vp/Vs*) can be estimated from the P and PS seismic sections via:

$$Vp / Vs = \left(2 \frac{\Delta t_{PS}}{\Delta t_P} \right) - 1 \qquad (1)$$

where Δt_P and Δt_{PS} are the time differences between the reflection events at the top and bottom of an interval of interest in the P and PS sections, respectively. Inherent in this technique is the assumption that the reflection events correlated between the P and PS sections originate from the same geological boundaries. Accurate correlation of reflection events on the P and PS seismic sections is the most critical and difficult step in the *Vp/Vs* analysis process.

The motivation behind *Vp/Vs* analysis is that the P-wave to S-wave velocity ratio is an effective indicator of lithology and/or fractures, cracks and pore space (Tatham, 1982). For example, sandstones will typically have *Vp/Vs* values in the range of 1.5 to 1.7, while shales have variable *Vp/Vs* values ranging from 2.3 to 2.9 (McCormack & others, 1984). The *Vp/Vs* in coal is typically about 2.5 (Stewart, 2003). Poorly consolidated or fractured material will also exhibit high *Vp/Vs* values. In addition, *Vp/Vs* analysis can yield estimates of Poisson's ratio (Sheriff, 1991):

$$\sigma = \frac{\left(\frac{Vp}{Vs}\right)^2 - 2}{2\left(\frac{Vp}{Vs}\right)^2 - 2} \qquad (2)$$

This elastic constant is an indicator of rock strength, and may be useful for determining additional information about roof and/or floor conditions in underground mining situations.

SYNTHETIC DATA TRIALS

A number of synthetic seismic data trials have been conducted to examine the resolution and accuracy of geological information recoverable via *Vp/Vs* analysis. Such numerical modelling provides an objective benchmark for analysing the overall accuracy and/or relevance of lithological information extracted from real multi-component data.

The synthetic data used in this research have been generated via the elastic finite-difference modelling technique of Virieux (1986). A causal, mixed-phase pulse (the derivative of a Gaussian pulse) with a dominant frequency of 90Hz has been used to approximate an explosive seismic source. Synthetic shot records are constructed at regular intervals along a specified earth model. The resultant P and PS seismic sections are produced using approximately the same processing sequences required to process real multi-component data. This helps to highlight issues relevant to real-data *Vp/Vs* analysis.

Detection of geological anomalies

Recall that *Vp/Vs* analysis involves computing the time difference between the P and PS reflection events at the top and bottom of a specific interval in the seismic sections, and calculating the P-wave to S-wave velocity ratio via Equation 1. It follows that *Vp/Vs* analysis can only be conducted on geological intervals that are thick enough for the top and bottom boundaries to produce discrete seismic reflection events (Sheriff, 1991) for further discussion on vertical seismic resolution limits).

In addition, the *Vp/Vs* attribute will only detect a lateral variation in lithology if the geological anomaly can be detected in the actual seismic sections (Sheriff, 1991) for further discussion on horizontal seismic resolution limits). That is, conventional seismic resolution limits govern the resolution of *Vp/Vs* analysis. However, while *Vp/Vs* analysis doesn't provide greater resolution than seismic imaging, it does provide the opportunity to acquire additional geological information about an observed anomaly.

Note that, it is possible for a lateral geological anomaly to not be seen in a conventional P-wave section, but be detectable in the corresponding PS section (or vice versa). This can occur because S waves respond differently to P waves in various geological situations. In this instance, the *Vp/Vs* attribute will detect a lateral change in lithology because the geological anomaly is imaged in at least one of the seismic sections.

Care must be taken to not over-interpret the *Vp/Vs* attribute. Synthetic data trials suggest that any *Vp/Vs* amplitude variations less than ~0.2 should be interpreted as 'background noise'. Such small variations in *Vp/Vs* can easily result from subtle (and common) discrepancies in the processing of P and PS data. This suggests that *Vp/V*s analysis is suitable for detecting zones of significant lithological difference (e.g. sandstone versus shale), but is not suited for delineating subtle changes within one lithology type.

Figures 2–5 illustrate the basic concept of *Vp/Vs* analysis. Figure 2 shows a simple two-dimensional (2D) coal-scale earth model comprising shale-rich country rock and two coal seams separated by a number of sandstone channels of varying widths. The corresponding noise-free 2D P and PS seismic sections are given in Figure 3. The two-way time (TWT) picks along the upper and lower coal-seam reflection events for these sections are shown in Figure 4. The computed *Vp/Vs* values for the geological interval between the two coal seams are given in Figure 5.

The average *Vp/Vs* estimate for the country-rock material lying between the two coal seams is ~2.4 (Figure 5) — this is consistent with shale-rich material. Note that, the absolute *Vp/Vs* value for the country-rock material is slightly over-estimated due to the fact that the two reflection events used to define the TWT picks at the top and bottom of the interval are in fact interference patterns created by the energy reflected from the top and the bottom of the two thin coal seams, respectively.

The resultant error in the measured seismic travel times through the geological interval of interest causes the absolute *Vp/Vs* values to be a little too high. Nevertheless, in this example, we are still able to determine that the country rock comprises shale-rich material.

Recall that for these noise-free synthetic data, *Vp/Vs* amplitude variations less than ~0.2 are not considered significant. Thus, the 2m and 5m wide channels in the synthetic earth model of Figure 2 are not reliably detected via *Vp/Vs* analysis. However, Figure 5 shows a significant drop in the *Vp/Vs* values over the 10m, 20m and 40m wide channels. Note that, the TWT horizons from the P-wave section (Figure 4a) only detect the 40m wide channel.

However, the 10m, 20m and 40m wide channels can be detected in the TWT picks from the PS section (Figure 4b). Consequently, the three channels can be detected via *Vp/Vs* analysis. (Note: the width of channel that can be detected via *Vp/Vs* analysis will change with the dominant frequency of the seismic dataset, the signal-to-noise ratio, the vertical thickness of the channel, and the relative *Vp* and *Vs* of the channel material with respect to surrounding material).

Prediction of physical rock properties

Ideally integrated P/PS interpretation would determine absolute *Vp/Vs* values for any specified geological interval to provide the best opportunity for mapping unique lithologies. However, as illustrated by the example given in Figures 2, 3,

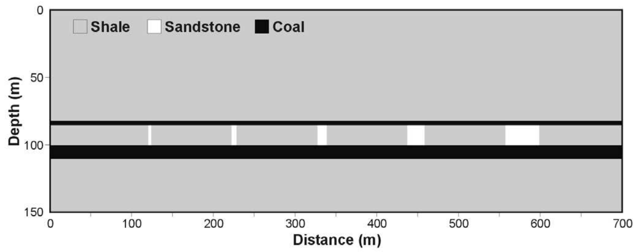

Figure 2: Synthetic earth model used to generate the P and PS seismic sections given in Figure 3. The shale-rich country rock has a *Vp/Vs* of 2.3 (*Vp*=3350m/s; *Vs*=1450m/s). The coal seams at depths of 82m and 100m (3m thick and 10m thick, respectively) have a *Vp/Vs* of 2.5 (*Vp*=2200m/s; *Vs*=880m/s). The five sandstone channels between the coal seams have a range of widths (2m, 5m, 10m, 20m and 40m, from left to right) and a *Vp/Vs* of 1.6 (*Vp*=3900m/s; *Vs* = 2450m/s).

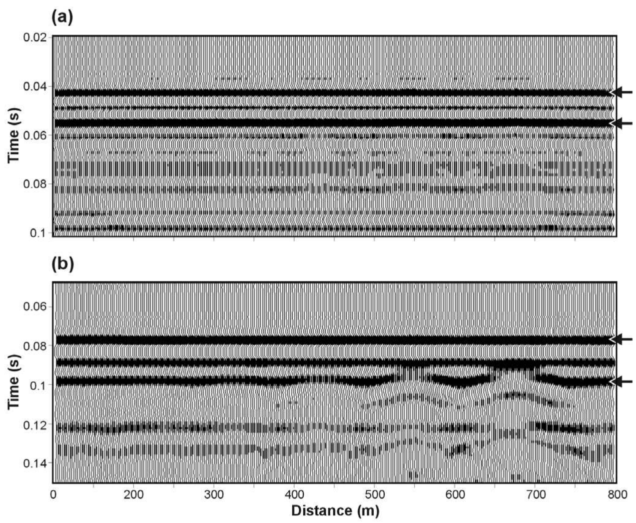

Figure 3: (a) The P and (b) PS seismic sections generated from the earth model given in Figure 2. The reflection events for the upper and lower coal seams are indicated by the arrows. Note that the time axes have been adjusted appropriately to provide a comparable depth perspective.

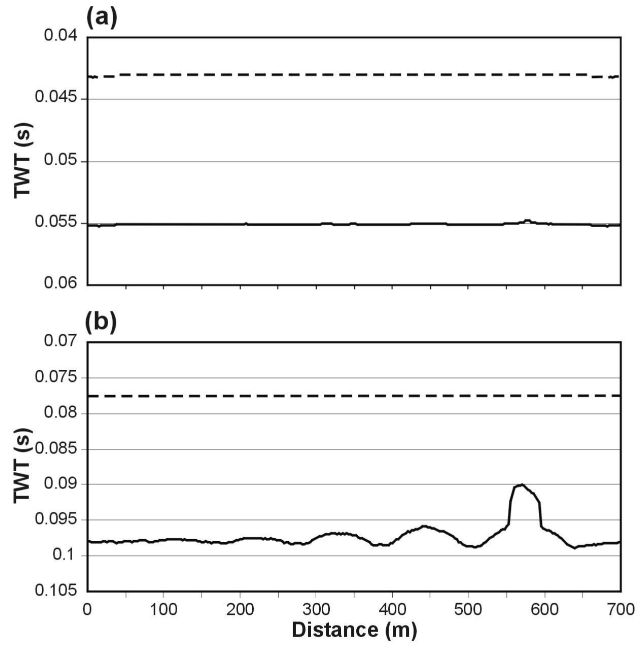

Figure 4: The two-way time (TWT) picks along the upper and lower coal-seam reflection events for (a) the P-wave section shown in Figure 3(a); and (b) the PS-wave section shown in Figure 3(b). The P data show only a subtle TWT variation over the 40m wide channel. The PS data show more significant TWT variations across the 10m, 20m and 40m wide channels due to the large contrast between the S-wave velocity of the shale-rich country rock and the sandstone channels. Note that the time axes have been adjusted appropriately to provide a comparable depth perspective.

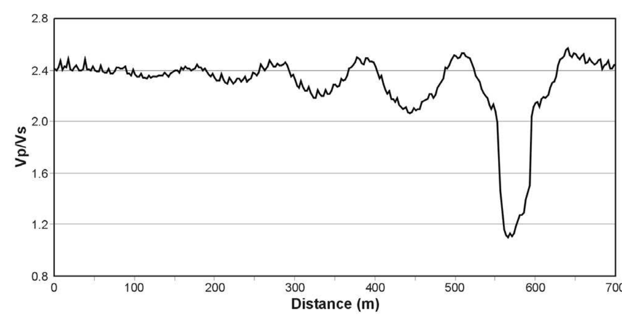

Figure 5: Vp/Vs measurements for the seismic data given in Figure 3. The background Vp/Vs is computed to be ~2.4 — consistent with the shale-rich interburden material. The 10m, 20m and 40m wide channels are correctly indicated by a relative decrease in Vp/Vs. Note however, the absolute Vp/Vs values of the detected sandstone channels are distorted due to the lateral resolution limits of the seismic dataset, and the interference of inter-bed seismic multiple energy.

4 and 5, seismic resolution limits influence absolute *Vp/Vs* values. The *Vp/Vs* estimates for the 10m and 20m channels in Figure 5 are too high because the widths of the channels are smaller than the lateral resolution limit of the seismic dataset (here the Fresnel zone radius is ~40m). While the lateral resolution limit suggests that the absolute *Vp/Vs* estimate across the 40m channel should be correct, in this case it is distorted by the PS reflection event at the base of the channel being affected by an inter-bed multiple reflection event (Figure 4b). That is, noise events will also influence absolute *Vp/Vs* values. Nevertheless, integrated P/PS interpretation of these data clearly indicates the presence of the 10m, 20m and 40m wide geological anomalies, and correctly reveals that they are comprised of material that contains more sand than the surrounding country rock. Such relative variations in *Vp/Vs* contribute to our knowledge of the earth model. This type of information would not have been possible using conventional P-wave data alone.

As expected, vertical seismic resolution limits will also influence absolute *Vp/Vs* values. This has been highlighted previously for petroleum-scale case studies (e.g. McCormack & others, 1984; Miller, 1996), and is illustrated here using a simple coal wedge model (Figure 6). *Vp/Vs* estimates for the coal layer, computed via interpretation of the corresponding P and PS sections, are given in Figure 7. For coal thickness ranging from 40m down to 14m, *Vp/Vs* analysis correctly computes an absolute coal *Vp/Vs* value of ~2.5 (recall, any variations in *Vp/Vs*≤0.2 are insignificant).

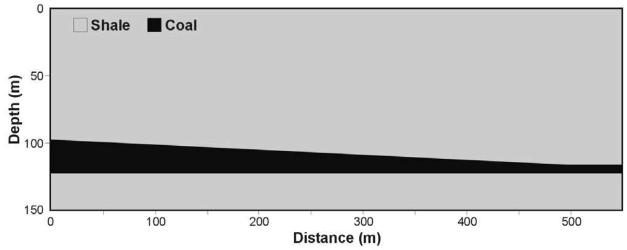

Figure 6: Synthetic earth model used to generate P and PS seismic sections for the *Vp/Vs* analysis results given in Figure 7. The coal wedge starts with a thickness of 40m and thins to 10m. The coal *Vp/Vs* is 2.5 (*Vp*=2200m/s; *Vs*=880m/s). The coal sits in shale-rich country rock with a *Vp/Vs* of 2.3 (*Vp*=3350m/s; *Vs*=1450m/s).

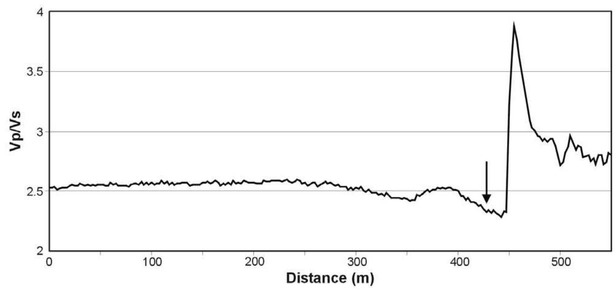

Figure 7: *Vp/Vs* measurements for the seismic data generated using the earth model in Figure 6. For coal thickness ranging from 40m down to ~14m (marked by arrow), *Vp/Vs* analysis correctly computes an absolute *Vp/Vs* of ~2.5. When the coal thickness drops below the seismic wavelength, the *Vp/Vs* estimates drop low before becoming spuriously high.

As the coal-seam thickness drops below ~14m (which is equivalent to the seismic wavelength for this dataset) *Vp/Vs* estimates drop low before becoming spuriously high. The point at which *Vp/Vs* analysis yields these significantly incorrect values is the point at which the reflection events from the top and bottom of the coal seam begin to interfere with one another.

Note: the seismic wavelength is dependent on frequency content of the seismic data, and the velocity of the material through which the seismic energy is travelling. Consequently, the distance between seismic reflectors for which *Vp/Vs* analysis ceases to yield accurate absolute *Vp/Vs* values will be site specific and dependent on local geology and data quality. (Typical coal-seismic wavelengths can vary between 12m and 40m.)

It is highly likely that many geological intervals of interest in the coal environment will have thicknesses close to or less than the seismic wavelength. This does not invalidate the *Vp/Vs* interpretation method in terms of mapping lateral changes within a single geological interval. It simply implies that the thin-interval *Vp/Vs* attribute must be interpreted in terms of relative physical rock property changes within the one interval. Further, comparison of absolute Vp/Vs values from different geological intervals should be avoided when the interval thicknesses are less than the seismic wavelength.

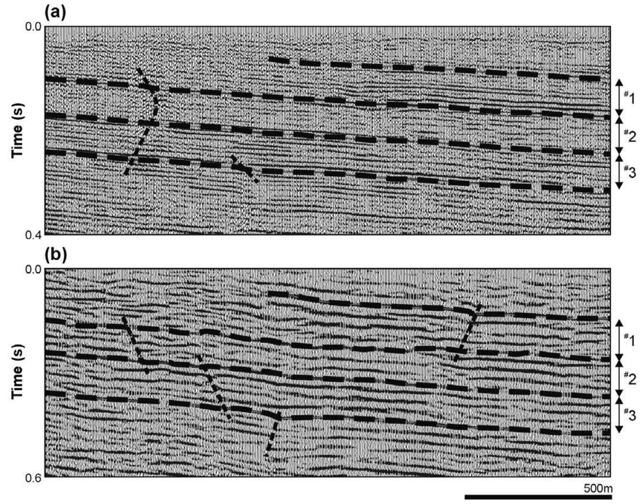

Figure 8: (a) Conventional P-wave image and (b) converted-wave (PS) image derived from the Bowen Basin trial. Interpreted faults are approximately marked. Interpreted horizons are indicated by the dashed lines. Three geological intervals have been defined. Note that the time axes have been adjusted appropriately to provide a comparable depth perspective.

BOWEN BASIN TRIAL

Of the four 2D converted-wave coal-seismic trials conducted in the Bowen Basin to date, two have been acquired in multi-seam environments suitable for trialing integrated P/PS interpretation. Here the results from one of these trials are presented. Figure 8 shows the final P and PS images from this Bowen Basin trial. Significant geological interfaces have been identified on both of the sections, and interpreted faults are indicated.

Note: in this instance, the reflection events defining the three geological intervals for *Vp/Vs* analysis do not interfere with one another (although multiple energy may still interfere with the primary reflection events). It is therefore possible that meaningful absolute *Vp/Vs* values could be recovered, in addition to *Vp/Vs* analysis indicating relative changes in lithology within each interval.

Figure 9 shows the corresponding *Vp/Vs* estimates for the three intervals. The uppermost interval (small dash) exhibits generally high *Vp/Vs* ratios, as might be expected in the shallower, less-consolidated part of the section. The second interval (dash) exhibits an abrupt lateral change in *Vp/Vs* (at distance of ~1200m). This is consistent with a change from shale-rich material on the right to sandy (or possibly gas-contaminated) material on the left. The deepest interval (solid) lies immediately above the target coal seam. This exhibits a more consistent *Vp/Vs* ratio, indicative of a shale-rich sequence. The abrupt increase in *Vp/Vs* at a distance of 500m for Interval 2 and at a distance of 750m for Interval 3 may be indicative of unconsolidated material associated with fracturing about a small fault. Note that, geological information from boreholes has yet to become available for confirmation of any aspects of this interpretation.

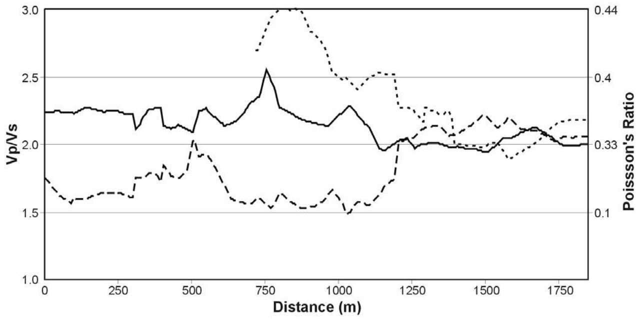

Figure 9: *Vp/Vs* for Interval 1 (small dash); Interval 2 (dash); and Interval 3 (solid) interpreted on the P and PS images show in Figure 8. A high *Vp/Vs* (greater than 2.2) corresponds to shale-rich layers or poorly consolidated material. A low *Vp/Vs* (less than 1.6) is indicative of high sand and/or gas content. As indicated on the right-hand axis, *Vp/Vs* is related to Poisson's Ratio.

CONCLUSIONS

Implementation of converted-wave seismic technologies in the coal environment provides the opportunity to take advantage of integrated P/PS interpretation methods. The potential of these methods to help characterise geological properties of the sub-surface has been evaluated here using both synthetic and real-data coal-seismic examples.

Conventional seismic resolution limits govern the resolving power of integrated P/PS interpretation. Absolute *Vp/Vs* estimates can be recovered for geological intervals thicker than the seismic wavelength, provided noise events or lateral resolution limits are not affecting the reflection events defining the interval. Thin-interval *Vp/Vs* analysis, which is likely to be more common in the coal environment, will yield relative *Vp/Vs* values. However, significant lateral variations in this thin-interval *Vp/Vs* attribute, coupled with behaviour of the individual reflection TWT curves, can be used to infer real changes in the physical properties of the geological interval.

Efficient processing of the converted-wave data and the accurate correlation of reflection events on the P and PS seismic sections are the most problematic components of integrated P/PS interpretation. Nevertheless, this preliminary evaluation of *Vp/Vs* analysis suggests there is merit in continuing to experiment with integrated P/PS interpretation methods and test their ability for improving the remote geological characterisation of coal environments.

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