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Converted-wave seismic reflection for open-cut coal exploration

Two 2D converted-wave seismic trials designed to image very shallow coal seams have been conducted in the Bowen Basin, Australia. Converted-wave seismic is an alternative seismic method that takes advantage of shear-wave seismic energy arriving at the surface during a seismic survey. In contrast, conventional seismic utilises only compressional waves arriving at the surface. Due to differences in the way compressional waves and shear waves propagate through the Earth, there is potential for converted-wave seismic to yield better quality images of very shallow targets compared to conventional seismic.

Some changes to conventional recording equipment and field procedures are necessary to accommodate converted-wave seismic acquisition. A multi-component geophone replaces the vertical geophones used for conventional acquisition at each receiver station. Processing of high-resolution converted-wave data is technically challenging and requires specialised approaches to shear-wave receiver statics, converted-wave normal moveout correction and common conversion-point binning.

The converted-wave image of Field Trial A provides a cleaner image of the shallow coal seam compared to the conventional seismic stack. For Field Trial B the conventional seismic section is unable to image the coal seam at depths less than approximately 45–50m. In contrast, the converted-wave seismic image can track the shallow coal seam along the full extent of the survey line, to depths of approximately 25–30m. These experiments demonstrate the potential for converted-wave seismic to yield high-resolution images of open-cut coal reserves.

INTRODUCTION

Seismic reflection involves using artificially-generated sound waves to map structural and stratigraphic features in the subsurface, and has become a valuable geophysical tool for the accurate and cost-effective imaging of coal seams ahead of longwall mining. In contrast, the seismic method is not often utilised for open-cut coal exploration. This is related to the fact that borehole drilling is relatively cheap for open-cut seam depths, and continuous imaging of the seam is not always as critical as it is for underground mine planning and development. In addition, conventional, economic seismic surveys tend to produce inconsistent results when imaging very shallow coal seams (less than approximately 50m in depth). When continuous mapping of open-cut coal seams is important, conventional seismic survey designs can be adjusted (e.g. source and receiver spacing reduced) to successfully image shallow coal seams.

However, such field-intensive surveys are necessarily more expensive and time consuming. Converted-wave seismic technology offers an alternative geophysical tool for the continuous mapping of open-cut coal reserves that, for some situations, may provide a more cost-effective approach than conventional seismic methods. ACARP-supported research conducted by Velseis Pty Ltd over the past three years (Velseis, 2003; Hendrick, 2004) has demonstrated the ability of converted-wave seismic to successfully produce coherent, high-resolution images of very shallow coal seams. This paper introduces the basic concepts of converted-wave seismic, and presents the results from two 2D converted-wave seismic trials conducted in the Bowen Basin, Australia. Despite technical challenges associated with producing the converted-wave seismic sections, these trials have successfully achieved their objective of imaging very shallow target coal seams.

CONVERTED-WAVE SEISMIC EXPLORATION

Seismic Waves

There are several types of seismic waves, including body waves, surface waves and air waves, that are generated during a seismic survey. In terms of imaging coal seams, the most important and useful seismic waves are body waves. Both compressional (P) and shear (S) waves are seismic body waves. P waves are longitudinal waves that have particle motion in the direction of travel. In contrast, S waves are transverse waves that have particle motion perpendicular to the direction of travel. Figure 1 is a schematic illustrating the ground vibrations associated with P and S seismic waves.

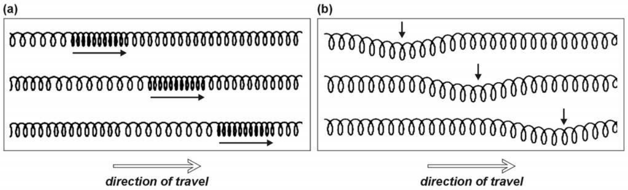

Figure 1: Ground vibrations associated with (a) P-waves and (b) S-waves. In this schematic, the seismic waves are travelling from left to right. The particle motion of the P wave is in the direction of travel. The particle motion of the S wave is perpendicular to the direction of travel.

Conventional vs Converted-Wave Seismic Surveys

Since coal-seismic sources (e.g. small dynamite explosions; mini-SOSIE) dominantly produce P-wave energy, the conventional approach to coal-seismic acquisition assumes that only P waves will arrive at the surface. Recall that the particle motion of a P wave is in the direction of travel. Hence reflected P-wave energy travelling upwards from a geological boundary will have particle motion with a strong vertical component at the surface receiver (Figure 2(a)). Conventional seismic acquisition records only the vertical component of seismic energy arriving at the receiver. This type of seismic recording can also be referred to as single-component (1C) recording.

In reality, both reflected P and S waves typically arrive at the surface during a seismic survey. 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 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. Coal seams are particularly efficient at generating strong PS waves (e.g. Fertig &Müller, 1978; Greenhalgh & others, 1986). Any PS-wave (converted-wave) energy arriving at the surface will have a dominantly horizontal component of particle motion (Figure 2(b)).

Multi-component seismic recording measures both the vertical and horizontal components of ground motion to enable exploitation of both the P and PS energy arriving at the surface. 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.

P- and PS-Wave Behaviour

The different modes of propagation of P and S waves mean they travel at different speeds through the earth, and respond differently to various geological situations. Of particular relevance to the imaging of very shallow coal seams is the fact that S waves typically travel at about half the speed of P waves. Thus reflected PS waves will arrive later than P waves from the same geological boundary. For very shallow target coal seams, this will mean that PS waves should arrive after near-surface noise that typically contaminates the corresponding P-wave reflection energy.

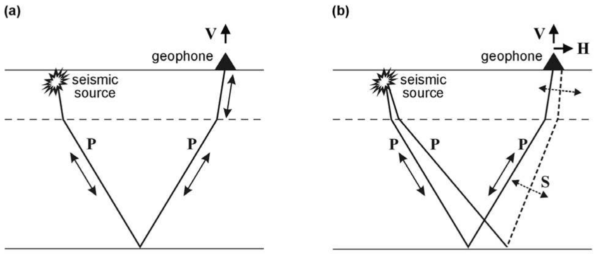

Figure 2: (a) Conventional seismic reflection assumes that only P waves arrive at the surface. Since the particle motion of an upward travelling P wave is largely vertical (indicated by the solid arrows), a vertically-oriented geophone is used for acquisition. (b) Multi-component seismic recording recognises 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.

Figures 3 and 4 show synthetic multi-component seismic records that illustrate the relative behaviour of P and PS reflection energy when imaging shallow coal seams. These seismic records have been generated via the elastic finite-difference modelling technique of Virieux (1986). As discussed above, the reflected P-wave energy will be dominant on the vertical-component record, while the PS reflection event will be dominant on the inline (horizontal) component. Note that, in addition to reflected energy, surface waves (groundroll energy), refracted arrivals, and surface and interbed multiples are generated by the forward-modelling scheme. The earth models used to generate these data comprise three layers — a 15m thick weathered surface layer, country rock and a single 7m thick coal seam. To generate the seismic data in Figure 3 the coal seam has been placed at a depth of 35m. In contrast, the earth model used to produce the records shown in Figure 4 has a coal seam at a depth of 23m.

In Figure 3(a) the hyperbolic P-wave reflection event from the coal seam has a zero-offset arrival time of approximately 0.05s. The corresponding PS reflection event (Figure 3(b)) has a zero-offset arrival time of approximately 0.074s. As expected, the PS reflection event from the target coal seam arrives approximately one-and-a-half times later than the P reflection event.

As illustrated in Figure 4, this delay is advantageous when the coal seam becomes shallower. The P-wave reflection event in Figure 4(a) has a zero-offset arrival time of 0.04s. However, the P energy has been contaminated by strong groundroll energy (steeply dipping linear noise) and base-of-weathering refraction events, and the target reflection event is difficult to detect. The resultant P-wave section would exhibit poor reflector coherency. In contrast, the PS reflection event (Figure 4(b)) has a zero-offset arrival time of 0.055s, and is sufficiently removed from the near-surface noise to facilitate reliable seismic imaging of the very shallow coal seam.

Converted-Wave Acquisition and Processing

Some changes to conventional recording equipment and procedures are required to accommodate both P-wave and PS-wave recording. The primary difference is the receiver device. A purpose-built high-resolution, high-output 3C geophone replaces the vertical geophone(s) used for conventional acquisition at each receiver station. Note that, the use of three recording channels at each receiver station also necessitates the use of additional field units and acquisition cables.

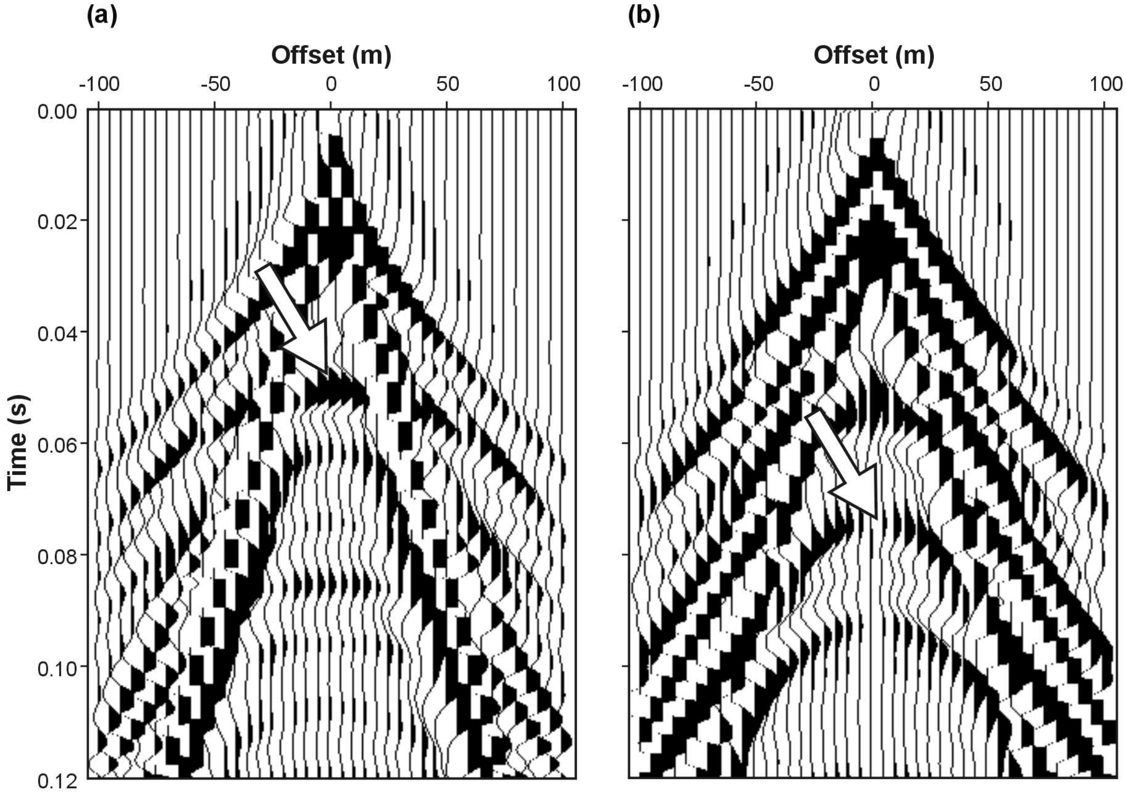

Figure 3: (a) Vertical-component and (b) inline-component of synthetic seismic record generated using an earth model with a coal seam at a depth of 35m. The P and PS coal-seam reflection events are indicated by the white arrows on the vertical and inline records, respectively. The horizontal axis represents offset, the distance between the source and each receiver. Seismic energy travelling to receivers with small offsets arrives earlier than energy that travels obliquely to receivers at far offsets. Hence reflection events will appear approximately hyperbolic in the seismic records.

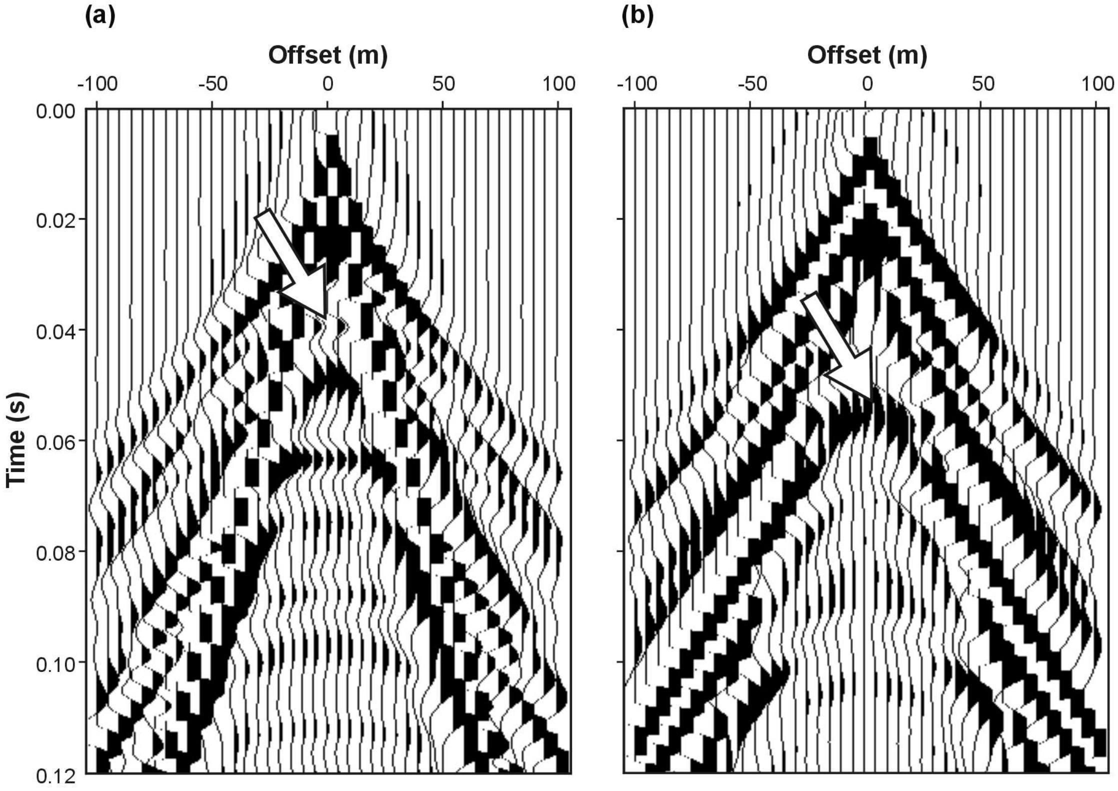

Figure 4: (a) Vertical-component and (b) inline-component of synthetic seismic record generated using an earth model with a coal seam at a depth of 23m. The arrival times of the P and PS coal-seam reflection events are indicated by the white arrows on the vertical and inline records, respectively.

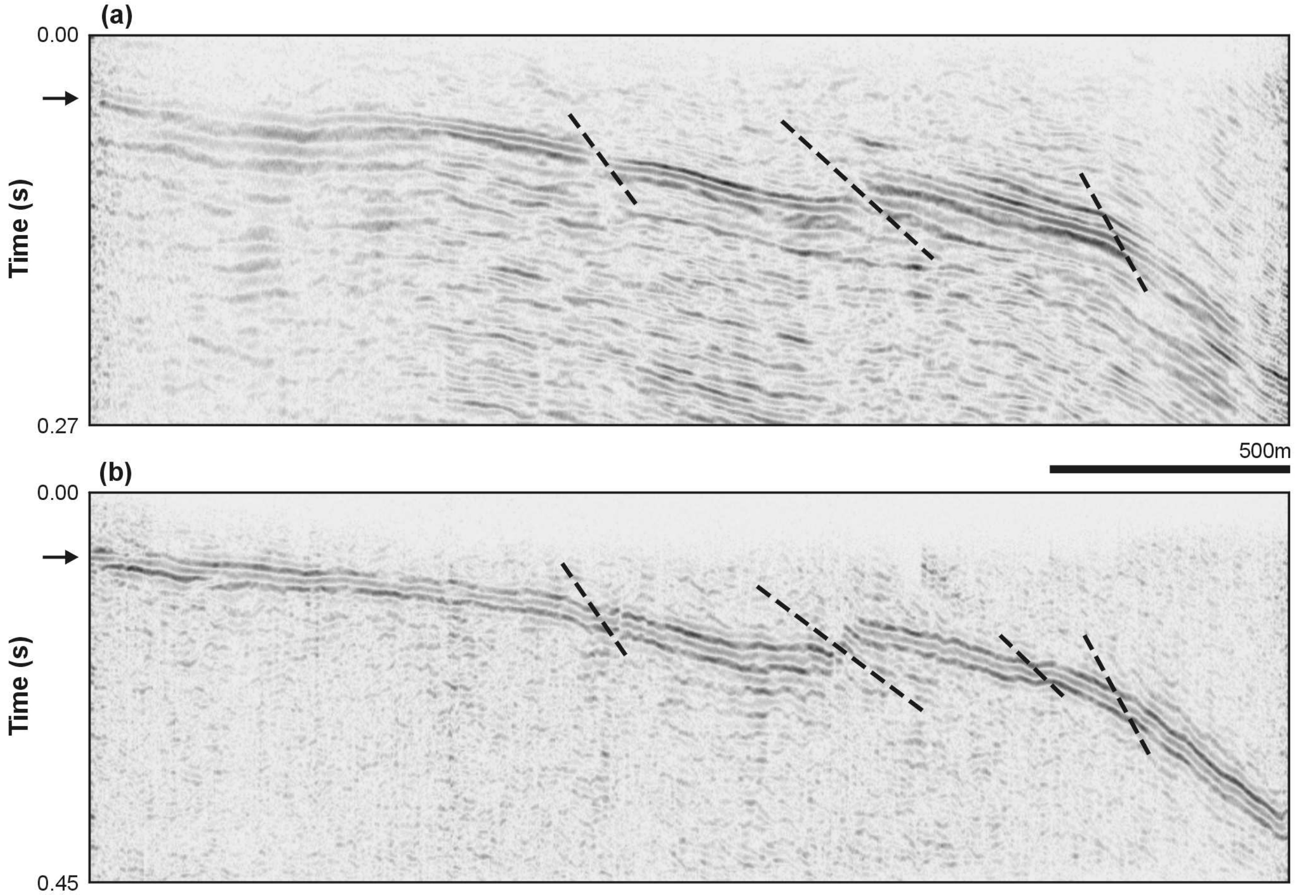

Figure 5: (a) Conventional P-wave image and (b) converted-wave (PS) image derived from Field Trial A. The target coal seam reflection events are indicated by the arrows. Interpreted faults are approximately marked by the dashed lines. The PS image exhibits greater resolution than the P-wave image where the coal seam is shallowest.

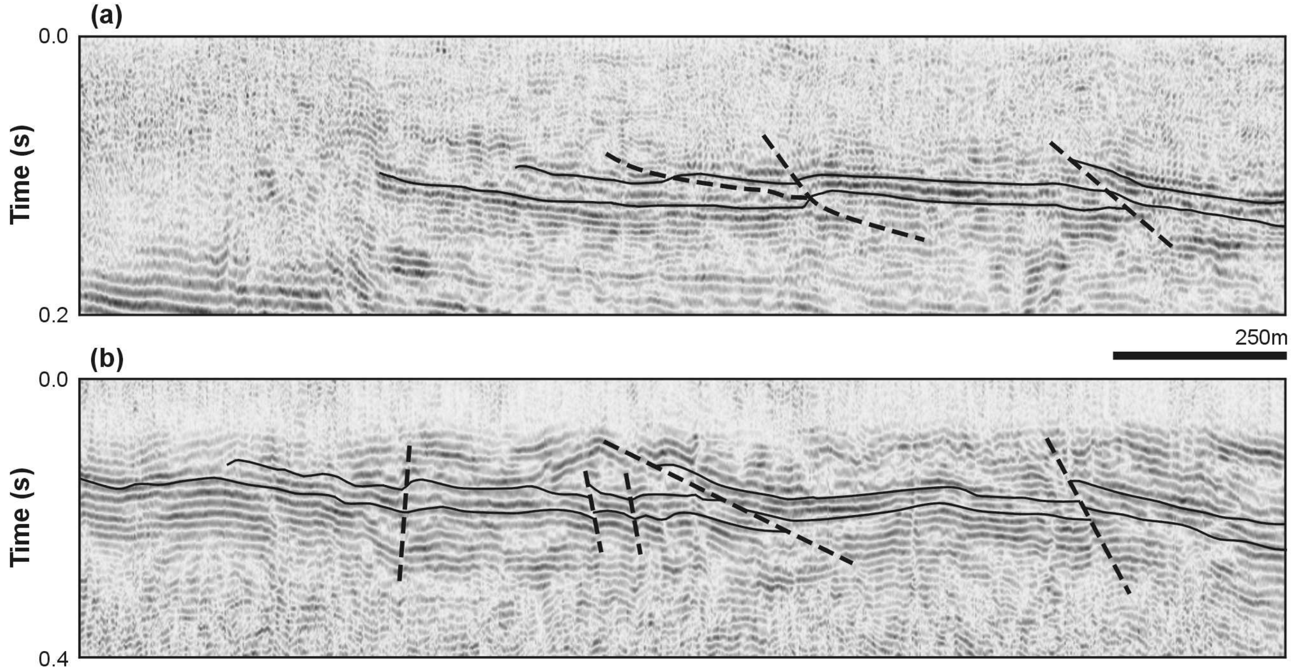

Figure 6: (a) Conventional P-wave image and (b) PS image from Field Trial B. The target coal seams are indicated by the solid lines. Interpreted faults are approximately marked by the dashed lines. The PS section is able to image the shallow coal seams to depths of approximately 25–30m.

Arrays of 3C geophones are not used since S waves are very sensitive to lateral variations in the near surface, and geophone arrays would severely distort any S energy arriving at the surface (Hoffe & others, 2002). Our field experiments indicate that the quality of the conventional P-wave data is not compromised by replacing arrays of vertical geophones with single geophones.

The vertical component of data recorded on a 3C geophone can be subjected to standard seismic-processing algorithms to produce a conventional P-wave seismic section. The converted-wave stack is generated via processing of the data acquired on the horizontal components of the geophone. This involves a number of steps that are substantially different from, and significantly more challenging than, conventional P-wave processing.

In particular, converted-wave processing involves specialised approaches to S-wave receiver statics, PS normal moveout (NMO) correction and common conversion-point (CCP) binning (Cary & Eaton, 1993; Zhang, 1996). Perhaps the most critical stage of processing high-resolution converted-wave data involves the computation of S-wave receiver statics. This information is required to compensate for delays associated with converted S-wave energy travelling through the weathered layer. S-wave receiver statics are generally not related in any way to the conventional P-wave receiver statics. This is largely due to the difference in effective thickness of the near-surface low-velocity layer that the P and S waves 'see' (e.g. S waves will only travel through solid material, and will therefore not be influenced by any near-surface water table; P waves will have their propagation speeds influenced by the presence of ground water). In addition, S-wave velocities in the near-surface can be up to ten times slower than P-wave velocities. Hence S-wave receiver statics are typically much larger than P-wave receiver statics. In practice, several iterations of S-wave receiver statics computations are necessary when trying to extract optimum static corrections.

BOWEN BASIN TRIALS

The past three years has seen a number of converted-wave trials conducted in the Bowen Basin, Australia (Velseis, 2003; Hendrick, 2004). Of these, two have been designed to specifically image very shallow coal seams (less than approximately 50m in depth). Processing of these converted-wave data has proven non-trivial. Nevertheless, viable PS images have been achieved for both of these multi-component surveys, highlighting the potential for converted-wave seismic to yield high-resolution images of open-cut coal reserves.

Field Trial A was conducted in an environment with a single target coal seam, using a buried dynamite source. Figure 5 shows the final P and PS images. As is conventional practice, the vertical scale of the PS image has been adjusted (based on an estimated P-wave to S-wave velocity ratio) to provide a comparable depth perspective to the P-wave image. The PS section yields structural information that is comparable to that derived from the conventional P-wave image. However, the most interesting aspect of this trial is the fact that the PS section (Figure 5(b)) has produced a better quality image over the left end of the line. This is due to the fact that the target coal seam is very shallow (less than 50m deep) along this portion of the line, and the later-arriving PS energy avoids contamination from refracted and surface waves. Consequently, the PS image exhibits greater vertical resolution than the P-wave image where the coal seam is shallowest.

Field Trial B was carried out in a multi-seam environment using a surface mini-SOSIE source. The final P and PS images for a portion of one of the 2D lines acquired as part of this experiment are shown in Figure 6. Significant faults interpreted on the conventional P-wave image have been independently validated by the converted-wave image. A number of additional structural features have also been identified on the PS section.

As for Field Trial A however, the most significant outcome of this experiment has been the success of the PS data to image the very shallow coal seams across the left end of the line. In contrast to the target P-wave reflection energy, the later-arriving PS energy has not been eliminated by near-surface noise. Consequently, the PS data can effectively map the target coal seams across the full extent of the survey line, to depths of 25 – 30m. The PS interpretation results along the left hand end of this line have been tested with borehole drilling, and have proven accurate.

CONCLUSIONS

Seismic reflection is not commonly utilised for open-cut coal exploration due to relatively cheap drilling costs and the inconsistency of conventional, economic seismic surveys to image very shallow coal seams. However, when continuous mapping of the coal seam is important, PS seismic technology offers a reliable alternative to more field-intensive P-wave seismic surveys for producing high-resolution images of open-cut coal reserves.

Some changes to conventional acquisition equipment and seismic surveying procedures are needed to record both P and PS energy. Single 3C geophones replace the conventional vertical geophones at each receiver station. In addition, greater numbers of field units and acquisition cables must be deployed to handle the larger number of live recording channels.

Our experience indicates that processing of PS data is significantly more challenging, and requires more geological input, than conventional P-wave processing. Nevertheless the two Bowen Basin converted-wave trials discussed here have yielded viable PS images and successfully achieved their objective of imaging very shallow coal seams.

Currently, the cost of acquiring a 2D integrated P/PS seismic survey is some 30% greater than for a standard P-wave survey if using a dynamite source, and approximately 45%

greater if using a mini-SOSIE source. In addition, processing and interpretation of the converted-wave dataset effectively doubles data processing and interpretation costs. These extra costs may be reduced in the future as acquisition and processing technology is refined, and converted-wave seismic becomes a more popular geophysical tool for open-cut coal mines. Nevertheless, our experiences to date suggest that, at least for certain situations, this impost is justified in terms of increased information content.

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