SEISMIC REFLECTION, A USEFUL TOOL TO ASSIST UNDERGROUND COAL GASIFICATION (UCG).

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Carbon Energy have developed the world's first commercial scale oxygen injected Underground Coal Gasification (UCG) facility, based at Bloodwood Creek, 55Km west of Dalby in South West Queensland. UCG is an alternative coal utilisation method; it provides an opportunity to access large reserves of otherwise inaccessible coal, via non-mechanical excavation. The process minimises the environmental impact of the mining process, by converting the coal in-situ to a syngas. This is then extracted through a borehole to be used for low emission power generation, alternatives to oil based fuel and the production of chemicals for agriculture and other businesses.

The successful application of the UCG process requires many key elements: for example; suitable coal quality (up to 50% ash) and thickness, lateral seam continuity and an understanding of the extent of previously gasified coal seams.

Between 2008 and 2009 Carbon Energy undertook the acquisition of firstly a 2D seismic dataset, to test the seismic response, and then a 3D dataset to better understand lateral seam continuity ahead of full scale mining operations.

This paper will firstly examine the results of the 2D (Mini-SOSIE) and 3D (Vibroseis) surveys, comparing the image quality and the characteristics of the two seismic sources. Questions relating to the lateral continuity of the target Walloon Coal Measures will be answered with the presentation of results from the 3D interpretation. Finally, through a combination of both forward modelling and advanced seismic attribute analysis, this paper illustrates that changes in the reflective properties of strata around the UCG cavity can be clearly identified.

Introduction

Underground Coal Gasification (UCG) involves the gasification of coal in-situ. To this end it is both a mining process involving the extraction of the raw material and a conversion process whereby the raw material is converted to a synthetic gas comprising elements such as carbon dioxide, carbon monoxide, hydrogen, methane and under pressure, hydrogen sulphide.

The process of Underground Coal Gasification (UCG) was first proposed in 1868 (Siemens 1868). Since this time the technique has been significantly refined, but its transformation to an industry accepted energy source has been limited to only a few locations throughout the world. Today, coal continues to be the largest and most affordable source of energy throughout the developed and developing world. However, the greenhouse gas emission targets proposed by governments and world climate bodies, has placed a new focus on the UCG process as a means of meeting these challenging targets. UCG already has many advantages over traditional coal mining e.g. greater resource – energy conversion and obvious health and safety benefits as the process is conducted remotely. Possibly the greatest of these relates to the fact the process takes place in-situ and eliminates the problems related to the disposal of solid waste (Shu-qin & Jun-hua 2002). Therefore, UCG in conjunction with Carbon Capture and Storage (CCS) has the potential for developing into an attractive low emissions energy source.

At Bloodwood Creek (55Km west of Dalby, Queensland, Figure 1) Carbon Energy has established a trial program, to explore the successful gasification of thermal coal. The coal utilised is from the Walloon Coal Measures, specifically the Macalister Seam, which sits in within the Surat Basin. This site was selected because it satisfied many of the key ingredients for a successful UCG project. That is, the coal is at a favourable depth and sufficient coal quality for successful gasification. UCG requires a reasonable water head to assist with the process of gas extraction and the hydrogeology of the area indicates favourable groundwater conditions also exist. Important for the success of the project, but initially not well understood, are the coal seam continuity and structural complexity of the area. To assist with answering these questions, Carbon energy embarked on a 2D seismic survey, which was subsequently followed by the acquisition of a 3D volume.

This paper presents the results for both the 2D and 3D seismic surveys. It then sets out to deliver not only information relating to the lateral continuity and structure of the Bloodwood Creek area, but also how the 3D seismic volume and forward modelling may be used to provide information relating to the coal seam and surrounding sediments post the gasification process.

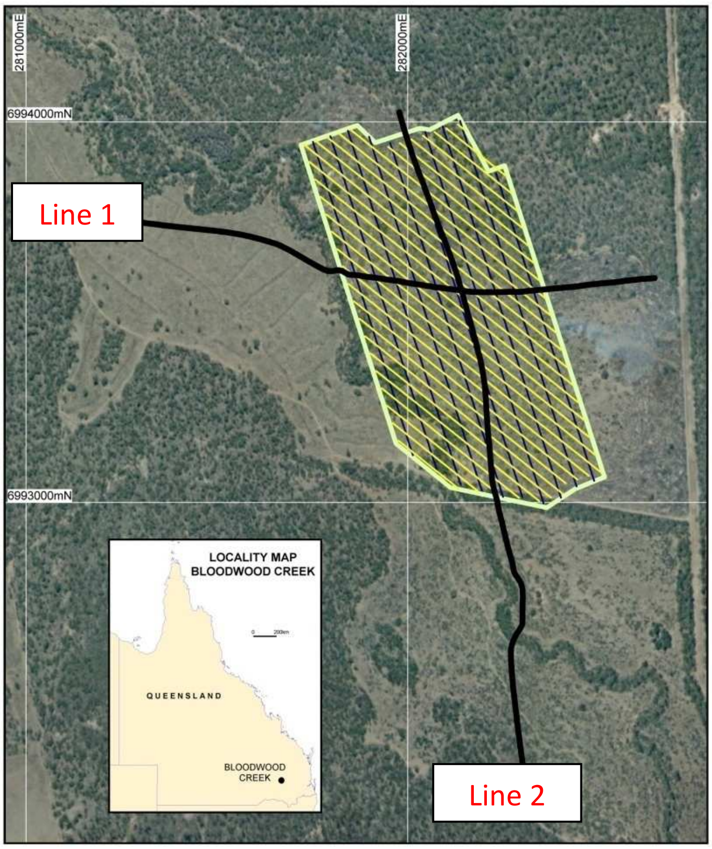

Figure 1 Trial Area Map showing 2D and 3D Locations

2D and 3D Seismic Survey Results

For over 30 years the seismic technique has been utilised to assist with coal seam extraction. The technique is considered the only geophysical tool which can produce remote, high resolution, laterally continuous images of a coal seam. For this reason, Carbon Energy considered it the ideal geophysical tool to assist in understanding the structure and seam topology of the Macalister seam within the Bloodwood Creek area.

2D Seismic Survey

By its nature 2D seismic acquisition is limited to delivering sub-surface imagery in a 2D plane (the place of acquisition). Therefore, the objective of the 2D seismic survey was limited to testing the seismic response in the Bloodwood Creek Trial area and reporting on any broad scale changes in the seam stratigraphy. Two seismic lines, lines 1 and 2, were acquired in the configuration illustrated by Figure 1. Two different commercial methods of UCG have evolved over time (UCG Partnership, 2007). The method adopted by Carbon Energy at Bloodwood Creek, uses dedicated in-seam boreholes and oxygen enriched air to produce a mobile controlled retraction injection point or CRIP. Line 2 was planned to follow approximately the line of the inseam hole used to supply oxygen for the gasification of the trial panel.

During the 2D survey planning stage, two different seismic sources were considered. These were Explosives, and one of the commonly used surface based sources, Mini-SOSIE. Within the survey area the Macalister seam thickness ranges from 8-13m. Therefore, whilst Dynamite provides superior resolution and the ability to detect very subtle changes in the seam structure, the thicker seam means that a surface energy source (lower resolution) may still deliver on the survey objectives of interpreting structure with at least half seam thickness, with significant cost saving to the project.

The acquisition parameters for the 2D and 3D surveys are outlined in Table 1. In both instances the survey parameters have been optimised for fold and offset to ensure a reliable image is produced at the Macalister seam. As illustrated by Figure 2 (a), the 2D sub-surface image quality is good and the Macalister seam may be easily interpreted across both seismic lines. Whilst signal to noise is one way to evaluate the success of a seismic survey within an area, consideration should also be given to the frequency content of a dataset. The ability to detect subtle changes in structure and the stratigraphy is controlled by the vertical and lateral resolution of the seismic dataset. There are a number of quasi-theoretical measures of vertical resolution, which may be used to determine the resolving power of P-wave seismic data. Vertical resolution may be calculated by considering both the overburden velocity and seismic frequency, whereas lateral resolution is calculated with the added consideration of reflector depth. Using Appendix A, and substituting a value of 50Hz for the dominant frequency (derived from the frequency spectra Figure (2b)) and 2000m/s as an indicative overburden velocity, the Rayleigh and Widess resolution criteria are calculated as 10m and 5m respectively. Further, the Fresnel Zone, which is an indicator of the lateral resolution, is determined to be 63m at a seam depth of 200m. Whilst the frequency content is lower than similar surveys conducted with a surface source in the Bowen Basin, the resulting resolution limits are comparable given that the average overburden velocity is lower. Therefore, as the thickness of the Macalister seam is between 8 – 13m, the vertical resolution limit proposed will be sufficient to detect changes in the coal seam stratigraphy with a magnitude of greater than half seam thickness.

Item	2D	3D
Geophones	30Hz, Array	
Filter hi-cut	375 Hz	375 Hz
Filter Lo-cut	40 Hz	Out
CDP Interval	2.5m	8m
Survey pattern	In-line	non-orthogonal (slant shot lines)
Live patch	Live patch	18 lines x 50 channels max patch size
Shot line spacing	-	48m
Shot point	5m	29m
Recv line spacing	-	48m
Receiver point	5m	16m
Receiver array	Receiver array	Single geophones
Fold	60 nominal	20 fold at seam
Energy Source	Mini-Sosie	Vibroseis (Enviro-Vib)
Sweep	-	20-140Hz
Size	60Kg	18000lb

Table 1. 2D and 3D Acquisition Parameters.

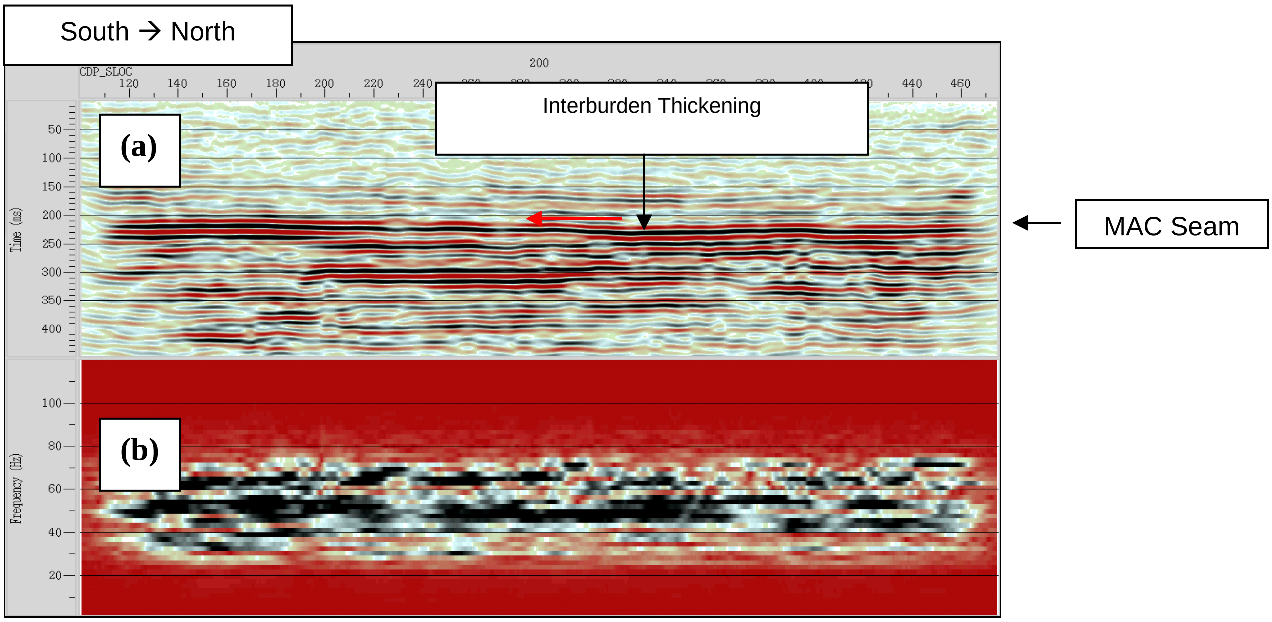

Figure 2 Seismic Line 2 (a) subsurface section (b) frequency vs. offset plot.

3D Seismic

The mine design for the process of UCG is similar to that of Longwall mining. That is, the gasification occurs within defined panels, with rib supports provided to ensure surface subsidence is kept to a minimum. Following the successful completion of the 2D seismic survey, Carbon Energy decided to acquire a 3D seismic survey over an area, which would constitute approximately 3 gasified panels (0.45 Km^2).

Whereas 2D seismic data acquisition is restricted to producing a sub-surface image in the plane of acquisition, 3D data acquisition has the added advantage, in that a grid of receivers records sound waves reflected from a coal seam. Acquiring seismic data in this fashion produces large volumes of spatial data, which when interrogated by modern interpretation systems produces high definition structural maps and laterally continuous coal seam profiles (Peters & Hendrick, 2005).

The Bloodwood Creek 3D volume was acquired with source and receiver parameters as indicated by the right side of Table 1. As with the 2D data, the 3D data quality was good and the Macalister seam was easily mapped across the entire survey area. Figure 3a represents the Macalister seam elevation profile and Figure 3b the Macalister seam amplitude map. Attribute maps such as amplitude are excellent indicators of changes in the coal seam stratigraphy. When viewing seismic data by colour section, often a fault plane will be obvious as a line of reduced amplitude. This is both a result of the destructive interference of the reflection and diffraction off the fault plane and a change in the acoustic properties surrounding the fault. When amplitude is mapped across a horizon these variations are represented spatially. The amplitude map for this particular survey has been very effective for the delineation of structure and as will be discussed shortly, excellent as an indicator as to the location of gasified coal.

For the majority of the survey area the Macalister seam exhibits little change in grade (Figure 3a). The exception to this is in the North western corner, where a structure apparent in both attribute maps (Figure 3) is observed. This fault, interpreted with a Normal sense of movement and downthrown to the west, exhibits a maximum displacement of approximately 16m ($^+_-$ 2m) and a fault plane dip of approximately 45 degrees. The size of this structure is certainly a boundary to the current UCG resource and will be avoided as mining progresses.

In addition to this major structure, a small anomaly in the Macalister seam amplitude map (red ellipse) is noted in the southern portion of the survey area. This anomaly presents as a distinct zone of low amplitude and by increasing the scale and modifying the colour intensity the anomaly (Figure 4a) becomes more prominent. Further investigation reveals that at this location the Macalister seam has already undergone gasification. The anomaly in amplitude is complemented by the Semblance attribute (Figure 4b). Semblance is a measure of seismic trace similarity, hence the anomaly on this map highlights the dissimilarity in seismic signature between the gasified and no-gasified coal.

The polygon annotated on these images (Figure 4) represents the approximate position of the gasified zone as constructed. When compared to this polygon, the attribute anomaly may be considered as two discrete zones of variance. The outer zone (large variance, red circle) extends approximately 18m outside the gasified polygon. This zone represents a zone of moderate wavelet interference and does not correlate particularly well to the gasified polygon. The inner zone (yellow ellipse), within which the seismic wavelet undergoes significant wavelet interference due to the cavity, correlates well to the constructed polygon. In this instance the variance between the zone of influence and the polygon is only 6m, which is less than a cdp bin. To better understand the accuracy of the seismic volume with respect to locating regions of gasified coal, a forward modelling study has been undertaken. A greater understanding of how the gasified cavity influences the seismic wavelet will enable the use of 3D seismic images as an aid in UCG cavity confirmation.

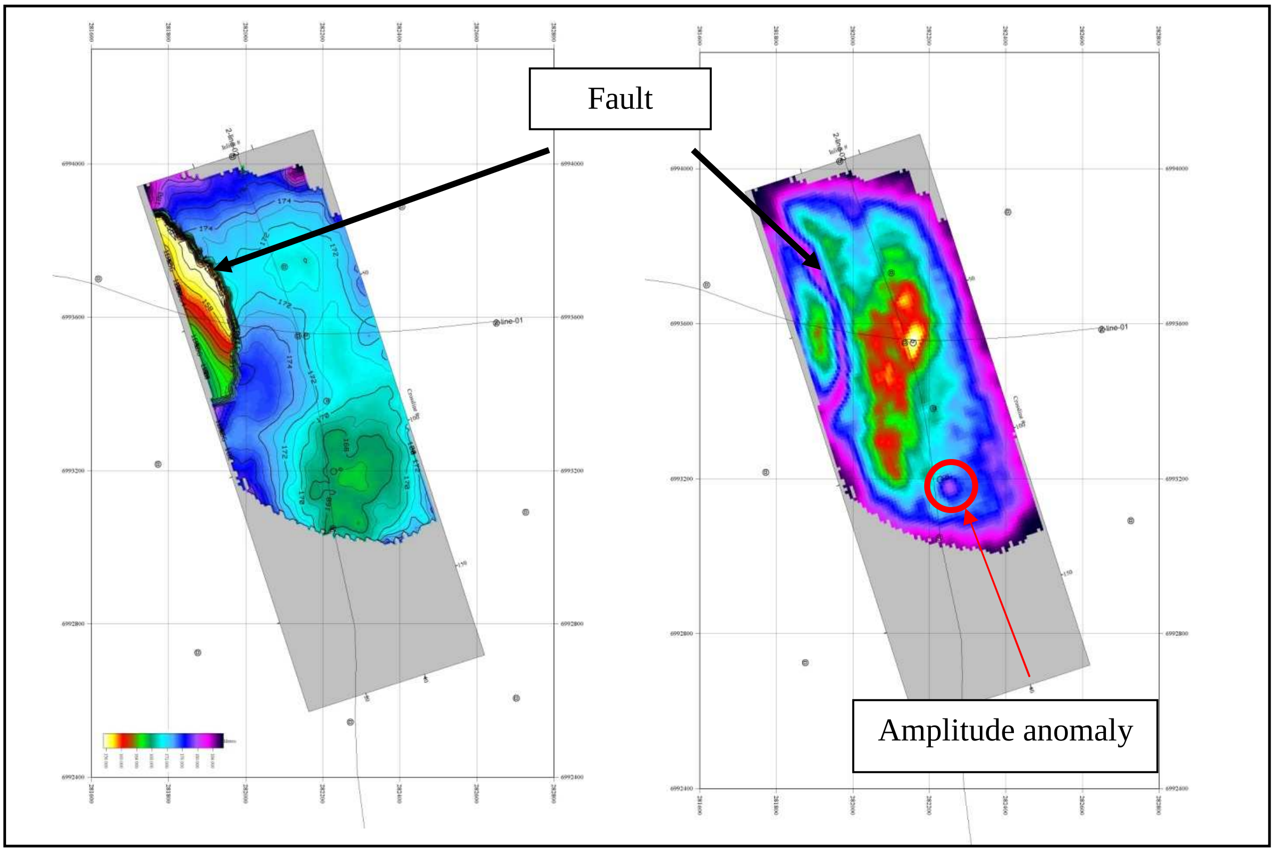

Figure 3 Macalister seam (a) elevation map (b) RMS amplitude

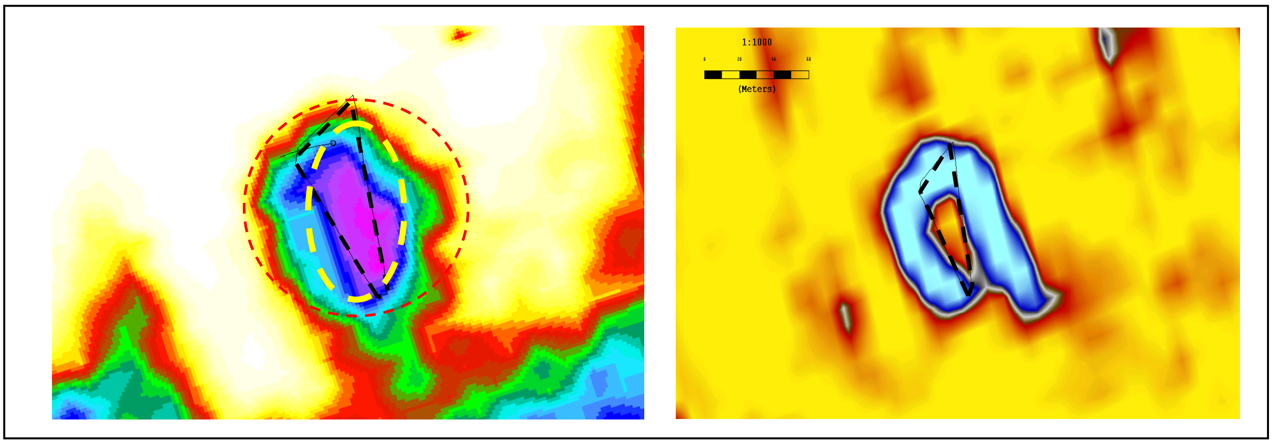

Figure 4 Macalister seam seismic attribute maps.
(a) Rms amplitude map (b) Time slice through Semblance volume (220ms).
Black polygon represents approximate position of gasified coal and seismic attributes appear to be modified around the cavity. Red circle represents a maximum variance between gasified polygon and moderate wavelet interference of up to 18m. Yellow ellipse identifying significant wavelet interference, is considerable more accurate with a maximum variance of 6m.

Forward Modelling

Forward Modelling is the name given to a group of techniques which attempt to estimate the seismic response given a defined geological model. The use of synthetic seismograms to associate coal seams to reflection horizons is the simplest form of Forward Modelling. Other methods by order of their complexity include Zero Offset and Finite Difference Acoustic modelling, and Elastic Finite Difference modelling. Whereas synthetic seismograms are limited to estimating the seismic response at a single borehole, these other methods allow the geological model to vary laterally. Varying the model in this way enables effective modelling of faulted zones, or in this case, zones exhibiting lateral changes in stratigraphy due to the UCG process. By comparing the model produced with the actual seismic data, a greater understanding of the limitations in seismic resolution and the overall accuracy of the seismic to detect these gasified zones may be obtained.

For the purpose of this exercise Zero Offset Acoustic modelling was chosen as a starting point. Carbon Energy provided a geological model representing the most likely seam stratigraphy post gasification (Figure 5). Important characteristics of this model are that within the gasified zone, the majority of the Macalister seam is replaced by both air and fused ash (clinker). In addition to this model, two additional models were constructed. These were identical to that shown by Figure 5 with the exception that the air filled cavity was replaced with a cavity filled with water and goaf respectively. Appropriate sonic and density values were assigned to the rock mass and to the varying cavity materials. The zero offset sections were constructed using a 20-70Hz Ricker wavelet, which is a similar bandwidth to the actual seismic data (Figure 2b). The resulting synthetic sections derived are illustrated by Figure 6. This figure shows the three modelled sections (Figures 6a – 6c) alongside a seismic cross line (extracted from the 3D volume), which intersects the zone of gasification.

Comparing the section characteristics (horizon shape and amplitude) at the Macalister seam level, the best correlation is achieved when the actual data (Figure 6d) is compared to the goaf model (Figure 6c). This implies that goaf material has most likely in-filled the cavity post gasification. Whilst the composition of the cavity is likely to be more complex and possibly a combination of all three components presented, this modelling exercise suggests that the cavity fill is dominated by goaf material.

Recall that some discrepancy is observed between the known position of gasified coal and the position suggested through the interrogation of seismic attributes (Figure 4). Limitations in lateral resolution can impact on the seismic datasets ability to reliably position such changes in seam stratigraphy. To investigate the reliability of the seismic data to accurately position the zone of gasified coal, a more rigorous modelling technique has been adopted to that described above. Using the Goaf model as the preferred composition of the cavity, a full Elastic Finite Difference algorithm was implemented to construct the synthetic section shown in Figure 7. Unlike Zero Offset Modelling, this approach constructs synthetic field records by modelling a variety of seismic wavefields (e.g. noise, P-waves, S-waves, multiples). The geometry of these records may be tailored to match the actual data so that when these synthetic records are processed, the resulting synthetic image is more realistic.

As illustrated by Figure 7b, the Finite Difference modelling has been successful in producing a realistic synthetic section. The correlation between the modelled section and that section extracted from the 3D volume, through the zone of gasification (Figure 6d), is excellent and improved when compared to the simplistic zero offset section (Figure 6c). When the spatial position of the cavity from the geological model (Figure 7a) is compared with the synthetic section, an 8m variance in this position is observed. This variance relates to limitations in the spatial resolution of the seismic technique and suggests that the maximum error between the true cavity position, and that which can be determined using the 3D seismic volume, is approximately 8m.

As previously mentioned, at the site of the UCG reactor there exists two zones of wavelet interference. Whilst the variance between the position of the outer zone and the constructed position of gasified coal is large (18m), the inner zone shows a maximum variance of only 6m. The positioning of this inner zone is not only accurate but also consistent with the expected error shown by modelling. Therefore, the 3D seismic volume can be utilised to not only estimate the characteristics of the gasified cavity, but also used to reliably locate zones of gasified coal.

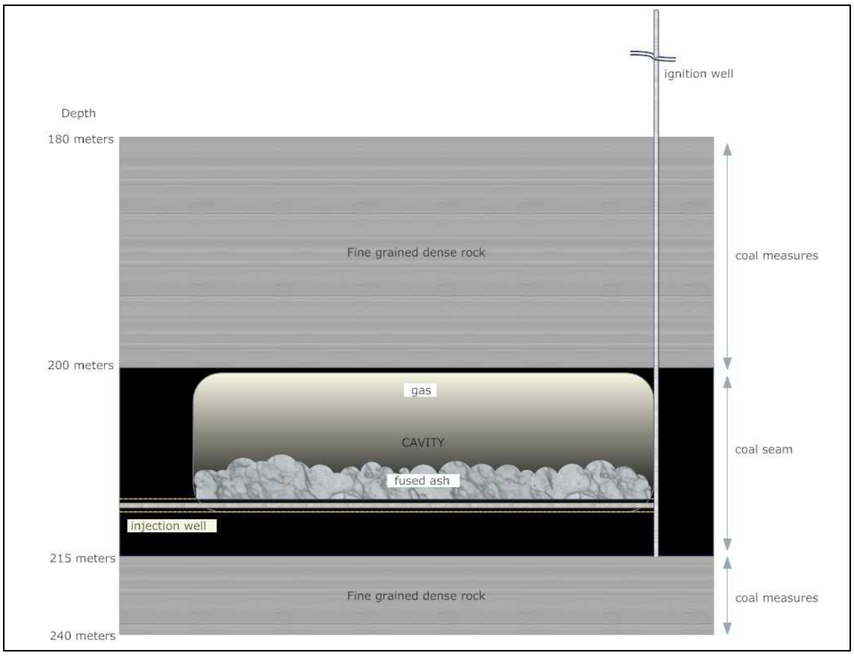

Figure 5 Macalister seam geological model (post gasification)

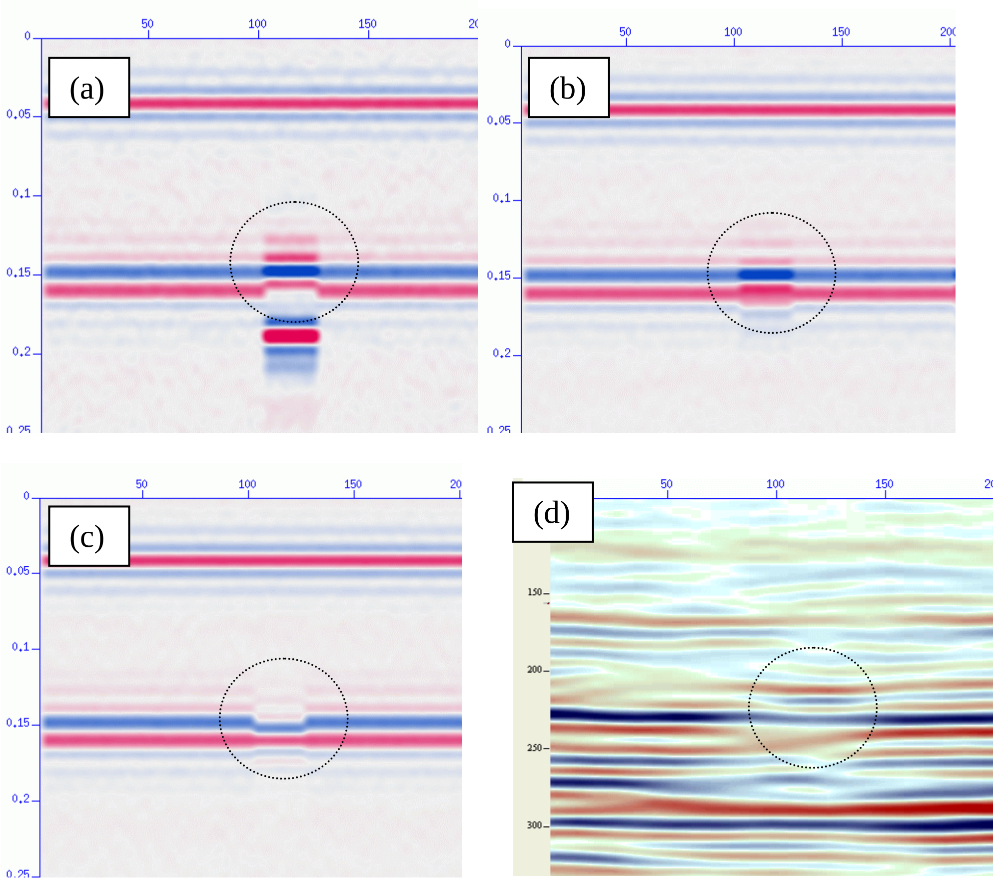

Figure 6 Comparison of Zero Offset Modelling and 3D Cross line intersecting gasified zone.
(a) Air filled Cavity model, (b) Water filled Cavity model, (c) Goaf filled cavity model.
(d) Representative cross line intersecting gasified zone.

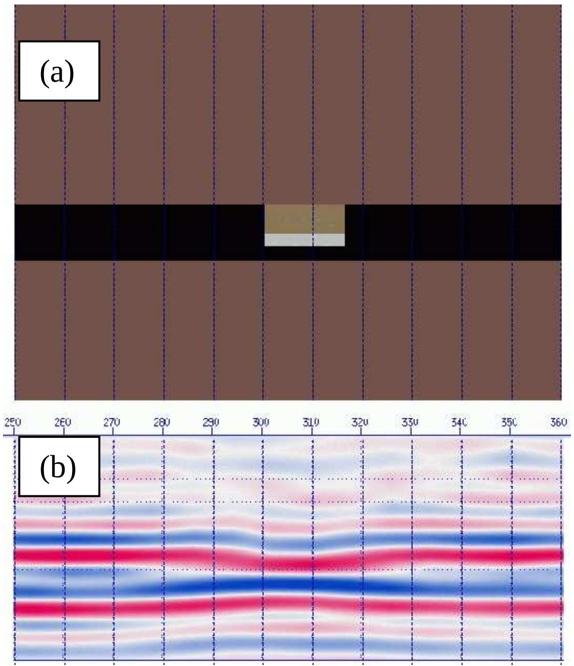

Figure 7 Result of Elastic Finite Difference modelling.
(a) Goaf geological model, (b) Resulting synthetic seismic section

Conclusion

At Bloodwood Creek Carbon Energy has developed the world's first commercial scale, oxygen-injected UCG Syngas production facility.

When initially proposed, the objectives for both the 2D and 3D seismic surveys were to test the seismic response within the Bloodwood Creek area and to provide information relating to the structure and stratigraphy of the Macalister seam. This paper has shown that in addition to achieving these objectives, the seismic technique in its 3D form, may be used to deliver valuable information by confirming cavity geometry and location. Specifically, this study has shown that by interrogating subtle changes in seismic attributes, the location and extent of gasified coal can be obtained with considerable accuracy. Developing this technique would be advantageous to the growing UCG industry as a tool to track resource recovery and assist with mine planning.

For the management of conventional oil and gas reservoirs, a 4D seismic approach is often adopted. That is, 3D seismic surveys are acquired at the same location and at regular intervals during production, to ensure maximum resource recovery. Whether a 4D approach is adopted at sites like Bloodwood Creek to assist with Syngas production, will ultimately be determined by economics and by the ability to locate these previously gasified zones by other methods.

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Acknowledgements

The Authors would like to thank Carbon Energy for granting permission to use the results of the seismic surveys conducted at Bloodwood Creek to compile this case study.

Appendix A

Vertical Resolution

The commonly used 'Rayleigh resolution limit', defined as the minimum separation of discrete seismic reflectors at which one can ascertain more than one interface is present (Sheriff, 1991), is $\lambda_D/4$. The 'Widess limit' is an alternative, and more optimistic definition, which states that two interfaces are resolvable if their separation is greater than or equal to $\lambda_D/8$ (Sheriff, 1991).

The 'detectable limit' is defined as the minimum layer thickness required to produce an observable seismic reflection (Sheriff, 1991). This is generally taken to be of the order of $\lambda_D/30$, where λ_D is the dominant wavelength of the P wave:

$$\lambda_D = \frac{V_{int}}{f_D}, \qquad \text{F-1}$$

f_D is the dominant frequency of the seismic wave, and V_{int} is the interval velocity of the geological layer being considered.

Horizontal Resolution

For simplicity it is generally assumed that data recorded at a receiver is reflected from a point on a seismic layer. However, in reality a circular zone of data contributes to each reflection event recorded at each receiver especially for unmigrated data. This zone of reflection is called the Fresnel zone, the size of which governs the horizontal accuracy of structural information that can be acquired from seismic data. The radius of the Fresnel zone is dependent on the reflection depth, frequency content and seismic velocity.

For a P wave the radius of the Fresnel zone (r_p) can be approximated by:

$$r_p = (z \lambda / 2)^{½} \qquad \text{F-2}$$

where: z equals the depth and; λ is the wavelength which is given by the average P-wave velocity divided by the dominant frequency