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Cross-well seismic modelling for coal seam delineation

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Summary

Finite-difference analyses is attempted to simulate a multi layered complex coal seam model in order to differentiate top and bottom of thin coal seam. Field data from the Australian region is utilized to generate a simplified model and generate synthetic seismic data for different source receiver configurations. The results reveal that seismic modelling with high frequency source (1000Hz) is feasible in delineating the top and bottom of thin coal layers for closer source and receiver configurations. The behavior of seismic amplitude could help in the detection of a sequence of thin coal layers. Amplitude versus Offset (AVO) analysis for transverse isotropic coal seam model shows negative anomaly for coal layers with considerable variation in reflection coefficient for different configurations. Interference of thin coal layers seems to diminish the reflectivity of the interfaces. We may conclude that 'a priori' knowledge can be gained through full waveform seismic modeling, and provide guidance in planning strategies for field surveys in a complex thin layered coal seams.

Keywords: *Coal Seam, Cross-well seismic, Multicomponent,*

Introduction

In the past decade the upsurge of interest in the exploration, exploitation and development of coal bed methane (CBM) in Australia represents a major opportunity to help Australia and the region move to a cleaner, less carbon-intensive future. This can be attributed to presumably high energy resource potential of this veritable resource. The likelihood of coal seams serving as viable sites for subsurface-geologic storage of CO2 in the foreseeable future constitutes another reason for the growing interest in CBM exploration in Australia and neighbourhood regions.

In the past few decades a significant progress has been made in the coal seismic prospect. With the advancement of seismic methods we are able to apply them to coal seam prospecting and mining. These methods could be used in mapping the structure of the coal, discontinuities in the coal seams and measuring the thickness of coal seam and even predicting CBM distribution (Lawrence, 1991). However, it would be worthwhile conducting forward modelling exercise before launching any field experiments as it provides 'a priori' information for sub-surface mapping. We evaluate the cross-well seismic response for a realistic multi layer coal seam model from an Australian region by using 2D finite difference simulations. The amplitude versus offset (AVO) analysis has been performed and the behaviour of reflection coefficients for coal seams has been studied. To this end we use realistic anisotropy parameters (Evapavuluri and Bancroft, 2001) and analyze the reflection coefficient variability of coal seams.

Materials and Methods

Forward modelling plays a critical role in understanding many imaging issues in structurally complex areas, and are particularly important in designing the optimal program for a cross-hole survey. All sound/seismic full-wave modeling schemes are deduced from the differential wave equation and the formula for the particle motion. They imply dependence of the wave propagation on a number of physical parameters distributed in space. Some of them are static, such as local wave velocity and density; the others are dynamic, such as the instant particle movement, pressure, etc. Static parameters do not vary with time and are known to computations of the dynamic ones. Since the present aim is to model the seismic response of the full wave field for complex subsurface models to study the seismic characteristics of coal seams, a finite difference technique of direct methods is appropriate. The investigations carried out here are based on full-wave modelling using a finite-difference solution for the vector wave equation (Rajput et al., 2008).

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Cross-well Seismic Modelling

Crosswell seismic is the process of acquiring seismic energy through the formation of interest, between two wells, rather than from the surface as with conventional seismic acquisition. Acquiring seismic data in this format eliminates the unconsolidated near surface layers and results in higher frequencies at the receivers; thus providing a high resolution profile of the reservoir between well bores (Meyer et. al., 2002; Somerville et. al., 2007). The application of cross-well seismic will assist in ensuring that locations are strategically placed thus reducing the environmental footprint and streamlining the development process. This is especially important as well density increases. There are a number of unique advantages realized when using crosswell seismic modeling to delineate shallow gas reservoirs. The high bandwidth and thus high spatial resolution make it possible to image subtle features including thin zones, sub seismic faulting, flow conduits, channel sands and impermeable shale stringers (Somerville et. al., 2007). In addition, crosswell seismic is referenced in depth thus eliminating the ambiguity of time to depth conversion. Here we used 2D finite difference method to model the cross-well seismic response for a realistic model from an Australian region. The model (Fig. 1) is a simplified version of the real lithological unit from an Australian region. The model parameters are listed in Table 1.

S. No.	Layer Description	From – to (m)	Thickness (m)	P-wave Velocity (m/s)	Shear Velocity (m/s)	ρ (density gm/cm^3)	Gradient
1	Sandstone	0-30	29	2500	1450	2.12	0.5
2	Coal	30-42	12	1800	1050	1.98	0.5
3	Sandstone	42-90	48	2650	1534	2.21	0.5
4	Coal	90-97	7	1850	1075	1.97	0.5
5	Sandstone	97-113	16	2700	1562	2.22	0.5
6	Coal	113-119	6	1900	1100	1.96	0.5
7	Sandstone	119-146	27	2500	1456	2.15	0.5
8	Coal	146-151	5	1875	1088	1.98	0.5
9	Sandstone	151-166	15	2550	1465	2.18	0.5
10	Coal	166-170	4	2115	1219	2.05	0.5

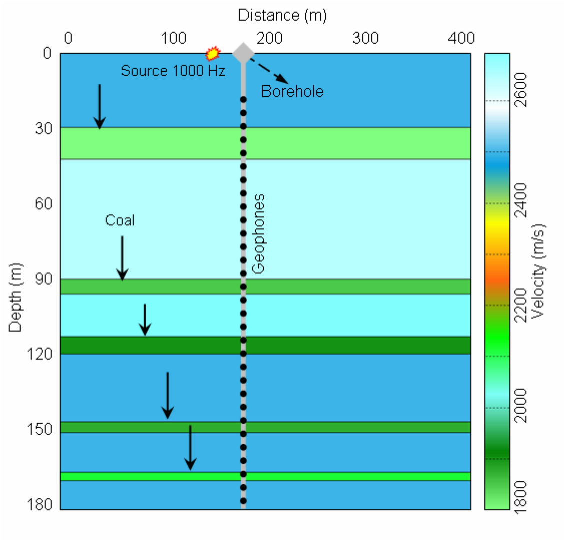

Figure 1: Flat stratigraphic layer model for vertical moving source and vertical receivers. Black arrows (solid line) are showing coal layers. Source-receiver distance is 10 m.

Transverse isotropy (TI) was considered in all the numerical simulations. TI is quantified through Thomsen parameters ε, δ, and γ. Parameter ε is a measure of P-wave anisotropy, which is the normalized difference in horizontal and vertical velocity whereas δ is more complex and has the strongest effect on P- and vertically polarized shear waves at intermediate angles. In this study, we disregard γ which only affects horizontally polarized shear waves. The measured anisotropic parameters (ε=0.12 and δ=0.24) for coal (Evapavuluri and Bancroft, 2001) are used in the model. Using the model (Fig. 1) synthetic seismograms have been calculated at two different source locations. Instead of considering all the source points only two scenarios were considered when the source is positioned at 1 m and 25 m depth. In both cases all the coal layers were identified. The top of the coal was reflecting reverse polarity due to the strong acoustic impedance contrast between sediments and coal. The only difference between the two different source location responses is related to the identification of the first coal layer which starts at 30 m depth.

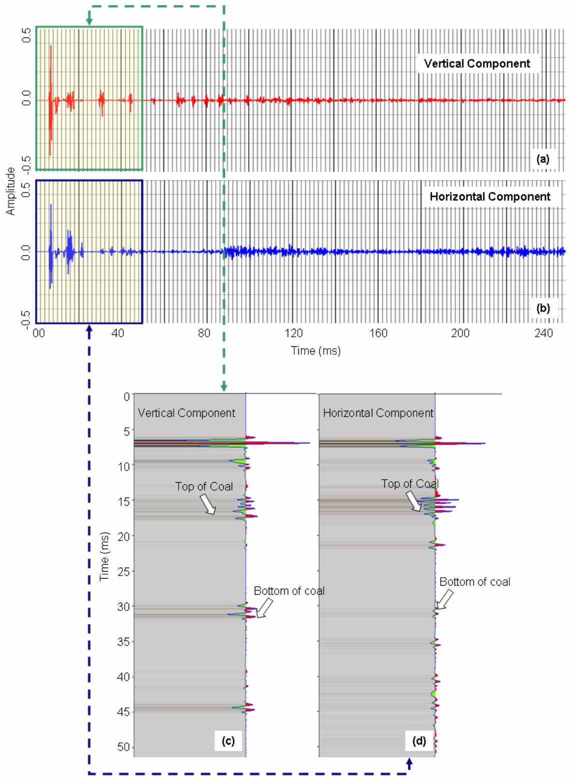

Figure 2: Single receiver response for two components (flat layer model Fig. 1). The source is positioned at 25 meter depth (a) Represents the vertical component response up to 250 ms. (b) shows the horizontal component response up to 250 ms. (c) Represents the enlarged green box area from 'a' up to 50 ms. (d) shows the enlarged blue box area from 'b' up to 50 ms.

Fig. 2 represents the simulated seismic responses where the source is positioned at 25m depth below the surface. After 120 ms the signal is not clear and requires sophisticated processing workflow. The top and bottom of the first coal layer has been identified and marked on all the components. Further, wave-field propagation at two different time steps (0.022 s and 0.052 s) was analysed to see the energy reflected from the coal layers and energy refracted/transmitted through the coal layers (Fig. 3). The top of the coal exhibited the reverse polarity compared to the bottom of the coal layer. Fig. 3a and b represents the snapshot of wave-field propagation at 0.022 and 0.52 s.

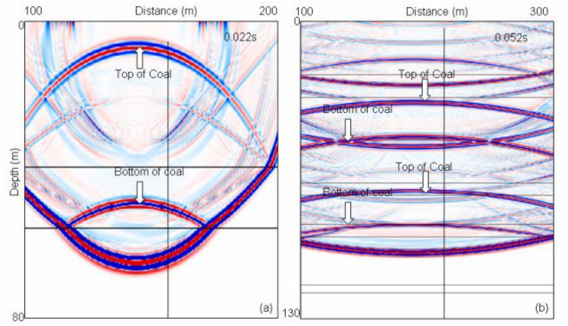

Figure 3: Wave-field propagation at two different time steps (0.022s and 0.052s). The elastic wave-field showing both (up and down going waves); the top of the coal layer exhibits the reverse polarity. (a) is a snapshot of wave-field at 0.22 s for flat layer model; (b) is representing the wave- field propagation at 0.52 s.

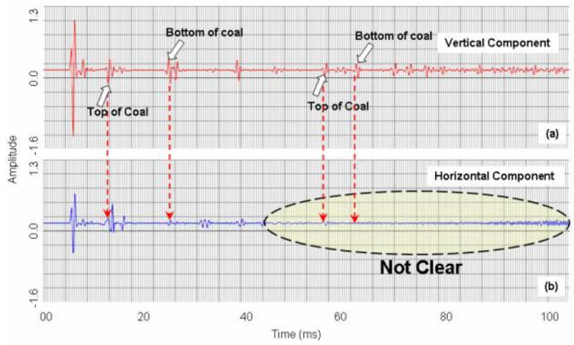

Figure 4: Simulated seismic response two components (flat layer model). The source is positioned at 1 metre depth and receiver positioned at 5 m depth with 50 m source receiver spacing. (a) Vertical component response up to 100 ms; (b) shows the horizontal component response up to 100 ms.

Fig. 3a shows the reflection from the top and the bottom of the first coal seam whereas Fig. 3b represents the reflected arrivals from three coal layers i.e. 30m, 90 m, and 113 m, and marked on the figure. The source receiver spacing was then increased to 50 while other parameters were kept unchanged.

The simulated seismic response for this scenario is illustrated in Fig. 4. It has been observed that vertical component is ideal for the identification of all the coal layers whereas due to the presence of converted shear waves the horizontal component requires more specialized workflow. The first layer is clearly identified. However, further layers detection solely on horizontal component poses some problems and requires further signal processing tools to interpret. Fig. 4 shows the vertical and horizontal components from 0-100 ms. After careful analysis it is possible to identify the top and bottom of the coal layers.

Further, wave-field propagation at two different time steps (0.018 s and 0.050 s) was analysed to see the level of energy travelling and reflecting off the coal layers. Fig. 5a and b shows the snapshot of wave field propagation at 0.018 s and 0.050s respectively. At this stage, two reflections (up going energy) from the top and the bottom of the first coal layer have been clearly identified. The top of the coal exhibits the reverse polarity. At 0.050s the reflected arrivals from three coal layers i.e. 90 m, 113 m, and 146 m have been recorded. Further, the top and the bottom of these layers have also been indentified and marked on the profile (Fig. 5).

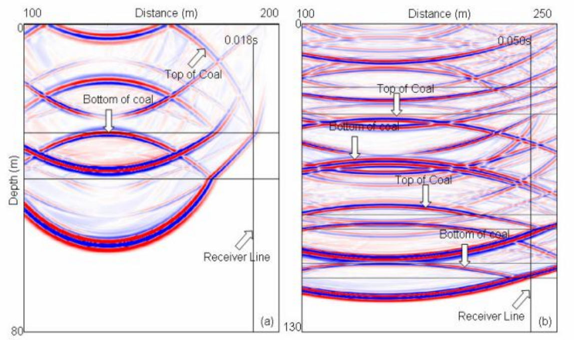

Figure 5: Wave-field propagation at two different time steps (0.018s and 0.050s), (a) is a snapshot of wave-field propagation at 0.18s; (b) is representing the wave-field propagation at 0.50 s.

AVO Characteristics

To see the AVO response, the reflection coefficients are calculated for all the coal layers (top of the coal) and plotted in Fig. 6. The graph depicts negative trend up to a critical angle (30°). The value of Thomson anisotropic parameters are ε=0.12 and δ=0.24 (Evapavuluri and Bancroft, 2001). The value of Q-compressional of 10 and Q-shear of 8 were used which is one order magnitude less than the reported value in the literature. The magnitude of the acoustic impedance anomaly suggests that a reduction in the elastic stiffness of the coal matrix frame may have been detected.

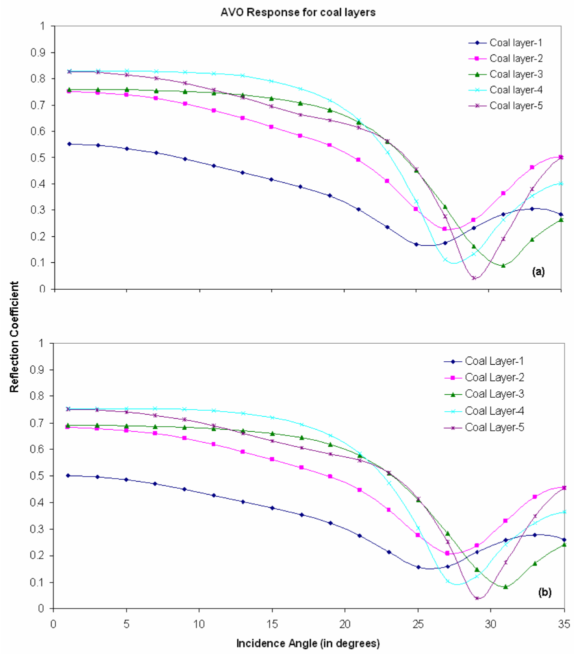

Figure 6: Comparison of AVO curves produced for a multi-layered anisotropic model. The reflection coefficient is calculated for all the five coal layers. The AVO response is modelled up to 35° (a) In this case the source receiver spacing is 50 m. (b) In this case the source receiver spacing is 10 m.

Conclusions

The modelling results show that the coal interval is mappable using seismic reflection technique. Thin coal layers can be detected on the cross-hole sections using vertical and horizontal components when the source and receiver are placed 10 m distance apart. However, only top two coal layers were identified, when the distance between the source and receiver was 50 m. The top of the coal exhibited reverse polarity due to the strong acoustic impedance contrast with respect to the host sediments. AVO response shows negative anomaly for all the coal layers which could be acceptable up to the critical angle (~30°). For the identification of coal layers, vertical component should be used as the processing of the horizontal component requires sophisticated tools. Forward modelling provided great insights that would help comprehend the field trial results.

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