Thickness prediction of tectonically deformed coal using calibrated seismic attributes: A case study

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SUMMARY

Tectonically deformed coal is a key factor affecting the phenomena of gas outbursts in coal mines. Seismic attributes associated with coal-bed reflections can represent this kind of coal, but the representation is indirect and ambiguous since both coal-bed thickness and lithology can affect the attributes. We propose a model-based function to calibrate seismic attributes from thin coal-bed reflections, and use the calibrated attributes to estimate the distribution of tectonically deformed coal. To eliminate the influence of coal-bed thickness on seismic attributes, we first build a synthetic model to simulate true geological condition of the coal bed. Then, we extract seismic attributes from the synthetic section and cross plotted the correlations between attributes and thickness. After the fitting of cross-plotted correlations with a Fourier series, we estimate the calibration functions of the attributes. Finally, true attributes of a mining zone are calibrated with those functions. The results presented here show much more observable correlation with the thickness of tectonically deformed coal than uncalibrated attributes.

Key words: tectonically deformed coal; thickness prediction; seismic attributes; model-based calibration.

INTRODUCTION

Gas outbursts from coal mining have caused hundreds of lives and millions of dollars in China. Tectonically deformed coal is a kind of coals with physically transformed and microstructurally altered forms. This kind of coal is a key factor affecting the phenomena of gas outbursts in coal mines (Cao et al., 2003; Cao et al., 2001; Chen et al., 2015; Wold et al., 2008). If one can accurately predict the distribution of tectonically deformed coal before mining, coal producers can locate the gas-outburst-prone zones and adopt appropriate methods to minimize the occurrence of gas outbursts (Lu et al., 2011). Therefore, accurate prediction of deformed coal distribution is vital for coal producers to prevent gas outbursts before mining.

Since the distribution prediction of tectonically deformed coal is so important for coal production, many researchers have attempted to qualitatively or quantitatively estimate the distribution of tectonically deformed coal. The strategies include two main methods: one method is that seismic attributes are classified by a support vector machine or an artificial neural network to discriminate tectonically deformed coal from normal coal-seam (Wang and Chen, 2014; Zhang et al., 2011), and the other method is that seismic inversion constrained by well logs or seismic attributes trained by a support vector regression to predict the thickness of tectonically deformed coal (Chen et al., 2015; Lu et al., 2011).

Since coal bed is normally thin, coal-bed reflections are typically composite waves. It is a real challenge for coal explorer to accurately estimate the distribution of tectonically deformed coal from coupled signals of thickness and lithology. If coal-bed thickness is known, it should be possible to isolate thickness influence and predict coal-bed lithology assuming that coal-bed roof and floor are lithologically homogeneous.

In this paper, we use a model-based function to calibrate seismic attributes of a thin coal-bed reflection, and use the calibrated attributes to estimate the distribution of tectonically deformed coal.

CALIBRATION METHOD

If coal-bed roof and floor are lithologically homogeneous and identical, the main influence factors of coal-bed reflections will be coal-bed lithology and thickness. For a thin bed (thinner than 1/8 of the seismic wavelength), its reflection wavelet $\boldsymbol{R}_d$ is (Widess, 1973)

$$\boldsymbol{R}_d = \left[\frac{4\pi Ab}{\tau V_b}\right]\sin\frac{2\pi t}{\tau} \tag{1}$$

where A is the incident amplitude, b is the bed thickness, V_b is the bed velocity, and τ is the predominant period of a seismic wavelet. The term in brackets is the maximum amplitude A_d of wavelet $\boldsymbol{R}_d$.

Because coal-beds are normally soft, some part of coal-beds will be tectonically deformed to deformed coal during previous tectonic movement. After the deformation, coal density decreases slightly, but coal velocity decreases sharply. For a given thin bed, if the bed is made up of normal coal, the maximum amplitude of reflection will be A_d; if the bed, in contrast, is made up of tectonically deformed coal, the maximum amplitude of reflection will be A^*. The ratio between those two amplitudes is given by

$$c = \frac{A^*}{A_d} = \frac{v}{v^*} \tag{2}$$

where v is the velocity of normal coal and v^* is the velocity of tectonically deformed coal. The ratio of c is an indicator of the existence of the deformed coal. The larger the ratio is, the wider the lithological difference between normal coal and deformed coal is.

Normally, coal-bed thickness can vary laterally. The maximum amplitude A_d is not only a function of coal-bed velocity, but also a function of coal-bed thickness. To eliminate the influence of thickness variation on the maximum amplitude of thin coal-bed reflection, we normalize the maximum amplitude with a constant or reference amplitude

$$A_0 = A\frac{4\pi b_0}{\tau V_b} \tag{3}$$

where b_0 is the thickness of a reference bed with normal coal. Then

$$A_N = \frac{A_d}{A_0} = \frac{b}{b_0}\frac{v}{v^*} = c\frac{b}{b_0} = cf(b) \tag{4}$$

where $f(b)$ is a calibration function for coal-bed thickness, and A_N is the normalized maximum amplitude. If we multiply $1/f(b)$ by A_N, the indicator of tectonically deformed coal "c" could be achieved.

In practice, the thickness of coal-bed is not always thin than 1/8 wavelength. In this case, the maximum amplitude of reflections is not a linear function of coal-bed thickness as A_d expressed, and the calibration function $f(b)$ will be a nonlinear function. In order to achieve this calibration function, we build a forward model to simulate true geology and use this model to derive the calibration function $f(b)$. Similarly, frequency attribute of coal-bed reflection can also be calibrated with a calibration function to characterize deformed coal distribution in coal bed.

ESTIMATION OF CALIBRATION FUCTION

In the northern China, the main targets of coal-beds are deposited in the Permo-Carboniferous period. The typical roof and floor of those beds are sandstone, and the direct roof and floor of those beds are thin mudstone. Furthermore, most of the coal beds are thin than 10 m. Considering the geological settings of this area, we build a wedge model (Figure 1a) and compute the synthetic seismograms (Figure 1b) with a 50 Hz Ricker wavelet. In Figure 1(b), the reflected trough and peak of the coal-bed are compounded in the left, detached in the middle, and separated completely in the right. If coal-bed is thicker than 16 m, coal-bed roof and floor will have independent reflections. In this situation, the travel-time difference between trough and peak is a direct indication of the thickness of the coal-bed. In contrast, if coal-bed is thinner than 16 m, the reflections of coal-bed roof and floor will compound together and form composite waves. Fortunately, the amplitude and frequency of those composite waves will directly correlate with coal-bed thickness.

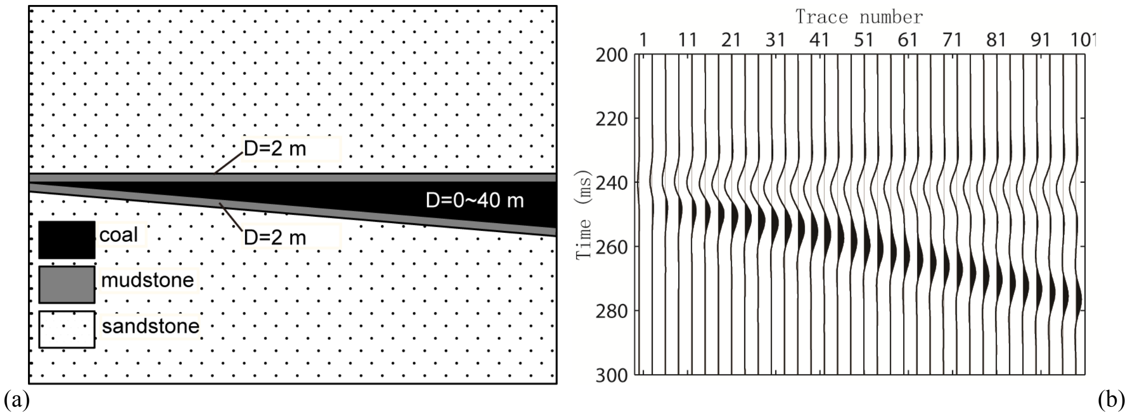
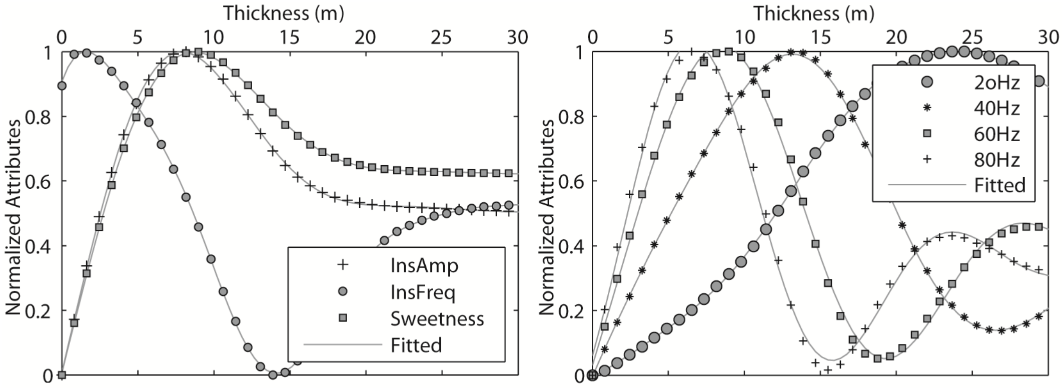


Figure 1: Wedge forward model (a) and its synthetic seismic section (b). For thick bed, roof and floor have independent reflections; for thin bed, the reflections of roof and floor are compounded together and form a composite reflection.

In order to calibrate the influence of coal-bed thickness and detect the distribution of tectonically deformed coal, we interactively pick the trough as the top of coal-bed horizon, and extract the seismic attributes such as instantaneous amplitude (InsAmp), instantaneous frequency (InsFreq), 'Sweetness' (InsAmp / sqrt [InsFreq]), and spectral decomposition (20Hz, 40Hz, 60Hz, and 80 Hz) (Hart, 2008; Marfurt and Kirlin, 2001; Zeng, 2010). Through cross-plotting those attributes with the coal-bed thickness, we obtain the correlation between coal-bed thickness and seismic attributes (Figure 2). For convenience, those correlations are fitted with a Fourier series independently (Equation 5). For a given trace, as we narrate in section two, we can calibrate the influence of coal-bed thickness and preserve the anomaly of tectonically deformed coal on the attributes.



(a) (b)

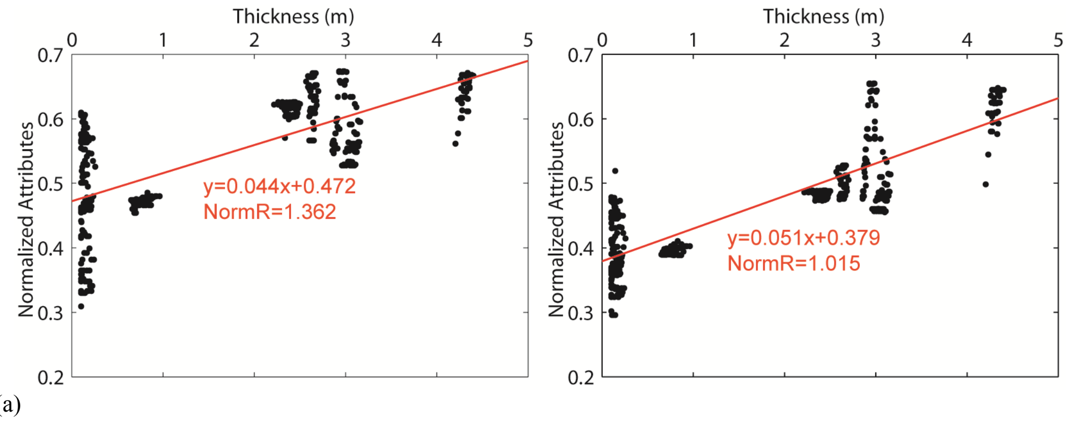
Figure 2: Cross-plotting between seismic attributes and coal-bed thickness. The attributes in (a) are instantaneous attributes, and the attributes in (b) are spectral decomposition attributes.

$$f(x) = a_0 + \sum_{i=1}^{N} a_i \cos(i\omega x) + b_i \sin(i\omega x) \tag{5}$$

where a_0, a_i, b_i and ω are fitting coefficients, x is the coal bed thickness, and $f(x)$ is corresponding attribute.

CASE EXAMPLE

We have applied the method described above to a field data acquired over a 3.45 km^2 mining zone. This zone is located in the northeast of Qinshui basin, Shanxi province (Lv et al., 2012). The target is 15# coal (Carboniferous Taiyuan Formation) with a thickness of 6.3 to 10.4 m. As the uncovered results of 13 in-zone wells, some parts of this bed have developed tectonically deformed coal in the bottom with a thickness of up to 4.3 m. To predict the thickness of bottom deformed coal using seismic attributes, we extract seismic attributes of near-well traces, and cross plot them with the deformed coal thickness. As an example, cross plots of 'sweetness' versus deformed coal thickness are shown in Figure 3. Before the calibration, 'sweetness' shows an ambiguous correlation with deformed coal thickness (Figure 3a). After the calibration, calibrated 'sweetness' shows a much more observable positive correlation with deformed coal thickness (Figure 3b). Furthermore, the smaller normalized residuals of Figure 3(b) indicates the predicted results of calibrated attributes are much more stable and reliable than the results of uncalibrated attributes.

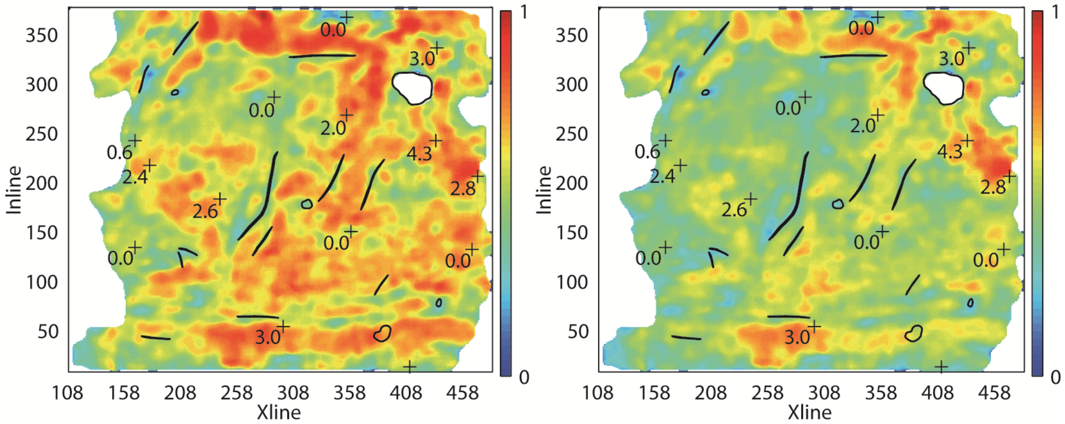


(a) (b)

Figure 3: Cross-plotting between normalized 'sweetness' and deformed coal thickness of near-well traces. Comparing those plots, the fitted gradient of uncalibrated plot (a) is obviously small than the fitted gradient of calibrated plot (b), and the fitted intercept of (a) is obviously larger than the fitted intercept of (b). Furthermore, the normalized residuals of (b) is obviously smaller than the normalized residuals of (a).

For the near-well traces, the model-based calibration can observably improve the positive correlation between the deformed coal thicknesses and 'sweetness'. This improvement is equally effective for the whole mining zone (Figure 4). Before model-based calibration, the most observable attributes of 'sweetness' in the mining zone are high anomaly and the most wells are located in the high anomaly area (Figure 4a). This indirect association between deformed coal thickness and 'sweetness' is an obstacle for the prediction of deformed coal thickness. After model-based calibration, the wells with thick deformed coal are located in high anomaly zone and the wells with thin or zero deformed coal are locate in low anomaly zone. This direct association is an advantage for the prediction of deformed coal thickness.

Although model-based calibration of seismic attributes can improve the predicting accurate of deformed coal thickness, the noise generated uncertainty is inevitable (Figure 3b and Figure 4b). In order to minimize this kind of uncertainty, appropriate field measurement and high-quality seismic processing are critical important for every survey project.



(a) (b)

Figure 4: 'Sweetness' of 15# coal before (a) and after (b) model-based calibration. The markers are the location of wells, the decimals beside those markers are uncovered thickness of tectonically deformed coal, and the curves are interpreted faults and column boundaries.

CONCLUSIONS

In this study, we have presented a model based approach for calibrating thickness influence on seismic attributes. As the model data revealed, different attributes have different response functions on the variation of coal-bed thickness. If the coal-bed is thinner than 1/8 wavelength, the calibration function is approximately linear; if coal bed is thicker than 1/8 wavelength, the calibration function is complex and can be represented with a Fourier function. From the example that we have shown, the calibrated 'sweetness' is much more observable with deformed coal thickness than uncalibrated 'sweetness'. Nevertheless, this improvement cannot eliminate the influence of noise. For a practical application, the estimation of the uncertainty is always desirable.

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