AVO Attributes of a Deep Coal Seam

Jinfeng Ma*
State Key Laboratory of Continental Dynamics, Northwest University, China
jinfengma@sohu.com

Igor Morozov
University of Saskatchewan, Saskatoon, SK, Canada

and

Jianyuan Cheng
Xi'an Branch of China Coal Research Institute, China

Summary

Based on rock physics theory and real well log data, we studied the AVO attributes of a deep coal seam in order to establish a coal seam prediction method by using seismic data. From well log data, coal seams typically have high elastic contrasts with the overlaying sandstones, and therefore most coal seams can cause strong seismic reflections similar to the bright spots in Class 3 gas sand cases. By using AVO intercept-gradient crossplots, most coal seams can be discriminated and still part of coaly shale beds could be interpreted as coal seam. Furthermore, the distribution of coal seams in intercept-gradient crossplots could indicate the high-porosity areas of sandstone.

Introduction

Great progress has been made in the coal seismic prospect since 1980s. Nearly all new seismic methods developed in oil and gas industry have been applied to coal seam prospecting and mining. These new seismic methods are used in mapping the structure of the coal, locating faults and discontinuities in the coal seams, mapping karstic collapse columns, measuring the thickness of coal seam and even predicting coal bed methane (CBM) distribution (Greaves, 1984; Lawrence, 1991; Peng et al., 2006). However, most seismic studies were focused on improving seismic resolution of thin coal seam, and very few studies used seismic methods for discriminating coal from other rocks, predicting content of CBM, estimating mine pressure and temperature in coal seam, and identification of ground water or karst collapses.

With shallow coal resources (less than 600-m deep) being gradually exhausted, especially in China, which has the largest consumption of coal in the world and use coal as the main energy source, coal prospecting and mining are moving from shallow to deep. In deep cases, more detailed geological information is required by the industry to evaluate coal reserves and avoid mining risk. With depth increasing, seismic resolution decreases. Ground stress, temperature, and coal methane pressure increase as well, which are hazardous to miners. Means for fast mapping the coal seam, for effective discrimination of coal from other reflections in seismic data, and for prediction and geological characterizations of coal seams under deep conditions are among the key problems in coal industry.

In this paper, we studied the relationship between AVO attributes and coal seam properties in order to establish efficient mapping rules for the deep coal. Rock physics theory and three borehole well log datasets including dipole shear-wave log data were used to create a realistic elastic model. In this model, AVO attributes of a coal seam were analyzed by using the exact and approximate Zoeppritz equations.

Method

In oil and gas reservoir AVO analysis, elastic parameters of covered shale are assumed to be constant, so that AVO variations are mainly caused by the underlying reservoir parameters. By contrast, most coal seams are covered by shaly sands. Therefore, AVO anomalies from the roof of coal seam are mainly caused by the variability in shaly sand properties. According to the rock physics theory, shaly-sand velocities and densities are functions of porosity, clay content, fluid saturation, differential pressure, and other parameters. Coal seam velocities and densities also vary with its metamorphic grade. Thus, the AVO effects of a coal seam are complex, and theoretical models are needed to study them.

Coal velocities and densities in different areas of the world could be different. However, generally speaking, within a small area, elastic parameters of coal should not change significantly. In this paper, we use the widely used coal parameters from Shaanxi province, northwest of China (Table1). The velocity-porosity-clay transformations by Han, Nur and Morgan (1986) are used to obtain P- and S-wave velocities of overlying shaly sand. Considering the depth of our research area to be from 600 m to1000 m, we use Han's velocity-porosity-clay transformations at 5MPa differential pressure (corresponding to 1500 inches) to calculate to P- and S-wave seismic velocities:

$$Vp=5.26-7.08\Phi-2.02Csh \quad \text{and} \quad Vs=3.16-4.77\Phi-1.64Csh. \qquad (1)$$

In this expression, Φ is the porosity and Csh is clay content. The density of shaly sand is calculated from Gardner's (1974) equation. Modeled elastic parameters of shaly sands are shown in Figure 1.

By means of Shuey's (1985) equation and given coal elastic properties (Table1), we calculated the possible gradient and intercept (Figure 2) assuming that clay content varies from 0 to 55% and porosity varies from 10 to 30% for shaly sands. The arrows in Figure 2 indicate the trend of increasing clay content and porosity in the overlying shaly sands which might be useful to indicate high-porosity area of coal seam. In Figure 2, we note that AVO attributes of coal seam are similar to that of Class 3 gas sand cases. Therefore, the seismic attributes of coal seams should be clear, and coal seams could be discriminated from other reflections by using AVO intercept-gradient crossplots.

Rock	*Vp* (m/s)	*Vs* (km/s)	ρ (g/cm^3)
Coal	2200.0	1108.0	1.4

Table 1: Coal parameters.

Well Name	Coal Depth (m)
G1-4	630-680.5
G21-1	845-858.5
G12-3	992-998.6

Table 2: Target coal seam depth.

AVO Analysis from Boreholes

In conjunction with our research, three boreholes were drilled and well log data were measured, including dipole shear wave data in Gaojiabao Coal Mine, Shaanxi province, Northwest of China. 2D seismic data acquired in this area as well. Production coal seams in three boreholes were interpreted from well log data (Table 2). All three boreholes G1-4, G21-1 and G12-3 are located in nearly the same line. The distance between G1-4 and G21-1 is 1.5 km, and the distance between G21-1 and G12-3 is 14.5 km.

The relations between elastic parameters were analyzed by using the well log data (Figure 3). In Figure 3a, we note that coal seam has a clear contrast from its wall rock. This contrast changes between the wells and depends on the depth of the coal seam. Also note that coal density increases with depth from G1-4 to G12-3 well, although the coal seam in all three wells has the same high quality. In the deepest borehole G12-3, the acoustic impedance and velocities of coal seam and shaly sand are larger (Figure 3b and c) than the other two wells. The acoustic impedance contrast between coal and coaly shale is small (Figure 3b). Consequently, coaly shale should have reflection character similar to that of coal. This may lead to interpretation traps and overestimated coal reserves.

Figure 4 compares AVO intercept and gradient of the roof of coal seam and coaly shale in the three wells. We picked the smallest and the largest acoustic impedance for the covering sandstones in the overlying formation in each well. Then we used all possible coal seam and coaly shale parameters in each well as the underlying formation to calculate the AVO intercept and gradient. Notably, the distributions of coals and coaly shales have parallel trends in this diagram. By comparing Figures 4 and 2, we can identify the high-porosity sandstone with brine in the coal seam. Figure 4 also shows that coal seam has similar seismic attributes as Class 3 gas sand, as was observed in modelled data above (Figure 2). AVO intercept and gradient could be used to quickly map coal seam and discriminate coal seam from coaly shale. However, coaly shale still has high risks to be interrelated as coal because they are not clearly separated remarkably in intercept-gradient crossplot (Figure 4).

Conclusions

AVO intercept-gradient crossplots can be used to quickly delineate coal seams, which have seismic attributes similar to those of Class 3 gas sands. The intercept-gradient distribution trend of coaly shale lies parallel to and above that of coal seam in intercept and gradient crossplot. However, coal and shaly coal still overlap crossplot making their discrimination difficult. AVO analysis based on rock physics theory may help us to identify fluid-filled high porosity sandstone area which might lead to flooding risk in coal mines.

Acknowledgements

This research has been supported by Chinese National Natural Science Foundation Grant 40474045, 40674041, China Hi-Tech Research and Development Program Grant 2006AA09Z313, National Basic Research Program of China (973) Grant 2006CB202208.

References

Gardner, G.H.F., Gardner, L.W. and Gregory, A.R., 1974. Formation velocity and density—the diagnostic basis for stratigraphic trust: Geophysics, **39**, 770–780.

Greaves, R. J., 1984, Coal prospect evaluation using high-resolution reflection seismology; a case study: The Leading Edge,**3**, 44-47.

Greenberg, M.L. and Castagna, J.P.,1992, Shear-wave velocity estimation in porous rocks: Theoretical formulation, preliminary verification and applications: Geophysical Prospecting, **40**, 195-209.

Han, D-H., Nur, A., and Morgan, D.,1986,Effects of porosity and clay content on wave velocities in sandstones:Geophysics,**51**, 2093-2107.

Lawrence, M. G., 1991, Advances in seismic reflection profiling for US coal exploration: The Leading Edge, **10**, 24-29.

Peng, S. Chen,H., Yang,R. Gao,Y. and Chen,X., 2006,Factors facilitating or limiting the use of AVO for coal-bed methane: Geophysics, **71**, C49–C56.

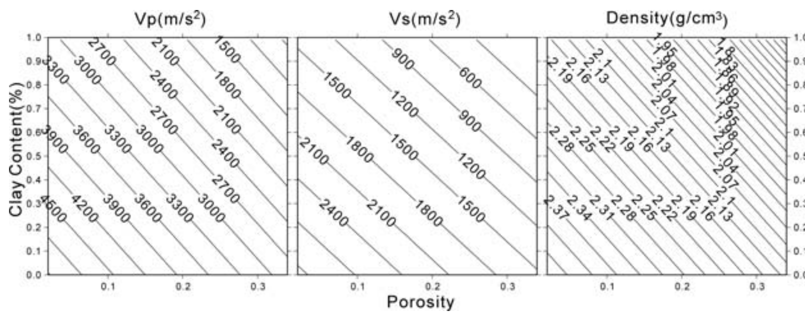

Figure1: Modeled brine saturated shaly sand P- and S-wave velocity and density versus clay content and porosity.

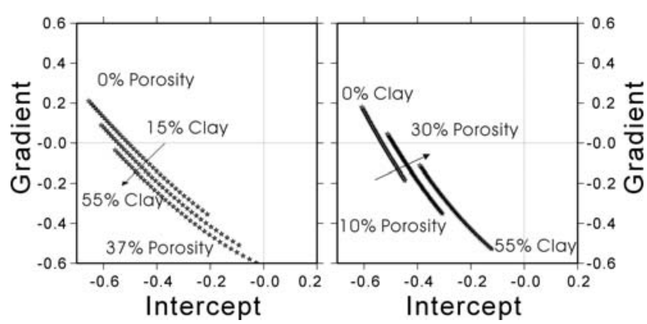

Figure 2: AVO intercept versus gradient cross-plots for modeled shaly sand (Fig.1) and coal seam (Table 1) boundaries.
Left: clay content 15%, 35%,55%, and porosity ranges from 0 to 37%.
Right: porosities are 10%, 20%, and30%, and clay content ranges from 0% to 55%.

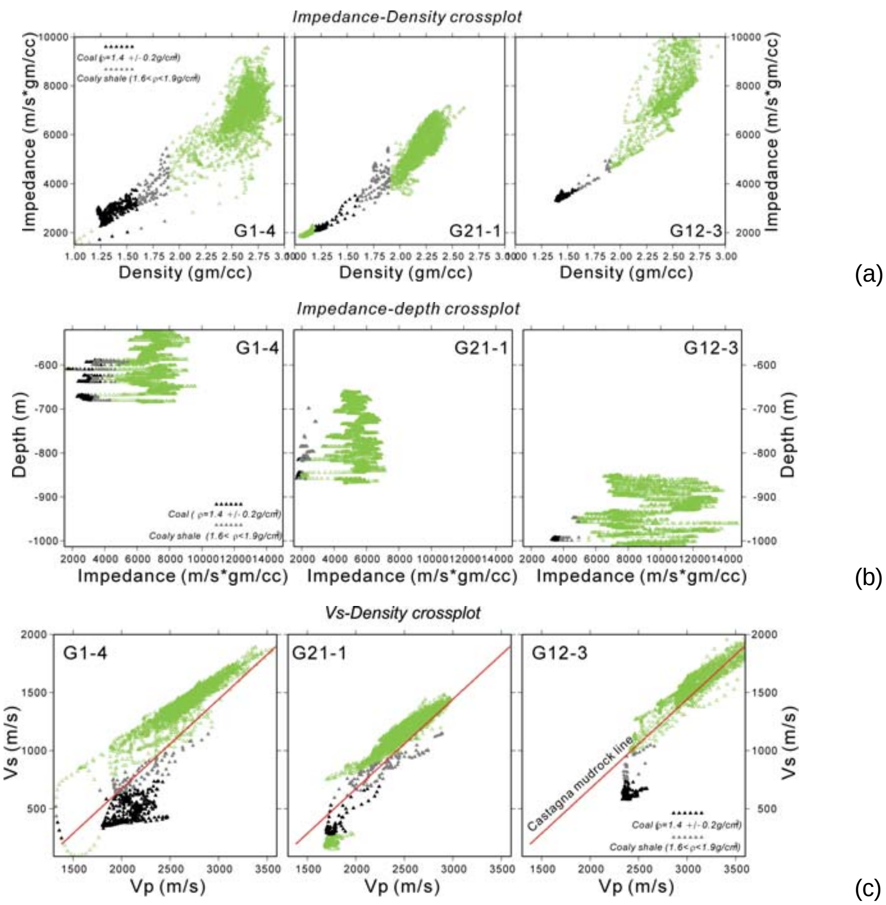

Figure 3: Cross-plot analysis at three wells between (a) impedance and density, (b) impedance and depth,(c)Vp and Vs. Red lines represent Castagna's (1992) mudrock line.

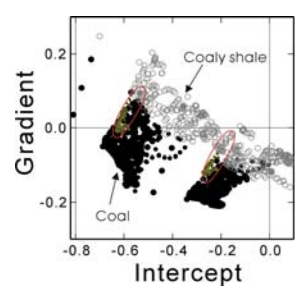

Figure 4: AVO intercept versus gradient from the roof of coal seam and coaly shale. Red circles indict the AVO attributes from well G12-3. The upper circle represents high acoustic impedance sandstone, which may have low porosity or clay content.