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Quantitative Prediction of Coalbed Gas Content Based on Seismic Multiple-Attribute Analyses

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Abstract. Accurate prediction of gas planar distribution is crucial to selection and development of new CBM exploration areas. Based on seismic attributes, well logging and testing data we found that seismic absorption attenuation, after eliminating the effects of burial depth, shows an evident correlation with CBM gas content; (positive) structure curvature has a negative correlation with gas content; and density has a negative correlation with gas content. It is feasible to use the hydrocarbon index (P*G) and pseudo-Poisson ratio attributes for detection of gas enrichment zones. Based on seismic multiple-attribute analyses, a multiple linear regression equation was established between the seismic attributes and gas content at the drilling wells. Application of this equation to the seismic attributes at locations other than the drilling wells yielded a quantitative prediction of planar gas distribution. Prediction calculations were performed for two different models, one using pre-stack inversion and the other one disregarding pre-stack inversion. A comparison of the results indicates that both models predicted a similar trend for gas content distribution, except that the model using pre-stack inversion yielded a prediction result with considerably higher precision than the other model.

Keywords: *coal-seam gas; gas content; multiple linear regression; pre-stack inversion; seismic multi-attribute.*

1 Introduction

Coalbed gas content data are essential for CBM exploration, selection and evaluation of an exploration area and development deployment. In practice, however, relatively few gas content data are available, so that prediction of gas content is required. Currently popular methods for gas content prediction include the gas content gradient method, composite geological analysis, and the sorption isotherms method [1-4]. These methods make a point-by-point estimation based mainly on data from exploration wells and coalmine boreholes, and cannot yield accurate predictions in a continuous and planar distribution. For areas with inadequate exploration and insufficient well numbers, the existing methods are frequently inapplicable.

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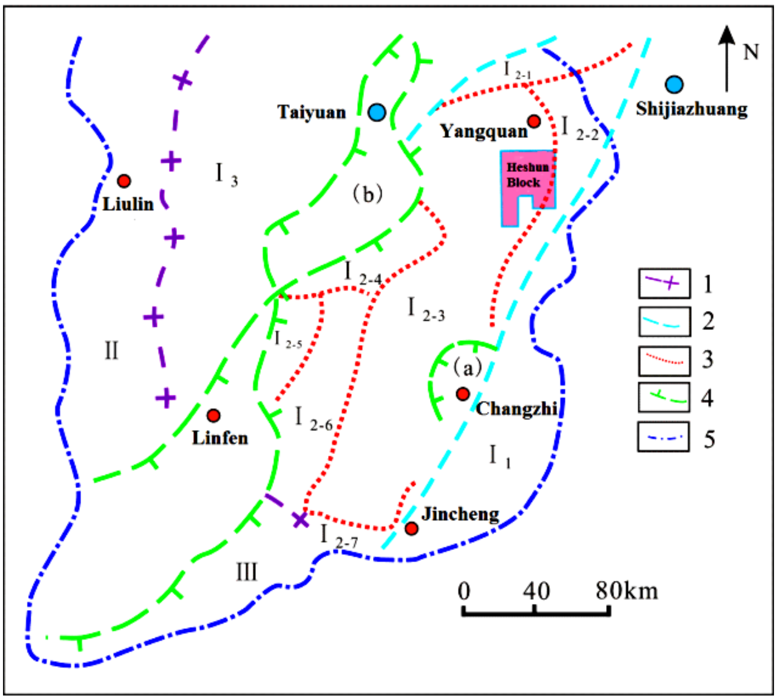
A number of research and application cases have demonstrated preliminary feasibility of applying the AVO (amplitude variations with offset) technique for gas content prediction [5-8]. Therefore, it is possible to use seismic attributes to predict gas content in a coal seam. In particular, use of pre-stack seismic data in AVO inversion studies has led to significant improvement in prediction reliability owing to the availability of a large amount of seismic gathers and well logging information, relative to that of post-stack acoustic impedance inversion [9]. However, high-level coalbed gas exists in coal seams mainly in absorbed form, causing great difficulty and uncertainty in the prediction if it is based solely on the seismic AVO technique [5]. A composite prediction based on a combination of multiple seismic attributes can effectively minimize the prediction uncertainties. For this purpose, this work focused on the Heshun block within the new coalbed gas exploration area in the northern part of the Qinshui Basin. This study combined post-stack attribute analysis, pre-stack simultaneous inversion, and pre-stack AVO inversion in terms of the seismic attributes, well logging, and testing data. Those seismic attributes that are highly dependent on the CBM content were identified and optimally selected. Then a multiple linear regression equation relating the gas content to these seismic attributes at the drilling well was obtained by mathematic modeling. Application of this equation to the seismic attributes from locations other than the drilling well accordingly yielded a quantitative prediction of the planar distribution of the CBM gas content.

2 Geological Background of the Study Area

In terms of tectonic structure, the Heshun block lies within the Zhanshang-Wuxiang-Yangcheng fold zone running north-northeast in the northeastern part of the Qinshui fault warp, and is characterized by a fold structure. The stratigraphic layer is relatively flattened and has a monoclinal structure with a generally northwest dip of around 15 degrees. The block is tectonically simple, and macroscopically it has a monoclinal structure with a northwest low dip. Faulted structures are not developed, and secondary wide and gentle folds exist, with the structural lineament stretching north-northeast (Figure 1) [10]. The stratigraphic units in the study area consist mainly of Palaeozoic-Cambrian, Ordovician, Carboniferous, Permian, Mesozoic-Triassic, Cenozoic-Tertiary, and Quaternary systems.

In terms of sedimentary structure, the Heshun block formed during the Cambrian and mid-Ordovician. At this time, the crust settled steadily and sediments consisting mainly of neritic-facies carbonates formed on top of an ancient crystalline basement. After the mid-Ordovician, the North China platform experienced an overall uplift because of the Caledonian tectonic event, which made the sediments from the late Ordovician to early Carboniferous erode and disappear in the study area. Until the middle Carboniferous period, the Hercynian orogeny caused crustal subsidence once again and led to sedimentation of interbedded marine-terrigenous facies that are comprised mostly of marine and transitional strata. The paleoclimate was warm and wet, and the vegetation flourished. Under a relatively steady environment in a certain Carboniferous-Permian period, the plants were sedimented as coal-bearing, interbedded marine-terrigenous strata, providing source materials for CBM formation [11-12].



1—primary tectonic boundary; 2—secondary tectonic boundary; 3—third-level tectonic boundary; 4—Cenozoic basin boundary; 5—provincial boundary; I—Lvliang-Taihang fault block; I_1—Taihang block ridge; I_2—Qinshui depression; I_{2-1}—Yuxian depression-rim tilting zone; I_{2-2}—Niangziguan-Pingtou depression-rim tilting zone; I_{2-3}—Zhanshang-Wuxiang-Yangcheng NNE trending fold belt; I_{2-4}—Pudong-Laiyuan NEE trending fold-thrust belt; I_{2-5}—Taiyue depression-rim tilting zone; I_{2-6}—Guodao-Anze near-NS trending fold belt; I_{2-7}—Xichengshan depression-rim tilting zone; I_3—Lvliang depression; II—Ordos fault block; III—Henan-Anhui fault block; a—Changzhi new fault depression; b—Taiyuan new fault depression; c—Linfen new fault depression

Figure 1 Regional tectonic map of the Heshun block.

The primary coal seams in the Heshun block belong to the Taiyuan formation of the upper Carboniferous series and the Shanxi formation of the lower Permian series. The Shanxi formation usually has 3-6 layers of coal, with an average total thickness of 2.82 m; the Taiyuan formation has 4-9 coal layers, with an average total thickness of 7.43 m. Among these coal seams, the most important targets are the No. 15 coalbed of the Taiyuan formation and the No. 3 coalbed of the Shanxi formation, which contain meager and anthracite coal, respectively. In this work we investigated only the Taiyuan No. 15 coalbed that has a relatively large and uniform thickness in the region.

3 Qualitative Prediction of CBM Gas Content Basedona Single Seismic Attribute

CBM gas content depends on numerous complicated conditions. According to the existing literature and its statistical data, the major factors relevant to gas content are seismic attributes and formation prediction parameters. The seismic attributes include absorption attenuation, structure curvature, density, impedance, Poisson ratio, and hydrocarbon index. The formation prediction parameters include burial depth of the coal seam, thickness of the coal seam, distance to the closest fault, thickness of roof mudstone, and thickness of roof limestone. This study focused on absorption attenuation, structure curvature, density, Poisson ratio and hydrocarbon index, and provides qualitative single-attribute analyses of gas content in terms of each of these parameters. These efforts can serve as a basis for quantitative and multiple-attribute prediction.

3.1 Absorption Attenuation and Qualitative Prediction of Gas Content

The study by Spencer indicates that attenuation of seismic waves in stratigraphic layers can be divided into formation attenuation and absorption attenuation; the latter plays a major role when the frequency exceeds 10 Hz [13]. Although absorption is hard to measure, it can cause attenuation of the seismic signal, which changes the seismic waveform and energy. Generally, seismic amplitude can be described as follows:

$$A = A_0 e^{-hx} \tag{1}$$

A_0 means initial amplitude, h means attenuation coefficient, and x means travel time. Therefore, the attenuation properties of the stratigraphic layers can be understood by determining the seismic attenuation from reflective seismic signals. Because high-frequency energy attenuates faster than low-frequency energy, the principal frequency of a received signal decreases if the target stratum is enriched with fluids. Hence, we can transfer the seismic data from the time domain to the frequency domain through Fourier transform, after which we can determine the attenuation characteristics of the CBM reservoir and predict the gas content through analysis of the frequency domain energy, i.e. the so-called wave field energy-frequency analysis technique [14,15]. In non-gas zones there is a higher and wider frequency spectral range; in gas zones there is a lower and narrower frequency spectral range, as a result of absorption attenuation of seismic waves (Figure 2). Also, we generally get a lower seismic resolution and a bigger prediction thickness using this method. Therefore, we used seismic attenuation attribution only for prediction of coalbed gas content and used the inverse outcome for prediction of the thickness of the coalbed in this study.

Based on this principle, we can use absorption attenuation features for gas content prediction, in which attenuation coefficients are important parameters for reservoir description and gas prediction.

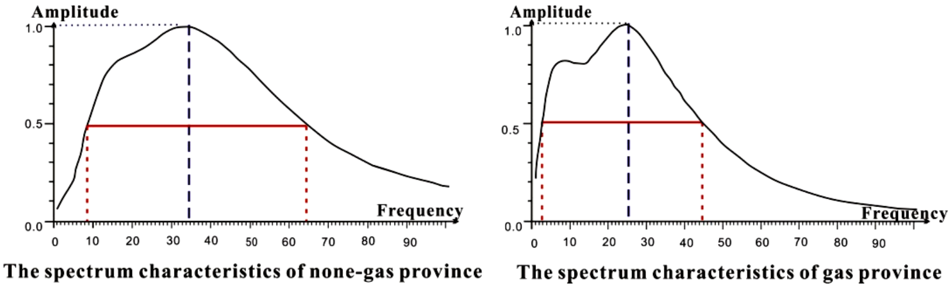
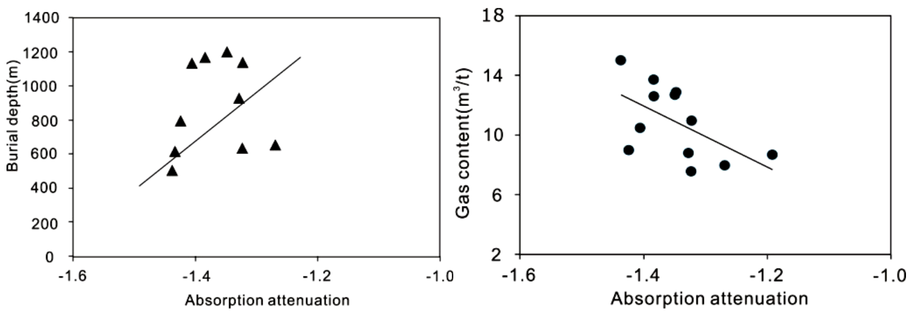


Figure 2 Frequency spectrograms with non-gas zones and gas zones



(a) Absorption attenuation vs. burial depth (b) Absorption attenuation vs. gas content

Figure 3 Plot of absorption attenuation (after eliminating the effects of burial depth) vs. gas content & burial depth.

The attenuation coefficient section of multiple through-wells in the Heshun block exhibits an evident and easily distinguishable feature of absorption attenuation at the coal segments. It is a typical section of an oversaturated reservoir. In methane-bearing coalbeds with low permeability, variation of CBM gas content has a smaller effect on frequency than on the rock framework. Therefore it is impossible to use absorption attenuation properties directly for qualitative prediction of CBM gas content and it is necessary to eliminate the effects of burial depth on absorption attenuation (Figure 3). The gas contents determined after elimination of burial depth effects show a clear positive correlation with absorption attenuation.

3.2 Structure Curvature and Qualitative Prediction of Gas Content

Structure curvature is a quantitative description of the geometrical configuration of a geologic structure, which uses the degree of curving to describe the curvature in all directions. Large curvatures occur at places such as both sides of a fold axis, tectonic transition zones, and both sides of a fracture plane. These places are commonly developing zones of cracks and fractures [9,16,17]. At locations with positive curvature (anticlines) coal beds experience stretching forces so that previously developed cracks open up or separation fractures develop well. As a result, CBM gas is subject to partial loss through dissipation, leading to relatively low gas content. At locations with negative curvature (synclines) coal beds are under compression and the CBM gas is isolated, so that a relatively high gas content is produced.

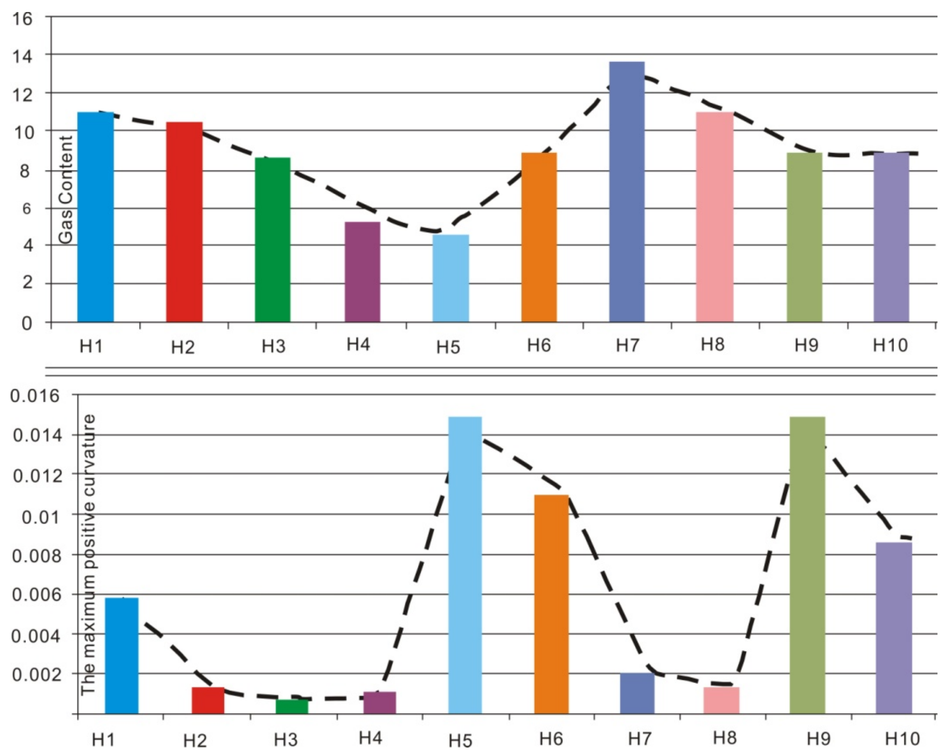


Figure 4 Comparative chart for the gas content of the No. 15 coalbed vs. the (positive) structure curvature.

Fairly abundant microstructures have developed in the Heshun block. By comparing the positive curvature of the top surface structure of the No. 15 coalbed and its CBM gas content, a negative correlation can be found between the maximum positive curvature and the gas content (Figure 4). The primary coalbed segments at two wells, H3 and H5, have relatively large positive curvatures, as well as abundant fractures and relatively good permeability. Because this region is near a large fault, enhanced permeability causes dissipation of the CBM gas.

3.3 Density and Qualitative Prediction of Gas Content

Currently, the cutting-edge pre-stack inversion technique uses a joint pre-stack and post-stack inversion and obtains the velocities of both longitudinal (P-) and transverse (S-) waves as well as density information. The main simplified equations of simultaneous inversion are the following:

$$R(\theta) \approx C_1 \frac{\Delta Z_p}{Z_p} + C_2 \frac{\Delta Z_S}{Z_S} + C_3 \frac{\Delta \rho}{\rho} \tag{2}$$

R(θ) means seismic reflection coefficient, Zp means P-wave impedance, Zs means S-wave impedance, and ρ means density. We look for a good correlation between density and gas content, so we can perform pre-stack inversion to obtain not only the P-wave and S-wave impedance attribution but also get the density attribution directly, which are then used to acquire the CBM gas content. This method takes the relationship between the wave velocities and density into account, so as to significantly improve its capability of differentiating rocks and fluids. In addition to the density, the Poisson ratio and Vp/Vs elastic parameters are also important parameters for gas content prediction, but because pre-stack simultaneous inversion is strongly influenced by logging data, in this work we selected the AVO technology to extract the elastic attributions, see Section 3.4.

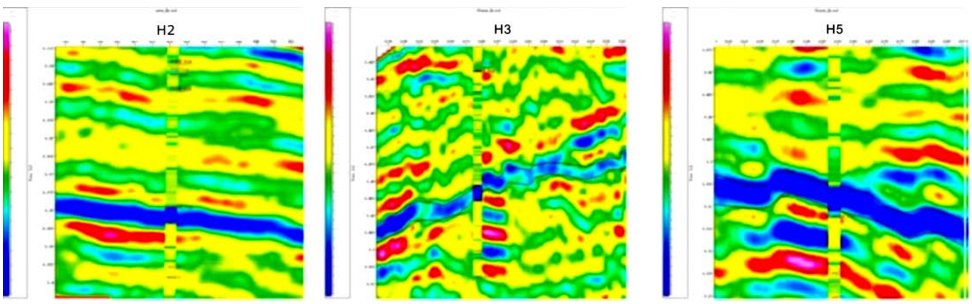


Figure 5 Correlation graph of density vs. gas content of the No. 15 coalbed.

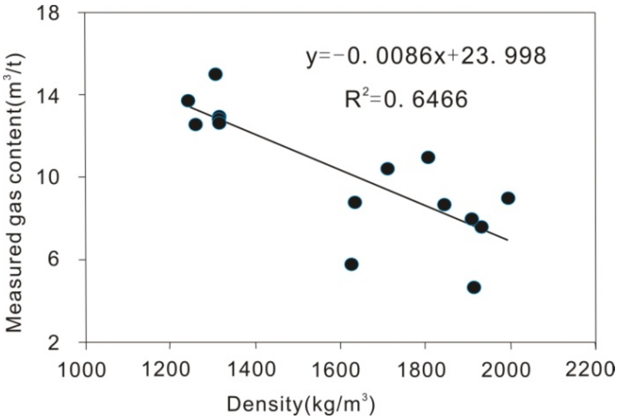


Figure 6 Correlation graph of density vs. gas content of the No. 15 coalbed.

The pre-stack density inversion for multiple through-wells in the Heshun block yielded a result that is consistent with the density section (Figure 5). In general, a coal seam with relatively ideal physical properties has high levels of gas content and relatively low densities. Fitting the relation between density and gas content it is feasible to convert density into gas content and thus achieve a gas content prediction (Figure 6).

3.4 Pre-stack AVO Inversion Parameters and Qualitative Prediction of Gas Content

According to the theory and implementation method of the AVO technique, we performed AVO angle gather processing and AVO attribution superimposition processing of the 3-D seismic data from the Heshun block in terms of pre-stack analyses. These analyses yielded attribute sections of hydrocarbon index (P*G), fluid factor, and longitudinal and transverse waves, which clearly represent the degree of accumulation of CBM gas in this region.

AVO analysis is a seismic technique that uses the dependence of seismic reflection amplitude on offset to distinguish rocks and measure gas content [6,18]. To date, essentially all the derivative AVO methods are built on the basis of Shuey's simplification of the Zoeppritz equation [19]. That is, when the incident angle is less than 30 degrees, the relationship between the reflection coefficient of the longitudinal wave and the incident angle can be approximately described by:

$$R(\theta) \approx P + G\sin^2\theta \tag{3}$$

The intercept attribute P denotes the intercept of AVO, which is commonly used as an input for wave impedance inversion. Its magnitude depends on the difference in P-wave impedance between strata. The gradient attribute G denotes the gradient of AVO, which is related to P- and W-wave velocities and rock density, and its magnitude is mainly determined by the Poisson ratio. The P*G attribute is the product of P and G, and is called the hydrocarbon index, which is commonly used in hydrocarbon detection.

There are two wells that have S-wave logging data in the study area. Through logging analysis it is easy to find that one of them (H10) is good. As we can see, the ratio of Vp/Vs distribution is reasonable, the P-wave and S-wave have a high similarity, and the Poisson ratio of the coal is relatively high compared to that of the surrounding rock, it can fit the elastic parameters patterns of coal seam, which, above all, has relatively high reliability (Figure 7). Therefore we can use the relationship between the P-wave and S-wave in this well to estimate the S-wave in the remaining wells.

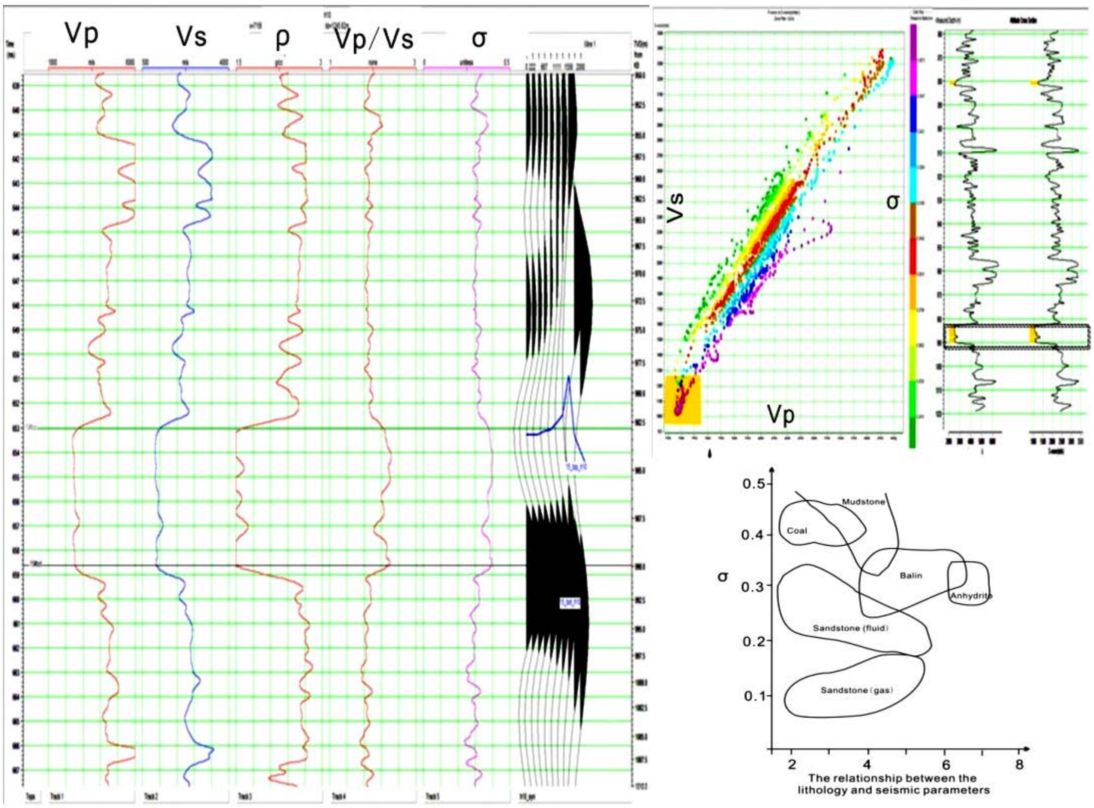


Figure 7 Well logging data analysis map for H10.

An AVO analysis of the actual gather from joint pre-stack gather and near-well seismic traces was performed for multiple CBM gas wells in the Heshun block. According to the analysis result, the primary AVO feature of these coal seams is that the amplitude decreases with increasing offset distance, which is typical of the fourth class of AVO. The variation features generated by forward-modeling of AVO resemble those from the AVO analysis of the actual gather.

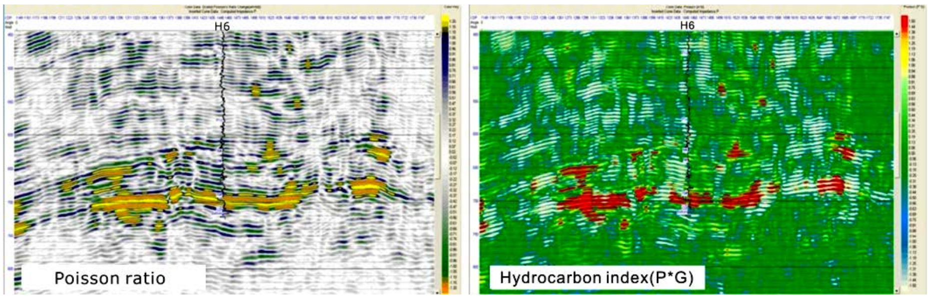


Figure 8 AVO attributes analysis of the oversaturated H6 well (in the No. 15 coalbed).

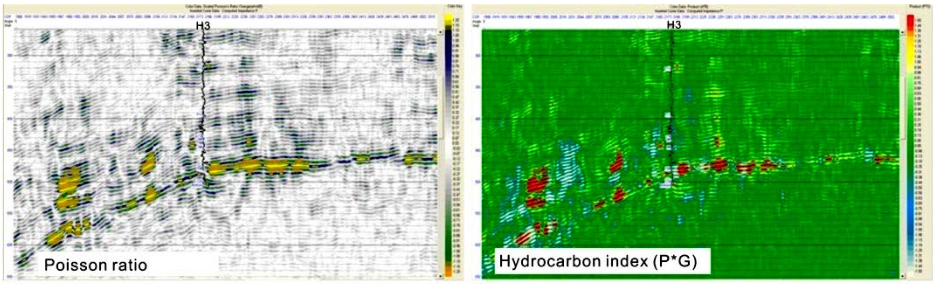


Figure 9 AVO attributes analysis of the oversaturated H3 well (in the No. 15 coalbed).

The AVO attribute section of the oversaturated H6 well (gas content 13.7 m^3/t) indicates that the hydrocarbon index (P*G) and Poisson ratio both show a good correlation with the accumulation degree of CBM gas (Figure 8). Another indication is that the pseudo-Poisson ratios and hydrocarbon indices are relatively large when CBM gas is enriched (gas content higher than 8 m^3/t). The AVO attribute section of the oversaturated H3 well (gas content 4.63 m^3/t) shows an analogously good correlation between the hydrocarbon index/Poisson ratio and CBM gas content. Lower gas content corresponds to smaller values for the pseudo-Poisson ratio and hydrocarbon index attributes.

Comparative analyses were made between the AVO attributes and gas content of more than 10 wells in the Heshun block (Figures 8 and 9). The results indicate that the reflection amplitude of a coal seam on the angle gather decreases with increasing offset distance when the coal seam contains no or little CBM gas. Again, both the hydrocarbon index (P*G) and pseudo-Poisson ratio show a good correlation with the degree of accumulation of CBM gas and thus they can be used as important parameters for gas content prediction. When these two AVO attributes are relatively large, the corresponding coal seam is likely an enrichment zone of CBM gas.

4 Quantitative Prediction of CBM Gas Content Based on Multiple Seismic Attributes

In order to obtain mutually complementary and corroborating results and to improve accuracy in gas content prediction, a comprehensive consideration of various factors that influence CBM gas content is required. Based on multiple-attribute analysis of the seismic attributes, this study selected those attributes that are highly relevant to CBM gas content by optimization. By mathematical modeling we attained a multiple linear regression equation relating the gas content to the seismic attributes at the 16 drilling wells in the Heshun block. Then, application of this equation to the seismic attributes at locations other than the drilling wells led to a quantitative prediction of CBM gas content.

For the multiple-attribute analyses, introduction of the seismic attributes usually follows a procedure from simplification to complication first, then back from complication to simplification. This so-called “from simplification to complication” means that it is suggested to take into consideration as many attributes that are relevant to reservoir prediction as possible at the early stage of proposing the prediction plan. In this way, we can make full usage of more information and adopt expert experience so as to improve the effectiveness of gas reservoir prediction. The so-called “from complication to simplification”, on the other hand, refers to eliminating attributes that are similar, repetitive, or of low relevance in multiple-attribute cross plotting analyses. This process not only ensures the accuracy of the prediction model, but also enhances the precision and efficiency of the calculations.

In view of the considerations above, we added a number of formation prediction parameters, such as impedance, coalbed burial depth, coalbed thickness, coalbed density, distance to the nearest fault, thickness of roof mudstone, and thickness of roof limestone, after numerous screening tests, besides the attributes mentioned above, which include hydrocarbon index, pseudo-Poisson ratio, absorption attenuation, structure curvature, and density. These additional parameters, as well as the statistics of coalbed gas content, are shown in Table 1. In this manner, we statistically analyzed all the parameters and gas content of the 16 drilling wells in the Heshun block. Next we performed a multiple linear regression and finally we arrived at a quantitative model for gas content prediction. In order to verify the reliability of the multiple-attribute prediction, this study performed regression calculations based on the prediction model for two cases of considering pre-stack inversion parameters and disregarding those parameters, respectively, and then compared the prediction results between the two cases.

Table 1 List of geological factors for the gas content of the No. 15 coalbed in the Heshun block.

Index	H	M	N	K	Z	L	S	F	D	P*G	Q	C
1	984	7.5	7.3	10.3	4898596	286.5	0.005923	-1.12	1801.4	-284.176	-1.947	n
2	1132	5.8	6.1	7.4	4849961	329.3	0.001435	-1.41	1709.8	-333.066	-2.148	10.48
3	927	6.0	5.9	8.9	4242096	169.9	0.000816	-1.19	1843.5	-267.891	-1.589	8.68
4	501	5.0	0.4	18.3	3267177	445.3	0.000100	-1.44	1305.1	-737.654	-4.222	15.00
5	617	5.6	5.2	15.9	3439229	618.1	-0.001134	-1.43	1625.4	-723.673	-4.271	5.78
6	704	5.0	5.5	17.3	3659398	5.7	0.014942	-1.37	1912.7	-827.119	-2.747	4.63
7	638	5.5	7.6	16.5	4386398	188.6	0.014137	-1.32	1929.6	-547.575	-2.748	7.58
8	927	7.2	4.8	12.0	3487271	988.7	0.010998	-1.33	1634.3	-665.091	-4.425	8.80
9	1172	6.2	6.6	15.0	4113357	725.4	-0.002122	-1.38	1239.5	-2041.593	-5.703	13.70
10	1206	6.2	7.0	15.3	4286338	899.3	0.000924	-1.35	1317.8	-1982.423	-5.168	12.68
11	1205	6.2	7.0	15.3	4284783	904.7	0.000902	-1.35	1315.1	-1987.145	-5.180	12.70
12	1172	6.2	6.6	15.2	4142091	625.8	-0.001795	-1.38	1258.0	-1972.482	-5.745	12.60
13	1206	6.2	7.0	15.3	4285634	901.8	0.000914	-1.34	1316.5	-1984.690	-5.174	12.90
14	1141	7.8	3.9	13.6	3945206	19.4	-0.001526	-1.32	1805.3	-316.285	-3.586	10.97
15	794	5.9	5.0	9.3	3732976	413.5	0.014994	-1.42	1992.4	-773.308	-4.857	8.99
16	651	5.6	5.0	7.4	4368318	1418.7	0.008666	-1.27	1905.0	-791.407	-2.482	7.96

Notes: H=coalbed burial depth (m); M=coalbed thickness (m); N=limestone thickness (m); K=mudstone thickness (m); Z=impedance (Ω); L=distance to the nearest fault (m); S=curvature (dimensionless); F=absorption attenuation (dimensionless); D=density (kg/m^3); P*G=hydrocarbon index (dimensionless); Q=pseudo-Poisson ratio (dimensionless); C=gas content (m^3/t); n=no data.

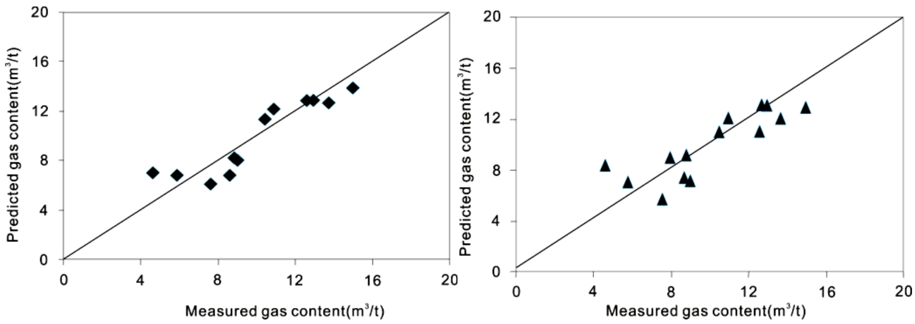
For the gas content prediction of the No. 15 coal seam in the Heshun block of the Qinshui Basin, two approaches were employed for comparison:

When considering the pre-stack inversion parameters, the fitted multiple linear equation is:

$$\begin{aligned} C = & -8.04\times10^{-4}\times P*G - 0.697\times Q - 0.338\times F + 0.0456\times M - 6.284\times10^{-3}\times S - 4.025\times10^{-3}\times D \\ & -1.745\times10^{-5}\times L - 1.343\times N + 4.267\times10^{-6}\times Z + 1.521\times10^{-3}\times H + 0.104\times K \qquad (R^2 = 0.86) \end{aligned} \tag{4}$$

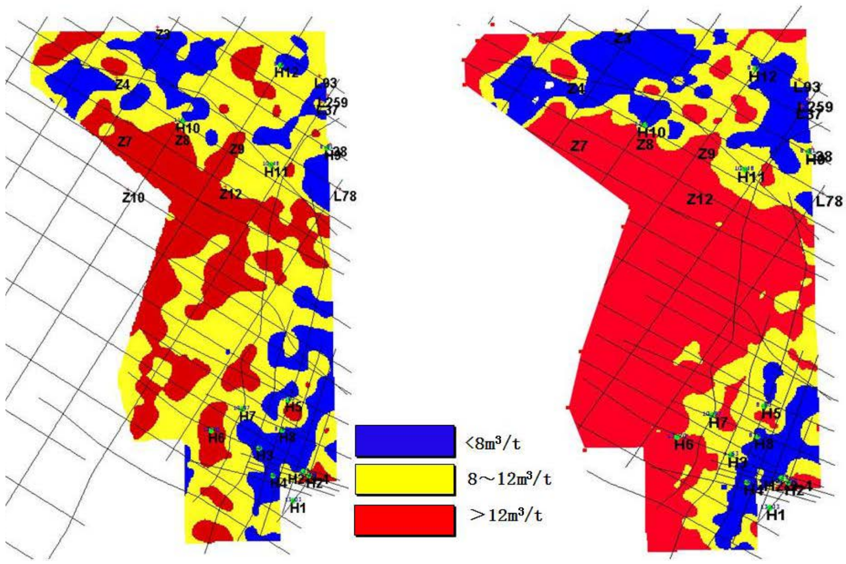
When disregarding the pre-stack inversion parameters, the fitted multiple linear equation is:

$$C = 0.447 \times F - 0.982 \times M - 6.664 \times 10^{-3} \times S + 2.502 \times 10^{-3} \times L - 1.318 \times N + 1.949 \times 10^{-6} \times Z$$
$$+ 1.066 \times 10^{-2} \times H + 0.367 \times K \qquad (R^2 = 0.83) \tag{5}$$



(Left: using pre-stack inversion. Right: disregarding pre-stack inversion.)

Figure 10 Correlation coefficient graphs the measured gas content vs. predicted gas content at the drilling wells.



(Left: using pre-stack inversion. Right: disregarding pre-stack inversion.)

Figure 11 Map of predicted planar distribution of CBM gas in the H15 coalbed in the Heshun block.

Comparison of the quantitative prediction results from the two models indicates that both models predicted a similar trend for gas content distribution, except that the case of considering the parameters yielded a result with better fineness than the other case. In addition, the gas content determined by multiple-attribute prediction when using pre-stack inversion showed a better correlation with the measured values as well as a higher precision than that when disregarding pre-stack inversion (Figures 10 and 11).

5 Conclusion

Qualitative prediction of coalbed gas content can be made in terms of the seismic absorption attenuation, density, and structure curvature attributes. The absorption attenuation property, after eliminating the effects of burial depth, has a positive correlation with the coalbed gas content. At places with relatively high gas content, the absorption attenuation feature is also evident. The density and (positive) structure curvature attributes both show a negative correlation with the coalbed gas content. Then the joint pre-stack inversion technique (which uses pre-stack inversion to obtain the density attribute first and then obtains the gas content from the density information) was applied to quantitative prediction of coalbed gas content. According to the results there exist various low-density zones around the H6, H3, H5, and H2 drilling wells. These zones are indicative of a relatively high CBM gas content.

By optimization we selected those attributes that are highly relevant to CBM gas content and then by mathematical modeling we attained a multiple linear regression equation relating the gas content to the seismic attributes at the drilling wells, so as to minimize interpretation ambiguity arising from single-attribute gas content prediction. Then application of this equation to the seismic attributes at locations other than the drilling wells, in combination with the geological attributes of the drilling wells, led to a quantitative prediction of the coalbed gas content. We also performed prediction calculations for two cases of using and disregarding pre-stack inversion, respectively. Comparison between the results indicates that both models predicted a similar trend for gas content distribution, except that the model using pre-stack inversion yielded a prediction result with considerably higher precision than the other model.

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