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Research article

Seismic prediction of sweet spots in the Da'anzhai shale play, Yuanba area, the Sichuan Basin

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Abstract

Burial depth, thickness, total organic carbon (*TOC*) content, brittleness and fracture development of shale reservoirs are the main geologic indexes in the evaluation of sweet spots in shale gas plays. Taking the 2nd interval of Da'anzhai shale of the Lower Jurassic as the study object, a set of techniques in seismic prediction of sweet spots were developed based on special processing of seismic data and comprehensive analysis of various data based on these geologic indexes. First, logging and seismic responses of high quality shales were found out through fine calibration of shale reservoir location with seismogram, which was combined with seismic facies analysis to define the macroscopic distribution of the shale. Then, seismic impedance inversion and GR inversion were used to identify shale from limestone and sandstone. Based on statistical analysis of sensitive parameters such as *TOC*, the uranium log inversion technique was used to quantitatively predict *TOC* of a shale reservoir and the thickness of a high quality shale reservoir. After that, fracture prediction technique was employed to predict play fairways. Finally, the pre-stack joint P-wave and S-wave impedance inversion technique was adopted to identify shales with high brittleness suitable for hydraulic fracturing. These seismic prediction techniques have been applied in sorting out sweet spots in the 2nd interval of the Da'anzhai shale play of the Yuanba area, and the results provided a sound basis for the optimization of horizontal well placement and hydraulic fracturing.

Keywords: The Sichuan Basin; Yuanba area; Shale gas; Seismic prediction; Early Jurassic; Total organic carbon (TOC), fracture (rock); Brittleness index

The success in exploration and development of shale gas in North America in recent years mainly attributes to the progress in directional horizontal well drilling and staged fracturing; meanwhile, geologic evaluation criterion for shale gas has been established, which mainly consists of buried depth, thickness, organic carbon content (*TOC*) and brittle mineral content (compressibility) of shale reservoirs [1—3]. The horizontal drilling and fracturing operation are higher in cost and face more difficulties in the exploration and development of shale oil and gas, so it is necessary to predict shale reservoirs accurately. However, as shale reservoirs are different from conventional reservoirs in geologic characteristics, the seismic prediction thought of shale gas reservoirs has made a big change from that of conventional oil and gas reservoirs. Jumping out of the regular thinking pattern of "looking for traps" in conventional petroleum exploration, in line with the brand-new concept of "seismogeology serves engineering", the seismic prediction of shale gas reservoirs aims to find unconventional oil and gas "sweet spots" characterized by "strong hydrocarbon generation potential, high brittleness of rocks, developed fractures and weak crustal stress heterogeneity" [4], and provide basis for well drilling and fracturing.

The 2nd interval of Lower Jurassic Da'anzhai member in the Yuanba area of the Sichuan Basin is an organic-rich mud shale, wide in distribution and stable, 30—50 m thick, higher

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in *TOC* (1.06% averagely), with rich oil and gas shows; medium- and high-yield industrial gas flow has been tapped from this interval in Wells YB101, YB102, YB11, YB5 and YB21. Therefore, the research on seismic prediction of "sweet spots" in shale gas play will be of great help in identifying the favorable sedimentary facies belt and favorable shale gas prospecting zones [2] in the 2nd interval of Da'anzhai member effectively, and will provide technological support for the optimization of directional horizontal well drilling and reservoir fracturing arrangement.

1. Seismic prediction of "sweet spots" in the shale gas play

1.1. Sedimentary facies features of Da'anzhai member

The peripheral mountain range activities were in a quiet period in the depositional stage of Da'anzhai member, when undeveloped large rivers, a small amount of terrigenous detritus entering the lake basin, clear water plus mild climate promoted the flourish of organisms like bivalve and gastropod, as a result, coquina bank was extensively developed in the shallow lake facies belt, forming a special set of Jurassic deposits. Da'anzhai member experienced a complete lake transgression − lake regression process. At the early stage of Da'anzhai member deposition (3rd interval epoch), a lake transgression, the maximal lake transgression in Early Jurassic started; at the middle stage of Da'anzhai member deposition (2nd interval epoch), the lake range was the most extensive, and shallow lake − semi-deep lake deposit was mainly developed in the Yuanba area; thereafter, lake regression started, and at the late stage of Da'anzhai member deposition (1st interval epoch), Yuanba area evolved into lakeshore − shallow lake deposits. Therefore, the shallow lake − semi-deep lake facies of the 2nd interval (2nd interval epoch) of Da'anzhai member is the favorable facies belt for the development of dark mud shale.

1.2. Seismic techniques for the prediction of high-quality mud shale thickness

1.2.1. Fine calibration and seismic response features of mud shale

Fine calibration of mud shale is the basis for seismic prediction of mud shale intervals, which includes calibrating the geologic horizon of mud shales accurately on the seismic profile based on the lithologic and physical properties of mud shale intervals. Calibrating the mud shale intervals of the 2nd interval of Da'anzhai member in Wells YB101, YB102 and YB21 shows that this mud shale interval has the following seismic response features: trough reflection at top; medium strong amplitude crest reflection, medium low frequency and relatively continuous reflectance signatures at bottom; meanwhile, high-quality mud shale is characterized by high *TOC*, high GR value and low wave impedance [5].

1.2.2. Seismic facies analysis

Stratimagic seismic facies analysis software was used to conduct seismic facies analysis. This software jointly uses artificial neural network (ANN) analysis technique, statistical clustering classification technique and principal component analysis (PCA) technique to conduct analysis and interpretation of seismic attributes and geological features reflected by them, enabling automatic division of seismic facies in the intervals defined by seismic traces, multi-attribute data volume, variant window/depth and iso-window/depth, and prediction of favorable sedimentary facies belts.

Fig. 1 shows the seismic facies analysis results of the 2nd interval of Da'anzhai member, i.e., the seismic facies is basically classified into 3 types in the whole area: Type I mainly refers to the blue area, i.e., the area south to the white dashed line in the figure. With high amplitude, low frequency and relatively continuous parallel seismic facies, this type mainly distributes in Wellblock YB16 and YB9 in the south of the study area; with an irregular northern boundary, this type corresponds to the semi-deep lake facies belt, where dark mud shale is developed. Type II is the red-yellow with light green area, i.e., the area between the yellow dashed line and the white dashed line in the figure. This type, with low frequency, medium-strong amplitude and relatively continuous parallel seismic facies, distributes in Wellarea YB21 and YB102 in the middle of the study area and the area east to it, in near EW direction on the whole, and corresponds to shallow lake facies belt, where ostracod-clastic limestone and dark mud shale interbed. Type III is the light blue − blue − green area, i.e., the area north to the yellow dashed line in the figure. With medium-high frequency, medium weak amplitude and relatively continuous parallel reflection seismic facies, this type distributes in Wellblock YB6 in the north of the study area in near EW direction on the whole, and corresponds to shore-shallow lake facies belt, where the sediment is dominantly sandstone and mudstone. It is concluded through analysis that the distribution area of types I and II seismic facies is the favorable sedimentary facies area for the development of dark mud shale.

1.2.3. Multiparameter seismic inversion of mud shale interval

1) High resolution wave impedance inversion of mud shale interval

Well constrained wave impedance inversion is a technique that uses post-stack seismic data to conduct inversion. Based on the test of inversion methods and the inversion effect, the sparse spike inversion module in the Jason inversion software was selected to conduct high resolution wave impedance inversion in this study [6]. Fig. 2 is the wave impedance inversion profile, which shows that the inversion not only improves the resolution, but also reflects more detailed geologic phenomena, which are basically consistent with those reflected by actual drilling data. The lakeshore facies of the 2nd interval of Da'anzhai member is sandstone-mudstone interbed deposits, exhibiting medium-high wave impedance (light blue − green − red); the shallow lake facies is ostracod-clastic limestone and dark mud shale interbed deposits, in

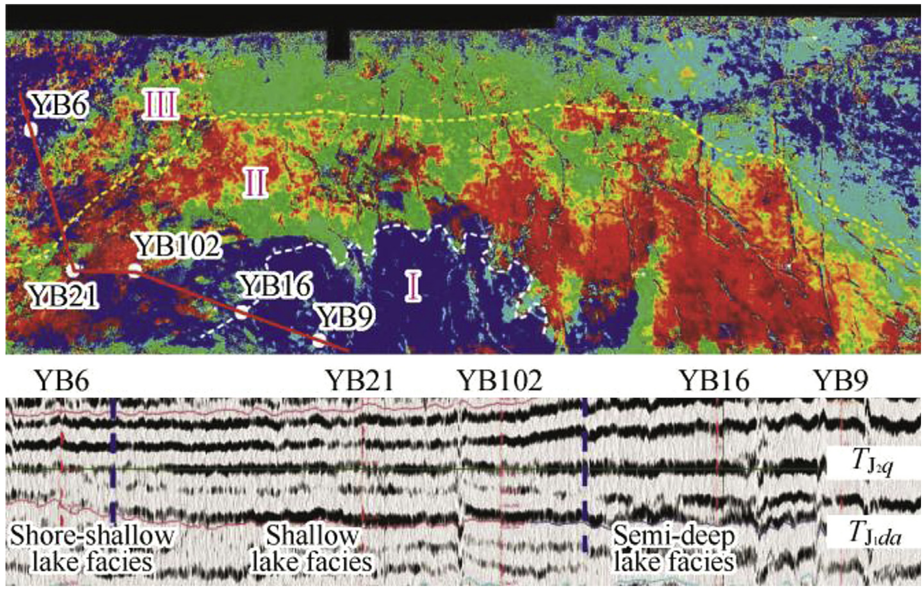

Fig. 1. Seismic facies plan view of the 2nd interval of Da'anzhai member in the Yuanba area.

which limestone exhibits high wave impedance (red yellow), while mudstone low wave impedance (blue); and the semi-deep lake facies is mostly mud shale deposits with low wave impedance (blue).

2) GR inversion of mud shale interval

The 2nd interval of Da'anzhai member mainly consists of ostracod-clastic limestone, sandstone and mudstone. The purpose of the study is to delineate the distribution of organic-rich dark mud shale in this section. The wave impedances of mudstone and other rocks (mainly sandstone and limestone) have overlap on the statistical histogram of wave impedance, showing that the mudstone cannot be distinguished from other rocks by using wave impedance features alone. Fig. 3a shows the statistical analysis results of GR and wave impedance of the objective intervals in all wells. It can be seen from this figure that mudstone can be distinguished from other rocks by GR, and it is concluded through analysis that GR = 66 API can be taken as the boundary to differentiate limestone and sandstone. The basic thought is as follows: take the wave impedance data volume as a soft constraint to conduct GR stochastic inversion, set GR threshold value based on well statistic results, conduct filtration on wave impedance data volume to remove the low GR limestone and sandstone, and finally obtain the wave impedance data volume reflecting genuine mud shale.

GR inversion was conducted by using the StatMod module in Jason software, and StatMod stochastic inversion provided 3D reservoir models based on the geostatistical information derived from StatMod Modeling (for instance, lithologic simulation volume, GR inversion data volume). These models not only conform with the seismic, geologic and logging data, but also the spatial distribution pattern of geostatistical variables, so the resolution of inversion data volume has been effectively improved (Fig. 3b). In addition, Fig. 3b also shows that the GR inversion results tally better with wells. After GR inversion, the influence of limestone and sandstone in wave impedance inversion data volume were eliminated, and the seismic prediction of mud shale reservoir became more accurate.

3) Uranium log inversion of mud shale interval

It is found through statistical analysis of wells that the *TOC* of mud shale has excellent positive correlation with uranium content (Fig. 4a), so this positive correlation was used to conduct uranium log inversion firstly, then, the uranium inversion results, its positive correlation with *TOC* and the correlation and analysis of wells were used to predict the high *TOC* value area.

Uranium log inversion was conducted by using Emerge multiattribute inversion software on the basis of wave impedance inversion. Emerge software was actually used to search for the relationship between seismic multi-attributes and target logs (internal attributes and external attributes), among which, wave impedance was input as an external attribute. At the same time, a series of internal seismic attributes of a composite seismic trace were figured out. The Bucong recursive method was used to find out the optimal attribute combination, and the attribute with the maximal coherence was used to predict and estimate the attributive features of the target logs, so as to achieve the objective of predicting the data volume of a target log. Fig. 4b shows the well-tie uranium inversion profile of Wells JL5 − YB6 − YB21 − YB102. It can be seen from this figure the uranium inversion results tally better with wells.

4) Prediction *of TOC of* mud shale interval and high-quality mud shale thickness

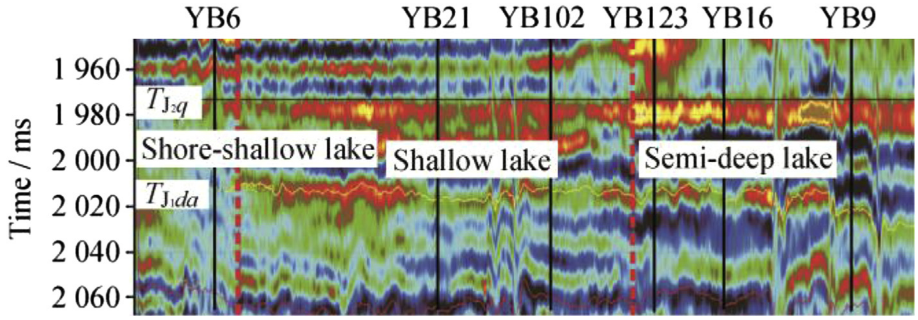

Fig. 2. Wave impedance inversion profile through Wells YB6 − YB9.

The positive correlation between *TOC* and uranium was used to convert uranium log data volume to *TOC* data volume to predict *TOC*. Fig. 5a is the *TOC* prediction plan view of the 2nd interval of Da'anzhai member, which shows that the *TOC* of dark mud shale increases gradually from northwest to southeast and from northeast to southwest, and TOC of shallow lake facies − semi-deep lake facies shale is more than 1%.

Based on the log interpretation results of *TOC*, it was believed that the dark mud shale with *TOC*>1% is an effective mud shale i.e., high-quality mud shale. Based on *TOC* inversion results, taking 11 600 [(m/s)·(g/cm^3)] as the wave impedance threshold of the 2nd interval of Da'anzhai member mud shale and *TOC* > 1.0 as the cutoff of high-quality mud shale, in the wave impedance volume of genuine mud shale in which the influence of limestone and sandstone was removed, the "relatively low wave impedance" anomalous sample point values with *TOC* > 1.0 and wave impedance less than 11 600 [(m/s)·(g/cm^3)] in the time windows of the top and bottom boundaries of the 2nd interval of Da'anzhai member were extracted to obtain the time thickness grid data of high-quality mud shales, which was then multiplied by velocity grids to get the thickness of high-quality mud shales of the 2nd interval of Da'anzhai member (Fig. 5b). Comparison shows that the predicted results are in high agreement with wells. It can be seen from Fig. 5b the thickness of gas-bearing mud shale of the 2nd interval of Da'anzhai member is controlled by sedimentary facies belt, and the mud shale thickness increases gradually on the whole with the facies changing from lakeshore, shallow lake to semi-deep lake from north to south. The mud shale is thicker in the area south to Wells YB11 − YB10 − YB4 − YL17, generally 30−50 m; but is relatively thin in Wellblocks YB27 − YB204 − YB205 − YB271 in the west of the Yuanba area, generally less than 30 m.

1.3. Fracture prediction of mud shale

1.3.1. Numerical simulation of stress field

Fractures are very important for the accumulation of shale gas [7,8]. Aiming at structures with tension cracks like anticlines, from the perspective of tectonic mechanics, geometric information (structural plane), lithological information (velocity, density) and petrophysical information (Poisson's ratio, Lame's constant, shear modulus) of strata were used to build a geological model, a mechanical model and a mathematical model; 3D finite difference numerical simulation method was used to simulate the stratigraphic stress field, to figure out the relationship between the geological factors like structures, faults, formation lithology thickness and regional stress field and the distribution of tectoclases. Simultaneously, the calculation of curvature tensor, deformation tensor and stress field tensor during simulation can be used to get parameters like principal curvature, principal strain, principal stress and principal stress direction, which are good indicators of the distribution and development level of tectonic-related fractures. The stress analysis on the 2nd interval of Da'anzhai member shows in the final formation stage of the structure, the directions of principal stress were primarily NE and NW; the tension cracks also stretched in these two directions; furthermore, the closer to the fault, the more developed the fractures are. Analysis combining with regional tectonic movements shows that the NW principal stress resulted from early Yanshanian movement, whereas the NE principal stress from late Himalayan movement.

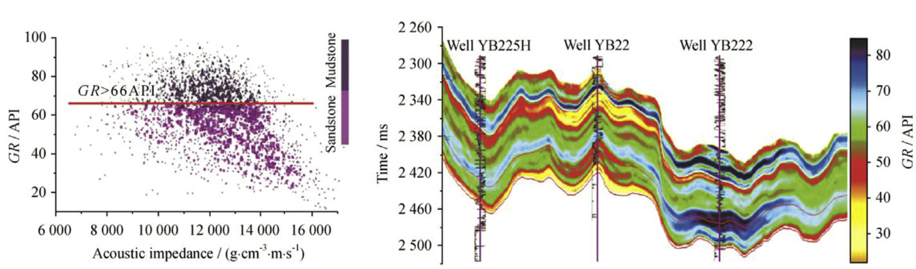

Fig. 3. Statistics on characteristic parameters and well-tie GR inversion profile of the 2nd interval of Da'anzhai member.

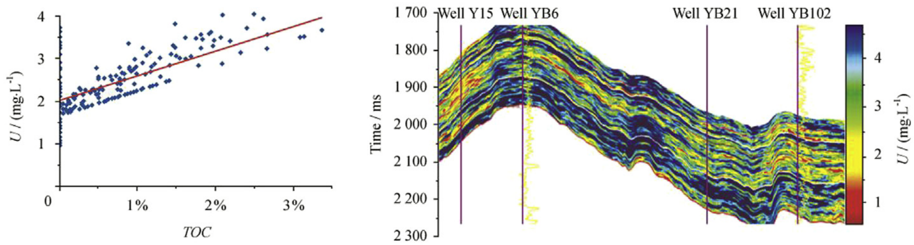

Fig. 4. *TOC* and uranium crossplot and well-tie uranium log inversion profile of the 2nd interval of Da'anzhai member.

1.3.2. Curvature analysis

Tectonism is a key factor affecting the formation of fractures. At present, the curvature attribute calculated by using 3D seismic horizon and 3D seismic data plays a major role in the prediction of microscale faults and fractures. The more serious the deformation of formation due to stress force, the higher the breaking degree possibly is, and the higher the curvature value should be. Because the curvature attribute is smaller in detection scale and highly sensitive to the formation folds, it is prone to the effect of noise; therefore, before calculation, the curvature volume attribute needs to be preprocessed to remove noise etc, and ultimately to get a better imaging effect and a clearer depiction of faults and microfractures. Fig. 6 is the curvature analysis plan view of the 2nd interval of Da'anzhai member extracted by using the above theory and method, which shows that microfractures are quite developed in the 2nd interval of Da'anzhai member in the Ziliujing Formation of the Yuanba area. It has been confirmed by drilling that microfractures are developed in Wells YB21 − YB101 (white dashed line area), and medium- and high-yield industrial gas flow was tested from Wells YB21, YB101, YB102 and YB11.

1.4. Prediction of mud shale quality area favorable for fracturing

1.4.1. Statistics on petrophysical sensitive parameters

Based on crossplot analysis of brittle mineral content (quartz content) and elastic parameters like Young's modulus and Poisson's ratio of the 2nd interval of Da'anzhai member in coring well YL4, the Young's modulus has a positive correlation with the brittle mineral content, whereas the Poisson's ratio has a negative correlation with it. Therefore, Young's modulus and Poisson's ratio data volumes were firstly obtained through joint inversion of prestack P-wave and S-wave impedances, then, brittleness index was worked out to predict the mud shale quality area favorable for fracturing [9−11].

1.4.2. Brittleness index prediction by joint inversion of prestack P-wave and S-wave impedances

The joint inversion of prestack P-wave and S-wave impedances is a technique that can synchronously invert P-wave and S-wave impedances and density data volume from partial angle gather stack data volume. Elastic parameter data volumes like Young's modulus and Poisson's ratio were obtained by using this technique, then, the computational formula of brittleness index (*BI*) based on elastic parameters presented by Rickman in 2008 was optimized based on the measured lithomechanical data of mud shale in the Yuanba area, and finally, the brittleness index inversion data volume was obtained by using the Young's modulus and Poisson's ratio inversion data volumes, which can satisfactorily predict the favorable fracturing area of mud shale in the Yuanba area [12]. In general, the shale with brittleness index of more than 30% is regarded as shale of good brittleness. Fig. 7 is the brittleness index prediction plan view of the 2nd interval of Da'anzhai member, which shows that the brittleness index is high in the north and central part of the study area, all higher than 30% (green − yellowish red area), indicating that they are areas favorable for fracturing and suitable for later fracturing stimulation; whereas the south area is low in brittleness index (magenta area). Based on the sedimentary facies features of Da'anzhai member in the Yuanba area, there developed lakeshore, shallow lake to semi-deep lake facies deposits from the north to the south. The brittle mineral content is relatively high in the lakeshore and shallow lake facies area; whereas in the semi-deep lake facies area in the south, it is relatively low, which is consistent with the predicted results.

2. Evaluation of favorable zones

The evaluation thought and principle are as follows: according to the characteristics of lacustrine mud shale in Da'anzhai member of the Yuanba area like young geologic age, low brittle mineral content and high heterogeneity, corresponding evaluation parameters like sedimentary facies belt, mud shale buried depth, organic-rich mud shale thickness, *TOC*, fracture development level and fracturing quality were selected. Meanwhile, the evaluation criteria for the selection of shale gas exploration and development targets both at home and abroad was consulted, and the actual conditions of lacustrine shale gas play in Da'anzhai member of the Yuanba area were considered to establish a set of shale gas fairway selection criteria (Table 1), which guarantees the accurate selection of favorable exploration zones of the study area and the confirmation of the “sweet spots” of shale gas, and provides basis for the optimization of directional horizontal drilling and the deployment of reservoir fracturing.

According to the above criteria and based on a comprehensive analysis of the sedimentary facies, mud shale distribution, organic abundance, physical characteristics, fracture development degree, lithologic association, oil and gas show

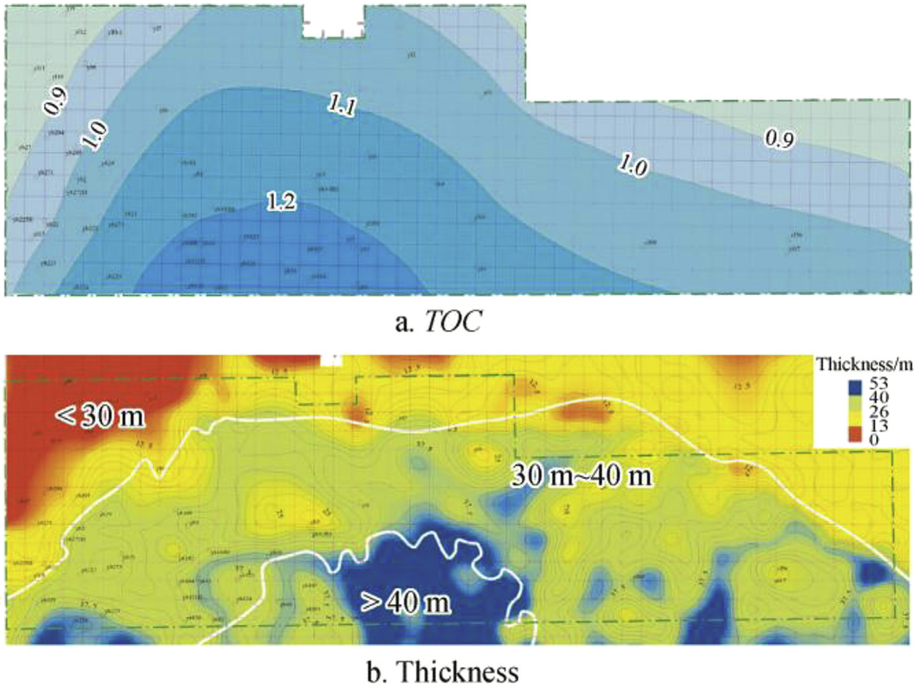

Fig. 5. Predicted *TOC* and high-quality mud shale thickness of the 2nd interval of Da'anzhai member.

and exploration results in Da'anzhai member, it is inferred that the shallow lake facies in the central part and the semi-deep lake facies in the south of the Yuanba area are the favorable facies belts for the exploration of Da'anzhai member shale gas, The lithologic associations of this facies belt is fit for the development of fractures. What's more, both the thickness of organic-rich mud shale (>30 m) and the buried depth (<4200 m) are good for shale gas exploration of Da'anzhai member. The gross area of the favorable zone is about 1719 km^2.

3. Conclusions

1) Based on the study of sedimentary facies and seismic response features of mud shale, the shallow lake facies belt in the central part and the semi-deep lake facies belt in the south of the Yuanba area were identified as the favorable sedimentary facies belts of the 2nd interval of Da'anzhai member by the seismic facies analysis technique. So far, medium- and high-yield industrial gas flow has been obtained from the shale interval of the 2nd interval of Da'anzhai member in Wells YB101, YB102, YB11, YB5 and YB21 located in the shallow lake facies belt in the central part, and low-yield gas flow has been obtained from Well YB9 located in the semi-deep lake − deep lake facies belt in the south of the Yuanba area.
2) Based on the study of the technique of seismic prediction on “sweet spots” of shale gas plays and the shale gas province selection and evaluation criteria for the Yuanba area, the areas with organic-rich mud shale of more than 30 m thick and less than 4200 m deep in the shallow lake facies area in the central part and the semi-deep lake facies area in the south of the Yuanba area are predicted as the favorable prospecting zones of shale gas, which covers an

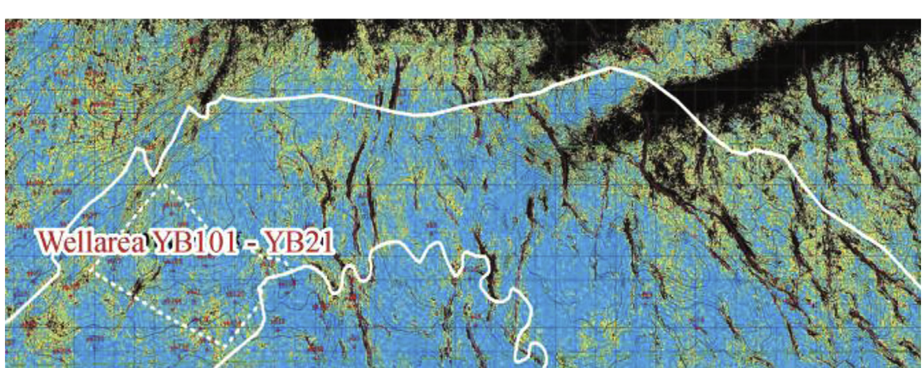

Fig. 6. Curvature analysis plan view of the 2nd interval of Da'anzhai member.

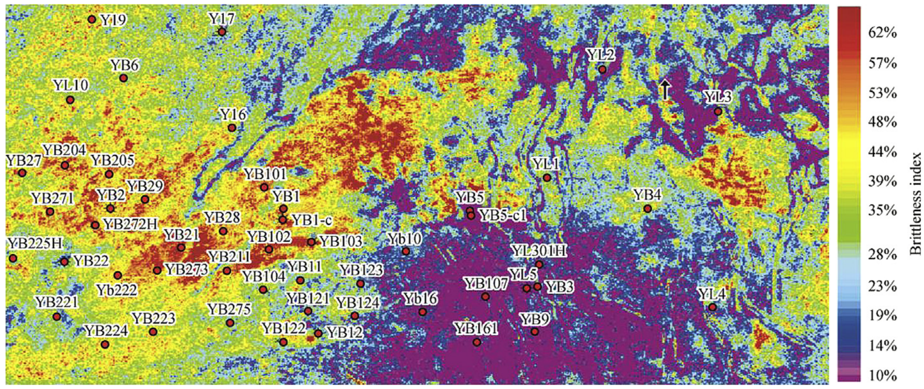

Fig. 7. Plan view of predicted brittleness index.

Table 1
Selection criteria of favorable shale gas provinces in the Yuanba area.

Evaluation parameter	Sedimentary facies belt	Mud shale thickness/m	*TOC*	Brittle mineral development degree (brittleness index more than 30%)	Buried depth/m	Fracture development degree
Evaluation criterion	Shallow lake, semi-deep lake	>30	>1%	Relatively developed, developed	<4200	Relatively developed − developed

area of 1719 km^2. This provides a basis for the optimization of directional horizontal wells in shale gas play and the deployment of reservoir fracturing. Besides, a set of seismic prediction techniques for "sweet spots" in shale gas plays are established.

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