Seismic Multi-attribute Prediction of Sandstone Gas-rich Areas: The Case of Yuwang Coal Mine

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Abstract

In order to predict the resource-rich areas of tight sandstone gas in the Yuwang coal mine, the seismic multi-attribute method was used to predict the gas-bearing sandstone areas. On the one hand, the lithology of the reservoir is predicted by statistical inversion to initially delineate the reservoir lithology. On the other hand, post-stack attribute coherents and curvature bodies are selected to accurately delineate the reservoir fracture zones. The results of the geostatistical inversion and fracture zone analysis were combined to predict the sandstone enrichment zone of the #1 coal seam in the exploration area, and the prediction results were good, indicating that the integrated seismic multi-attribute prediction of the sandstone gas enrichment zone is feasible. This method can be used as a reference for the exploration of gas-bearing sandstones in other regions.

Keywords

Statistical Inversion; Sandstone Gas; Fracture Zones; Enrichment Zones.

1. Introduction

The development of multi-phase and multi-type sedimentary basins in China, with a long evolutionary history and extensive development of tight reservoirs, determines that China is quite rich in tight gas resources [1]. Dense gas has been discovered in China as early as the 1960s in the Sichuan Basin [2]. However, it has not gained scale for a long time due to immature technology and low production per well. However, in recent years, with the advancement and large-scale application of horizontal well and large fracture modification technology, it has greatly reduced the cost and increased the production per well, improving the economics of the resource [3]. Tight sandstone gas is an unconventional gas with abundant reserves and high recovery value. However, it has not been well exploited due to its complex reservoir characteristics and the difficulty of exploration [4]. Accelerating the exploration and exploitation of its unconventional natural gas from coal-bearing strata is of strategic importance to alleviate China's energy tension, energy structure and achieve green development [5]. And finding its enrichment zone is one of the objectives of conducting exploration and reservoir evaluation, which can provide important directions for reservoir utilization and drilling development.

Since the new century, the prediction of unconventional gas-rich areas using geostatistical inversion techniques has been very successful in the oilfield field [6]. However, seismic exploration of unconventional natural gas for coal-bearing strata is less common, and its theoretical basis is relatively blank. In this paper, actual seismic data from the Yuwang mine in Huainan City are used as an example to predict and investigate the dense sandstone gas enrichment zones.

The hydrocarbons in dense sandstones originate from coal seams and are preserved in the sandstones through a series of transports to form stable sandstone gas. Therefore, the thickness and location of the coal seam is an important reference for the prediction of the enrichment area of dense sandstone gas. Sandstone gas is transported in fractures and fractures and reaches stability, and its coal seam top and bottom lithology, coal seam thickness, and fracture zone distribution can be analysed by statistical inversion and seismic attributes. According to the seismic data of Yuwang coal mine, its coal seam distribution is complex, with more thin coal seams, which are far below the seismic resolution and difficult to predict accurately by traditional inversion methods. The distribution of tectonic fractures is also more complex. For the complex reservoir environment of Yuwang Mine, on the one hand, the fracture tectonic area can be divided based on the seismic attribute coherent body and curvature body, on the other hand, the seismic statistical inversion can be used to predict the coal seam thickness, top and bottom slab lithology, outline the 3D geological model, and accurately predict the distribution area of gas-bearing sandstone.

2. Overview of the Study Area

The Yuwang coalfield is located on the northern edge of the South Asian belt of the Qinling latitudinal tectonic belt and the southeastern edge of the North China plate. It is connected to the Bengbu uplift in the north, adjacent to the Hefei depression in the south, with the Tanlu Fault of the New Huaxia System in the east, and ends at the Shangqiu ~ Macheng Fault in the west. It is 180 Km long in an east-west direction and 15-25 Km wide in a north-south direction, covering an area of about 3200 Km2.

The geometric configuration and combination of formations in the Yuwang Coalfield show a south-to-north thrusting action, and form a pattern of two flanking opposing thrusting structures. The Sungongshan fault and the Fufeng fault on the southern flank form the south-to-north thrusting body of Sungongshan, Bagongshan and Liuzhuang, while the Shangyeol-Minglongshan-Shantang fault group on the northern flank forms the north-to-south thrusting body of Shangyeol and Minglongshan. The overburden forms a stacked fan; within the fault block on the southern flank, the stratigraphic dip is steeply inverted and folds are developed. Within the compound oblique is a series of broad and gentle folds, with the Chenqiao-Panji backslope uplift being the largest and the main structure within the compound oblique. The dip of the strata within the complex oblique is gentle, generally 10-20°, and the axial direction of each fold extends along the N70-80°W direction, generally dips to the east at an angle of 3-5°. The coal seams are shallow in the western part of the field and deep in the eastern part. The low hills on the two flanks of the complex oblique reveal the Swire Group, the Lower Palaeogene Fengtai Group, the Upper Palaeogene Qingbaikou Series Bagongshan Group, the Aurignacian Xuhuai Group, the Palaeozoic Cambrian and Ordovician. The coal-bearing strata in the oblique axis are covered by thicker red strata of the Upper Permian Shiqianfeng Group or Cenozoic strata. The undulating Chenqiao-Panji backslope is covered by Permian coal-bearing strata, except for the Cambrian and Ordovician strata that are exposed due to weathering and denudation in some parts of the backslope axis. The 1# coal seam in this study area is a stable giant thick coal seam in the whole region, which has good gas source rock and hydrocarbon generation capacity, making it a huge CBM reservoir.

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3. Coal Seam Crushing Zone Analysis

The dense sandstone gas in the Yuwang Basin formed in dense reservoirs around the Permian period, and the sandstone gas formed in this period needed to overcome the high capillary pressure of the dense reservoirs, thus limiting the large-scale long-distance subduction of the gas during its hydrocarbon generation phase, and the high gas saturation of the reservoirs close to the source rocks, indicating that under dense reservoir conditions, gas is mainly aggregated by close transport. This is characterised by the close proximity of the source reservoir and the proximity of the reservoir to the vertical transport. The location of the coal seam is critical to the prediction of the gas-bearing distribution of sandstone gas. The analysis of the fracture zone is mainly the interpretation of faults and fractures.

3.1. Fault Interpretation

For the accurate interpretation of the faults with the accuracy of the basic information, the reasonableness of the technical process, the experience of the interpreters and the science, this seismic data interpretation adopted an interactive interpretation method of seismic and borehole, with the regional interpretation based on seismic and supplemented by drilling, and the local multi-well area interpretation based on drilling and supplemented by seismic. To ensure the accuracy of the stratigraphic calibration, a combined single-well and multi-well calibration technique was used to establish a comparative relationship between the coal stratigraphy and the seismic reflection layer, laying a solid foundation for further interpretation work. On the basis of the layer calibration, the latest three-dimensional tectonic interpretation method, the fault spreading method, was selected for the regional tectonic interpretation based on the geological characteristics of the seismic 3D area of Yuwang Mine. The process of this method is as follows: 1) Make a number of horizontal slices and coherent slices for each of the shallow, middle and deep layers, with the main survey line and contact line first diluted and then encrypted, and synchronize the interpretation with the slices and cross-reference them, carrying out the "three determinations" of "slicing the direction, sectioning the tendency and common production". 2) Strengthen the interactive interpretation of connecting lines, contact lines and arbitrary lines to ensure the closure of layers.) Make use of the three-dimensional visualisation function of the interpretation system to check each interpretation layer in three dimensions and from multiple angles to ensure the rationality of the tectonic interpretation and the consistency of the multi-layer structure.

During the interpretation process, various techniques such as compression, enlargement, arbitrary line combination, isochronous slicing, coherent body slicing and automatic tracing, seed point tracing and three-dimensional display of seismic sections are fully utilised to improve the accuracy and efficiency of the interpretation. For blocks with abundant borehole data, the information from boreholes, logging and test mining is fully applied to establish fine stratigraphic comparisons, carefully analyse the distribution pattern of coal seams, and finely interpret faults, fault-related structures and low-amplitude structures.

3.2. Cracks Explained

In order to better study the distribution of fractures, the distribution of fractures can be analysed in combination with a variety of seismic attributes. Seismic attributes are those geometric, kinematic, kinetic or statistical characteristics of seismic waves that are derived from pre-stack or post-stack seismic data, after mathematical transformation. Seismic attributes that are sensitive to the distribution of fractures are coherence, curvature, instantaneous phase, instantaneous frequency, root mean square amplitude attributes, etc. Combined with the geological characteristics of the fracture-prone zone, some effective attributes are preferentially selected to participate in the study through multi-attribute analysis. It is found that the attributes with the highest weight in this project are the coherence attribute and curvature attribute, which have certain advantages in qualitatively obtaining the fracture-prone zone or fracture area, and can spread the distribution range of fractures more objectively. Fig. 1 shows the curvature attribute map of #1 coal seam, and Fig. 2 shows the coherence attribute map of #1 coal seam.

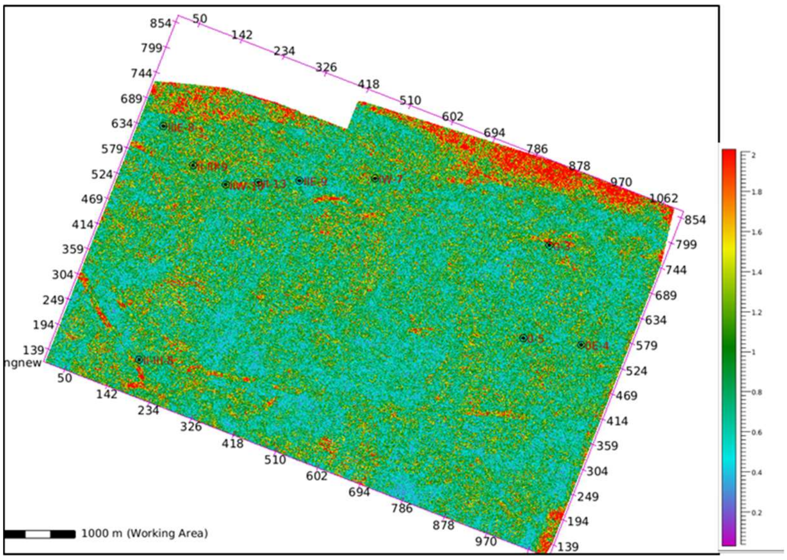

Fig. 1 Curvature property map for #1 coal seam

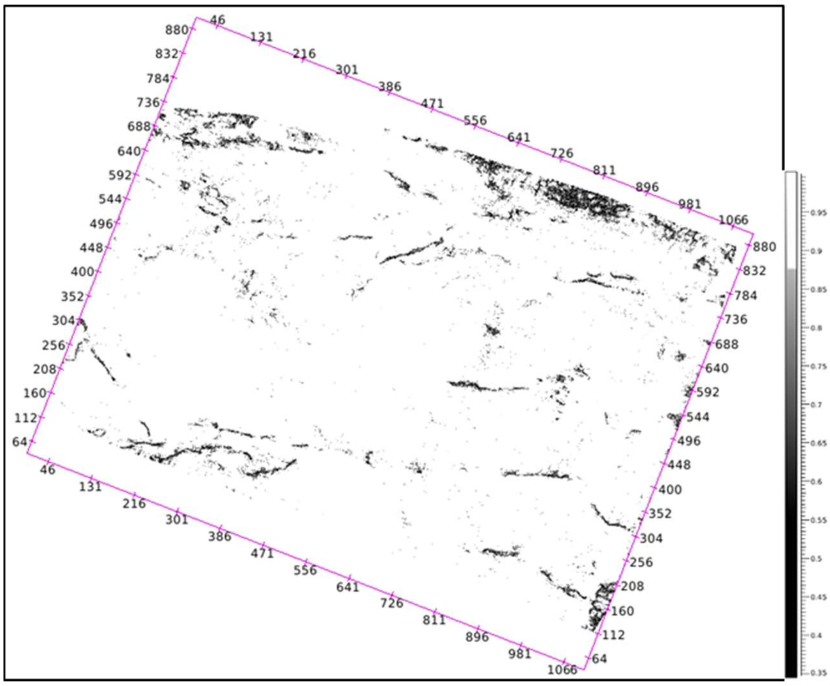

Fig. 2 Coherent properties map for #1# coal seam

Based on the above attribute analysis, the analysis of enhanced coherent attributes is better for the prediction of fractures. Coherent body technology refers to the high-precision coherent processing of the main frequency data body, and linear enhanced coherent body technology calculates the dissimilarity of seismic data in different directions from three-dimensional space through high-precision coherent processing technology, from which information on the discontinuity of the stratigraphy and the difference of the deposition process can be compared and extracted to predict fracture development from macroscopic favourable The zone is

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predicted to be favourable for fracture development from a macroscopic perspective. Combining the above attribute prediction results, the multiple seismic attribute prediction results are fused and combined with the fault interpretation results to delineate its fracture zone distribution area, which is divided into Class I fracture zone and Class II fracture zone, as shown in Fig. 3.

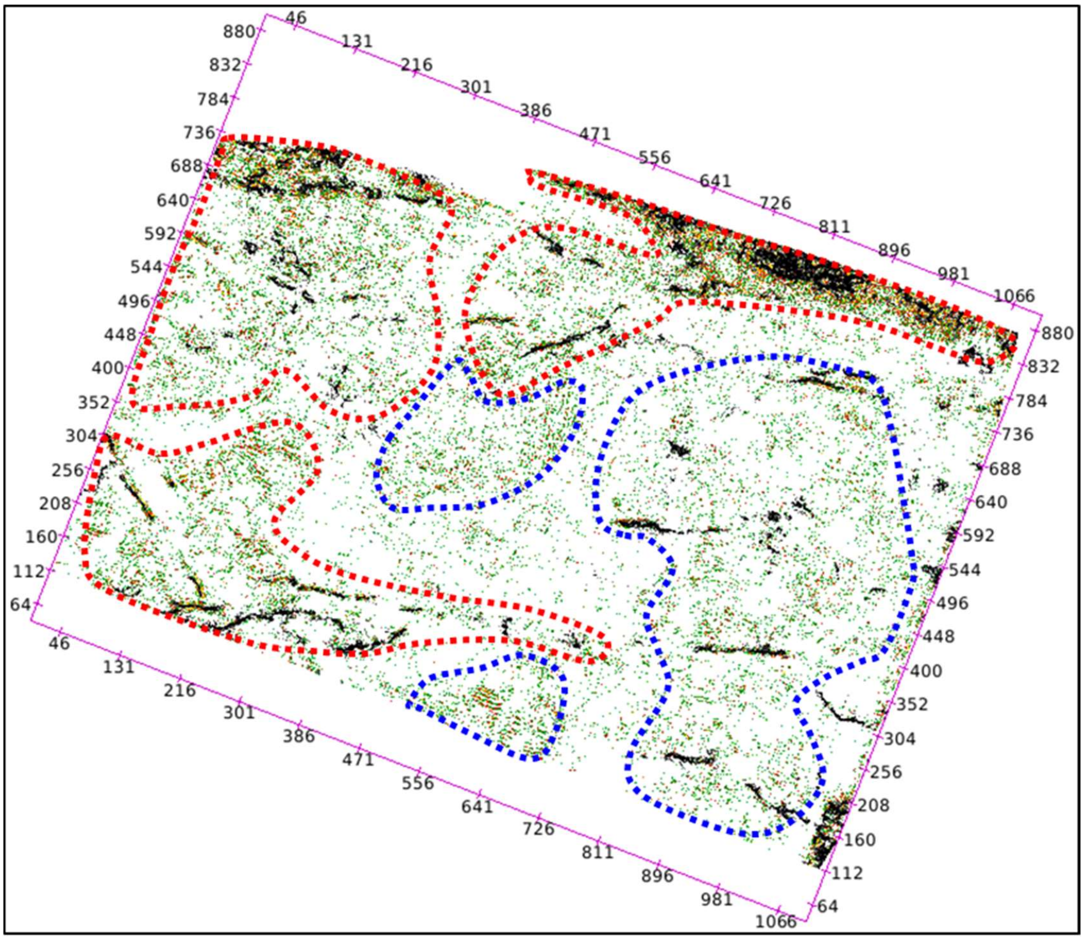

Fig. 3 Comprehensive analysis of the 1# coal crushing zone

This project takes a time window of 10ms above and below the top and bottom of the coal seam to calculate the linearly enhanced coherent body and curvature body for coal #1. The calculated linearly enhanced coherent body, curvature body and bottom contour superimposed map can well portray the fracture development in this area, and a larger time window is used for areas with larger dip angles to well portray the range of fracture-prone zone development in this area. The range circled by the red dashed line is the distribution range of the Type I fracture zone, which has anomalies in both coherence and curvature properties, indicating that the fracture system has both fault or trap columns and fracture development; the range circled by the pink dashed line is the distribution range of the Type II fracture zone, which only has anomalies in curvature properties and is mainly fracture-based.

4. High-resolution Inversion of Target Stratigraphy in Dense Sandstone Gas Reservoirs

The high-resolution geostatistical inversion uses a rigorous Markov Chain Monte Carlo (MCMC) algorithm that combines constrained sparse pulse inversion and stochastic simulation techniques into a new stochastic inversion algorithm. A rigorous probability distribution model is defined by combining information from seismic lithologies, logging curves, probability density functions and variance functions. Firstly, the probability density function and variation function are obtained from the analysis of the logging data and geological information; secondly, the sophisticated MCMC method obtains a statistically significant correct set of sample points based on the probability distribution function (PDF), i.e. what type of results can be obtained based on the probability distribution function, and the built-in constrained sparse pulse inversion engine ensures that, within the effective bandwidth of the seismic data, these simulation results are at least as good as InverTrace+ results are at least as accurate as those from InverTrace+; based on an “information synergy” approach, the high-resolution geostatistical inversion results reproduce a real coal seam with well-defined, sharp-edged lithologies in the right places and much more detail. Because geostatistical inversions provide a great deal of detail beyond the bandwidth of seismic data, while trending in exactly the same way as seismic data, this results in a perfect balance of qualitative and quantitative interpretation.

Well seismic calibration is particularly important in the inversion process. Well seismic calibration is the bridge between seismic and logging data, establishing a time-depth relationship to mark the stratigraphic relationship and therefore the location of the coal seam and top and bottom plates. As shown in the graph below, the well seismic calibration has a good correlation of over 80%. A good well seismic calibration result is provided for subsequent inversion and lithological interpretation, and subwave estimation is performed on the fully superimposed data body to extract the final average subwave with a 50 Hz main frequency.

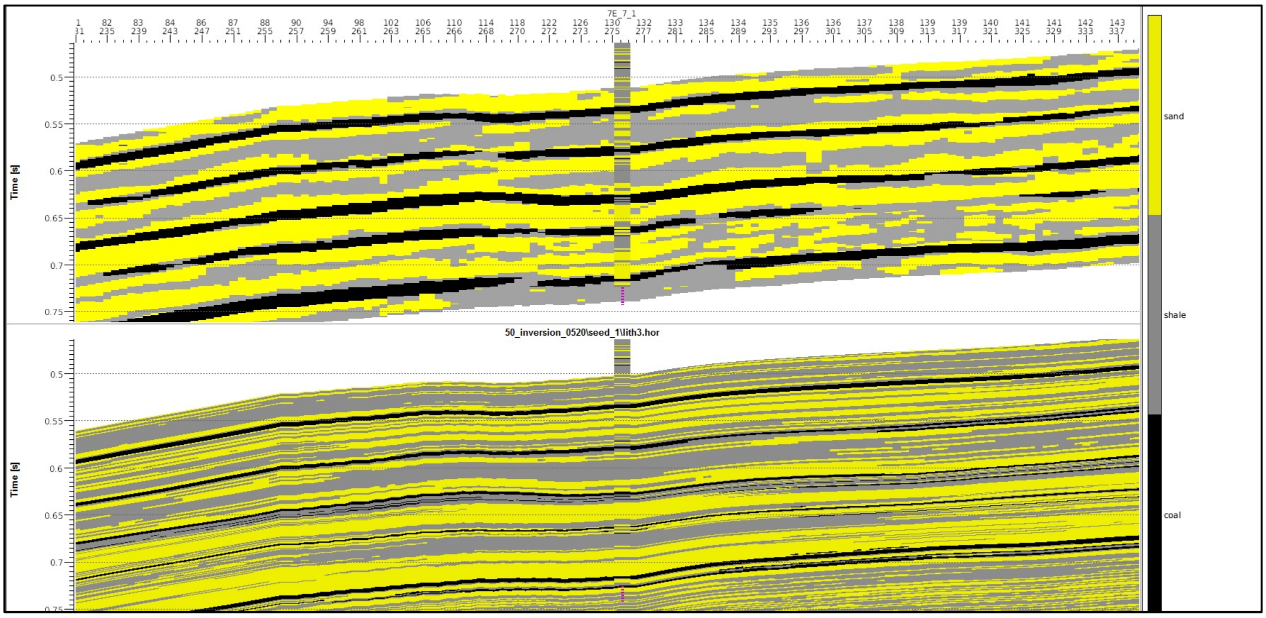

Fig. 4 Comparison of conventional inversion lithologies (top) and high resolution inversion lithologies (bottom)5 Sandstone gas-rich areas

The lithology prediction of tight sandstone gas enclosing rocks is directly related to the extraction of tight sandstone gas. The different physical properties such as porosity and permeability of different lithologies will affect the tightness of the tight sandstone gas reservoir, affecting the storage capacity as well as the construction design of drilling and fracturing during tight sandstone gas extraction. By clarifying the distribution and location of each lithological formation within the coal formation, the drilling trajectory and fracturing parameters of the extraction wells can be provided as a reference. The prediction of the thickness of the thin sand bodies and the surrounding lithology can be effectively solved by geostatistical inversions for the thin sandstone phenomenon that exists in the coal-bearing strata in the study area. From the results of the conventional seismic inversion method and the geostatistical lithology inversion in Fig. 4, it can be seen that the geostatistical inversion has a higher resolution of the formation and a smoother interface of each lithology; from the comparison between the inversion results and the drilling lithology data, the geostatistical inversion results are in better agreement with the drilling data.

The enrichment area of sandstone gas is influenced by the lithology of the top and bottom of the coal seam, the thickness of the coal seam, and the regional distribution of fracture zones. Areas with well-developed fracture zones are more conducive to the transport of sandstone gas, making it stable and enriched in the sandstone. The thicker the coal seam, the more likely it is that sandstone gas will be enriched. The mudstone at the top and bottom of the coal seam has a confining effect on the sandstone gas. Combining the above factors, the sandstone gas sweet spot area of the #1# coal seam is divided as shown in Fig. 5.

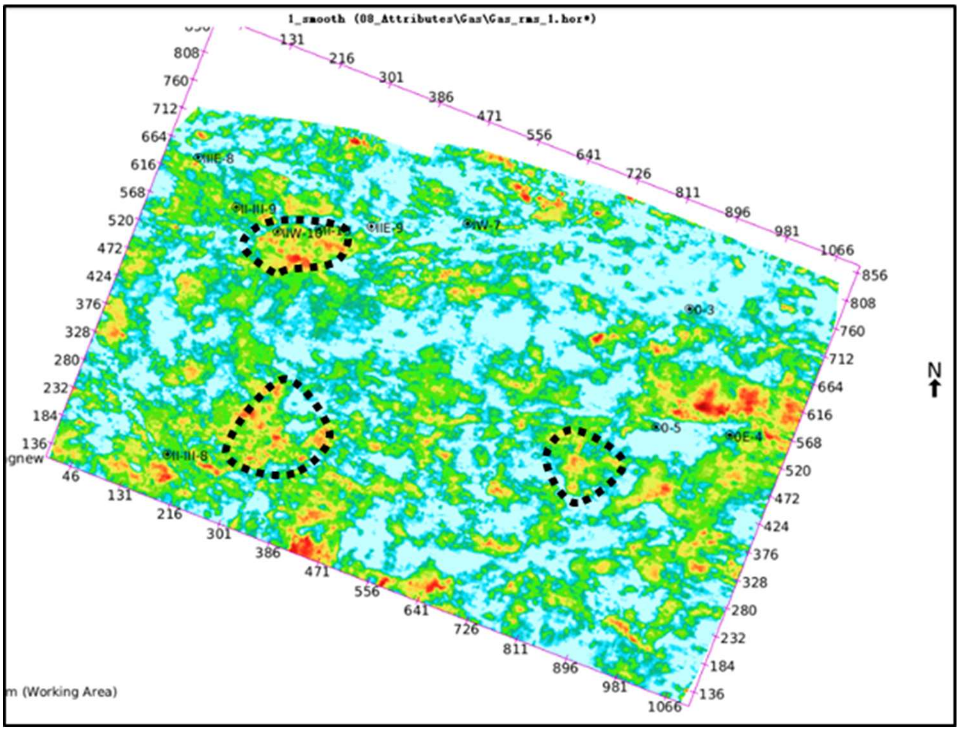

Fig. 5 Map of sandstone gas enrichment areas

5. Summary

(1) Fault interpretation based on seismic data and seismic attributes such as curvature bodies and coherent bodies are more accurate in predicting the distribution areas of fracture zones.

(2) Statistical inversion can predict the lithology of the top and bottom of the coal seam and the thickness of the coal seam more accurately.

(3) Based on the results of geostatistical inversion and fracture zone analysis, the sandstone gas enrichment areas can be predicted better, and the sandstone gas enrichment areas can be analysed from different perspectives, providing a new idea for the exploration and exploitation of sandstone gas.

Acknowledgments

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