

## Research Article

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# Seismic prediction of lithofacies heterogeneity in paleogene hetaoyuan shale play, Biyang depression, China

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**Abstract:** Shale lithofacies identification and prediction are of great importance for the successful shale gas and oil exploration. Based on the well and seismic fine calibration, extraction, and optimization of seismic attributes, root mean square (RMS) amplitude analysis is used to predict the spatial–temporal distribution of various lithofacies in the fifth organic-matter-rich interval, and the prediction results are confirmed by the logging data and geological background. The results indicate that in the early expansion system tract, dolomitic shale and calcareous shale were widely developed and argillaceous shale, silty shale, and argillaceous siltstone only developed in the periphery of deep depression. With the lake level rising, argillaceous shale and calcareous shale were well-developed, and argillaceous shale interbedded with silty shale or argillaceous siltstone developed in deep or semi-deep lake. In the late expansion system tract, argillaceous shale was widely deposited in the deepest sag; calcareous shale presented in eastern sag with belt distribution.

**Keywords:** seismic attributes, lithofacies heterogeneity, calcareous shale, shale oil storage, Biyang depression

## 1 Introduction

Lithofacies have been utilized in geology, especially in stratigraphy and sedimentology, for more than seventy years. In recent years, the great success of shale oil and gas explorations in North America has promoted researches on organic-rich shales, especially for the classification and identification of lithofacies and their sedimentary environments and reservoir characteristics. Recently, a limited number of lithofacies studies of shale reservoirs have appeared, but have been concentrated in the Barnett Shale of Texas. Loucks and Ruppel [1] focused on both depositional and diagenetic aspects of the Barnett Formation and recognized lithofacies on the basis of mineralogy, fabric, biota, and texture. Hickey and Henk [2] analyzed and summarized the lithofacies characteristics of various local rocks based on the geological background of Barnett Formation in North America. Singh [3] established Barnett Shale sequence stratigraphy based on observations of continuous cores and wireline logs, integrated with analytical data. Using advanced geochemical and NMR logs, Jacobi et al. [4] and Mitra et al. [5] recognized shale lithofacies and demonstrated their influence on the distribution of total carbon content (TOC) and porosity. The lithofacies of shales are closely related to their mineral compositions and organic matter contents, which will directly influence their hydrocarbon generation and reservoir capacities, as well as the rock mechanical properties [6]. Therefore, the identifications and predictions of lithofacies have become increasingly important for the geological evaluations and regional selections within the shale gas and oil explorations.

Data of X Ray Diffractions (XRD) and thin sections can be applied to identify the shale lithofacies at the core-scale. The well-scale lithofacies could be identified by establishing a quantitative relationship between the core-scale lithofacies and conventional log curves, using the multivariate statistical methods of principal component analysis, cluster analysis, and discriminant functions, as well as the artificial intelligence algorithms of

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neural networks and fuzzy logic [7,8]. The specific seismic attributes can qualitatively reflect the petrophysical properties, and thus the geophysical methods based on seismic attributes can also be applied to predict lithofacies distribution [9,10]. In addition, a more accurate and reliable prediction of the lithofacies can be achieved through the combination of seismic attributes with logging and geological data. For example, Wang and Carr [11] established a 3D model of Marcellus shale lithofacies by the sequential indicator simulation on the basis of 3D seismic, sedimentary environment, sequence stratigraphy, logging curves, and so on and revealed the spatial-temporal distribution of lithofacies. Zhang [12] used the combination of seismic attributes and geological parameters to realize the plane prediction of shale facies in the lower Sha 3 Member of Bonan depression.

The Paleogene Hetaoyuan Formation shale in Biyang depression is widely developed with large thickness and high abundance of organic matter, indicating great advantages for the exploration and development of shale oil. However, to date, due to the more heterogeneity of shale and less core data, there is still a lack of detailed research on the distribution of the shale lithofacies. In this case, it is particularly important to study the lithofacies using seismic attribute data.

## 2 Methods

This article presents the lithofacies prediction by means of seismic reflections and attributes, in order to describe the lithofacies heterogeneity of the fifth organic-matter-rich interval (ORI 5) in the study area, to predict the lithofacies at a region scale through seismic attributes, and to analyze the spatial-temporal distribution of the various lithofacies and its effect on shale oil storage.

### 2.1 Study area and geological settings

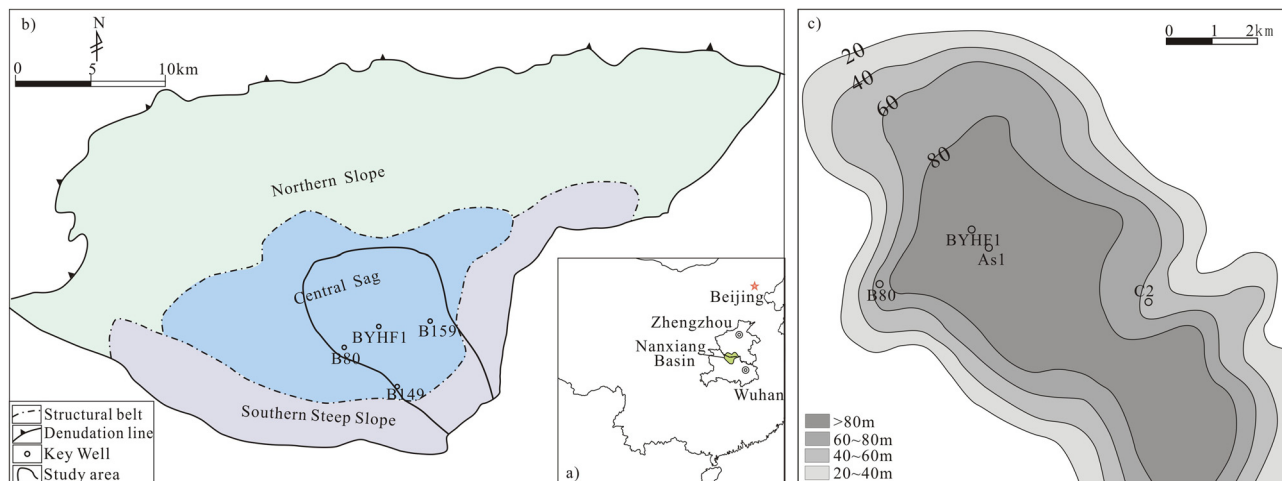
The Biyang depression is a half graben-like depression as a sub-tectonic unit in the eastern Nanxiang Basin (Figure 1a and b). The depression underwent three tectonic deposition stages: the Late Cretaceous and Paleogene initial-rifting, the Eocene and Oligocene main-rifting, and the post-rift depression [13]. The Paleogene in the study area developed from bottom to top Liaozhuang Formation, Hetaoyuan Formation, Dacangfang Formation, and Yuhuangding Formation.

The Hetaoyuan Formation is the main exploration target stratum, which can be further divided into He-3, He-2, and He-1 Members from bottom to top. According to seismic, logging, and core data, combined with tectonic evolution and climate change characteristics in this area, He-3 Member is divided into four third-order sequences; it contains major reservoir and source rocks [14].

The Paleogene Hetaoyuan Formation shales in the Biyang depression are widely developed with large thickness and high abundance of organic matter, being of great advantage for the exploration of the shale oil and gas. However, due to the strong heterogeneity of shales but limited core data, detailed researches on the shale lithofacies distributions are scarce. By means of multiple regression analysis, 73 wells in the study area were evaluated for shale organic carbon content logging, and the organic-rich shale segments were identified and their thickness was counted, thus the thickness contour map of organic-rich shale formation was compiled. Six ORIs have been divided by the standards with the TOC > 2%, the single layer thickness >10 m, and the continuous shale layer >20 m (with interbedded sandstone thickness <3 m). Taking an example from the fifth organic-matter-rich interval (ORI) in the He-3 Member of the Paleogene Hetaoyuan Formation, the ORI 5 developed during the expanding system tract (EST) of sequence III is the main exploration target for shale oil, with the thickness of 23.5–145 m (Figure 1c), the buried depth of 2,150–3,195 m, and the TOC content of 1.49–4.35% (avg. 2.44%).

### 2.2 Seismic attributes analytic technique

Seismic attributes are metrics that reflect seismic wave geometry, kinematics, statistics, or dynamics characteristics derived from pre-stack or post-stack seismic data and transformed by various mathematical algorithms. Seismic attribute analysis technology is to transform these metrics into reservoir lithology, physical properties, oil-bearing properties, and other parameters, which can be used to predict reservoir lithology and reservoir characteristics and carry out physical property changes, fluid motion, and other research. Commonly used seismic attributes include root mean square (RMS) amplitude, reflection intensity, instantaneous frequency, arc length (AL), coherence cube, wave impedance, etc. [15–18]. The seismic attribute parameters reflecting the lithology characteristics of the formation mainly include amplitude, waveform, frequency, phase and correlation analysis, energy, reflection intensity, etc.



**Figure 1:** (a) Sketch map showing position of the Nanxiang Basin; (b) structural units of the Biyang depression and location of study area (BYHF1 is the first pilot test well of shale in SINOPEC, China; it is a horizontal exploratory well of continental shale oil and gas. “BY” is the phonetic abbreviation of Biyang shale gas; “HF” refers to horizontal well fracturing, which is the abbreviation of “Horizontal” and “Fractured”); (c) isopach map showing distribution of the ORI 5 in Biyang depression (after drilling wells data in internal reports).

The early seismic attribute analysis is mainly based on single attribute analysis. Because some attributes are not one-to-one correspondence with geology, the analysis results often have multiple solutions. Therefore, multiparameter comprehensive analysis, selection, and storage are usually needed. Seismic attributes related to layer earthquake prediction are preferably mutually verified for sensitive attribute parameters, thereby effectively avoiding single-parameter application risks and improving prediction accuracy. The application of seismic attribute analysis technology in reservoir prediction mainly includes the extraction, optimization, and analysis of seismic attributes.

### 2.2.1 Seismic attributes extraction

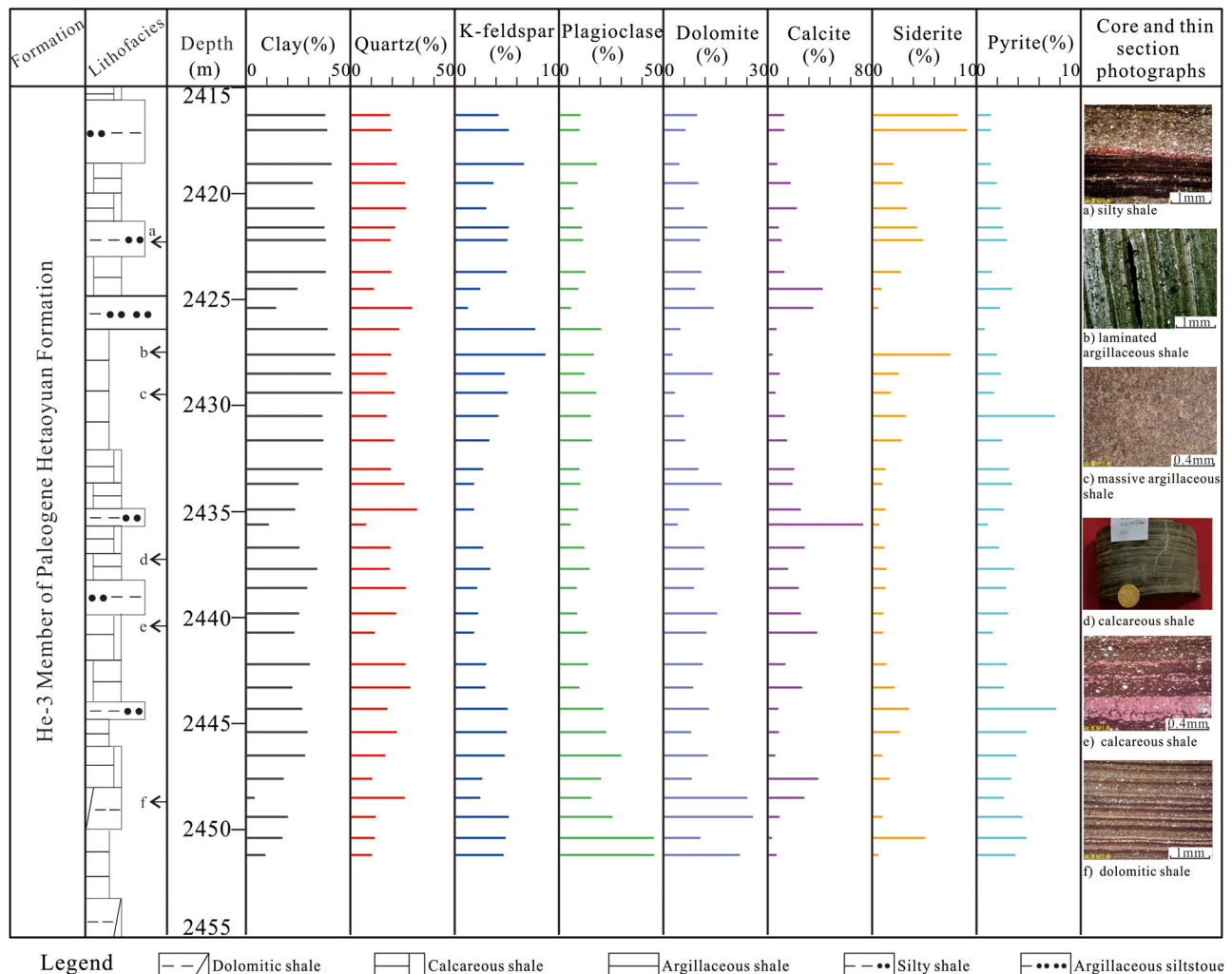
Generally, for a specific area, it is generally difficult to determine how and to what extent the change of the reservoir environment affects the seismic data. Therefore, before selecting the sensitive attribute parameters, it is necessary to conduct a general survey of the seismic attributes of the target interval and extract various attributes. This not only helps to filter sensitive parameters, but also to uncover some unexpected changes in properties.

In the research process, first of all, detailed interpretation and regional closure are carried out for each target interval, then the average reflection intensity, average peak amplitude, RMS amplitude, total energy (TE), average instantaneous frequency (AIL), maximum peak amplitude, maximum absolute amplitude, and other attribute parameters are extracted for comparison and discrimination,

and then the characteristics of the plane change are analyzed. This work laid the foundation for the selection of seismic attribute parameters that are suitable for the region to effectively reflect the law of reservoir plane variation. The layer attribute extraction is to extract various seismic information along the reflection interface or a certain time interface representing the target layer. It is a special way of extracting three-dimensional body attributes (selecting a certain time window length), and obtaining information that various attributes change laterally along the interface, and is often used to predict hidden oil and gas reservoirs related to thin reservoirs and micro-faults. The horizon seismic attribute is a time window along the target interval, and the correlation between the records in the window is analyzed by autocorrelation, power spectrum, Fourier spectrum, autoregression, and other statistical features to extract the relevant seismic attributes. The choice of predictive time window should not be too large or too small. If it is too large, the useless information is incorporated, which affects the prediction effect; if it is too small, the useful information cannot be completely added and the effect is also affected. In order to conduct a better study, this time, the interpretation of the fifth shale layer is set to 15 ms time window interval for attribute extraction.

### 2.2.2 Seismic attributes optimization

In the attribute extraction process, the typical drilling is selected first and the seismic attribute calibration standard template is established. The seismic attribute



**Figure 2:** The lithofacies, mineral content, core, and thin-section photograph of the ORI 5 in the Well BYHF1.

characteristics of different shale are qualitatively determined from the aspects of amplitude and energy. In this case, the well Anshen 1 is selected as the standard drilling, combined with the logging data and the single well logging curve. The shale facies of the 5th shale layer can be used to identify three types of mudstone, pure mudstone, silty mudstone and gray mudstone. Mudstone dolomite and silty fine sandstone can be seen in the upper part. Combined with drilling data and well seismic calibration, the RMS amplitude property, average reflection intensity property, and AL property are extracted.

### 3 Results

A total of 35 core samples and 60 thin sections are collected from ORI 5 of Well BYHF 1 with the depth of 2415.72–2450.15 m. On the basis of the whole rock and

thin-section analysis of core samples from Well BYHF 1 with a depth range of 2416.3–2451.2 m, the studied shales reveal lamellar and massive structures, with 3.30–46.40% clay, 6.70–31.80% quartz, 0–8.70% k-feldspar, 4.70–45.80% plagioclase, 2.10–25.80% dolomite, 1.70–73.30% calcite, 0–9.10% siderite, and 0.60–7.60% pyrite on average (Figure 2). Based on the nomenclature guidelines [19], the lithofacies were classified into four main groups, including silty shales, calcareous shales, dolomitic shales, and argillaceous shales (Table 1). The ORI 5 can be further divided into four parasequences based on the analysis of the conventional logs and wavelet transforms [20]: parasequence 1 dominated by dolomitic shales and argillaceous dolomites; parasequence 2 by calcareous shales and dolomitic shales; parasequence 3 by silty shales and argillaceous shales; and parasequence 4 by argillaceous shales and argillaceous siltstones (Figure 3).

Table 1: The characteristics of different lithofacies

Lithofacies	Laminated argillaceous shale	Massive argillaceous shale	Calcareous shale	Dolomitic shale	Silty shale
Color	Grey and dark grey	Dark grey, grey, and black	Dark grey, grey, and black	Grey	Grey and dark grey
Sedimentary structure	Horizontal bedding	Massive	Horizontal bedding	Horizontal bedding	Horizontal bedding
Mineral	43.6	47.9	26.9	22.6	29.5
content	35.5	36.2	33.5	38.6	51.8
(avg%)					
Storage spaces	9.8	7.5	26.7	5.9	7.9
	7.5	5.2	8.1	27.5	7.8
	Intercrystalline pores, organic pores, and interlaminated fractures	Intercrystalline pores, organic pores, and interparticle pores	Interlaminated fractures, organic pores, intercrystalline pores, and dissolution pores	Interlaminated fractures and intercrystalline pores	Interparticle pores, dissolution pores, and structural fractures
TOC (avg [%])	2.52	2.25	4.09	1.14	2.12
Porosity (avg [%])	4.7114	4.5552	5.9780	4.5658	5.1350
Permeability (avg [mD])	0.0069	0.0020	0.0096	0.0024	0.0035
Oil abundance (avg [%])	1.718	1.070	2.489	1.326	2.009

## 4 Discussion

### 4.1 Seismic predictions of the shale lithofacies

#### 4.1.1 The extraction and calibration of seismic attributes

Based on the interpretation of seismic horizons within the ORI 5, seismic attributes of RMS amplitude, TE, AIF, and AL were extracted by the horizontal slice method, and the relationship between the core lithofacies of Well BYHF1 and seismic attributes was established. The argillaceous shales and argillaceous siltstones/silty shales are characterized by high values of RMS, AL, and TE attributes and a medium-low value of AIF attribute. Calcareous shales and dolomitic shales show high-medium values of TE and AL attributes, a medium-low value of AIF attribute, and a low value of RMS attribute. Dolomitic shales and argillaceous dolomites are characterized by medium-low values of RMS and AL attributes, a high-medium value of AIF attribute, and a low value of TE attribute (Table 2).

The comprehensive comparison and calibration of different seismic attributes reveal that the RMS amplitude is relatively sensitive to the variable clay contents, which is viable for the lithofacies predictions. This time, the shale layer of the fifth shale beds is mainly extracted by the stratification of the stratigraphic slice. Considering that the fifth shale beds are located in the lake progressive system tracts, the T5-Mid horizon is added in the middle to more accurately reflect the change of the period. From bottom to top, it is divided into four cycles. The standard RGB color code is used in the process of attribute extraction, and the colors are gradually changed from red, yellow, cyan, blue, and purple, respectively, which represent the change of the attribute value from large to small (Figure 4). It can be seen from the RMS amplitude distribution map of the parasequence 1 in the fifth shale beds (Figure 4a) that the amplitude attribute value is mainly the medium-low values, and the high value area is only distributed in the north of the study area and gradually goes to the south to the cyan-blue. The color transition reflects that the shale in the study area is dominated by mudstone, with silty mudstone or lime (dolomitic) mudstone. Only near Well Bi 289 and Bi 371 in the north, there are more sands, which may be the interbedding of siltstone and mudstone. It can be seen from the RMS amplitude attribute map of parasequence 2 in the fifth shale beds (Figure 4b) that the distribution area of purple area, which has lower attribute value, becomes larger and the change of red area



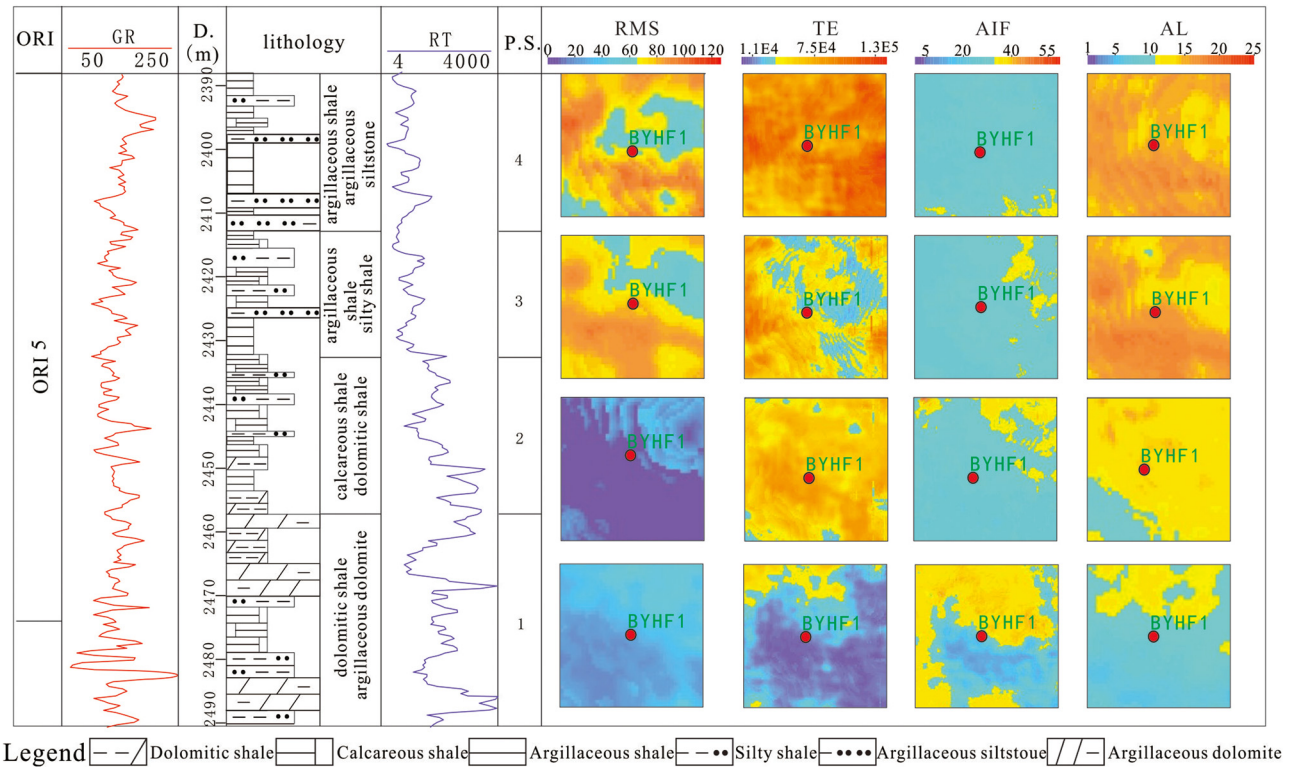


Figure 3: The lithofacies and seismic attributes calibration of the ORI 5 in the Well BYHF1.

is not obvious. The results of regional geological data and single well calibration show that the whole area is pure mudstone or limestone (dolomitic) mudstone, and the distribution range of siltstone is basically the same as that of the previous period. Compared with the previous period, the amplitude attributes value of parasequence 2 in the fifth shale beds has changed obviously, and the area with high value of yellow-red attributes has increased significantly, showing the characteristics of convergence in the northwest, southwest, and northeast directions towards the center of deep depression area (Figure 4c). It shows that the range of siltstone–mudstone interbedding in the study area has expanded, and the other areas are mainly mudstone with thin siltstone or limestone (dolomitic) mudstone. It can be seen from the RMS amplitude attribute map of parasequence 4 in the fifth shale beds (Figure 4d) that the total value of the study area is medium-low, and the high value area of the attribute, i.e., the red area, is obviously reduced, showing strip

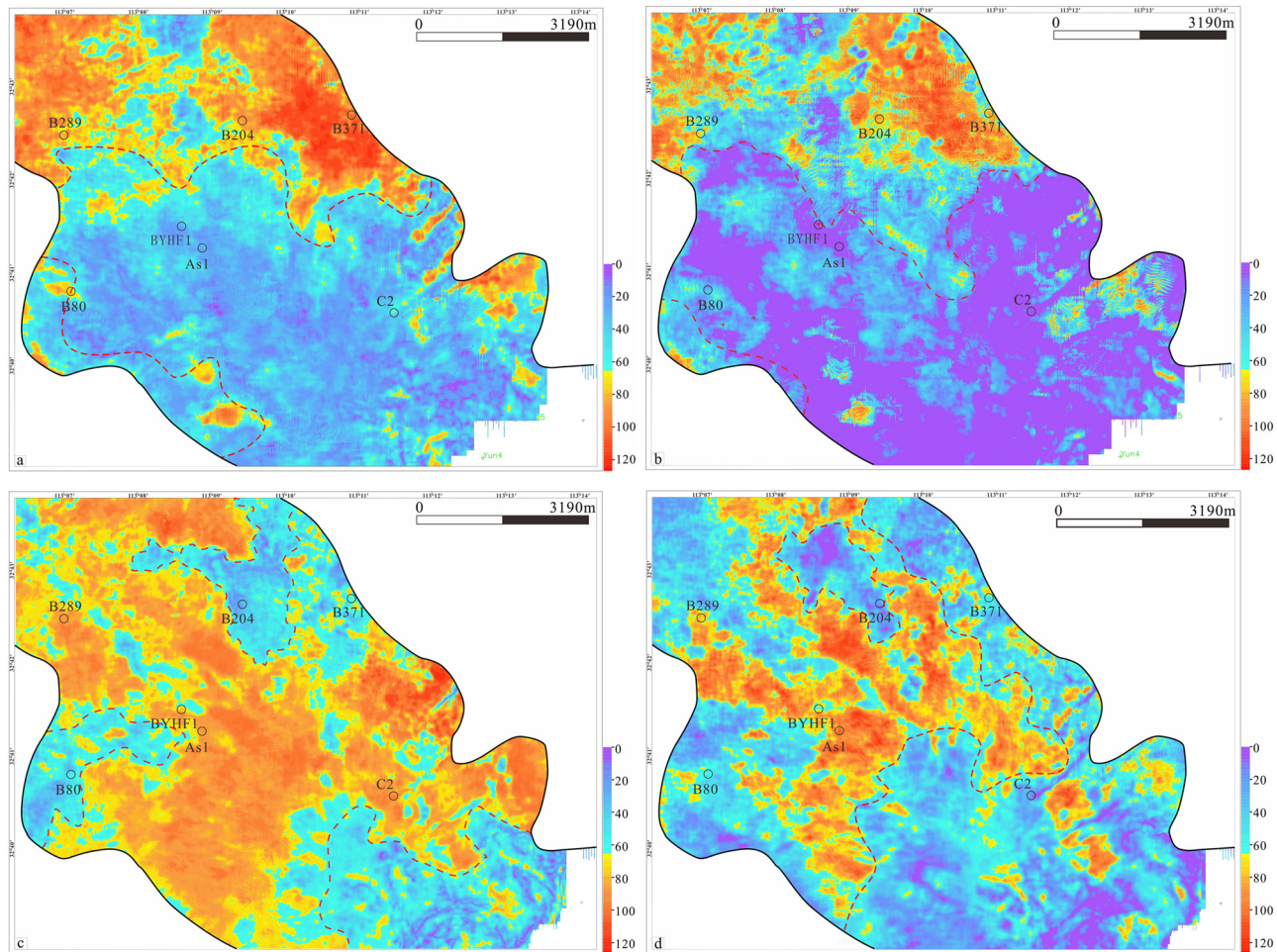
distribution, reflecting that, at this time, mudstone with limestone (dolomitic) mudstone deposits are dominant and siltstone content is less.

4.1.2 The spatial–temporal distribution of various lithofacies

In the early EST with relatively low lake-level, dolomitic shales and calcareous shales widely developed in the study area, while argillaceous shales, silty shales, and argillaceous siltstones developed in the periphery of deep depression areas (Figures 5a and b). With the lake level rising, the distribution of dolomitic shales decreases significantly. Argillaceous shales and calcareous shales developed in the northern and southeastern study area (Figure 5c). In the late EST, argillaceous shales were deposited in the deepest sag, while calcareous shales developed in the east and southeast of the sag (Figure 5d).

Table 2: The seismic attributes characteristics of different lithofacies

Lithofacies	RMS	TE	AIF	AL
Argillaceous shale and silty shale	High	High	Medium	High
Calcareous shale and dolomitic shale	Low	Medium to high	Medium	Medium to high
Dolomitic shale and argillaceous dolomite	Medium to low	Low	Medium to low	Medium to low



**Figure 4:** The lithofacies and RMS amplitude prognostic map of the ORI 5 in Biyang depression. ((a) parasequence 1 of the ORI 5 in Biyang depression; (b) parasequence 2 of the ORI 5 in Biyang depression; (c) parasequence 3 of the ORI 5 in Biyang depression; (d) parasequence 4 of the ORI 5 in Biyang depression.)

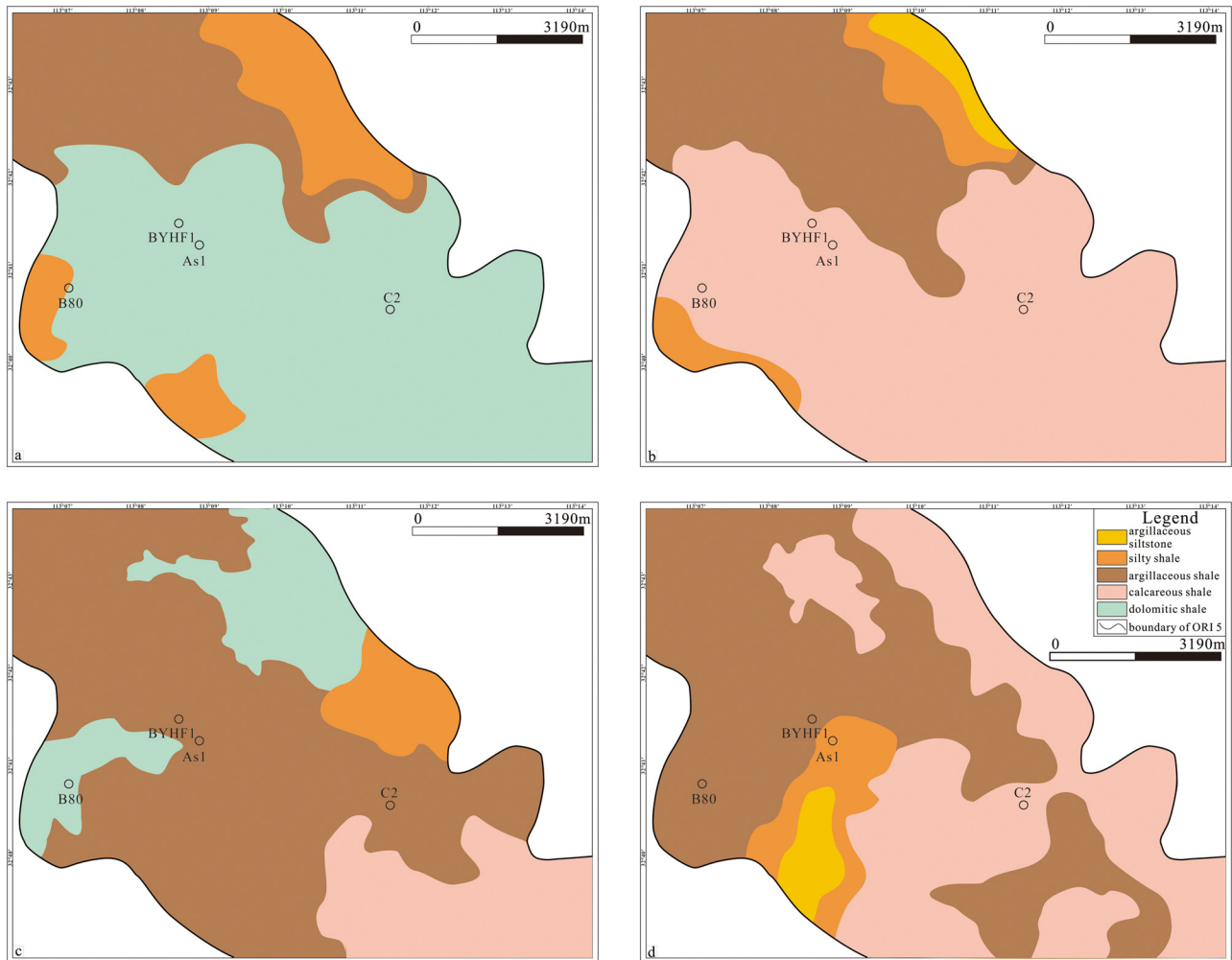
#### 4.1.3 Comparison between the prediction and the logging and geological data

During the lower ORI 5 when the climate was arid and hot with a low lake-level, calcareous shales and dolomitic shales widely developed in the study area, while argillaceous shales, silty shales, and argillaceous siltstones were confined in the periphery of deep depressions. During the lake level rising, argillaceous shales and calcareous shales developed in the study area with the decreasing carbonate content and increasing clay mineral content. Meanwhile, the enhanced supply of terrestrial materials leads to a farther extending of the braided river delta and favored the development of slumps and turbidite fans in the lacustrine. This is supported by the presence of argillaceous shales intercalated with silty shales/argillaceous siltstones. The above analysis indicates that the lithofacies prediction results are consistent with the geological background and

depositional environment in the study area. Meanwhile, the results are also consistent with that from the prediction by establishing logging interpretation models of clay minerals, silt, and carbonate minerals on the basis of regression analysis between core sample XRD data and corresponding log curves [20].

#### 4.2 Effect of reservoir characteristics on shale oil storage

Thin sections, cores, and SEM observation indicate that interlaminated fractures and dissolution pores are common in all lithofacies; intercrystalline pores commonly occur in calcareous shales and dolomitic shales, while interparticle pores and organic pores are well-developed in silty shales and calcareous shales, respectively. The experiment results show that calcareous shales and silty shales have relatively



**Figure 5:** The lithofacies distribution of parasequences of the ORI 5 in Biyang depression, which is based on the RMS amplitude analysis. ((a) parasequence 1 of the ORI 5 in Biyang depression; (b) parasequence 2 of the ORI 5 in Biyang depression; (c) parasequence 3 of the ORI 5 in Biyang depression; (d) parasequence 4 of the ORI 5 in Biyang depression.).

higher porosity and permeability, followed by argillaceous shales, and dolomitic shales have the lowest. Meanwhile, calcareous shales have the largest amount of oil (avg. 2.489%); the second highest is silty shales, with an average of 2.009%. In contrast, argillaceous shale and dolomitic shales have the lowest oil abundance.

Due to the high TOC content, good porosity and permeability, and well-developed pores and fractures, particularly organic and intercrystalline pores, calcareous shales have the highest shale oil storage capacity. In addition, the lithofacies association of argillaceous shales with silty shales interlayers has higher silica content and contains retained oil in the shales and migrated oil in the interbedded silty laminae, resulting in high productivities after hydraulic fracturing. These have been demonstrated by the exploration practice in marine Jiaoshiba shale of Sichuan Basin, lacustrine

Zhangjiatan Shale of Ordos Basin, and Kimmeridge Clay Formation of the North Sea [21–23]. Therefore, calcareous shales and the lithofacies association of argillaceous shales with silty shales interlayers are key exploration targets for shale oil.

## 5 Conclusions

1. Through the verification of logging and geological data, we can see that the lithofacies analysis based on seismic attributes is reliable in predicting the lithofacies plane distribution of the fifth shale beds of Eh3 in Biyang Depression. This method can effectively predict the spatial-temporal distribution of shale facies in new work areas with or without wells.



2. The prediction results reveal that the early lime shale or dolomitic shale in the lake progressive system tracts is widely developed in the deep depression, and the clay shale, silty shale, and argillaceous siltstone are only distributed in the periphery of the deep depression. With the rise of lake level, clay shale and lime shale are mainly developed in the whole area. In the semi-deep lake-deep lake area, clay shale with silty shale (argillaceous siltstone) interlayers can be seen. The late period of the lake progressive system tracts is dominated by clay shale in the deep depression, and the lime shale get distributed in strips in the eastern part of the study area.

Actual test results indicate that the method of seismic attributes analytic technique is feasible to predict the spatial distribution of various lithofacies, and it has certain reference significance for the prediction of complex lithofacies reservoirs in other areas.

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