Study on the application of seismic sedimentology in a stratigraphic-lithologic reservoir in central Junggar Basin

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Abstract. This paper discusses the research idea of description for stratigraphic-lithologic reservoir based on seismic sedimentology methods. The sandstone reservoir of Jurassic XiShanyao Formation in Junggar Basin is studied according to the theory and approaches of seismic sedimentology. By making full use of borehole data, the technologies of layer correlation based on the stratigraphic sequence framework, the forward seismic modeling, the stratal slicing and lithologic inversion are applied. It describes the range of denudation line, the distribution characteristics of sedimentary facies of the strata, the vertical and horizontal distribution of sand bodies and the favourable oil-gas bearing prospective area. The results shows that study area are dominated braided delta deposition including underwater distributary channel and distributary bay microfacies, the nip-out lines of the formation are northeast to southwest from north to south, the second Middle Jurassic sand body is the most widely distributed one among three sand bodies, the prospective oil-gas bearing area located in the south part and around the YG2 well area. The study result is effective on the practice of exploration in study area.

1. Introduction

The theory of seismic sedimentology by Zeng Hongliu is first proposed in 1998, which is a subject aims to study the sedimentary rocks and the formation process using seismic data [1-2]. It is a new technology using of well logging and seismic data to study sedimentary evolution, comprehensive geological interpretation mainly for stratigraphic-lithologic reservoirs. In recent years, many good results of oil and gas exploration and development have been obtained in the delta, meandering river, braided river, lacustrine gravity flow sedimentary system and carbonate reservoirs of the reef in the continental rift basins in eastern China [3-8], based on seismic sedimentology technology carried out by many scholars. However, few studies have carried out for stratigraphic-lithologic reservoirs description in central region of Junggar basin. In this paper, the thin sandstone reservoir of the Jurassic formation is studied based on the theory and method of seismic sedimentology by using the high resolution 3D seismic data in the paleo-uplift area of the middle Junggar Basin. The reservoir has the following features, the layer is deeply buried, and the thickness of single layer is thin which is controlled by structure type, unconformity surface and sedimentary microfacies. Specifically, this study aims to:(1) analysis the sequence division and the small layer correlation model of deep braided river delta sedimentary sand body; (2) explore the application of forward and inversion method of sand correlation and reservoir prediction based on seismic sedimentology, forming a set of ideas and
methods for reservoir prediction and hydrocarbon detection in study area; and (3) enrich and develop the research results of seismic sedimentology.

2. Geological setting
The tectonic units in the middle part of the Junggar basin include the central depression belt and the central uplift belt which extend in N-E direction. From early Permian to Jurassic period the central part is a large basement inherited paleo-uplift named as “Che-Mo paleo-uplift”. The study area is located in the south wing of the uplift and the main exploration target is the Middle Jurassic (J2x) sandstone deposited in fluvial, delta, shore meare and shallow lacustrine facies. By the influence of Yanshan movement, the evolution of Che-Mo paleo-uplift reached its peak in the Middle Jurassic. At that time, the paleo-uplift has become the main area for oil and gas accumulation from hydrocarbon generating sags of both sides and created conditions for lithologic trap, stratigraphic pinch out trap and stratigraphic drape trap \[9\]. Since the Paleogene, affected by the Himalayan movement, the Junggar basin was tilted to the north, and the Che-Mo paleo-uplift was transformed into a monoclinic structure from the north to the south \[10\]. The oil saturation of reservoirs near the north wing is always low because of strong structure deformation. On the contrary, the structure deformation in study area located in the south wing is weak, which is favourable to retain a wide range of the original strata denudation lithologic oil and gas reservoir. YG1, YG2 and YG6 three exploratory wells reveal the upper and middle Jurassic stratigraphic traps and stratigraphic-lithologic traps controlled by the Cretaceous bottom unconformity. However, because of the target layer buried deeply, the thickness of the single layer is thin, it is difficult to identify the stratigraphic-lithologic traps and predict the reservoir.

3. Layer correlation in isochronous stratigraphic framework

3.1. Stratigraphic and sequence characteristics
In the study area, the J2x formation is partly eroded and the residual thickness is 180 m to 200 m. It is unconformable contact with the overlying the lower Cretaceous Qingshui River Formation (K1q). The lower section of J2x is consisted with grey fine sandstone, grey mudstone, argillaceous sandstone and siltstone with black carbonaceous mudstone and coal seams inter-beded, deposited in the braided river delta plain and swamp. The J2x-1 sand group is one of the oil and gas reservoirs developed under the coal layer. The upper section of J2x is mainly characterized by braided river delta, which is consisted with grey conglomerate sandstone, pebbly fine sandstone and red brown mudstone, including J2x-2 and J2x-3 two sets of oil sandstone reservoirs.

The establishment of isochronous stratigraphic framework is not only the essence of sequence stratigraphy, but also the prerequisite for the application of techniques of seismic sedimentology \[11\]. According to the regional sequence stratigraphy studies \[12-13\], combined with drilling, logging and seismic data the J2x can be divided into 2 third order sequences of SQ I and SQ II, within a sequence can identify the lowstand (LST), transgressive (TST) and highstand (HST).

3.2. Layer correlation and forward modeling
Based on the study of sequence stratigraphy, this paper establishes the isochronous stratigraphic framework, under the hierarchical order and the system domain as the unit by the method of combining geological and seismic data. In the middle and lower part of the Xishanyao Formation, there are three sets of coal seams and can be used as the correlation marker layer because of the wide distribution, relatively stable lithology and thickness and obvious characteristics in logging curves. The bottom of the Cretaceous unconformity is the regional marker, which is the top boundary of the third order SQ II (Figure 1). There is a set of thick bedded conglomeratic sandstone in the bottom of Cretaceous of the well YG1 and YG6, which can be recognized easily as the resistivity curve is characterized as box. The YG2 bottom conglomeratic sandstone is divided into two beds, and it is more reasonable to define the boundary of the unconformity at upper bed by seismic horizon calibration.
The correlation results show that the J2x-1 sand group underlying the coal layer developed in HST at the bottom of the sequence SQ I which is progradational reverse grain size in ascending order. A sand body developed at the top of sequence SQ I only can be found in well YG1. J2x-2 and J2x-3 sand group which developed in TST can be identified from top to bottom of the SQ II. J2x-3 sand group is partially eroded in well of YG1 and YG2, however, it is well developed in YG6 and can be divided into 4 retrogradational sand bodies which turn thin from top to down.

In order to verify the accuracy of sequence division, sand body correlation, the well-to-seismic calibration, and to further test the reliability of interpretation scheme, the seismic forward modeling is carries out in this study. The seismic response characteristics of sand bodies with different scales in the forward model can provide the basis for the identification of stratigraphic-lithologic traps. According to the lithological features of the target layer, the method of diffraction scanning wave equation is used to generate the seismic forward model (Figure 2).

Seismic forward simulation shows that the reflection characteristics of the regional markers of Xishanyao Formation is obvious and the bottom boundary of the coal layer corresponding to the strong reflection interface from negative to positive. The angular unconformity between the bottom boundary of Cretaceous system and the underlying strata is also a strong reflection in the seismic profile which shows normal polarity, low frequency, good continuity and easy to trace. There is two
wave reflection response to two sets of sand group $J_{2x-2}$ and $J_{2x-3}$ under the unconformity surface. All these characteristics further verify the rationality of the interpretation and stratigraphic correlation.

4. Comprehensive application and analysis of seismic sedimentology

4.1. Analysis of denudation line and distribution of sedimentary facies

4.1.1 Prediction of the denudation line. The stratigraphic traps are related to the strata denudation in this area so it is an important basic work to describe the distribution range of denudation line accurately for the oil and gas exploration. Seismic petrology and geomorphology is the core content of seismic sedimentology [14]. The stratal slice is a very effective method to describe the geological characteristics of fault and denudation line. Coherent attribute is not only usually used to study fault system, but also to characterize the denudation line. The dip coherence is a new generation of coherent technology which can be used to analyze the local variation of the seismic phase axis, and further improve the resolution [15].

After a basic understanding of erosion line by using the amplitude of time slice and the well correlation with the seismic interpretation, the stratal dip coherence slice of the Cretaceous bottom unconformity is extracted to accurately describe the horizontal distribution of denudation line. Figure 3 is the coherence slice map, in which the denudation line of three sand groups ($J_{2x-1}$, $J_{2x-2}$ and $J_{2x-3}$) and the coal layer are identified by the un-coherence black bands. In study area, the strata of Xishanyao Formation is eroded from north to south and northwest to southeast in turns which reflects the uplifting process from northwest to southeast of the Che-Mo paleo-uplift during the Yanshanian period.

![Figure 3](image)

**Figure 3.** The stratal dip coherence slice and prediction of erosion line

4.1.2 Study on the distribution of sedimentary facies. In the stratigraphic sequence, the change of sedimentary facies is mainly manifested as changes in lithology and sedimentary structure. The technology of studying sedimentary facies by seismic sedimentology is based on the single well facies through the core and logging data and the analysis of seismic reflection structure, amplitude, frequency and other information. Previous research [16] shows that the seismic attributes of amplitude domain and frequency domain are well correlated with lithology, fluid characteristics and stratigraphic sequence, which can be used to predict the distribution of sand bodies.

In this paper, the study on the distribution of sedimentary facies in the upper strata of SQ 1 through the analysis of the seismic amplitude slice of the coal layer in Xishanyao Formation, based on the analysis of seismic facies and the sedimentary facies of individual well. The result shows that the strata overlying the coal layer in SQ 1 are mainly composed of braided river delta facies including two microfacies of underwater distributary channel and distributary bay. Shallow lacustrine deposits are distributed in the south area and the delta sand in the middle. It is predicted that northeast area is the
braided river delta plain facies in which the sand body thickness and grain size are relatively large, because of the reflection strength and amplitude increased gradually.

4.2. Prediction of sand bodies distribution by seismic inversion

The technologies of 90° phase inversion, stratal slice and interpreting with frequency are the three key technologies used in previous sedimentology research work. In this paper, the seismic inversion method is used to determine the impedance information of sandstone, and characterize the spatial distribution of sand bodies.

In consideration of the depth of the target layer in the area is about 6000 m, the frequency of seismic data is low (about 30 Hz), and the main sand body is thin (5 m to 10 m), in this study the method of progressive reservoir prediction is used. Firstly, perform the well-constrained impedance inversion to identify the large set of sand bodies and the reflective interface with significant difference in impedance (such as unconformity surface, coal seam, etc.). Secondly, lithology inversion is carried out in order to further identify and predict the thin sand bodies, under the constraint of seismic attributes, impedance and logging information.

The analysis of the relationship between lithology and impedance by using logging data shows that the impedance characteristics of the three wells are very different. The sand body in the YG1 well shows low impedance, the corresponding layer of YG6 well is high impedance. Therefore, the mudstone and sandstone can not be distinguished effectively by the impedance. It is found that the natural gamma ray (GR) log is sensitive to sand and shale by the analysis of three well logging curves. Therefore, the GR inversion constrained by geologic model and seismic is carried out based on the GR curve, combined with seismic attributes and impedance information. In the GR inversion profile the lithology of the three wells can be well identified (Figure 4).

![Figure 4. GR inversion profile for Xishanyao Formation](image)

The single sand body can be traced in the GR inversion profile, then, the distribution characteristics of the sand bodies in the plane can be obtained.

4.3. Prediction of potential development area by seismic and geological information

As previously mentioned, it makes use of the sedimentary geological information of the well and stratal slice to the identification of denudation line and description of sedimentary facies. However, the data has not been combined with the hydrocarbon geological information. The prediction of potential development area should comprehensively use the seismic sedimentary description results, hydrocarbon-bearing features of reservoirs, structural features and other geological information. This paper uses the multi-attribute hydrocarbon detection technology to predict the favorable areas based on the description of reservoir sedimentary and structural characteristics.

First of all, more than 60 seismic attributes are extracted such as root mean-square amplitude, average reflection energy, average instantaneous frequency, weighted average frequency, cut-off
frequency energy, and so on, and the attributes related hydrocarbon, stratum and lithology and lithofacies are selected. And then, the mathematical method is used to reduce the dimension of seismic attributes according to the calibration with the interpretation of wells to achieve the optimal combination. Finally, the eight kinds of attributes are optimized including the amplitude, frequency, velocity, attenuation, waveform and time, and so on. They are independent and the correlation coefficient between them is below 0.2. It enhances the correlation between attributes and geological information and increases the reliability of prediction results. Figure 5 shows the potential development area integrated the prediction of hydrocarbon-bearing, sand body thickness by GR inversion, structure and denudation line characterization. It can be seen that the thick sand bodies located in the structure slope belt where is the most favorable hydrocarbon-bearing area (red colour zone). Therefore, there is a good correlation between the predicted results which reflects the characteristics of lithologic-stratigraphic reservoirs. The southeast slope is the most favorable hydrocarbon-bearing area and the second is the YG2 well area. The monitoring well YG8 with great oil and gas show is located in the predicted sand body distribution range which verifies the prediction results are reliable.

![Figure 5. The synthetic prediction of favorable hydrocarbon-bearing area](image)

5. Conclusions
It is an effective way to study the spatial distribution of reservoirs by using the theory and method of seismic sedimentology. Sequence division, well-to-seismic calibration, layer correlation in the isochronous sequence stratigraphic framework is the important basis for the study of seismic sedimentology. The seismic forward modeling can be used to verify and modify the sequence division and layer correlation.

The paleo-geomorphology in late Jurassic and sedimentary facies distribution of the Middle Jurassic strata is predicted accurately by the dip coherence and amplitude slice. The coal layer and the three oil-bearing sand bodies are denuded from northeast to southwest which reflects the uplifting from northwest to southeast process of Che-Mo paleo-uplift in Yanshan period. The strata above the coal layer is braided river delta deposits, which mainly consist of two microfacies of subaqueous distributary channel and distributary bay.

The lithology inversion technique can make up for the problem of the resolution of the logging constrained impedance inversion. According to the results of the GR inversion, the thickness and the distribution range of the three oil-bearing sand bodies in the study area are described. Based on the calibration of oil and gas information in wells, the technique of stratal slice can be applied to the hydrocarbon detection of reservoirs. The results show that the structure slope belt is the most favorable hydrocarbon-bearing area, which is consistent with the characteristics of sand body distribution predicted by GR inversion. This method extends the application of seismic sedimentology, and shows its effective application in comprehensive reservoir evaluation.
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