minerals

*Article*

# Study on the 3D Sedimentary Characteristics of Sandstone Type Uranium Reservoir Based on 3D Seismic Attribute

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**Abstract:** It is of great significance to quickly obtain the sedimentary characteristics of sandstone type uranium reservoir for guiding prospecting sandstone type uranium deposits. In order to solve this problem, a method based on the extraction and optimization of 3D seismic attributes is proposed. The target stratum of the uranium reservoir is accurately located by using the gamma and acoustic logging data together. The well seismic calibration for the uranium reservoir is carried out by making full use of the logging and seismic data. The high-density fine horizon tracking is implemented for the top, bottom, and obvious adjacent interfaces of the target stratum. Various seismic attributes along the target interface are extracted using stratigraphic slices. Analyzing the consistency between the results obtained by various seismic attributes and drilling data, the one that can best characterize the sedimentary characteristics of the target uranium reservoir is selected as the optimal seismic attribute. The sedimentary and its evolutionary characteristics of the target uranium reservoir are obtained by extracting the above optimal seismic attribute. A case study shows that we can obtain the 3D sedimentary characteristics of the target uranium reservoir fast and efficiently using the method based on the 3D seismic attribute. They can be used for providing important reference information for the exploration of sandstone type uranium deposits.

**Keywords:** 3D seismic data; seismic attribute; sandstone type uranium deposits; uranium reservoir; sedimentary characteristics



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## 1. Introduction

As a strategic clean energy source, sandstone-type uranium deposit is of great significance to the utilization of nuclear energy in the world [1–3]. It is the second richest uranium ore and exists in different regions of the world [4–8]. As a sedimentary type mineral, the sedimentary element is one of the most important control factors in the formation of sandstone-type uranium deposits [9–12]. Some researchers pointed out that the sedimentary environment is an extremely important part of the research field to sandstone-type uranium deposits [13–16]. It plays an important role in the search for in-situ leachable sandstone-type uranium deposits. Therefore, how to extract the sedimentary elements accurately has important theoretical and practical significance to the study of the metallogenic mechanism of sandstone-type uranium deposits.

At present, in the study on the sedimentary characteristics of sandstone-type uranium deposits, the most common methods include the method based on the analysis of plane sedimentary facies [17], the method based on the analysis of sedimentary facies of drilling data [18], the method based on the analysis of sedimentary facies in well and in the plane [19] and the method based on the analysis of resistivity in well [20]. Among the above four methods, the first method has the ability to obtain the plane sedimentary facies distribution map of a certain stratigraphic interface in the uranium reservoir. It can be used for analyzing the relationship between sedimentary characteristics and uranium mineralization and predicting the prospect of ore production [17]. By analyzing a certain number of core samples, a large number of researchers adopt the second method to obtain the sedimentary characteristics of the target uranium reservoir and its relationship with uranium mineralization. Their results are helpful for the mining prospecting [18]. Using the third method, we can also obtain the sedimentary system map and drilling profile of the target uranium reservoir. The results can be used to get the relationship between the sedimentary environment and the development of sandstone-type uranium deposits [19]. Based on the fourth method, we use the planar distribution of the apparent resistivity to study the sedimentary characteristics in the plane for sandstone-type uranium deposits [20]. In general, these methods have the ability to obtain the sedimentary distribution characteristics of sandstone-type uranium deposits on a plane or section directly. The methods and techniques for the study of the sedimentary characteristics of uranium reservoir can also be provided by them [17–20]. However, they all directly or indirectly require the analysis of sedimentary features in well or the inter-well interpolation. Obviously, they can only get the sedimentary characteristics of a formation in a well or a small area around the well. Due to the need for inter-well interpolation, the planar sedimentary characteristics obtained by the above methods are very unreliable when the drilling and logging data are scarce. In addition, it is difficult to achieve good results or even unable to be carried out by using them in new exploration areas with few or without wells.

Different from the above four methods, the method based on the 3D seismic attribute has the ability to penetrate deep into the interior of ore bodies and obtain the sedimentary characteristics in 3D [21,22]. The drilling and logging data are not necessary, and they are only the verification information for determining sedimentary facies. The researches on the sedimentary characteristics based on the 3D seismic dataset have been extensively applied in the exploration and development of oil and gas. The seismic sedimentology has been developed based on them [23]. It is a science of studying the sedimentary characteristics of a stratum through the extraction and optimization of seismic attributes [21,22]. Appropriate seismic attributes are not only directly sensitive to the geological structure but also sensitive to the properties of the reservoir in the target stratum. It helps us to determine the sedimentary environment of the target stratum and further infer its characteristics or properties. The sedimentary environment of Clastic reservoirs can be described finely by seismic attributes. In the 1970s, seismic attributes were paid wide attention to with the gradual development of seismic stratigraphy. At the same time, a new research field of seismic geomorphology has also been produced with the combination of seismic attributes and sedimentation. The workflow of seismic geomorphology is to comprehensively use seismic attributes, time slices, interface slices, stratigraphic slices for drawing the maps of geological bodies that have occurred in a specific geological time. Normally, stratigraphic slices are obtained by picking the top and bottom boundaries of the target stratum and dividing their thickness equally. These slices are all proportional to the two boundaries. They correspond to the same geological time.

In particular, the stratigraphic slices obtained by the extraction of 3D seismic attributes can be used for imaging the sedimentary environment of a certain stratum (such as the distribution of river channels). Some obvious effects have been got by this technique in the Mesozoic and Paleozoic stratum [23]. The petroliferous basins with a large amount of sandstone are usually covered with 3D seismic data. 3D seismic attributes have unique advantages in describing the sedimentary environment of Clastic reservoirs, where most of the sandstone-type uranium deposits are formed. Therefore, we use the method based on the extraction and optimization of 3D seismic attributes to study the 3D sedimentary characteristics of sandstone type uranium deposits in this paper. First, we have to do high-density seismic horizon tracking. It is the basis for the extraction of stratigraphic slices. Then, we extract and optimize the stratigraphic slice of the 3D seismic attribute for the target uranium reservoir. We also have to establish the method to describe the sedimentary environment and its evolution for the target uranium reservoir.

In fact, the statistical data from the International Atomic Energy Agency in 2013 [24] show that 89% of sandstone-type uranium deposits are located in petroliferous basins. For the exploration and development of oil and gas, these basins are usually covered by abundant 3D seismic datasets. By coincidence, similar to oil and gas, sandstone-type uranium deposits are also sedimentary minerals. Therefore, these 3D seismic datasets can be used to study the sedimentary characteristics of sandstone-type uranium deposits based on the rapid development theories and methods of sedimentary seismology in the oil and gas field. A new way is opening up to explore oil and uranium simultaneously by using these historical 3D seismic datasets.

In the current research of sandstone-type uranium deposits, there are some studies based on 3D seismic data [25–34]. Among them, most of the research works focus on tectonic characteristics [25–28]. Dentith and Randell [29] in 2003 analyzed the geophysical characteristics of the sandstone-type uranium deposits in South Australia and North America. White et al. [30] in 2007 gave an overview of seismic methods for uranium exploration. Recently, Panea [31] 2019 showed some results obtained by the shallow seismic reflection investigation of unstable sedimentary deposits in the Dăneasa Area, Romania. Darijani et al. [32] in 2020 presented a clustering and constrained inversion of seismic refraction and gravity data for overburden stripping and applied it to the uranium exploration in the Athabasca Basin, Canada. Wu and Huang [33] report on a case study of the indications of sandstone-type uranium mineralization based on 3D seismic data. However, the above studies [25–33] are rarely related to the sedimentary characteristics of sandstone type uranium deposits. Sun et al. [34] in 2020 reported a 3D field dataset example about the reservoir characterization of sandstone type uranium deposits. In this work, the method for getting the sedimentary characteristics of sandstone type uranium deposits based on 3D seismic data was mentioned. However, the detailed theoretical method and technical process were not studied and stated carefully. A large number of works have shown that seismic slices are a good tool for studying the structure of the sedimentary system [23]. In the extraction of seismic attributes, slices along with the time and the interfaces are now the most common methods. However, in the sedimentary facies analysis, these two methods have some limitations. The slice along with time is the geological time interface only when the geological interface is in a horizontal sheet-like shape. The slice along the interface can be used in the stratum with a structural dip, but the stratum must be sheet-like. The seismic slices obtained by these two methods are often far from the true geological age of the stratum [23].

To avoid the defect mentioned above, Zeng et al. [35,36] in 1998 introduced the concept of the stratigraphic slice. If you want seismic attributes represent a sedimentary unit as accurately as possible, they must be extracted along with a sedimentary interface. We call such a seismic interface a stratigraphic slice. In the process of extracting stratigraphic slices, we only need to first extract the top and bottom boundaries of the target stratum. Then, the stratigraphic slices are generated proportionally between the two interfaces. The stratigraphic slices consider the variation of the thickness in a stratum. The extracted slices are proportional to the two boundaries. It can obtain the correct slices in both the sedimentary wedge and the growth block. These slices all correspond to a single geological time node [23]. Therefore, the stratigraphic slices are a powerful method to describe the internal mechanism of the sedimentary system. The basic theories and methods of sedimentary seismology based on a seismic attribute in the oil and gas field are introduced and revised to analyze the sedimentary characteristics of sandstone-type uranium deposits in this paper. There are some different research contents comparing with the sedimentary seismology of the oil and gas field, such as locating and calibrating of uranium anomaly, extracting the seismic stratigraphic slices carefully in a thin stratum for a uranium reservoir and the sedimentary evolution of a uranium reservoir. Finally, a 3D field dataset example is introduced to verify the feasibility of our method.

## 2. Background and Workflow

The sandstone-type uranium deposits, oil, and gas are all accumulated in the clastic rock stratum of the sedimentary basin. They have some similarities in sedimentary characteristics. Therefore, the relevant theories, methods, and techniques of sedimentary seismology in the oil and gas field can be used for the sandstone-type uranium deposits. The study of the sedimentary characteristics of the sandstone-type uranium mineralization stratum based on 3D seismic data is theoretically feasible. However, we do not discover the relevant research or some case studies about it in this field. In fact, these two minerals also have some differences in sedimentary characteristics. Considering the applied conditions of sedimentary seismology and the specific characteristics of sandstone-type uranium deposits, we have to change the traditional method of sedimentary seismology based on 3D seismic attributes. The target stratum of a sandstone-type uranium reservoir should be located and calibrated accurately by using the gamma and acoustic logging data together, not just relied on acoustic logging data in the oil and gas field. Next, we introduce a suitable method of sedimentary seismology called stratigraphic slices to efficiently and accurately extract the sedimentary characteristics for sandstone-type uranium reservoir. Finally, to ensure the reliability of our result, we analyze the uniformity between the sedimentary characteristics in wells and the ones obtained by 3D seismic attributes.

To implement the above schemes, we draw up the workflow shown in Figure 1. In this workflow, the geological and drilling data are mainly used to analyze and study the large scale sedimentary facies and regional background of the target stratum in the work area. The logging data are mainly used to accurately locate the precise location of the sandstone-type uranium reservoir in the well and implement the well-seismic calibration. The 3D seismic data is mainly used for the calculation and extraction of seismic attributes. The precise positioning of the target stratum for the sandstone-type uranium reservoir is mainly determined by logging data, which is characterized by high gamma. Fine well seismic calibration is mainly based on acoustic logging data by making synthetic seismic records and comparing them with seismic profiles. The seismic horizon tracking is based on the well seismic calibration through the well profile and the main seismic profile comparison and is achieved by tracing the target horizon one by one. It is also necessary to adopt some measures to check and control the quality of the target horizon tracking, such as the closure section to the cross-well profile, flattening inspection to target horizon, and depth color mark inspection to target horizon. The various seismic attributes include frequency, phase, energy, maximum amplitude, geometric mean, arithmetic mean, minimum amplitude, root mean square, etc. The attributes along the interface are calculated and extracted sequentially by dividing the target stratum thickness into some small equal parts. The purpose of the preferred attribute is to obtain the seismic attributes that best represent the sedimentary characteristics (such as fluvial facies, lacustrine facies, fan deltas, alluvial fans, etc.) of the target sandstone-type uranium reservoir. The geological and drilling data are mainly used to ensure the consistency between our results and the ones obtained by geological knowledge and wells. The seismic attributes with the best consistency are the final optimal ones that best represent the sedimentary characteristics of a sandstone type uranium reservoir. The final extracted sedimentary facies are characterized simply and intuitively through the seismic attributes along with the stratum. The sedimentary characteristics at any depth of the target stratum can also be represented by it. Furthermore, all the vertical changes of seismic attributes along the stratum can also be used for analyzing the sedimentary evolution of the target stratum. Next, we discuss the various aspects involved in the above workflow in the following contents.

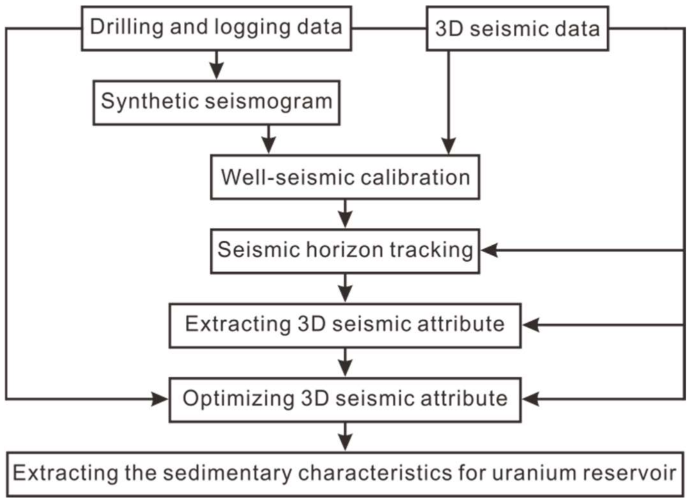


**Figure 1.** The workflow of extracting the sedimentary characteristics for uranium reservoir.

## 3. Datasets Description and Processing

### 3.1. Drilling and Logging Datasets

Drilling and logging data are very important in our workflow. Before carrying out the research on sedimentary seismology, it is necessary to determine the completeness of drilling and logging data. We should check the number and distribution of wells and their logging data in the target stratum in the study area. Specific to each well, it is also necessary to verify the completeness of the drilling and logging data. The drilling data needs to include the lithological section, color, bedding, sandstone content, formation, and comprehensive interpretation of the core. The logging data needs to include well radius, acoustic logging, natural gamma, resistivity, spontaneous potential, neutron, density, etc. After checking the completeness of the data, it is also necessary to confirm the quality of the data. The logging data needs to be confirmed whether the logging scale is accurate, the lithological and the comprehensive interpretation are reasonable. It also needs to be corrected for the environment, well radius, standardized processed, reconstructed, and other inspections. The purpose of the above processing to logging data is to avoid impacts on our work caused by the logging environment, borehole collapse, logging period and instrument differences, and missing logging data for the target stratum. After completeness and quality inspection, the drilling and logging data play an important role in the entire workflow. The drilling data is mainly used to assist the precise positioning of the target uranium reservoir, seismic-well calibration, and the optimization of seismic attributes. The precise positioning of the target uranium reservoir is achieved by comprehensively using drilling and logging data. The main characteristics of the uranium reservoir in the well are that the lithology of the drilling core is sandstone, and the logging performance is high resistivity and high gamma.

### 3.2. 3D Seismic Dataset

3D seismic data is the most important basic data in our workflow. We also need to do the inspection to completeness and assessment of quality before putting them into our workflow. The inspection to completeness includes the coverage area and the blank areas of the 3D seismic data. The assessment of quality includes the main frequency, bandwidth, and signal-to-noise ratio of the 3D seismic data in the target stratum. The completeness and quality of 3D seismic data are the basis of the extraction and optimization of the seismic attribute. The main frequency and bandwidth of the 3D seismic data are related to the accuracy of horizon tracking and the resolution of the seismic attribute. If the frequency bandwidth is limited, we can increase the frequency bandwidth of the 3D seismic data on the basis of ensuring the main spatial structure of the data is not destroyed. The key issue of the increasing frequency bandwidth is to strengthen the high frequency band of the 3D seismic data. The signal-to-noise ratio of the seismic data is related to the degree of correlation of well seismic calibration and the accuracy of the seismic attribute. We can perform appropriate de-noising processing to the 3D seismic data without destroying the effective signal of the target stratum. It can be done by the structure-oriented filter. The purpose of all the above processing is to lay a foundation for ensuring the accuracy of horizon tracking.

After the inspection to completeness and assessment of quality to the basic data of drilling, logging, and 3D seismic data, as well as do corresponding processing of these data, we also need to ensure the spatial uniformity of the well in the area covered by 3D seismic data. So it satisfies the spatial control effect of drilling and logging data to 3D seismic data when we implement the well seismic calibration and optimization of the seismic attribute.

### 3.3. Well Seismic Calibration

Well seismic calibration is an important way to establish the time and spatial correspondence between the seismic data and logging data. Before calibration, the target uranium reservoir should be accurately located first. As shown in Figure 2a, the precise positioning of the target uranium reservoir is mainly determined based on the drilling and logging data, comprehensively. A sandstone type uranium reservoir is mainly characterized by high gamma, high resistivity, and the lithology of sandstone in drilling and logging data. Therefore, we use the gamma and resistivity of logging data to determine the location of the target stratum with high gamma and high resistivity and select its part in which the lithology of sandstone in drilling data as the final target uranium reservoir. After the target uranium reservoir has been located, we can do the well seismic calibration for it now.

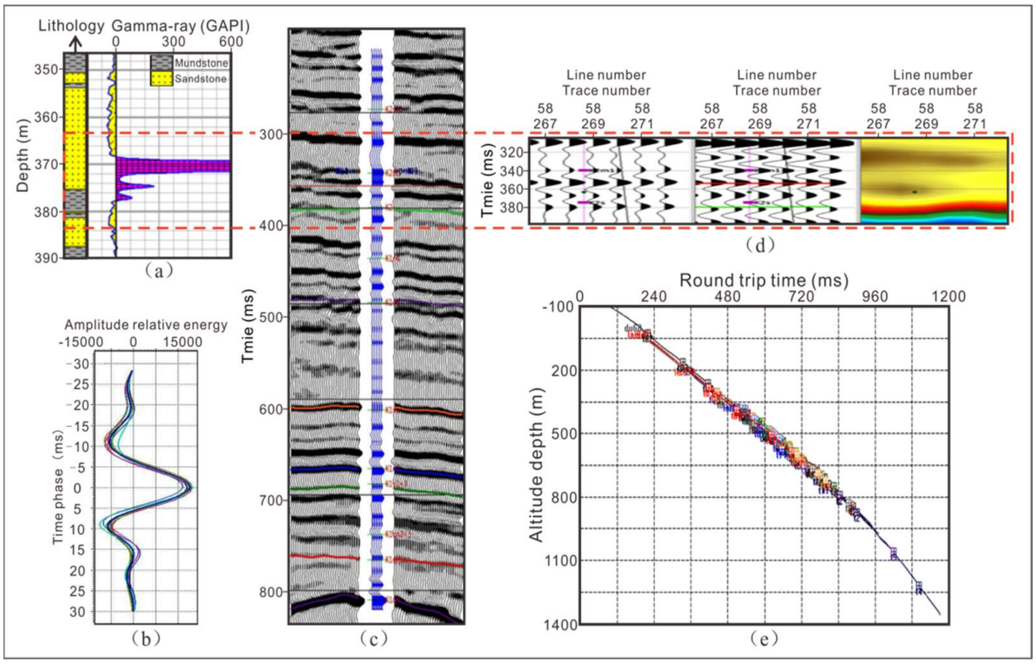


**Figure 2.** Accurate location and well seismic calibration of target uranium reservoir. (**a**) Drilling and logging data, (**b**) Wavelet extraction, (**c**) Synthetic seismogram, (**d**) Measured seismic data (left), synthetic seismogram (middle) and their correlation (right), (**e**) Consistency check for the time-depth relationship of multi wells.

Different from oil and gas fields, sandstone-type uranium deposits are usually accumulated in a very thin target stratum of fluvial facies. The seismic event of this stratum has the characteristics of poor lateral continuity, low energy, and uneven distribution. Therefore, the calibration of this target stratum is difficult. To solve this problem, we adopt a comprehensive calibration method using the large and small synthetic seismic records combined with sedimentary cycles in the well. We find the standard reflected interface with obvious wave group characteristics and stable waveform in the entire seismic data volume firstly. These standard interfaces can be tracked continuously throughout the entire area. They can be used as reference points and control points during the synthetic modeling (Figure 2b,c). Then, under the control of the standard reflected interface, accurately locating the overall time position of the target uranium reservoir section in the seismic data is carried out (Figure 2c). Next, we can extract the well-side tracing wavelet (Figure 2b) carefully to carry out well seismic calibration in the target uranium reservoir section. Only the well seismic calibration that meets the required degree of correlation (Figure 2d) between synthetic seismic records and seismic data can be implemented. Finally, if there is still a situation of inconsistency between well and seismic, we locate the geological stratification at the position of the sedimentary cycle by the method of sequence stratigraphy on the basis of respecting the stratification of most wells.

After completing the well seismic calibration, we assess the quality of the calibration. It can be controlled in two aspects. At first, as shown on the rightmost side of Figure 2d, we assess the quality of calibration for a single well by calculating the correlation between the synthetic seismic record and the seismic trace beside the well. Then, the evaluation for multi wells can be achieved by plotting their time-depth correspondences together and ensuring their consistency (Figure 2e). Based on the above two sets of large and small synthetic seismic records combined with sequence stratigraphic methods, we can establish the time-depth correspondence between the seismic data and logging data of the target uranium reservoir.

## 4. Seismic Sedimentology Method

### *4.1. Seismic Horizon Tracking*

Seismic horizon tracking is the basis for the extraction and optimization of the 3D seismic attribute. The stratigraphic slices extracted from the 3D seismic attributes can well image the sedimentary environment of a certain stratum. It is extracted proportionally between the top and bottom strata interface of the target uranium reservoir. The tracking of the boundary between the top and bottom of the target uranium reservoir is particularly important. The stratigraphic slices obtained under the accurate top and bottom stratum interface can reflect the sedimentary environment of the same geological period. If the top and bottom interfaces are not tracked accurately, an obvious time-crossing phenomenon occurs when the stratigraphic slices are extracted. It means that the sedimentary characteristics of different geology periods are placed in the same stratigraphic slices. Therefore, the accuracy of 3D seismic horizon tracking is very important.

Based on the calibration results in the well, we first compare the well profile and the main seismic profile. Then, in the 3D seismic data volume, the target top and bottom interfaces of the uranium reservoir are tracked line by line (Figure 3a,b) and checked interface by interface using the interface leveling technique to avoid tracking errors caused by human error. The closed check of the well profile is carried out on all the horizon tracking results so that the tracking results of the main survey line are consistent with the connected survey lines (Figure 3c). The target horizon depth color mark inspection method is used for the entire results of the 3D horizon tracking to control the quality of the target horizon tracking (Figure 3d).

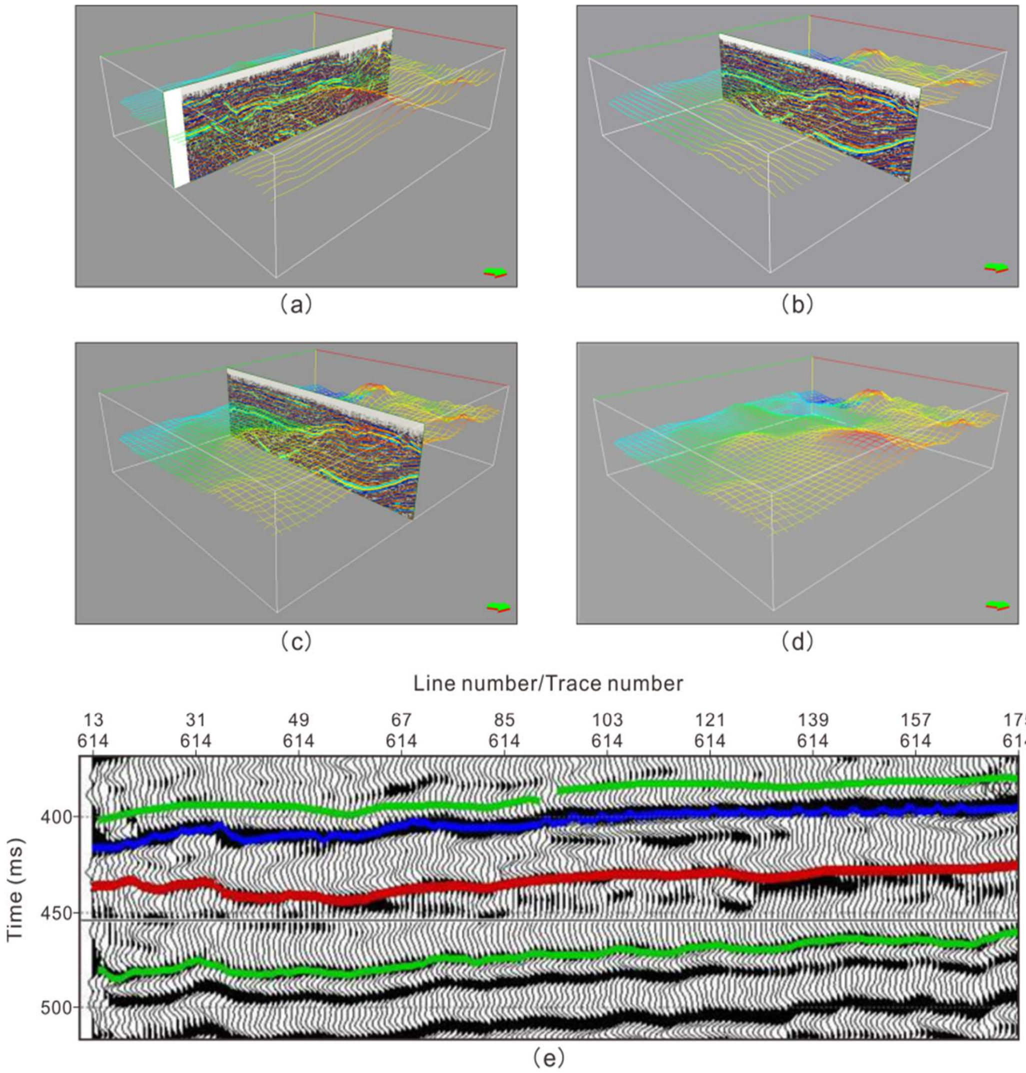


**Figure 3.** An example of seismic horizon tracking result. (**a**) The horizon tracking result along the inline direction, (**b**) The horizon tracking along the cross-line direction, (**c**) The cross closure check, (**d**) The final output result of the horizon tracking, (**e**) The range of horizon tracking result determined by the obvious standard interface.

The above steps of horizon tracking are implemented with quality control using three methods. However, unlike the horizon tracking in the conventional oil and gas field, the top and bottom interfaces of the target strata in the uranium reservoir are usually non-marked reflective horizon interfaces. Their wave group characteristics are relatively inconspicuous, and the lateral waveforms are not very stable. Therefore, the adjacent fairly obvious standard interfaces can be adopted to ensure the relatively stable change of the stratum thickness.

To obtain the complete stratigraphic slices of the target uranium reservoir, we usually extend the horizon up and down to find a relatively stable marker reflector in the vicinity of it. As shown in Figure 3e, the blue and red interfaces are the top and bottom interfaces of the target uranium reservoir. To extract the complete stratigraphic slices in this target stratum, we extend up and down to the green reflected interface with a relatively stable model. Then, the extraction of stratigraphic slices is carried out between these two green reflected interfaces. Finally, for the interfaces in the sandstone-type uranium reservoir are relatively undulating with the developed faults, the dislocation of the target horizon is more serious. In order to describe the undulations of the interface for the target uranium reservoir stratum more precisely and ensure the accuracy of the stratigraphic slices as much as possible, the high-density tracking method should be used when we do horizon tracking in the 3D seismic data. Especially in the areas where the interface of stratum undulates severely and faults are developed, we have to use the highest density of horizon tracking, which can minimize the time errors of stratigraphic slices during its extraction.

### 4.2. Stratigraphic Slices

The stratigraphic slices have unique advantages in describing the complex internal structure of the sedimentary system. We use the stratigraphic slices to extract the sedimentary characteristics of the sandstone-type uranium reservoir. The seismic events with the same geological time have been picked up after the 3D seismic fine seismic calibration and horizon tracking. They are the top and bottom interfaces of the target uranium reservoir in the horizon tracking (the blue and red interfaces in Figure 4). At the same time, in order to obtain the stratigraphic slices of the entire target uranium reservoir, the top and bottom interfaces are also extended appropriately to the adjacent and more obvious seismic events with the same time markers (the green interface in Figure 4). After determining the marked seismic event, a linear interpolation function can be used to establish a stratigraphic time model between the two events to approximate the actual stratigraphic time structure (a series of thin green lines in Figure 4). The stratigraphic time model has the same coordinate system as the original 3D seismic data in the horizontal direction and relatively isochronous geological time vertically. It is the bridge between the 3D seismic data and amplitude stratigraphic slices data. After having the stratum isochronous model, we could use a time slice along each stratum to calculate the corresponding seismic attribute data from the original 3D seismic data and then obtain a seismic attribute that corresponds to the stratigraphic slice. There are many seismic attributes which include: frequency, phase, energy, maximum amplitude, geometric mean, arithmetic mean, minimum amplitude, root mean square amplitude, etc. We use a different algorithm to calculate each seismic attribute. Their ability to represent sedimentary characteristics is also different. Then, we have a question which seismic attribute can best characterize sedimentary characteristics? This question brings up the optimization of seismic attributes.

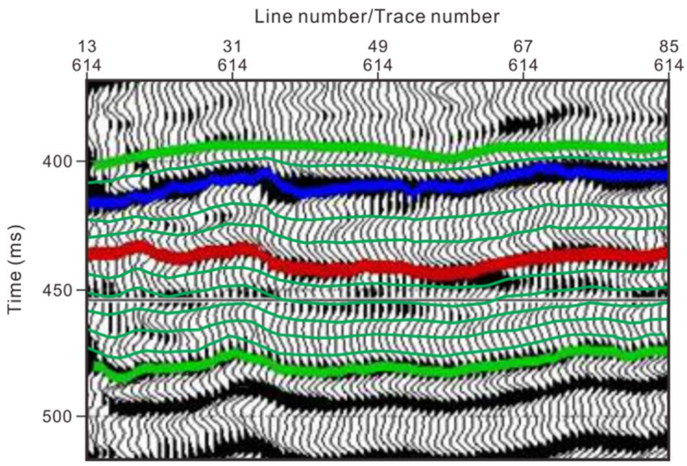


**Figure 4.** An example result of extracting stratigraphic slices.

### 4.3. Optimization of 3D Seismic Attribute

Seismic attributes are a certain kind of measurement of seismic data. Different measurement methods result in different seismic attributes with different uses and sensitivity to different geological problems. Some seismic attributes are susceptible to the structures. For example, coherent attributes are sensitive to faults [21,22]. The purpose of optimizing seismic attributes is to use the prior geological information to select the seismic attribute that best characterizes the sedimentary characteristics of the reservoir. Therefore, prior geological information is essential. The prior information of sedimentary characteristics is usually achieved by analyzing sedimentary facies in the well. Therefore, we use the optimizing technique of seismic attributes under the restriction of in-well sedimentary facies in this paper. We analyze the sedimentary facies of the target uranium reservoir in wells by analyzing the macroscopic sedimentary characteristics of drilling data in the study area. After that, we compare all the seismic attributes extracted by stratigraphic slices and select those seismic attributes that can well reflect the macro-sedimentary features. The one with the highest resolution to the macro-sedimentary feature is the final optimal seismic attribute.

### *4.4. From Seismic Attribute to Sedimentary Facies*

Based on the above extraction and optimization of seismic attributes, we can acquire the sedimentary characteristics from the seismic attributes that best match the sedimentary facies got by the analysis of drilling data. We can realize the transformation from the seismic phase to the sedimentary phase. It has some significant benefits. Compared with the conventional method, the method based on 3D seismic attributes does not require inter-well interpolation because of the support of 3D seismic data. We can obtain both the sedimentary facies on the entire plane of a certain geological interface and the characteristics of the full 3D space sedimentary evolution for the entire stratum. Because the drilling data is not necessary, this method can be applied to get full 3D sedimentary characteristics of the target uranium reservoir in an area with few even no wells. It is of great significance to study the sedimentary characteristics in a new area of exploration with few or without wells.

The above section explains the significance of the transition from seismic facies to sedimentary facies based on 3D seismic data. However, we have to pay special attention to the new exploration with few or no wells. If there is no verification of drilling data, the sedimentary characteristics are only a result based on the seismic data and the experience obtained in other research areas. It is only a reference for the exploration in a new area. We have to use them carefully for the existence of potential risks.

## 5. A 3D Field Dataset Example

### *5.1. Geological Background*

The study area is located in the western slope region of the Songliao Basin. The area is covered by 380 km$^2$ 3D seismic data. Songliao Basin is located in the northeast of China. It is a composite sedimentary basin with six first-order structural units [37,38] and contains the Clastic sedimentary stratum of Jurassic and Cenozoic ages of more than 10 km [12]. The generalized stratigraphic column (Figure 5) shows it includes Qingshankou, Yaojia, Nenjiang, Sifangtai, and Mingshui formations during the Upper Cretaceous with lacustrine and terrigenous fluvial Clastic rocks [38–40].

The target stratum of our study is the Sifangtai formation. Many drilling and logging data acquired here show that some apparent uranium anomalies exist at the bottom of the Sifangtai formation (Red arrow in Figure 5). They are deposited during the transition period from dry hot to humid hot of paleoclimate [12]. Therefore, we choose the area with high gamma logging values to accurately locate the target stratum in this study. In addition, the analysis of sedimentary facies in the well shows that the Sifangtai formation is mainly deposited in a fluvial sedimentary system with red intercalated gray medium-fine Clastic rocks intercalated with mudstone deposits. It can be divided into two third-order sequences [12]. The lithology is mainly composed of brown-red mudstone, sandy mudstone, and gray-green sandy mudstone.

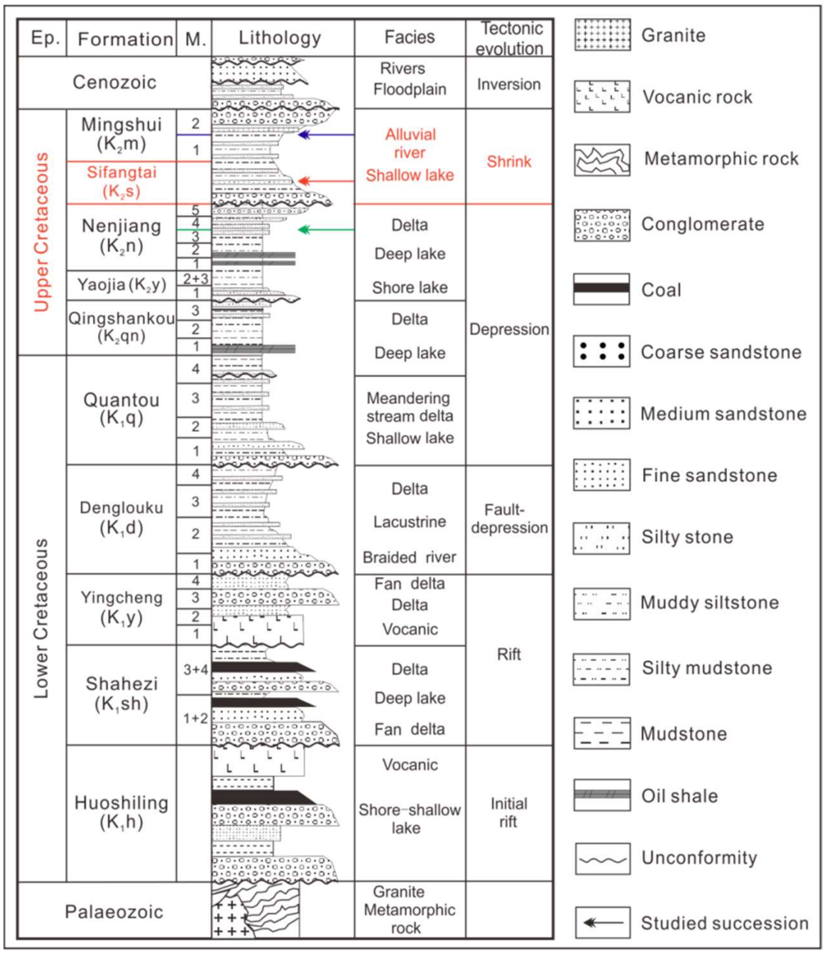


**Figure 5.** Generalized stratigraphic column of Songliao Basin. It is modified from Hu et al. in 2019 [12]. Ep. = epoch, M. = member.

### *5.2. The Result of Seismic Attribute Analysis*

According to the analysis of drilling data shown in Figure 5, the sedimentary facies of the target uranium reservoir is the obvious meandering river. We contrast the sedimentary characteristics expressed by the various seismic attributes extracted according to the method of stratigraphic slices to the sedimentary characteristics of the meandering river obtained from the well analysis. Figure 6a–d shows the attributes of frequency, maximum amplitude, geometric average, and root mean squares, respectively. The basic form of the sedimentary environment represented by the four seismic attributes can be found by comparative analysis. Among them, the sedimentary characteristics of meandering rivers cannot be characterized by the attribute of frequency (Figure 6b). Some parts of sedimentary characteristics can be reflected by the attribute of maximum amplitude (Figure 6c). However, the continuity of the meandering river is limited (Figure 6c). The river channel is not very clear in some places (Figure 6c). The sedimentary characteristics of the meandering river in which the channel has a good continuity can be shown by the attribute of geometric average (Figure 6d). The clear spatial characteristics of the river channel can be given by the attribute of root mean square amplitude. The attribute of geometric mean and the root mean square amplitude attribute is selected in this step for further optimization. Compared with the attribute of geometric mean, the attributes of root mean square amplitude has a higher resolution in depicting the whole river and its boundary. Therefore, we select the attributes of root mean square amplitude as the final optimal seismic attribute.

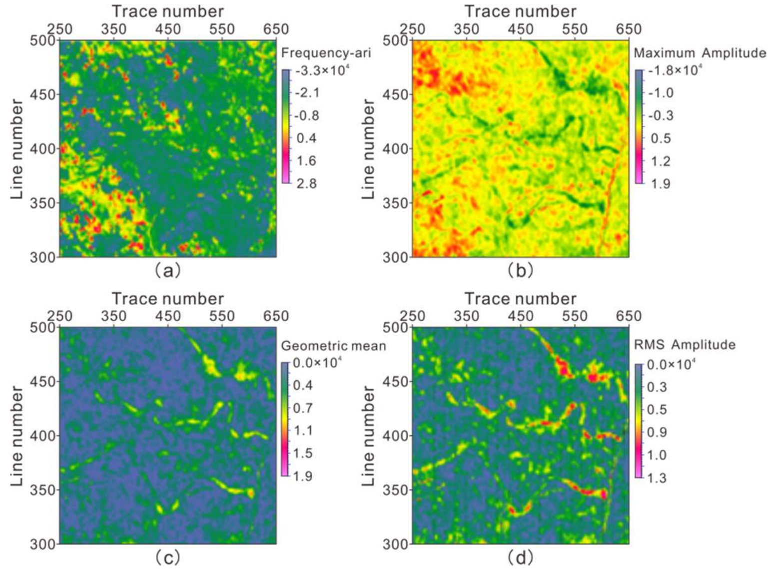


**Figure 6.** The result of Seismic Attribute Analysis. (**a**) The attribute of frequency, (**b**) The attribute of maximum amplitude, (**c**) The attribute of geometric mean, (**d**) The attribute of RMS amplitude.

### *5.3. Sedimentary Characteristics of Uranium Reservoir*

In this area, we use the method shown in Figure 4 to extract the stratigraphic slices at the bottom interface of the Sifangtai formation. Through the optimization of seismic attributes, as shown in Figure 6b–d, the seismic attribute that is most consistent with the sedimentary facies from the well analysis in this area is the attribute of root mean square amplitude. Figure 7a shows the sedimentary facies represented by the stratigraphic slices at the bottom of the Sifangtai formation. The fluvial facies and the river-lake delta facies deposits with very developed rivers are the same as the sedimentary facies obtained from drilling data. In addition, to analyze the sedimentary characteristics, we draw the detailed boundaries of rivers and lakes in Figure 7b. The area covered the red and yellow tones are circled out by the black lines. A very obvious river and river delta facies sedimentary system is shown in Figure 7b.

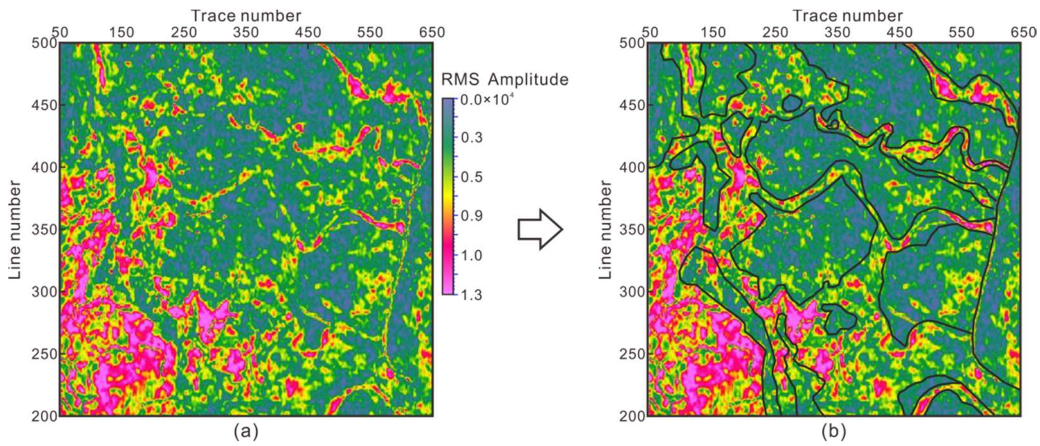


**Figure 7.** Sedimentary characteristics of the interface at the bottom of the Sifangtai formation. (**a**) The seismic attribute of RMS amplitude, (**b**) The division of sedimentary facies.

### 5.4. Sedimentary Evolution of Uranium Reservoir

In addition to obtaining the sedimentary characteristics of a specific stratigraphic interface (geological period) as above, we can also obtain the sedimentary evolution characteristics of the target uranium reservoir by extracting each stratigraphic slice from bottom to top of a target stratum. In order to study the complete sedimentary evolution of the Sifangtai formation, the target stratum is extended up to the lower part of Mingshui formation (Blue arrow in Figure 5) and down to the upper part of Nenjiang formation (Green arrow in Figure 5). As shown in Figure 8, we extract all vertical seismic attribute slices changes in the target sandstone-type uranium reservoir. The total number of slices is 20. They are extracted along with the interface of the target stratum from deep to shallow. The even-numbered slices of 02, 04, 06, . . . , 16, 18, and 20 are shown in Figure 8. Combined with the verification of the prior information obtained by the analysis of the drilling data in the wells (Figures 9 and 10) [41], we can get the sedimentary evolution of the target sandstone type uranium reservoir, which is: floodplain retreat (the slice 20 and 18 in Figure 8) → concentrated small lakes (the slice 16 in Figure 8) → scattered small lakes and braided rivers (the slice 14 in Figure 8) → braided rivers and low meander rivers (the slice 12 in Figure 8) → low meander rivers transformation (the slice 12 in Figure 8) → a new round of lake invasion (the slice 10, 08 and 06 in Figure 8) → delta (the slice 04 in Figure 8) → floodplain after lake invasion (the slice 02 in Figure 8). This sedimentary evolution is of great significance for analyzing the sedimentary elements of sandstone-type uranium deposits.

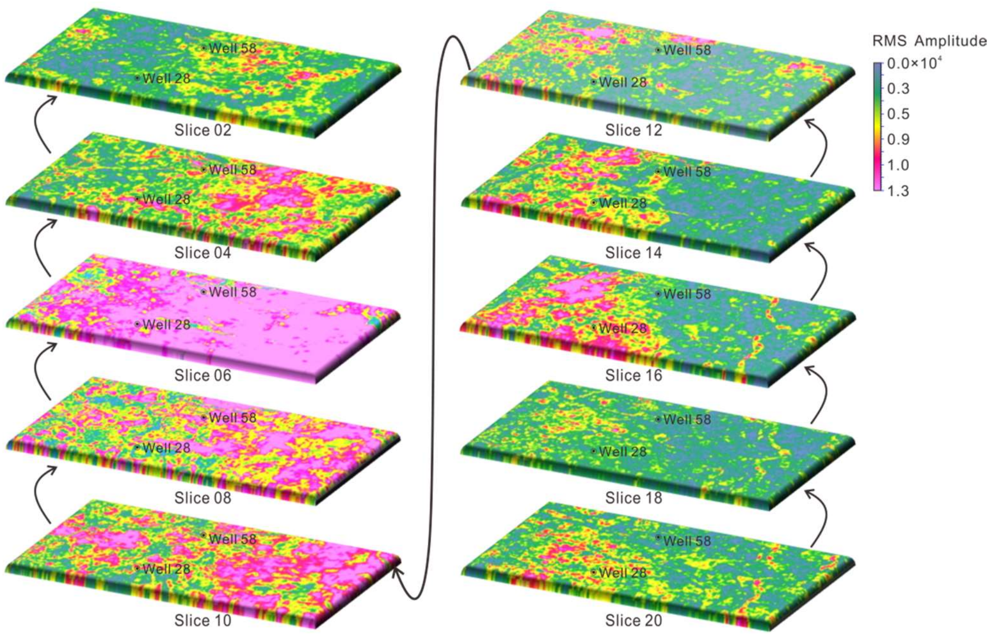


**Figure 8.** Sedimentary evolution of the target sandstone-type uranium reservoir.

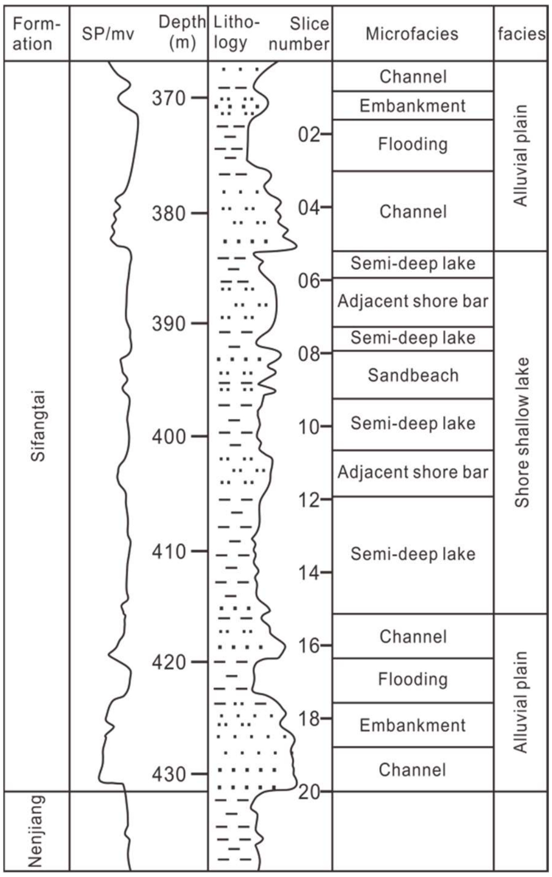


**Figure 9.** Sedimentary evolution in well 28. It is modified from Chen et al. in 2013 [41].

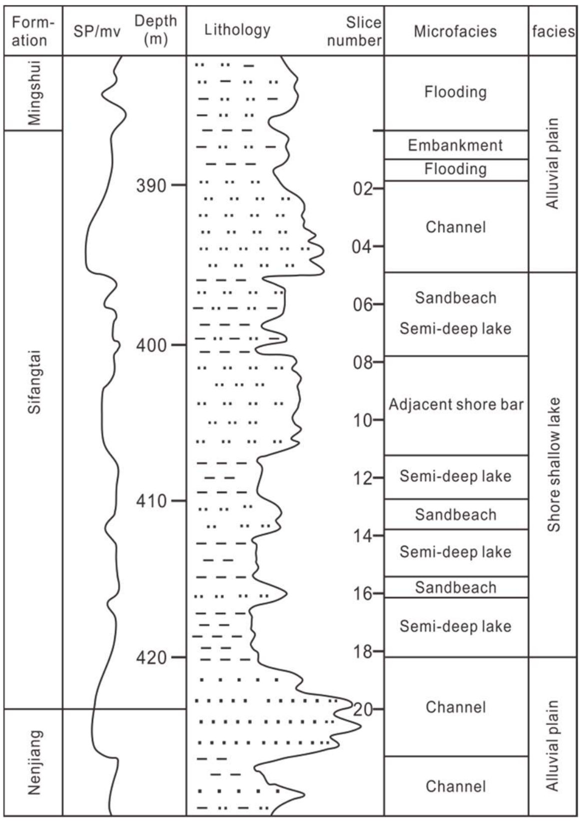


**Figure 10.** Sedimentary evolution in well 58. It is modified from Chen et al. in 2013 [41].

## 6. Conclusions

This study finds that the stratigraphic slice of the 3D seismic attribute is an effective tool for acquiring the sedimentary characteristics of the uranium reservoir. The root mean square amplitude attribute is the most representative seismic attribute for describing the sedimentary environment of the fluvial facies and the river-lake-delta facies in our study area. The high-density horizon tracking of 3D seismic data is an important step for ensuring that the extraction of seismic attributes can be unified to the stratigraphic slices with the same geological period, especially when the target interface of the stratum is undulating violently.

In addition to obtaining the sedimentary characteristics of a target geological interface, we can also get the sedimentary evolution of the entire target uranium reservoir by extracting the stratigraphic slice from the bottom to the top of the target stratum. Therefore, we can fast realize the 3D transparency and visualization of the sedimentary characteristics for sandstone-type uranium reservoirs by using 3D seismic data. They are of great significance for summarizing the metallogenic mechanism of sandstone-type uranium reservoirs from the perspective of sedimentation.

The drilling data is only a sufficient non-essential condition for the verification of sedimentary facies. The method proposed in this paper still has wide application potential in a new exploration area with few or no drilling and logging data. Furthermore, we can provide an important sedimentary prospecting guide for exploring and developing sandstone-type uranium deposits by using our method.

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