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Sequence and sedimentary characteristics of upper Cretaceous Sifangtai Formation in northern Songliao Baisn, northeast China: Implications for sandstone-type uranium mineralization

Fei Hu[a,b,c], Jianguo Li[d,e,*], Zhaojun Liu[a,b,c], Dingming Zhao[a,b,c], Tao Wan[a,b], Chuan Xu[a,b]

[a] College of Earth Sciences, Jilin University, Changchun, Jilin 130061, China
[b] Key-Lab for Oil Shale and Paragenetic Minerals of Jilin Province, Changchun, Jilin 130061, China
[c] Key Laboratory for Evolution of Past Life and Environment in Northeast Asia (Jilin University), Ministry of Education, China
[d] Tianjin Center, China Geological Survey, Tianjin 300170, China
[e] Laboratory of Non-fossil Energy Minerals, Tianjin Center of China Geological Survey, Tianjin 300170, China

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ABSTRACT

Sequence and sedimentary characteristics play an important role in the mineralization of sandstone-type uranium deposit. Two third-order sequences, including four system tracts namely lowstand system tract (LST), transgression system tract (TST), highstand system tract (HST) and regression system tract (RST), and two sedimentary facies, including braided-meandering river and meandering river are identified in the Upper Cretaceous Sifangtai Formation in northern Songliao Basin. Sandstones with better porosity and permeability formed in LST are good uranium reservoir, and the compacted fine-grained deposits in TST are good confining layers. They form a reservoir-confining assemblage that is beneficial to uranium mineralization. The uranium is mainly hosted in the braided-meandering river depositional system, the channel bar ore-hosting sandstones are connective and have good reservoir property, the maximum porosity and permeability are 42% and 1140 mD, respectively. Suitable thickness and sand percentage of sand bodies are beneficial to uranium enrichment, the industrial grade uranium deposits mainly occur in areas with sand percentage of 0.6–0.8 and sand body thickness of 8–12 m. Organic matter and sulfur act as adsorbents and reducing agents in the progress of uranium mineralization, braided-meandering river with strong hydrodynamic conditions bring a large amount of terrestrial carbon debris, which creates conditions for the formation and adsorption of sulfur and uranium. A sequence and sedimentation uranium metallogenic model of Sifangtai Formation has been established, large and high grade uranium deposits are formed in braided-meandering river sand bodies of LST, which have good reservoir properties, suitable thickness, sufficient organic matter and reducing sulfur content, and regional confining bed.

1. Introduction

Sandstone-hosted uranium deposits occur on nearly every continent and are an economically significant source of uranium throughout the world (Min et al., 2005a). Sandstone-type uranium deposit is the second richest uranium deposits in the world and occupies an important position in the world uranium resources (Wang, 2002; Chen et al., 2003; Lorilleux et al., 2003). Examples include the Colorado Plateau and the Tertiary Basin of Wyoming, USA (Melin, 1964; Dahl and Hagmaier, 1974), East Kalkarod, Goulds Dam, Honeymoon and Manyingee, Australia (IAEA, 1996; Subhash et al., 2015), Irkol, Kanzhugan, KyzYLtu, Mynkuduk and Uvanas areas of Kazakhstan, Agron, Aktau, Bukeenai and Uchkuduk areas of Uzbekstan and South Kharat area of Mongolia (IAEA, 1996; Min et al., 2005a; Pei et al., 2007). Meanwhile, sandstone-type uranium deposits in China have been discovered in several sedimentary basins, such as Ili, Turpan-Hami, Ordos and Erlian basins (Min et al., 2005b; Yang et al., 2007; Wu et al., 2009; Bonnetti et al., 2015).

Sequence and sedimentology were used adequately at the beginning of sandstone-type uranium study in European and American countries

* Corresponding author at: Tianjin Center, China Geological Survey, Tianjin 300170, China.
E-mail address: ljianguo@mail.cgs.gov.cn (J. Li).

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(Galloway and Hobday, 1983; Franz, 1993; Maithani et al., 1995), and the corresponding metallogenic models were established (Finch, 1985; Sanford, 1992). In recent years, these technologies have been successfully applied to the exploration, evaluation and directional prediction of sandstone-type uranium in continental basins in China. For example, in the southern margin of the Ili Basin, the development of uranium deposits is controlled by deltaic depositional system. The mud-sand-mud assemblage composed of delta front sand body and delta plain marsh and pre-delta mudstone provides a good structural model for uranium mineralization (Qiu et al., 2017; Liu and Jia, 2011). In the typical uranium deposits in the southwestern margin of Turpan-Hami Basin, the main ore-hosting layers of early Jurassic Xishanyao Formation located in braided river sand bodies of lowstand system tract (Jiao et al., 2004a,b, 2006) are characterized by large thickness, good permeability and rich in reducing mediator such as organic matter and pyrite, which provide conditions for uranium enrichment (Wu et al., 2009; Qiao et al., 2013; Nie et al., 2018). Similarly, the typical ore-hosting sand bodies of Dongsheng sandstone-type uranium deposit in Ordos are also developed in braided river of lowstand system tract of Jurassic Zhiluo Formation, and the uranium mineralization is controlled by river channel (Wu et al., 2003; Yang et al., 2009). The metallogenic strata of typical uranium deposits in the central and northern Erlian Basin are Saihan Formation of Lower Cretaceous, which is divided into three third-order sequences, the main ore-bearing layers are developed in the uppermost sequence (Zhao et al., 2018a,b). Uranium deposits are mainly hosted in braided and meandering channel sand bodies and belong to relic phreatic-interlayer oxidized sandstone type uranium deposits (Nie et al., 2015; Christophe et al., 2015; Kang et al., 2017). In summary, although the metallogenic conditions of typical sandstone-type uranium deposits, as well as, the temporal and spatial distribution of ore-hosting sand bodies in China are different, sequence and sedimentology play an important role in the study on prediction and distribution of uranium ore-hosting sand bodies.

The Songliao Basin is one of the biggest continental Cretaceous basins in the world and contains abundant oil, gas, and oil shale resources (Feng et al., 2010; Liu et al., 2011). In recent years, production-grade sandstone-type uranium deposits have been found in Yaojia Formation in Qianjiadian area of southern Songliao Basin (Chen et al., 2008; Yu, 2009). Qianjiadian uranium deposit is an interlayer oxidized sandstone type uranium deposit, which occurs in sandstones of braided river. The channel is intercalated with lenticular mudstone and heterogeneous, which can hinder the flow of uranium-bearing oxidizing water and form oxidation-reduction transition zone, and the uranium is concentrated in neighboring sandstones. Regional metallogenic models of Qianjiadian uranium deposit have been established (Zhang, 2006; Chen et al., 2007; Luo et al., 2007; Xia et al., 2010). Currently, a certain amount of production-grade uranium mineralization layers have been discovered in Sifangtai Formation in northern Songliao Basin. Compared with southern Songliao Basin, northern Songliao Basin is a newly discovered uranium deposit area, and the characteristics and minerogenetic conditions of sandstone-type uranium deposits are different due to their different tectonic characteristics, provenances and water systems (Wang et al, 1994; Liu et al., 2002; Cai and Li, 2008; Luo et al., 2012), and more different from other basins in northwest China.

The main aim of this paper is to study the sequence and sedimentary characteristics of uranium ore-hosting layers of Sifangtai Formation in northern Songliao Basin, and discuss their controls on the mineralization process of sandstone-type uranium deposits. The study will provide

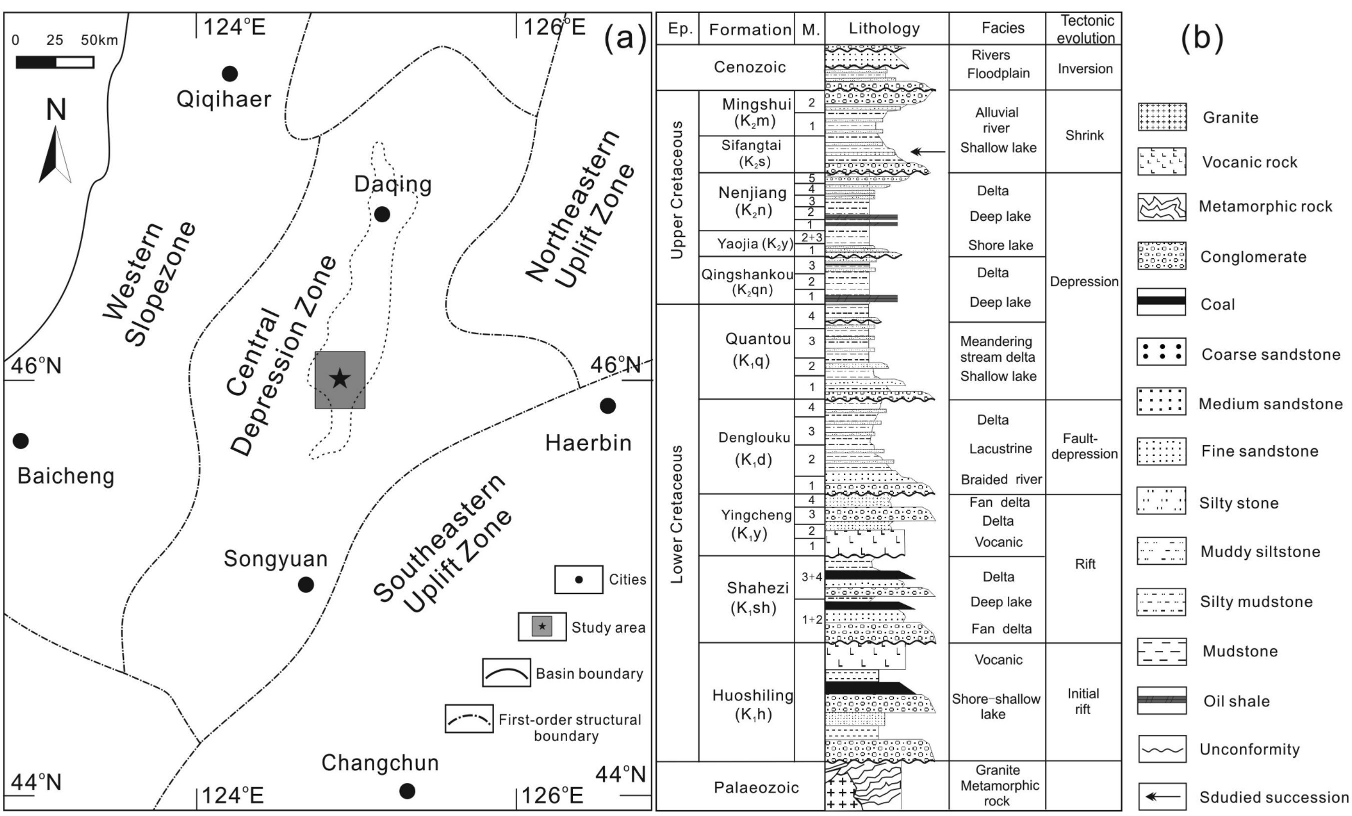

Fig. 1. Location map showing the Songliao Basin and its structure units. Generalized stratigraphic column is modified from Feng et al. (2010). Ep. = epoch, M. = member.

a basis for revealing the uranium metallogenetic regularity and uranium deposit distribution of Sifangtai Formation in northern Songliao Basin.

2. Geological setting

The Songliao Basin is located in northeastern China and covers an area of approximately 260 000 km^2. It is a Meso-Cenozoic composite sedimentary basin with a fault-depression dual structure (Gao et al., 1997; Mi et al., 2010; Bechtel et al., 2012; Jia et al., 2013). Based on the basement and regional geological characteristics of the caprock, the Songliao Basin can be divided into six first-order structural units: the Northern Plunge, the Northeastern Uplift, the Southeastern Uplift, the Central Depression, the Western Slope and the Southwestern Uplift (Feng et al., 2010; Cao et al., 2015; Fig. 1a). The study area is situated in the Central Depression, mainly in the south of Daqing placanticline (Fig. 1a), the main oil producing region of Daqing Oilfield Company.

The Songliao Basin contains clastic sediments of Jurassic and Cenozoic age with a total thickness of more than 10 km (Feng et al., 2010; Li et al., 2012). During the Upper Cretaceous, the Qingshankou, Yaojia, Nenjiang, Sifangtai and Mingshui formations were extensively subsided and deposited, mainly consisting of terrigenous fluvial and lacustrine clastic rocks (Bechtel et al., 2012; Jia et al., 2012; Xu et al., 2015; Fig. 1b). Sifangtai Formation is the target stratum of this study and developed on the shrinking stage of basin evolution (Fig. 1b). It is mainly deposited in fluvial sedimentary system and can be divided into two third-order sequences. Uranium deposits are deposited during the paleoclimate transition period from dry hot to humid hot at the bottom of Sifangtai Formation (Fig. 2).

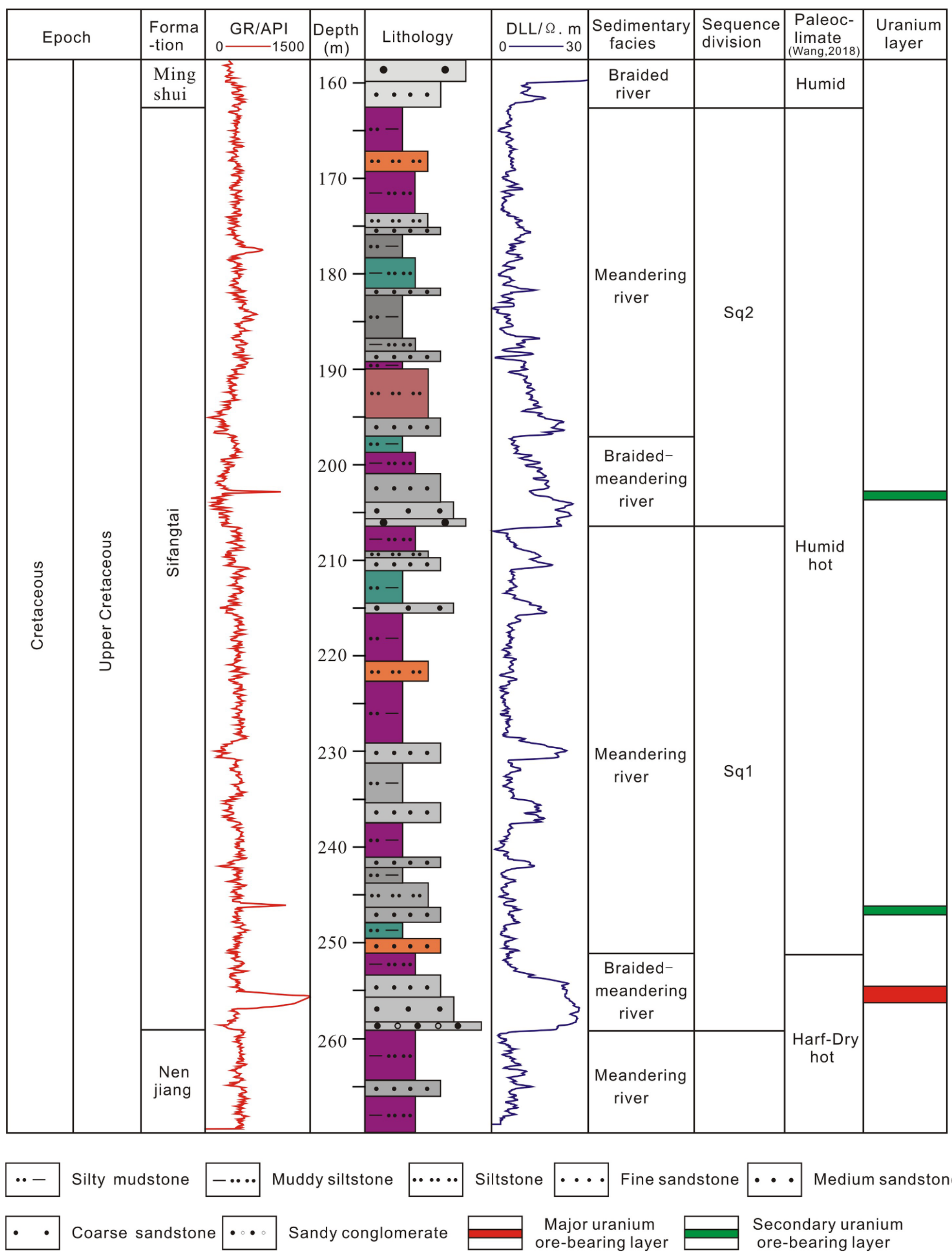

Fig. 2. The comprehensive stratigraphic sequence map of the ore-bearing strata of Sifangtai Formation.

3. Materials and methods

The database for this study includes 104 full-hole coring boreholes covering most of the central depression in northern Songliao Basin. Rock types are described by core, including lithology (hand specimens and thin sections), primary sedimentary structures and biological characteristics. Rock types and sedimentary structures are divided into assemblages representing different sedimentary facies, which were described and correlated on two cross sections, respectively. The sedimentary facies maps are mainly based on the analytical isoline maps including thickness of stratum, sandstone, mudstone, and sandstone/stratum percentage isoline maps. Sequence stratigraphy including third-order sequence, system tract and parasequence are discussed by the cores, loggings and sedimentary facies. Based on the statistics of 104 boreholes, the uranium mineralization data are classified, and the correlation between them is analyzed in combination with the sequence and sedimentary results.

In addition, 10 sandstone samples were analyzed for trace elements, total organic carbon (TOC), total sulfur (S) and electron probe. The concentrations of trace elements were measured in dissolved samples with a POEMS ICP–MS at the Beijing Research Institute of Uranium Geology, following the criteria of DZ/T 0223-2001. The discrepancy between the triplicates is less than 2% for all the elements. The analyses of the standards are in agreement with the recommended values.

The TOC and S analyses were carried out at the Key Laboratory for Oil Shale and Paragenetic Energy Minerals, Changchun, China. The total organic carbon (TOC) was measured using a Leco CS-230 instrument on samples pre-treated with concentrated HCL. The total sulfur (S) contents were determined with the same instrument, following the criteria of GB/T 19145-2003. The analytical precision for the elements has been estimated to be less than 5%.

Electron probe analysis was completed in the Laboratory of Tianjin center, China geological survey. The test instrument is EPMA-1600 produced by Shimadzu Company of Japan. Working conditions: accelerating voltage is 15 kV, electricity is 20nA, and the beam spot diameter is 1–5 μm. The peak computing time is 20–60 s. Data correction by ZAF method.

4. Results

4.1. Types of sedimentary facies

Previous studies have shown that the Sifangtai Formation mainly develops meandering river facies in the central depression (Li et al., 2007; Han et al., 2009; Zhang et al., 2009), including the research results of SK1, a scientific exploration well located in the Qijia-gulong sag in the western of the study area (Cheng et al., 2009; Wang et al., 2011). Whereas, on the basis of a large number of core investigations and log interpretation, besides meandering river facies, braided-meandering river facies of Sifangtai Formation have also been identified in this study.

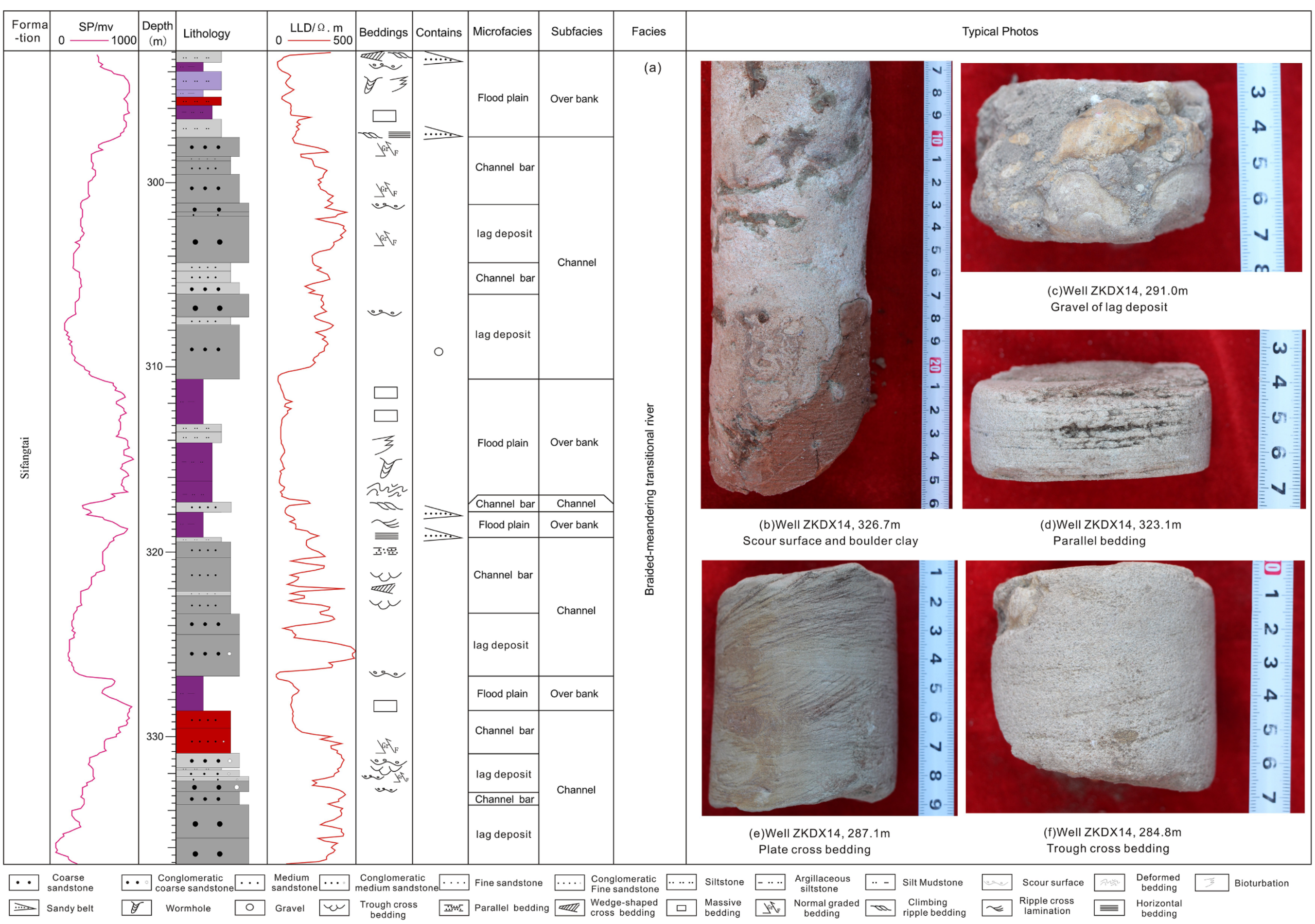

Fig. 3. Comprehensive analysis of braided-meandering transitional river facies in ZKDX14 well column and the core phenomenon.

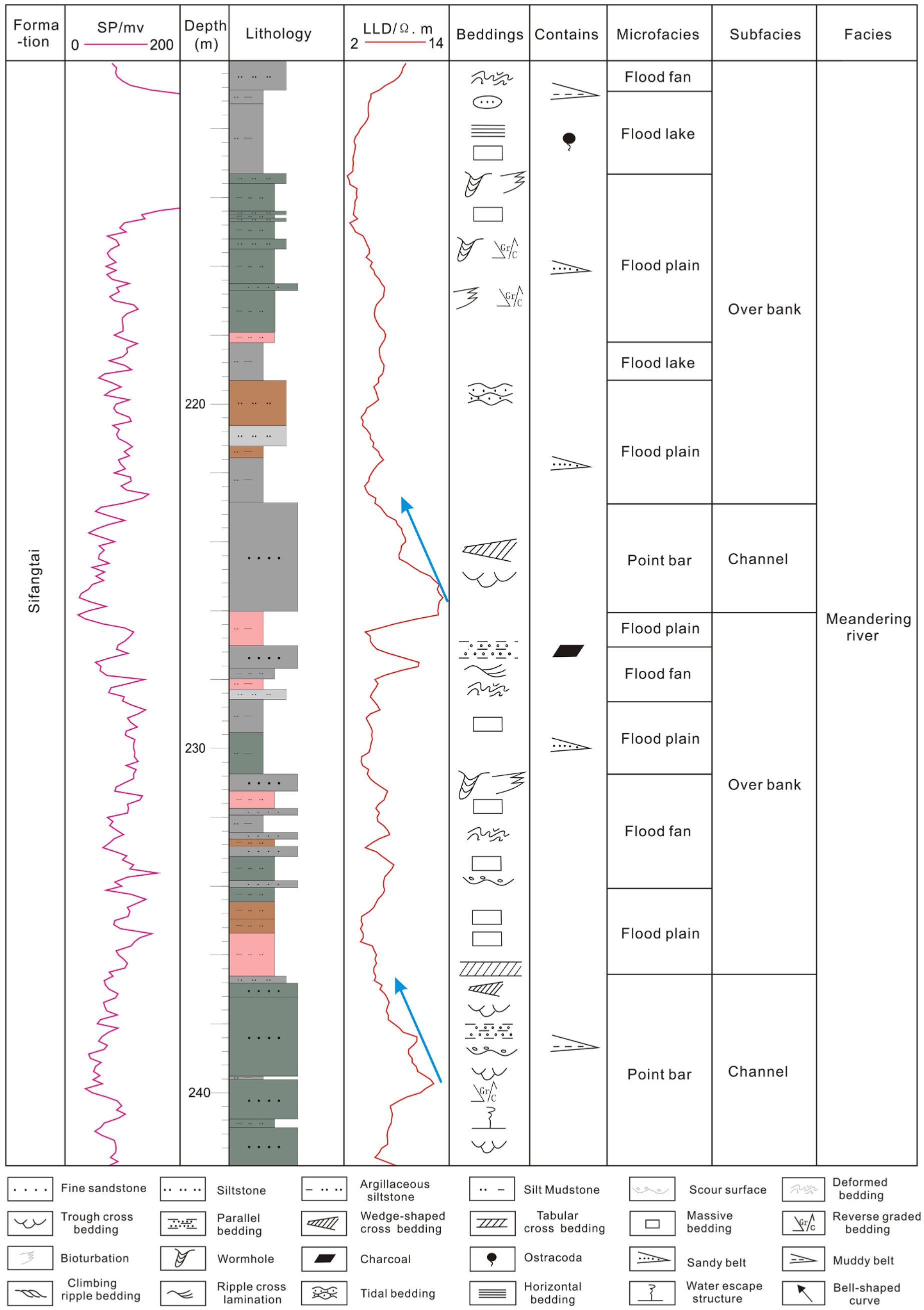

Fig. 4. Sedimentary facies division and logging identification characteristics of meandering river of well 167D27-2.

4.1.1. Braided-meandering river facies

The fluvial facies has a “dual structures”, i.e., lateral accretion sediments deposit in the lower part, and vertical accretion sediments deposit in the upper part. The braided-meandering river facies is characterized by well-developed channel subfacies and the deposits account for more than 50% of the total braided-meandering river facies, while the over bank subfacies is less developed (Fig. 3a). Channel consisting of channel lag and channel bar deposits, the former are characterized by scour surfaces (Fig. 3b) and conglomerates (Fig. 3c), the latter are mainly composed of pebbly medium sandstone and fine sandstone. Parallel bedding (Fig. 3d), tabular cross-bedding (Fig. 3e) and trough cross-bedding (Fig. 3f) are developed in the channel bar deposits. Thin-bedded red brown siltstones, silty mudstones and mudstones represent over bank deposits (Fig. 3a).

4.1.2. Meandering river facies

Compared with the braided-meandering river facies, the meandering river facies is clearly characterized by obvious “dual structures” and significantly increase vertical accretion ratio (Fig. 4), consisting of channel, bank and overbank subfacies.

The channel subfacies are mainly composed of a channel lag and point bar deposits. The channel lag deposit is almost undeveloped in the

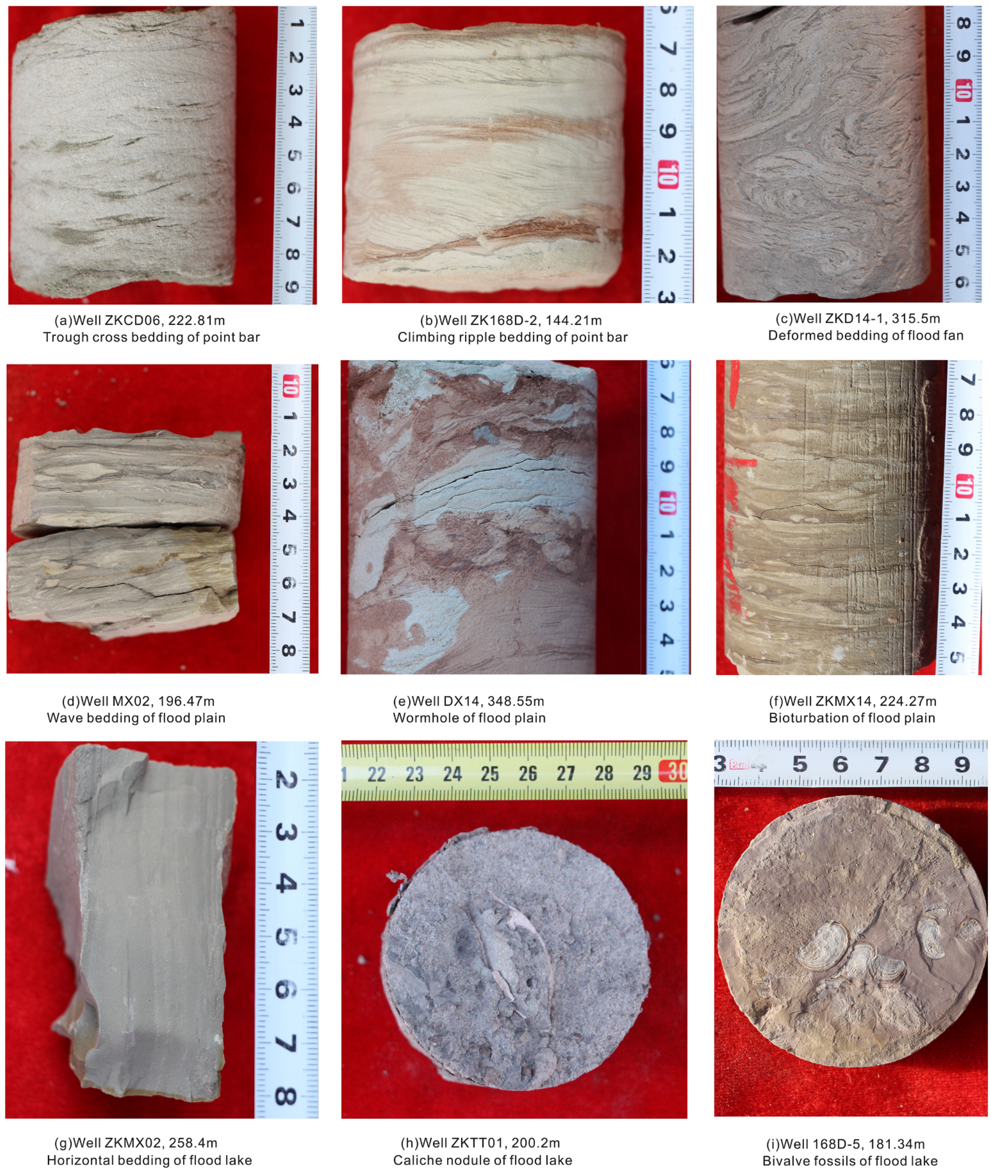

Fig. 5. Typical sedimentary structure phenomenon in core of meandering river facies.

study area, consisting of pebbly medium sandstones. The point bar is well-developed and characterized by directly contact with scour surface, mainly composing of gray fine sandstones and siltstones. The occurrence of trough cross-bedding (Fig. 5a), parallel and climbing bedding (Fig. 5b) are common in these deposits. In the logging curves, the self-potential and apparent resistivity curves are mainly bell-shaped (Fig. 4), but the amplitude is lower while compared with braided-meandering river channel.

The bank subfacies are mainly composed of natural levee and flood fan microfacies. Natural levee sediments are often eroded by the meandering channel and difficult to be preserved. The flood fan is sandwiched in the floodplain (Fig. 4), consisting of gray fine sandstones and siltstones, and characterized by deformed bedding (Fig. 5c) and scour-fill structures.

The overbank subfacies is composed of flood plain, flood swamp and flood lake microfacies, and flood swamp has not been identified in the study area. The flood plain is typically characterized of red or red brown silty mudstones and mudstones, horizontal bedding and wavy bedding (Fig. 5d), wormhole (Fig. 5e), biological disturbances (Fig. 5f) and block structures are common. The flood lake deposit is composed of gray or grayish green silty mudstones and mudstones with horizontal bedding (Fig. 5g), caliche nodule (Fig. 5h) and animal and plant fossils (Fig. 5i) are common, indicating the still water environment.

4.2. Sequence stratigraphy

Sequence stratigraphy studies strata stacking patterns in a chronological framework (Catuneanu et al., 2009). The process of sequence division generally includes the division of parasequence and system tract and the determination of sequence boundary (Liu et al., 2002). The sequence division in this paper is mainly based on the core observation and logging interpretation of 104 wells.

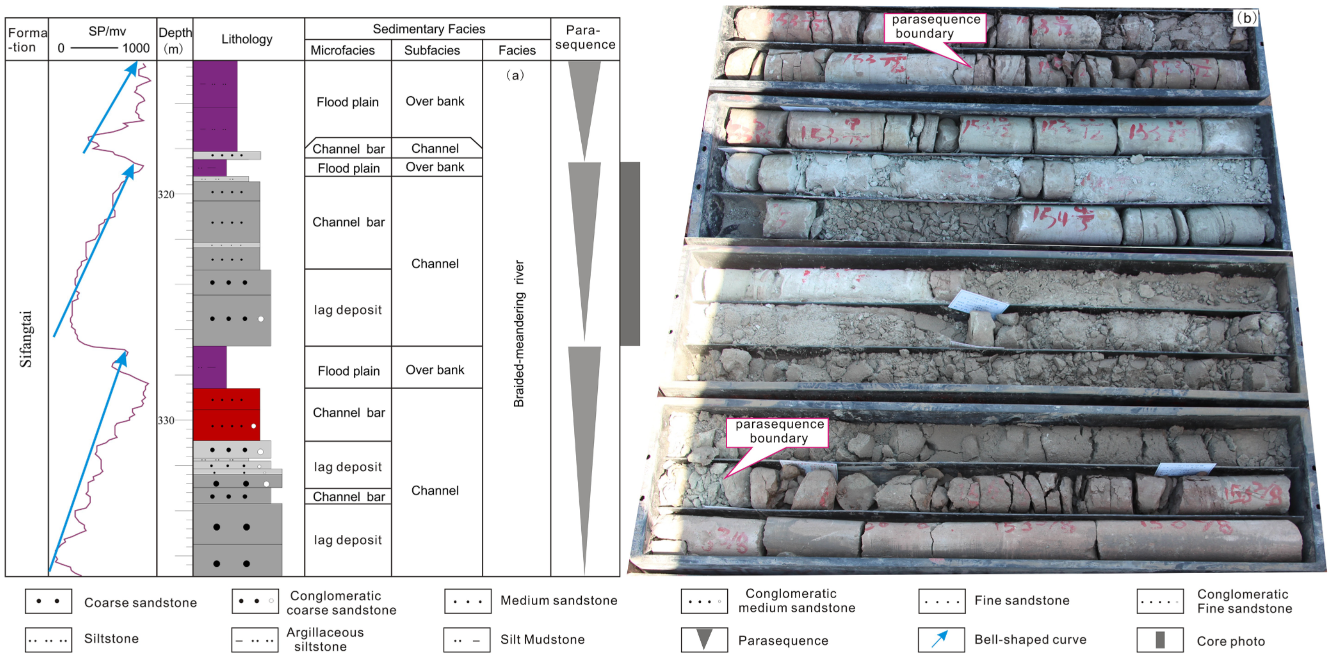

Fig. 6. Parasequence identified from core and logging.

4.2.1. *Parasequence*

Parasequence, equal to the fifth-order sequence stratigraphic unit, is the stratigraphic overlap when the water depth increases suddenly. Each parasequence of siliceous rocks is a facies combination with their sedimentary environment become shallow and shallow upwards (Van wagoner et al., 1990), which can be clearly observed both in lithology and logging.

Sifangtai Formation in the study area is dominated by fluvial facies. Each parasequence of fluvial facies is a channel deposit (Fig. 6a), and presented as the channel filling with the rising of base level (Miall, 1985; Ji et al., 1996). The parasequence boundaries are marked by scouring surface and coarse-grained clastic sediments, dominated by medium-fine sandstones and deposited at the interface. The parasequence is characterized by positive rhythm of lithologic combination and sedimentary facies assemblage by lower channel and upper over bank (Fig. 6b). Well logging of self-potential is bell-shaped (Fig. 6a).

4.2.2. *System tract*

System tract is the fourth-order sequence, corresponding to a parasequence set, referring to a genetic contemporaneous sedimentary system (Browm et al., 1977). According to Galloway (2004), system tracts were defined as genetic stratigraphic units that incorporate strata deposited within a synchronous sediment dispersal system. According to the four division schemes in the third-order sequence of continental basins, a complete sequence consists of four system tracts, namely, lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and regressive systems tract (RST) (Liu et al., 2002).

Different system tracts correspond to different stacking patterns of parasequences, resulting in different shapes of logging curves. LST is characterized by small scale aggradational parasequence sets with high amplitude box-shaped apparent resistivity curve. TST consists of regressive parasequence sets with bell-shaped apparent resistivity curve, and the amplitude decreased upwards. HST is presented as aggradational parasequence sets and the apparent resistivity curve have low amplitude and little changes. RST is mainly consisted of progradational parasequence sets with funnel-shaped apparent resistivity curve, and the amplitude increases upwards (Fig. 7).

The braided-meandering river transitional facies in the study area is the product of LST and is clearly found at the bottom of the sequence. That is because the quick drop of base level during the LST period leads to the serious erosion of the river, and the channel slope reaches its maximum. Subsequently, with the gradual rise of the base level, the rivers mainly deposit laterally, forming a braided meandering river with coarse clastic deposits. The meandering river facies is clearly characterized by upward fining successions and vertical accretion, and belongs to the products of TST, HST and RST (Fig. 7).

4.2.3. *Sequence boundary*

According to core observation in the study area, sequence boundaries are marked by abrupt interface of lithofacies assemblages. The boundary of SB1 is a regional angular unconformity interface, which separates shallow lake mudstones and sand barrier beneath from conglomeratic coarse sandstones and medium sandstones above. For example, in well 168D-5, beneath the SB1 boundary is a beach bar deposit in a shallow lake, and above the boundary is pebbly sandstone (Fig. 7).

Logging curves can also be used to mark the sequence boundaries. It is often shown as “curve break” in amplitudes and shapes of logging associations in the vicinity of sequence boundaries, representing unconformity and corresponding conformity surfaces. In wells ZKMX21, ZKMX06 and 168D-5 (Fig. 8), there are obvious differences in logging associations, indicating that the wells has an isochronous sequence boundary.

Combining with the method of system tract division, Sifangtai Formation in the study area is divided into two third-order sequences (SQ1 and SQ2), each of which includes 4 complete system tracts.

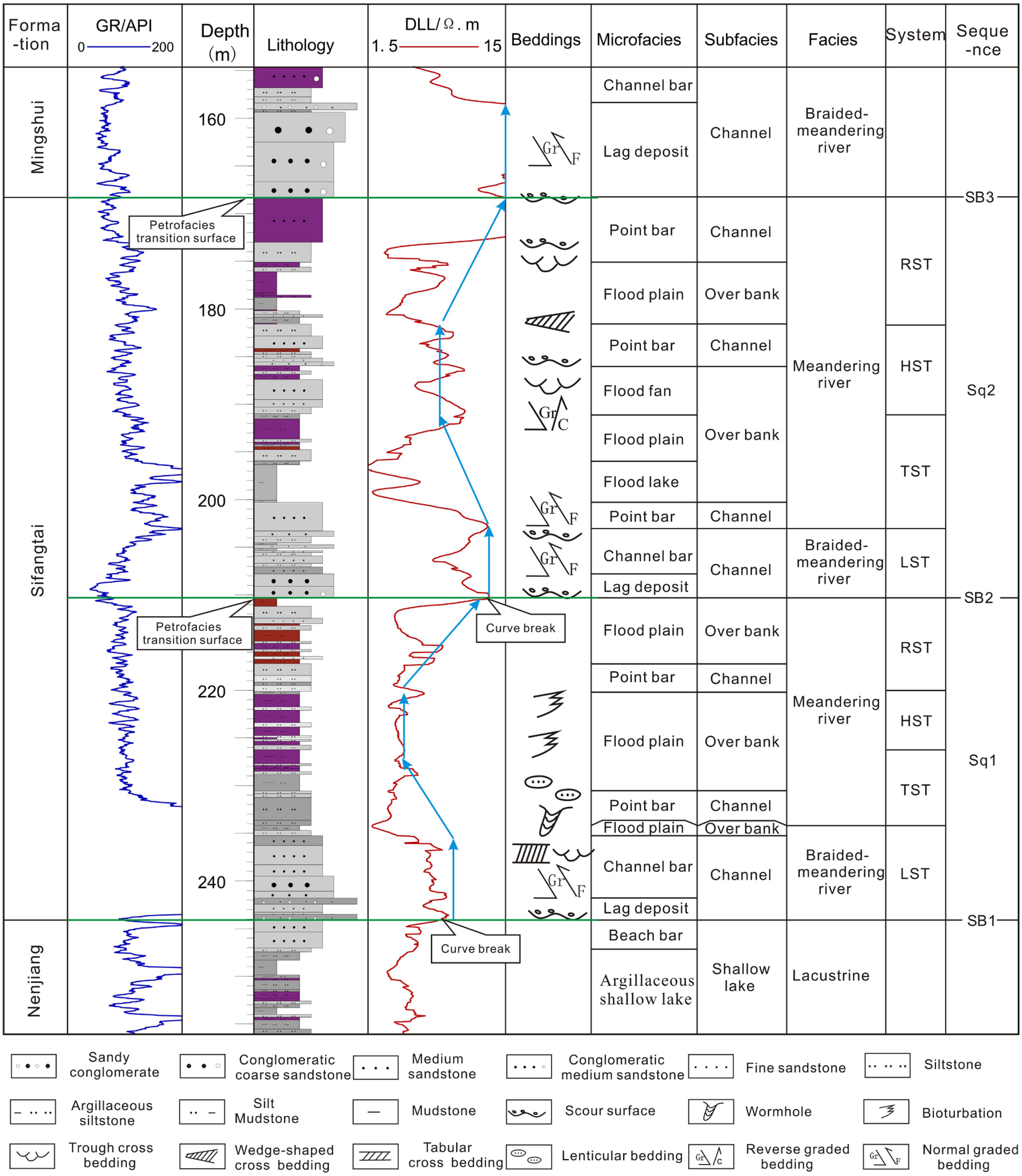

Fig. 7. System tracts and sequence boundary identified from core and logging.

4.3. Sedimentary facies and sand body distribution

The distribution characteristics of sedimentary facies and sand bodies are discussed within the sequence stratigraphic framework. From the east and west direction (Fig. 8), the sand bodies in the western area are developed and are channel deposits. From the south and north direction (Fig. 9), the channel sand bodies in the south are relatively developed, while in the north are relatively reduced. In the middle part, fine-grained sediments of flood plain and meandering flood fan sand bodies are dominated, and flood lake deposits are locally intercalated.

From the perspective of vertical evolution, LST is characterized by channel bar sand bodies of braided-meandering river. TST is dominated by flood plain deposits intercalated with discontinuous lenticular point bar sand bodies of meandering river. HST is mainly composed of flood lake and flood fan of meandering river. RST is mainly consists of flood plain intercalated with meandering river point bar deposits, and the continuity of point bar sand body is poor (Figs. 8, 9).

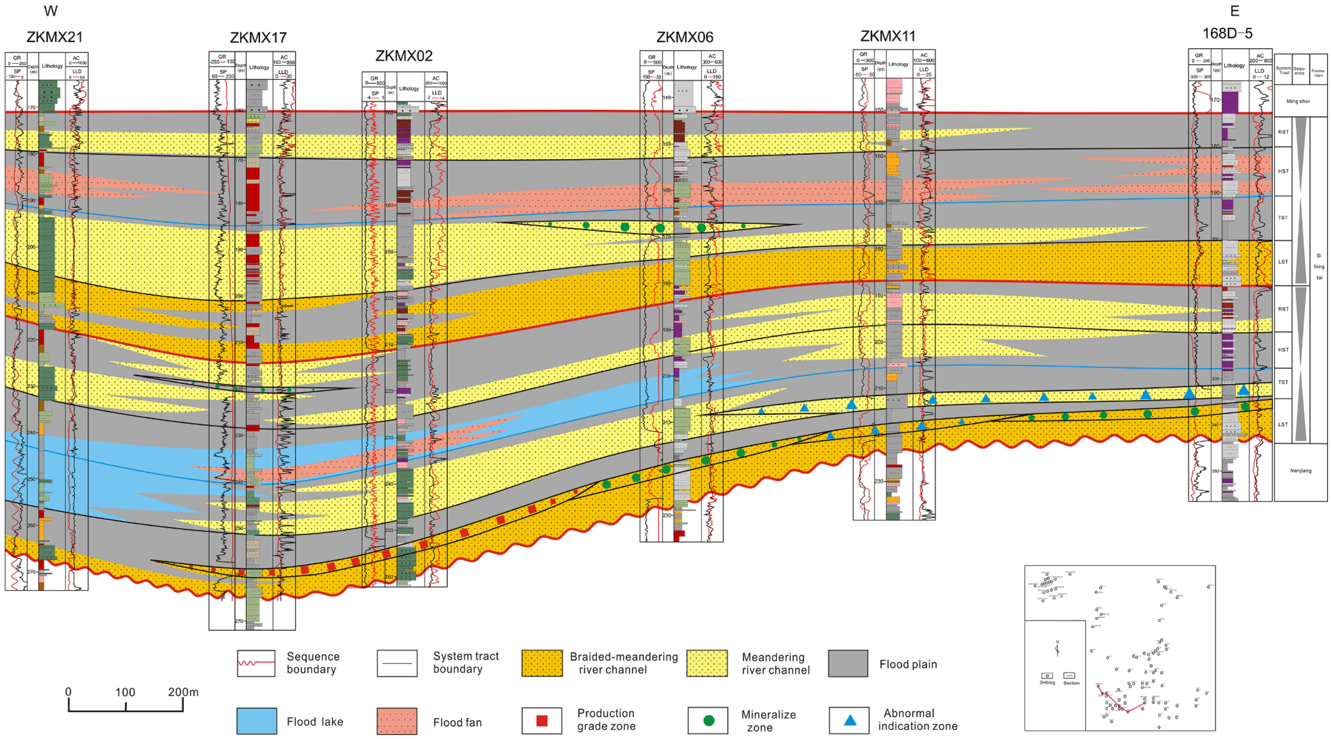

Fig. 8. East-west direction profile of sedimentation and uranium mineralization distribution in system tract from well 168D-5 to well ZKMX21.

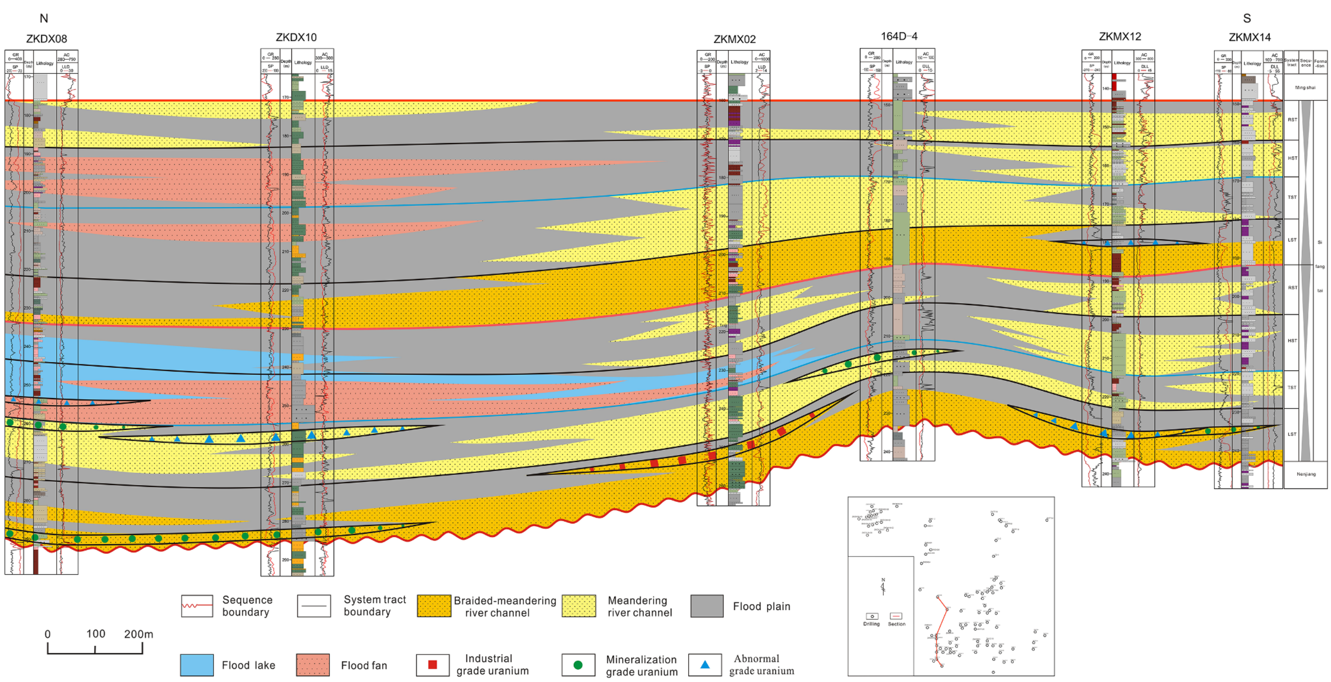

Fig. 9. South-north direction profile of sedimentation and uranium mineralization distribution in system tract from well ZKMX14 to well ZKDX08.

Table 1
Statistical data of different uranium mineralization grade in drillings.

Sequence	System tract	Industrial grade	Mineralization	Abnormal	Unmineralized
SQ2	RST	0	1	2	101
	HST	0	4	8	92
	TST	0	7	10	87
	LST	0	9	15	80
SQ1	RST	0	5	12	87
	HST	1	9	9	85
	TST	2	9	8	85
	LST	11 (11 in Channel)	28 (24 in channel)	4 (3 in channel)	61

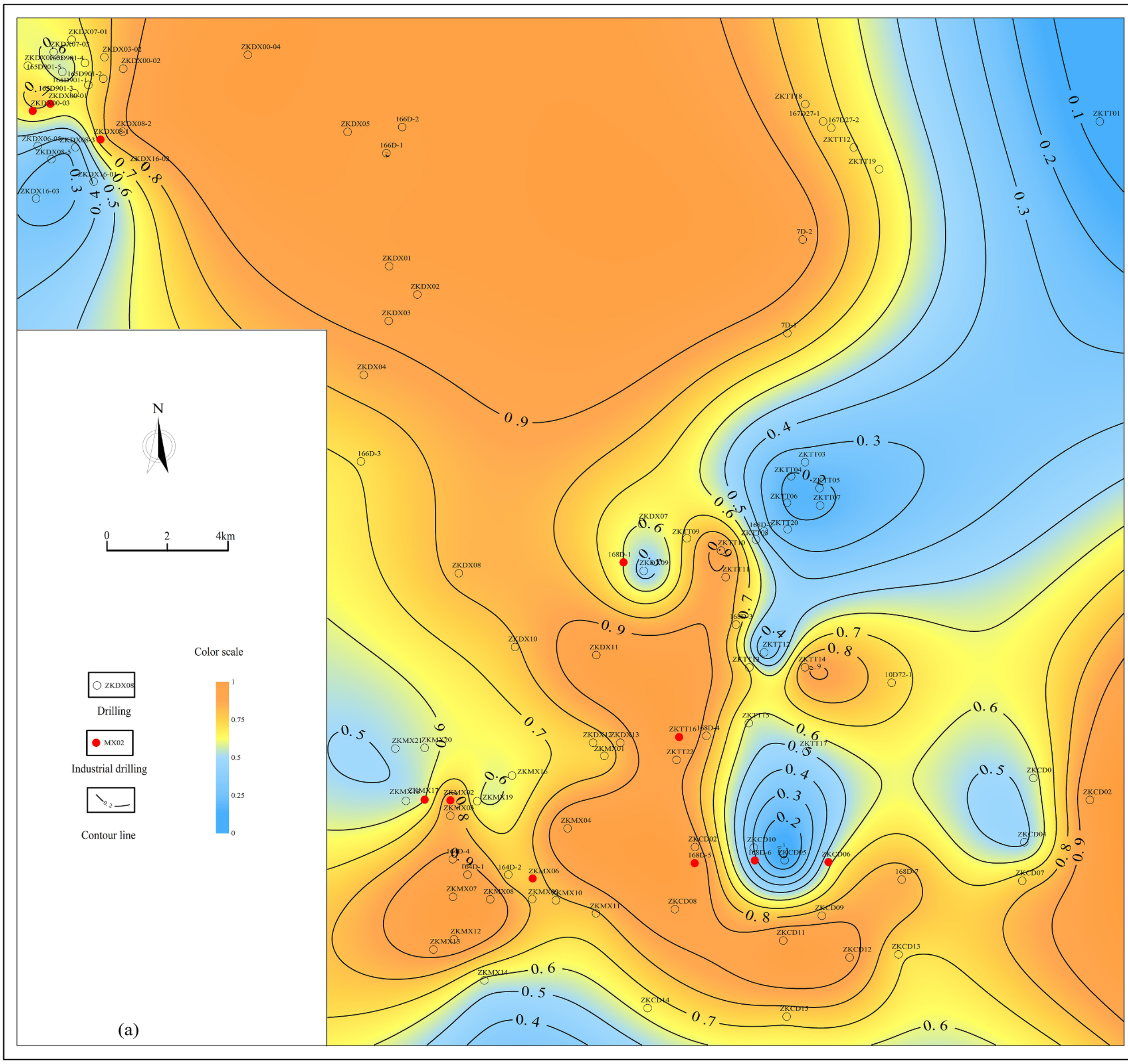

Fig. 10. Contour maps and sedimentary distribution of the LST in Sq1 of study area. *a: Sandstone percentage contour map; b: Sandstone thickness contour map; c: Mudstone thickness contour map; d: Sedimentary facies distribution map.*

5. Discussions

Based on the analysis of sequence stratigraphic and sedimentation of Sifangtai Formation in northern Songliao Basin, the relationship between sedimentation, sequence stratigraphy and uranium mineralization has been statistically analyzed (Table 1).

5.1. Sequence stratigraphic and uranium mineralization

A regional unconformity developed at the bottom of Sifangtai Formation is mainly formed by the uplift and erosion after the deposition of Nenjiang Formation. It shows angular unconformity in the margin and parallel unconformity in the centre of Songliao Basin (Wang

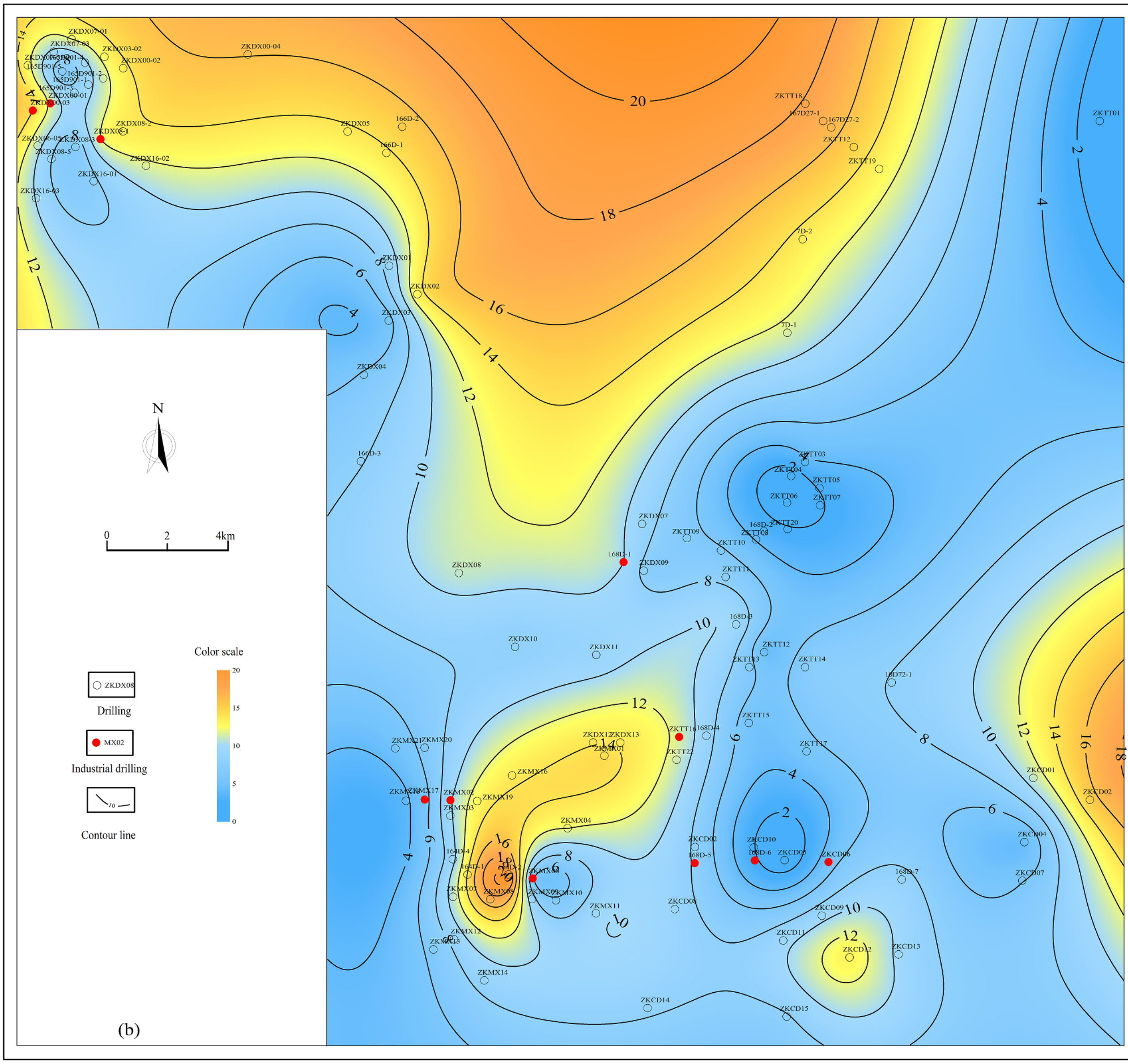

Fig. 10. (*continued*)

et al., 1994; Liu et al., 2002; Lin et al., 2007; Zhang et al., 2009). Fine-grained sediments of Nenjiang Formation below unconformity is a good water-resisting layer, and LST of SQ1 above unconformity is dominated by progradational braided-meandering river sediments. The thick and well-connected braided-meandering river sand bodies are favorable uranium reservoir, and the industrial grade uranium exposed by boreholes is mainly concentrated in these sand bodies (Table 1).

TST is formed on LST, deposited fine-grained sediments after rapid deepening of water level, and become a good barrier and confining bed after compaction and diagenesis, forming a good reservoir-confining assemblage, and the uranium-containing fluids migrate to the channel and floodplain transition zone, and unload the uranium. Meanwhile, TST can form lenticular sand bodies with a certain scale, and mineralization can be carried out when other metallogenic conditions exist (Figs. 8, 9).

HST is mainly composed of fine-grained sediments, lacking favorable reservoirs and uranium source conditions, which makes it difficult to mineralize. RST has some sand bodies, but the upper part of the system tract contacts with the LST of SQ2, which is difficult to mineralize due to the lack of confining beds (Fig. 8, Table 1).

5.2. Sedimentation and uranium mineralization

5.2.1. Depositional systems

All industrial wells and most mineralized wells are developed in braided-meandering depositional system. In order to further understand

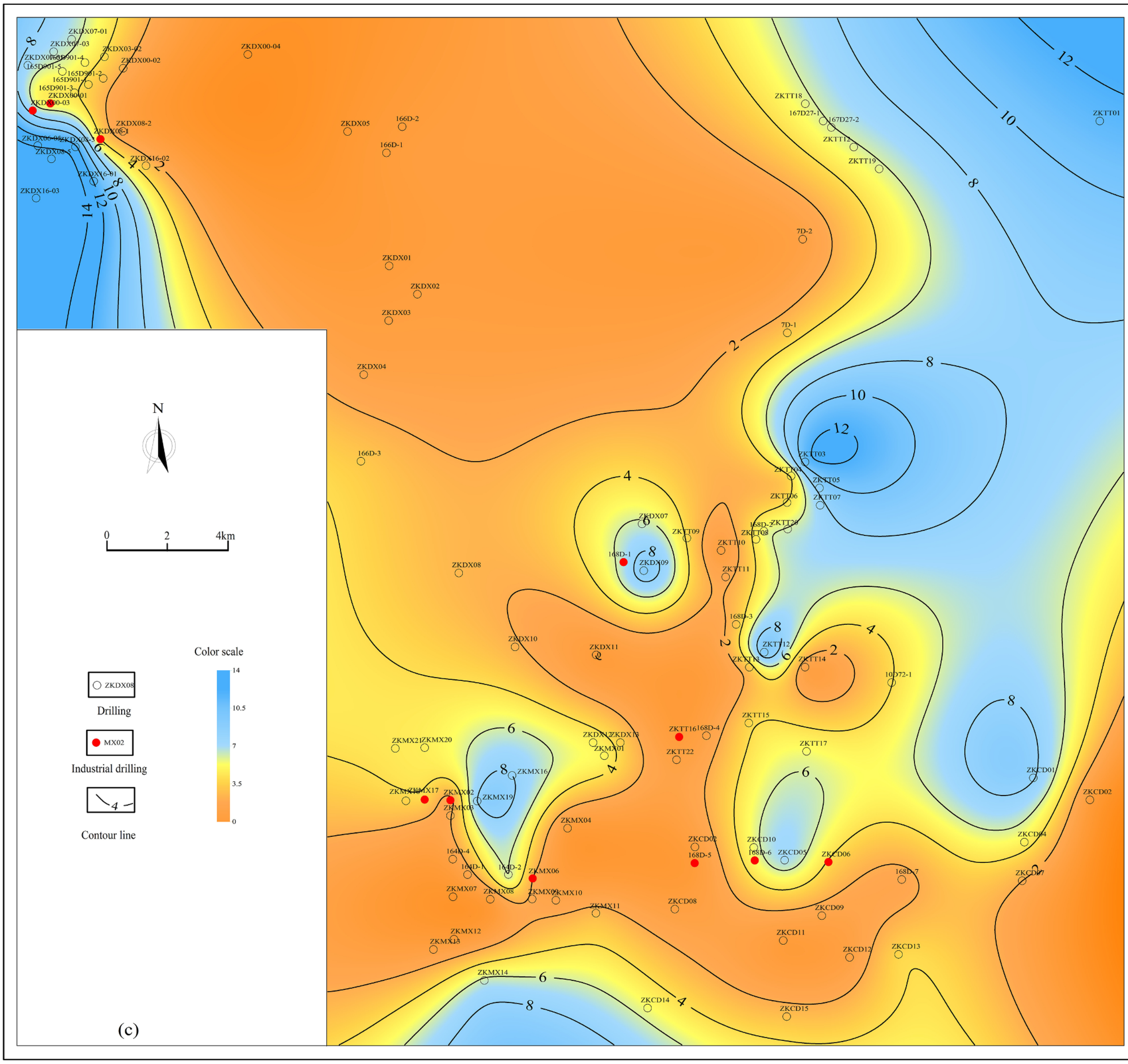

Fig. 10. (*continued*)

the relation between the depositional systems and uranium mineralization, several lithologic contour maps have been drawn based on 104 boreholes drilling for uranium exploration (Fig. 10a–c), sedimentary facies maps are mainly based on these contours and modified by other parameters (Fig. 10d). The results show that LST is dominated by a large scale braided-meandering channel, the channels are widely developed in the north and southeast, while flood plains are deposited in the northeast (Fig. 10d). According to the statistics of uranium mineralization data, the industrial grade uranium boreholes in the study area are mainly located in the transition zone between channel and floodplain, which indicates that the transition zone between channel and floodplain is beneficial to uranium mineralization

5.2.2. *Stability and thickness of the sand body*

Stability and thickness of sand bodies are one of the factors affecting uranium mineralization (Jiao et al, 2006). The uranium mineralization in the study area is mainly developed in braided-meandering channel sand bodies, which have good continuity and high sand percentage. According to the statistics of sand percentage in the metallogenic system tract, the main mineralization occurs between 0.5 and 0.95, of which the value between 0.6 and 0.8 is the highest (Fig. 10a). Furthermore, after the Nenjiang Formation was deposited, the structure of the central depression in Songliao Basin was relatively stable, and only experienced compressive tectonics mainly local folding at the end of Mingshui Formation and Paleogene (zhao et al, 2018a,b), which made the stability of ore-hosting sand bodies in the study area preserved.

The mineralization potential is controlled by the thickness of the skeletal sandstones. Mineralization is directly proportional to the scale of the sandstone bodies that is because large scale channel sandstones provided abundant space for migration of uranium-bearing fluids (Jiao

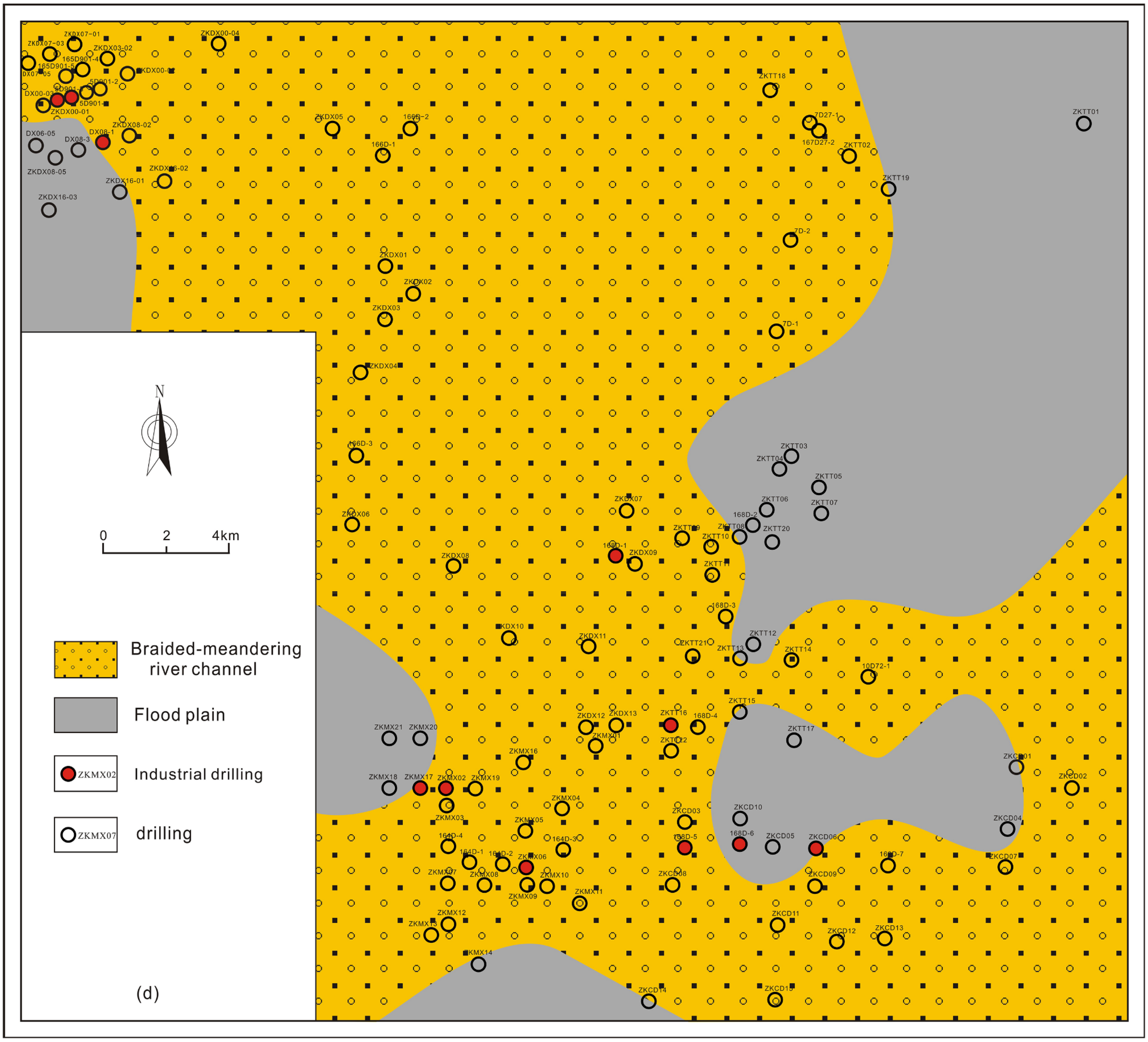

Fig. 10. (*continued*)

et al., 2005, 2006). According to the ore-forming probability of sand bodies, the optimum thickness of ore-forming sand bodies in the study area is between 8 and 12 m (Fig. 10b), and the corresponding mudstone thickness is between 2 and 6 m (Fig. 10c). The combination structure of thick sandstone and proper mudstone is beneficial to ore-forming.

5.2.3. Porosity and permeability of the sand body

The mineralization potential is also related to the porosity and permeability of sandstone. The main ore-hosting sand body in the study area is dominated by braided-meandering river channel bar deposits, consisting of medium-fine sandstone with good physical properties. Owing to the relatively loose ore-hosting sand body, it is difficult to directly obtain the physical property data. However, by testing the siltstone in well cemented ore-barren layers, the porosity and permeability data of sand bodies in different sedimentary facies can be retrieved by logging curves, the results show that the porosity and permeability of rocks varies with different genetic facies in the depositional system. The braided-meandering river sand body has the best reservoir physical properties, and the maximum porosity and permeability is 42% and 1140 mD, respectively. However, the reservoir physical properties of meandering river sand bodies, whether ore-bearing or ore-barren, are obviously decreased, and the scale and probability of mineralization are also decreased (Fig. 11).

5.2.4. Organic matter and sulfur content of the sand body

Uranium hosted in sandstone mostly exists in the form of coffinite with fine particles and occurs as granular and spotted (Fig. 12a). Its precipitation and enrichment are influenced by organic matter, sulfur and clay mineral content. Organic matter is an important medium affecting the uranium metallogenic flow condition, which helps the uranium accumulation by reduction and absorption. Abundant plant remains in skeletal sandstones afford suitable conditions for the

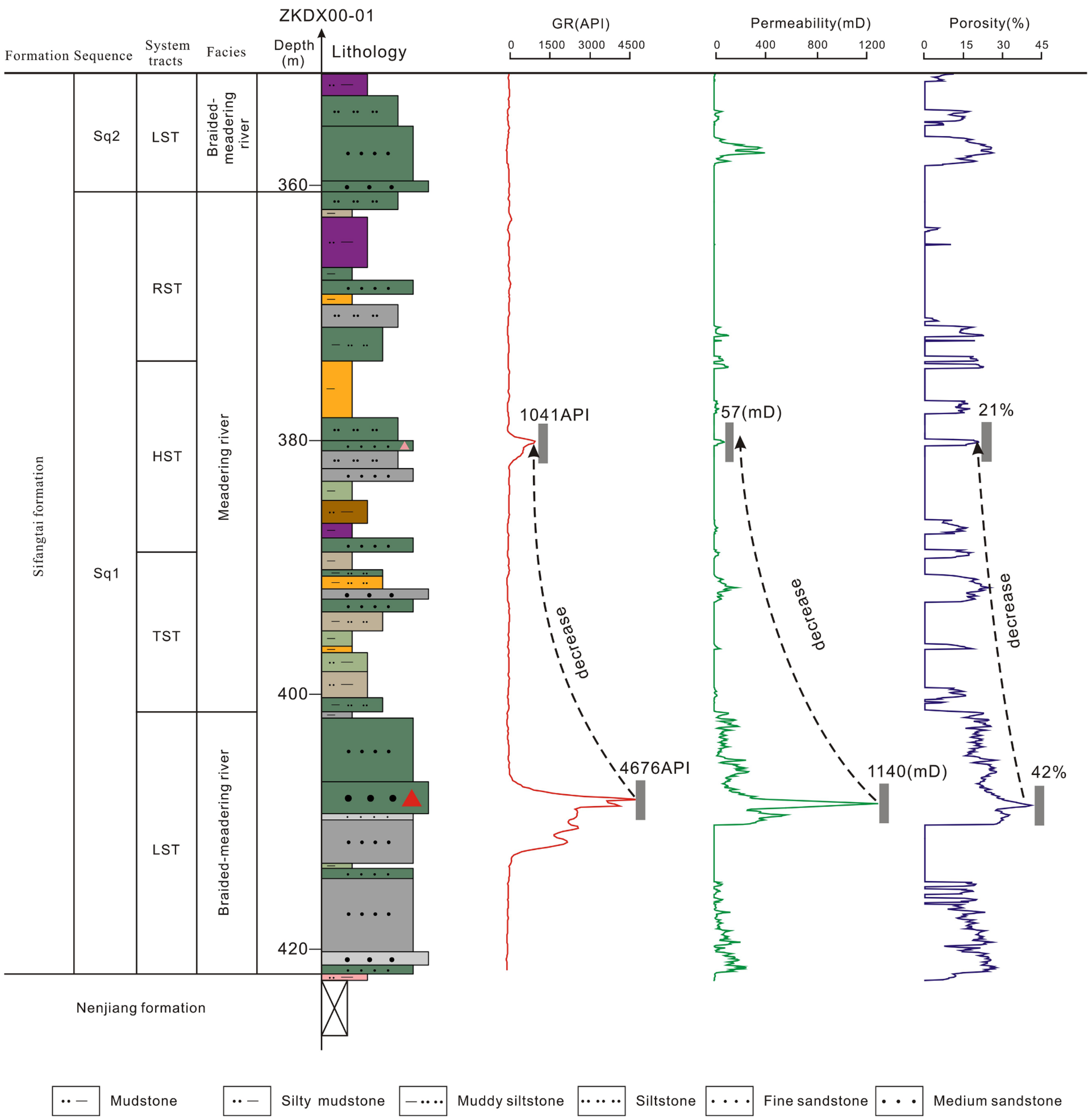

Fig. 11. Normal grading cycle of porosity and permeability in braided-meandering and meandering river depositional system.

absorption of uranium (Liu, 2004; Cai et al., 2005). In the study area, the braided-meandering river with strong hydrodynamic conditions brings about abundant terrigenous organic debris, which makes the channel bar sand body contain a large number of carbonized plant fragments, providing the necessary reduction environment for uranium mineralization, while playing an important role in absorption for uranium accumulation (Fig. 12b). At the same time, clay minerals on the surface of clastic particles (Fig. 12c) also have strong adsorption for uranium.

The pyrite is the most common sulfide mineral and one of the most important components in various uranium-bearing mineral assemblages in sandstone-type uranium deposits (Min et al., 2005a; Scott, 2007; Ingham et al., 2014), which play an important role of providing a macro or micro reduction environment. The pyrite related to clay minerals or carbonaceous debris not only acts as reductant and enhances the reducibility of reservoir, but also provides space for adsorption or replacement of uranium (Goldhaber et al., 1987; Eglizaud et al., 2006; Cai et al., 2007; Qafoku et al., 2009). Pyrite in the braided channel sand bodies in the study area is mostly associated with carbon debris (Fig. 12b), while coffinite is mostly associated with pyrite (Fig. 12d). It is suggested that organic matter and pyrite play an important role in uranium mineralization, which is also supported by geochemical data (U, S, TOC) from uranium ore-bearing and ore-barren layers. The data shows that the U, S, and TOC contents of uranium ore-bearing layers are relatively high, among which U and TOC, U and S all present good positive correlation (Table 2). All these indicate that organic matter and

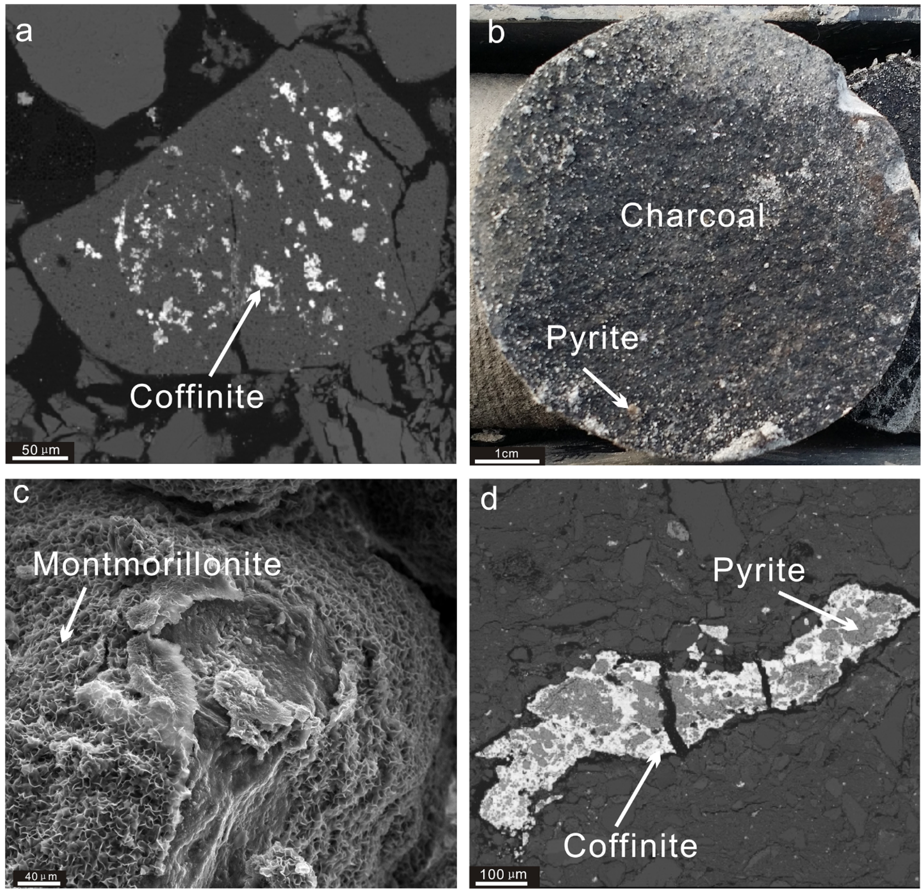

Fig. 12. A series of macro and micro photographs. *a: Uranium exists in debris particles in electron probe backscattering images; b: Carbon debris and pyrite are abundant in ore-forming sandstone; c: Montmorillonite Clay Membrane Developed on the Surface of Clastic Particles; d: Coffinite is associated with pyrite.*

Table 2
Geochemical data of sandstones from uranium hosting layer of well D35-1.

samples	D35-1-CY-1	D35-1- CY-2	D35-1- CY-3	D35-1 CY-4	D35-1 CY-5	D35-1 CY-6	D35-1 CY-7	D35-1 CY-8	D35-1 CY-9	D35-1 CY-10
U/ppm	4200	1200	150	92.5	75	110	187	92.8	29.6	48.8
Toc/ppm	1.45	0.18	0.02	0.25	0.05	0.04	0.34	0.02	0.04	0.26
S/ppm	2.32	0.24	0.05	0.03	0.05	0.05	0.15	0.03	0.05	0.08

sulfur play an important role in uranium enrichment process.

Therefore, braided-meandering river channel sandstone is rich in organic matter and has favorable porosity and permeability, which not only provides space for the migration of uranium-bearing fluids and uranium mineralization, but also contains reductant for uranium mineralization. Braided-meandering river channel sandstone is the most favorable uranium reservoirs in the study area.

5.3. Sequence and sedimentary metallogenic model

Based on the analysis of sequence and sedimentary control on uranium mineralization, a sandstone-type uranium metallogenic model of Sifangtai Formation in northern Songliao Basin is established (Fig. 13).

In LST, braided-meandering channel bar sand bodies are continuously distributed, with good reservoir physical properties, suitable thickness, abundant organic matter and reducing sulfur content, and regional confining bed, which can form large-scale and high-grade uranium deposit. While the sand bodies, that have a certain reservoir property, organic matter, reducing sulfur content and limited confining bed, can form low-grade uranium deposition.

TST mainly provides regional confining bed. In addition, the discontinuous point bar sand bodies of meandering river in TST have a certain reservoir properties and regional confining beds, if there is a certain amount of organic matter and sulfur in sandstone, a certain scale of uranium mineralization can be formed. It is difficult to form uranium mineralization in HST and RST due to the lack of good reservoir trap assemblages and uranium source conditions.

6. Conclusions

1. Two sedimentary facies including braided-meandering and meandering river are identified in Sifangtai Formation, which can be further divided into 4 subfacies and several more detailed microfacies, the uranium ore mainly developed in the channel bar microfacies. The channel bar sand bodies with high sand percentage (the best is from0.6 to 0.8), optimum thickness (the best is from 8 to 12 m), high porosity and permeability (the highest is 42% and 1140 mD, respectively) are the best reservoir for the uranium.
2. Sifangtai Formation is divided into two third-order sequences (SQ1 and SQ2). Each sequence consists of four complete system tract, i.e., LST, TST, HST and RST. LST forms uranium reservoir with good properties, TST forms good confining layers, forming a reservoir-confining assemblage together with sand bodies in LST, which is beneficial to uranium mineralization.

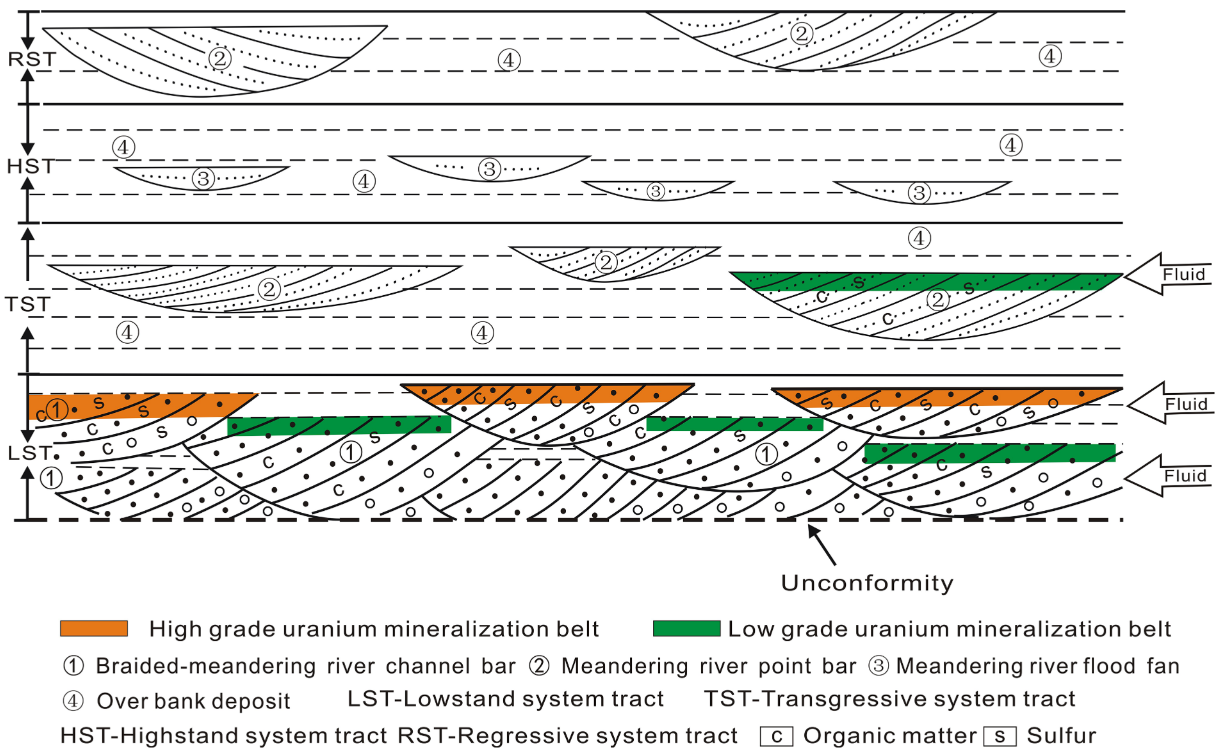

Fig. 13. Uranium metallogenic model of sequence and sedimentary of Sifangtai Formation in northern Songliao Basin.

3. Organic matter and pyrite play an important role in uranium mineralization. The braided-meandering river with strong hydrodynamic conditions brings about abundant carbonized plant fragments, providing the necessary reduction environment for uranium mineralization. Pyrite in the braided channel sand bodies in the study area is mostly associated with carbon debris, while coffinite is mostly associated with pyrite.
4. The channel bar sandstones with good reservoir properties, suitable thickness, regional confining bed, sufficient organic matter and reducing sulfur content, can form large and high grade uranium deposits, while the point bar sandstones with a certain reservoir property, organic matter, reducing sulfur can only form low grade uranium deposit.

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References

Bechtel, A., Jia, J., Strobl, S.A., Sachsenhofer, R.F., Liu, Z., Gratzer, R., Püttmann, W., 2012. Palaeoenvironmental conditions during deposition of the Upper Cretaceous oil shale sequences in the Songliao Basin (NE China): implications from geochemical analysis. Org. Geochem. 46, 76–95.

Bonnetti, C., Cuney, M., Malartre, F., Michels, R., Liu, X.D., Peng, Y.B., 2015. The Nuheting deposit, Erlian Basin, NE China: synsedimentary to diagenetic uranium mineralization. Ore Geol. Rev. 69, 118–139.

Brown, L.F.J., Fisher, W.L., 1977. Seismic stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull apart basins. In: Payton, C.E. (Ed.), Seismic Stratigraphy-Applications to Hydrocarbon Exploration. Am. Assoc. Petrol. Geol. Mem., pp. 213–248.

Cai, C.F., Li, H.T., Qin, M.K., Luo, X.R., Wang, F.Y., Ou, G.X., 2007. Biogenic and petroleum related ore-forming processes in Dongsheng uranium deposit, NW China. Ore Geol. Rev. 32, 262–274.

Cai, Y.Q., Li, S.X., 2008. Sedimentary environment analysis of Yaojia formation- the ore-hosting stratum of Qianjiadian uranium deposit. Uran. Geol. 24 (2), 66–71 (in Chinese with English abstract).

Cai, G.Q., Zhang, Z.M., Li, S.X., 2005. Elemental geochemistry of the interlayer oxidation zone in the Shihongtan sandstone type uranium deposit, Xinjiang. Acta Geol. Sin. – English Ed. 79, 835–842.

Cao, H., Guo, W., Shan, X., Ma, L., Sun, P., 2015. Paleolimnological environments and organic accumulation of the Nenjiang formation in the Southeastern Songliao Basin, China. Oil Shale 32 (1), 5 (in Chinese with English abstract).

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.S.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. Earth Sci. Rev. 92, 1–33.

Chen, Z.Y., 2003. World uranium resources and exploration. World Nucl. Geosci. 20 (2), 63–69 (in Chinese with English abstract).

Chen, X.L., Xiang, W.D., Li, T.G., Xia, Y.L., Zheng, J.W., Pang, Y.Q., 2007. Lithofacies characteristics of ore-hosting horizon and its relationship to uranium mineralization in Qianjiadian uranium deposit, Songliao basin. Uranium Geol. 23 (6), 335–341 (in Chinese with English abstract).

Chen, X.L., Fang, X.H., Guo, Q.Y., Xia, Y.L., Pang, Y.Q., Sun, Y., 2008. Re-Disscussion on uranium metallogenesis in Qianjiadian sag, Songliao Basin. Acta Geol. Sin. 82 (4), 553–561 (in Chinese with English abstract).

Cheng, R.H., Wang, G.D., Wang, P.J., Gao, Y.F., 2009. Uppermost Cretaceous sediments: sedimentary microfacies and sedimentary environment evolution of Sifangtai Formation and Mingshui Formation in SK-I(n). Earth Sci. Front. 16 (6), 085–095 (in Chinese with English abstract).

Dahl, A.R., Hagmaier, J.L., 1974. Genesis and Characteristics of the Southern Power River Basin Uranium Deposits, Wyoming, USA. Formation of Uranium Ore Deposits. Int. Atom. Energy, Vienna, pp. 201–216.

Eglizaud, N., Miserque, F., Simoni, E., Schlegel, M., Descostes, M., 2006. Uranium (VI) interaction with pyrite (FeS_2): chemical and spectroscopic studies. Radiochim. Acta 94, 651–656.

Feng, Z.Q., Jia, C.Z., Xie, X.N., Zhang, S., Feng, Z.H., Cross, T.A., 2010. Tectonostratigraphic units and stratigraphic sequences of the nonmarine Songliao basin, northeast China. Basin Res. 22 (1), 79–95.

Finch, W.I., 1985. Sandstone-type Uranium Deposits—Summary and Conclusions. IAEA, pp. 401–408.

Franz, J.D., 1993. Uranium ore Deposits. Springer-Verlag, Berlin Heidelberg, pp. 250–319.

Galloway, W.E., 2004. Accommodation and the sequence stratigraphic paradigm. Reservoir, Can. Soc. Petrol. Geol. 31, 5, 9–10.

Galloway, W.E., Hobday, D.K., 1983. Terrigenous Clastic Depositional Systems –Applications to Petroleum, Coal, and Uranium Exploration. Springer, New York Heidelberg., pp. 423.

Gao, R.Q., Cai, X.Y., 1997. Formation Conditions and The Distribution of Oil and Gas Fields in Songliao Basin. Petrol. Ind. Press, Beijing, pp. 104–106 (in Chinese).

Goldhaber, M.B., Hemingway, B.S., Mohagheghi, A., Reynolds, R.L., Northrop, H.R., 1987. Origin of coffinite in sedimentary rocks by a sequential adsorption-reduction

mechanism. Bull. Miner. 110, 131–144.
Han, J.H., Wang, Y.M., Li, S.Q., Zhang, G.T., 2009. Sequence structure and depositional filling of Northern Songliao Basin during shrink age stage. Acta Sediment. Sin. 27 (3), 479–486 (in Chinese with English abstract).
IAEA, 1996. Guidebook to Accompany IAEA Map: World Distribution of Uranium Deposits. IAEA, Vienna, pp. 20–210.
Ingham, E.S., Cook, N.J., Cliff, J., Ciobanu, C.L., Huddleston, A., 2014. A combined chemical isotopic and microstructural study of pyrite from roll-front uranium deposits, Lake Eyre Basin, South Australia. Geochim. Cosmochim. Acta 125, 440–465.
Ji, Y.L., Zhang, S.Q., 1996. Lacustrine Fault Basin Sequence Stratigraphic. Petrol. Ind. Press, Beijing (in Chinese).
Jia, J., 2012. Research on the Recognition and Resource Evaluation of the Upper Cretaceous Oil Shale Based On Geochemistry-Geophysics Technique in the Songliao Basin (NE China). Jilin University Doctoral Dissertation (in Chinese with English abstract).
Jia, J.L., Liu, Z.J., Bechtel, A., Strobl, S.A., Sun, P.C., 2013. Tectonic and climate control of oil shale deposition in the Upper Cretaceous Qingshankou Formation (Songliao Basin, NE China). Int. J. Earth Sci. 102 (6), 1717–1734.
Jiao, Y.Q., Lv, X.B., Wang, Z.H., Wang, M.F., 2004a. Two distinct geological environments from sedimentary to diagenesis stages: examples from sandstone-type uranium deposits, Turpan-Hami Basin. Earth Sci. 29, 615–620.
Jiao, Y.Q., Lv, X.B., Yang, S.K., Wang, Z.H., Yang, Q., Wu, L.Q., 2004b. The identification of uranium metallogenic strata at the southwest margin of the Turpan-Hami Basin. Geoscience 18 (3), 346–352.
Jiao, Y.Q., Chen, A.P., Yang, Q., Peng, Y.B., Wu, L.Q., Miao, A.S., Wang, M.F., Xu, Z.C., 2005. Sand body heterogeneity: one of the key factors of uranium metallogenesis in Ordos basin. Uranium Geol. 21 (1), 8–16 (in Chinese with English abstract).
Jiao, Y.Q., Wu, L.Q., Yang, S.K., Lv, X.B., 2006. Sedimentology of Uranium Reservoir: The Exploration and Production Base of Sandstone-Type Uranium Deposits. Geol. Publ House, Beijing (in Chinese).
Kang, S.H., Yang, J.X., Liu, W.S., Zhao, X.Q., Qiao, P., Du, P.F., Lv, Y.H., 2017. Mineralization characteristics and potential of paleo-valley type uranium deposit in central Erlian Basin, Inner Mongolia. Uranium Geol. 33 (4), 206–214 (in Chinese with English abstract).
Li, S.Q., Wang, Y.M., Li, Z.J., 2007. Sequence stratigraphy classification and hydrocarbon features in the shallow layers, North Songliao Basin. J. Southwest Petrol. Univ. 29 (sup.1), 12–15 (in Chinese with English abstract).
Li, S.Q., Chen, F.K., Siebel, W., Wu, J.D., Zhu, X.Y., Shan, X.L., Sun, X.M., 2012. Late Mesozoic tectonic evolution of the Songliao basin, NE China: evidence from detrital zircon ages and Sr-Nd isotopes. Gondwana Res. 22 (3–4), 943–965.
Lin, C.M., Feng, Z.Q., Zhang, S., Zhao, B., Zhuo, H.C., Li, Y.L., Xue, T., 2007. Characteristics of the cretaceous supersequence in northern Songliao Basin. J. Palaeogeogr. 9 (6), 619–634 (in Chinese with English abstract).
Liu, J.H., 2004. Application of by geochemistry model to the determination of mineralization of sandstone type uranium ore. J. Mineral. Petrol. 24 (1), 65–70.
Liu, Z.J., Dong, Q.S., Wang, S.M., Zhu, J.W., Guo, W., 2002. In: Terrestrial Sequence Stratigraphy Introduction and Application. Petrol. Ind. Press, Beijing, pp. 58–62 (in Chinese with English abstract).
Liu, W.S., Jia, L.C., 2011. Sedimentary formation features and it's relationship with sandstone-type uranium ore formation in Yili Basin. World Nucl. Geosci. 28 (1), 1–5 (in Chinese with English abstract).
Liu, Z.J., Sun, P.C., Jia, J.L., Liu, R., Meng, Q.T., 2011. Distinguishing features and their genetic interpretation of stratigraphic sequences in continental deep water setting: a case from Qingshankou Foramtion in Songliao Basin. Earth Sci. Front. 18 (4), 171–180 (in Chinese with English abstract).
Lorilleux, G., Cuney, M., Jebrak, M., Rippert, J.C., Portella, P., 2003. Chemical brecciation processes in the Sue unconformity-type uranium deposits, Eastern Athabasca Basin (Canada). J. Geochem. Explor. 80, 241–258.
Luo, Y., Ma, H.F., Xia, Y.L., Zhang, Z.G., 2007. Geologic characteristics and metallogenic model of Qianjiadian uranium deposit in Songliao Basin. Uranium Geol. 23 (4), 193–201 (in Chinese with English abstract).
Luo, Y., He, Z.B., Ma, H.F., Sun, X., 2012. Metallogenic characteristics of Qianjiadian sandstone uranium deposit in Songliao basin. Miner. Deposit. 31 (2), 391–400 (in Chinese with English abstract).
Maithani, P.B., Taneja, P.C., Singh, Rajendra, 1995. A sandstone-type uranium deposits at Phlangdiloin, West Khasi Hills, Meghalaya, India. J.At. Miner. Sci. 3, 55–60.
Melin, R.E., 1964. Description and origin of uranium deposits in Shirley basin, Wyoming. Econ. Geol. 59, 835–849.
Mi, J.K., Zhang, S.C., Hu, G.Y., He, K., 2010. Geochemistry of coal-measure source rocks and natural gases in deep formations in Songliao Basin, NE China. Int. J. Coal Geol. 84, 276–285.
Miall, A.D., 1985. Architectural element analysis: a new method of facies analysis applied to fluvial deposits. Earth Sci. Rev. 22, 261–308.
Min, M.Z., Xu, H.F., Chen, J., Fayek, M., 2005b. Evidence of uranium biomineralization in sandstone-hosted roll-front uranium deposits, northwestern China. Ore Geol. Rev. 26, 198–206.
Min, M.Z., Chen, J., Wang, J.P., Wei, G.H., Fayek, M., 2005a. Mineral paragenesis and textures associated with sandstone-hosted roll-front uranium deposits, NW China. Ore Geol. Rev. 26, 51–69.
Nie, F.J., Li, M.G., Yan, Z.B., Xia, F., Zhang, C.Y., Yang, J.X., Kang, S.H., Shen, K.F., 2015. Segmentation of the target layer Saihan Formation and sandstone-type uranium mineralization in Erlian Basin. Geol. Bull. China 34 (10), 1952–1963 (in Chinese with English abstract).
Nie, F.J., Zhang, C.Y., Jiang, M.Z., Yan, Z.B., Zhang, X., Zhang, J., Qiao, H.M., Zhou, W., 2018. Relationship of depositional facies and microfacies to uranium mineralization in sandstone along the southern margin of Turpan-Hami Basin. Earth Sci. 43 (10), 3584–3602 (in Chinese with English abstract).
Pei, C.K., Huang, X.F., Zhang, B.J., 2007. A review on uranium resources in Mongolia. World Nucl. Geosci. 24 (2), 88–95 (in Chinese with English abstract).
Qafoku, N.P., Kukkadapu, R.K., Mckinley, J.P., Arey, B.W., Kelly, S.D., Wang, C.M., Resch, C.T., Long, P.E., 2009. Uranium in framboidal pyrite from a naturally bioreduced alluvial sediment. Environ. Sci. Technol. 43, 8528–8534.
Qiao, H.M., Xu, G.Z., Zhang, F.X., Shang, G.F., Song, Z., Liu, Z.G., 2013. Study on iron geochemical behavior in the interlayer oxidation zone sandstone-type uranium metallogenetic process: A case from Shihongtan uranium deposit in the Turpan-Hami Basin of Xinjiang. Acta Sediment. Sin. 31 (3), 461–467 (in Chinese with English abstract).
Qiu, Y.B., Du, M., Wang, Q.Q., Yang, J.F., Sun, X., 2017. Controlling effect of sedimentation to the mineralization of inter-layer oxidation zone sandstone type uranium deposit in the southern margin of Yili Basin. Morden Min. 3 (3), 40–45 (in Chinese with English abstract).
Sanford, R.F., 1992. A new model for tabular type uranium deposits. Econ. Geol. 87, 2041–2055.
Scott, T.B., Tort, O.R., Allen, G.C., 2007. Aqueous uptake of uranium onto pyrite surfaces; reactivity of fresh versus weathered material. Geochim. Cosmochim. Acta 71, 5044–5053.
Subhash, J., Ian, C.R., Evgeniy, B., Liu, S.F., 2015. Basin-related uranium mineral systems in Australia: a review of critical features. Ore Geol. Rev. 76, 360–394.
Van Wagoner, J.C., et al., 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores and Outcrops Concepts for High-resolution Correlation of Time and Facies. Am. Assoc. Petrol. Geol, Oklahoma, USA.
Wang, Z.B., 2002. Current status and prospects of uranium geology developments of foreign in-situ leachable sandstone type uranium deposits. Uranium Geol. 18 (1), 9–21 (in Chinese with English abstract).
Wang, G.D., Cheng, R.H., Wang, P.J., Gao, Y.F., Wang, C.S., Ren, Y.G., Huang, Q.H., 2011. Centimeter-scale sedimentary sequence description of Upper Cretaceous Sifangtai Formation: lithostratigraphy, facies and cyclostratigraphy, based on the scientific drilling (SK1) borehole in the Songliao Basin. Earth Sci. Front. 18 (6), 263–284 (in Chinese with English abstract).
Wang, D.P., Liu, Z.J., Liu, L., 1994. Evolution and Sea Level Change of Songliao Basin. Geol. Publ. H (in Chinese).
Wu, R.G., Chen, A.P., Yu, D.G., 2003. Analysis on depositional system and discussion on ore-formation conditions of channel sandstone type uranium deposit— taking Dongsheng area, Ordos Meso-Cenozoic basin as an example. Uranium geol. 19 (2), 94–99 (in Chinese with English abstract).
Wu, L.Q., Jiao, Y.Q., Roger, M., Yang, S.K., 2009. Sedimentological setting of sandstone-type uranium deposits in coal measures on the southwest margin of the Turpan-Hami Basin, China. J. Asian Earth Sci. 36, 223–237.
Xia, Y.L., Zheng, J.W., Li, Z.Y., Li, L.Q., Tian, S.F., 2010. Metallogenic characteristics and metallogenic model of Qianjiadian uranium ore deposit in Songliao Basin. Miner. Deposit 29 (Sup.), 154–155 (in Chinese with English abstract).
Xu, J.J., Liu, Z.J., Bechtel, A., Meng, Q.T., Sun, P.C., Jia, J.L., Cheng, L.J., Song, Y., 2015. Basin evolution and oil shale deposition during Upper Cretaceous in the Songliao Basin (NE China): implications from sequence stratigraphy and geochemistry. Int. J. Coal Geol. 149, 9–23.
Yang, R.C., Han, Z.Z., Fan, A.P., 2007. Sedimentary microfacies and sequence stratigraphy of sandstone-type uranium deposit in the Dongsheng area of the Ordos Basin. J. Stratigr. 03, 261–266 (in Chinese with English abstract).
Yang, X.Y., Ling, M.X., Lai, X.D., 2009. Metallogenic model of the Dongsheng in-situ leaching sandstone-type uranium deposit in the Ordos Basin. Earth Sci. Front. 16 (2), 239–249 (in Chinese with English abstract).
Yu, W.B., 2009. Research on Metallogenic Conditions of Sandstone Type Uranium Deposit of Cretaceous in Southern Songliao Basin. Jilin University Doctoral dissertation (in Chinese with English abstract).
Zhang, Z.Q., 2006. Study on Metallogenic Conditions of Upper Cretaceous System for in-situ Leachable Sandstone Type Uranium Deposit in South Songliao Basin. Northeastern University Doctoral Dissertation (in Chinese with English abstract).
Zhang, L., Wang, Y.M., Li, S.Q., Han, J.H., Zhang, X.T., Zhu, Y.H., Wang, G.Y., Yang, T., 2009. High-resolution sequence stratigraphic characteristic and favorable hydrocarbon accumulation prediction of Sifangtai to Mingshui formation in the north of Songliao Basin. J. Central South Univ. (Sci. Technol.) 40 (6), 1679–1688 (in Chinese with English abstract).
Zhao, Z.H., Bai, J.P., Lai, T.G., 2018b. Reversal structure and its relation to metallization of sandstone type uranium deposit in northern Songliao Basin. Uranium Geol. 34 (5), 274–279 (in Chinese with English abstract).
Zhao, Y., Shao, L.Y., Xu, Q., Zhao, X., Wang, J.X., Ding, R., 2018a. Sequence stratigraphy and uranium mineralization model of uranium-bearing rock series in the southern margin of Erlian Basin. J. Min. Sci. Technol. 3 (4), 323–334 (in Chinese with English abstract).