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ПРОСТРАНСТВЕННО-ВРЕМЕННОЕ РАЗМЕЩЕНИЕ И ГЕНЕТИЧЕСКАЯ СВЯЗЬ РУДНЫХ ЗАЛЕЖЕЙ УРАНА, УГЛЯ И УГЛЕВОДОРОДОВ И ИХ ЗНАЧЕНИЕ ДЛЯ ПОИСКОВ УРАНА (*на примере мезокайнозойских ураноносных бассейнов Северного Китая*)

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Широко известен тот факт, что уран, уголь, нефть и другие руды встречаются в одном осадочном бассейне. Сравнивая пространственные и временные соотношения между распределением урана, угля и углеводородов, мы обнаружили, что рудоносные урановые и угольные пласты в пределах одного бассейна, как правило, переслаиваются или примыкают друг к другу. Тем не менее в целом урановые месторождения пространственно удалены от нефтяных. Мы проанализировали генетическую связь между нефтью, углем и ураном путем сопоставления результатов многочисленных геологических изысканий, анализов и предыдущих исследований Илийского, Сонляо и других бассейнов в Северном Китае. Считается, что мягкий и влажный палеоклимат должен быть важным фактором, влияющим на формирование угольного пласта, верхних и нижних аргиллитовых водоупоров и вмещающих пород, богатых органическими веществами. Таким образом, эти районы добычи угля, возникающие на краях бассейнов, заслуживают детального изучения для разведки на уран. Кроме того, металлогенические эпохи примерно аналогичны эпохам миграции углеводородов и тектонических событий. Существующие данные разведки на нефть могут быть использованы для выяснения региональной и местной тектонической эволюции бассейна, связанного с урановой минерализацией. И, наконец, была представлена грубая взаимосвязь между урановым оруденением и углеводородами. Отметим, что углеводороды не только способствуют формированию урановых месторождений, но также могут ингибировать транспортировку и минерализацию урансодержащих материалов. Регионы с неглубинными месторождениями углеводородного сырья или с большими залежами рассеянных углеводородов не являются идеальными для геолого-разведочных работ на уран.

Углеводороды, уголь, уран, энергетический бассейн, пространственно-временное распределение, урановое оруденение, генетическая связь

SPATIAL-TEMPORAL COLLOCATION AND GENETIC RELATIONSHIP AMONG URANIUM, COAL AND HYDROCARBONS AND ITS SIGNIFICANCE FOR URANIUM PROSPECTING: A CASE FROM THE MESOZOIC-CENOZOIC URANIFEROUS BASINS, NORTH CHINA

Z. Feng, F. Nie, J. Deng, H. Zhang, and B. Liu

The fact that uranium, coal, oil, and other ores occur in the same sedimentary basin has been extensively recognized. By comparing the spatial and temporal relationships among uranium, coal, and hydrocarbons, we found that the ore-bearing uranium and coal layers within the same basin are commonly interbedded or adjacent to each other. In general, however, uranium deposits are spatially distant from oilfields. We analyzed the genetic relationship among oil, coal, and uranium by compiling numerous geological surveys, test analyses, and previous studies of the Ili, Songliao, and other basins in North China. It is considered that the mild and humid paleoclimate should be an important factor affecting the formation of coal reservoir, mudstone as the upper and lower aquifuges, and the host rocks with rich organic matter. Thus, these coal-mining areas occurring at the edges of basins deserve to be studied in detail for uranium exploration. In addition, the metallogenic epochs are roughly similar to the epochs of hydrocarbon migration and tectonic events. These existing data of oil exploration can be used to unravel the regional and local tectonic evolutions of the basin related to uranium mineralization. Finally, a rough relationship between uranium mineralization and hydrocarbons was presented. Note that hydrocarbon is not just beneficial for the formation of uranium deposits but may also inhibit the transportation and mineralization of uranium-bearing materials. Regions with shallow hydrocarbon fields or large quantities of hydrocarbon dissipation are not the ideal exploration locations for uranium.

Hydrocarbon–coal–uranium, energy basin, spatiotemporal allocation, uranium mineralization, genetic relationship

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1. INTRODUCTION

In North China, a series of sandstone-hosted uranium deposits have been discovered in the Ili, Ordos, Erlian, and Songliao basins [Bonnetti et al., 2014, 2015; Cai et al., 2007; Dai et al., 2015; Gao et al., 2008; Li et al., 2009; Min et al., 2007; Wu et al., 2009b; Yue et al., 2011; Zhang et al., 2005, 2017; Zheng et al., 2015]. So far, the type of uranium deposits accounts for more than 50% of known uranium resources in China (OECD-NEA/IAEA, 2014). The coexistence of uranium deposits, hydrocarbons, and coal fields within the same basin is a common feature in North China, even in the Central-east Asia metallogenetic domain (Li et al., 2009; Liu et al., 2006, 2007a, 2007b). The idea of comprehensive multi-energy mineral exploration has been recently put forward in China [Dai et al., 2015; Liu et al., 2008; Wang et al., 2014]. This phenomenon has previously attracted the attention of many scholars [Chi and Xue, 2011, 2014; Deng et al., 2005; Liu et al., 2006, 2007a]. The Dongsheng uranium deposit related to hydrocarbon and coal in the Ordos Basin represents the most interesting uraniferous area [Cai et al., 2007; Fan et al., 2007; Li and Li., 2011; Li et al., 2006; Liu et al., 2007b; Sun et al., 2007; Tuo et al., 2010; Xue et al., 2010, 2011; Yang et al., 2009; Zhang et al., 2017]. Liu et al. (2008) suggested that coal and hydrocarbon generally exhibit a close association with uranium due to a specific geological background and similar geochemical behaviors. In addition, a large amount of research efforts related to the methods of photomicrographs, fluid inclusion oil biomarkers, X-ray diffraction, electron microprobe, as well as scanning electron microscopy, had been conducted to try to understand the relationship among hydrocarbon, coal, and uranium [Cai et al., 2007; Deng et al., 2005; Fan et al., 2007; Li et al., 2007; Wu et al., 2009a; Yang and Zhang, 2007]. Many of them suggested that hydrocarbon is favorable for the formation of uranium deposits [Cai et al., 2007; Fan et al., 2007; Li et al., 2006; Li et al., 2007; Liu et al., 2006; Wu et al., 2007; Xue et al., 2011]. However, we argue that the magnitude of the influence from hydrocarbon is limited in the Ili and Turpan-Hami basins. Moreover, hydrocarbon may inhibit uranium mineralization under particular unified conditions, but related research is still rare.

Here the spatial and temporal relationship among uranium, coal, and hydrocarbons in North China are elucidated by compiling numerous geological surveys, a few test analyses, and previous studies of the Ili, Songliao, and other basins of China. Then we present a brief comparative analysis of factors which may have controlled the formation of uranium deposits or anomalies within the Ili and Songliao basins. In addition, we provide detailed discussions of the relationships among uranium, hydrocarbons and coal and finally present a pattern regarding the relationship between uranium mineralization and hydrocarbons.

2. SPATIO-TEMPORAL COLLOCATION AMONG OIL, GAS, COAL AND URANIUM

2.1. Spatial distribution among uranium, coal, and hydrocarbons

2.1.1. Lateral distribution

The Central-east Asia metallogenetic domain, more than 6000 km long from the western Caspian sea to the Songliao Basin in Northeast China, is one of the most important hydrocarbon-producing areas in the world, and also contains abundant other natural resources [Liu, et al., 2007a]. The exogenic uranium deposit is the major of uranium ore-forming types across the metallogenic domain, especially the sandstone-hosted uranium deposit [Dai et al., 2015].

In Central Asia, resources of the Koldzhatsk and Nizhneillisk deposits are as large as 37,000 t, and 60,000 t of uranium, respectively [Kislyakov and Shchetochkin, 2000]. A number of smaller uranium deposits were found in the Kansk-Achinsk basin, Primorski Krai, southern Urals, and Transbaikalia [Yudovich and Ketris, 2001, 2006; Seredin and Finkelman, 2008]. These deposits mentioned above occur in the coal bearing basins [Seredin and Finkelman, 2008; Dai, et al., 2015]. In China, the known sandstone-hosted uranium deposits are mainly discovered in the Meso-Cenozoic sedimentary basins in North China [Fig. 1; Bonnetti et al., 2014, 2015; Cai et al., 2007; Dai et al., 2015; Gao et al., 2008; Li et al., 2009; Min et al., 2007; Wu et al., 2009b; Yue et al., 2011; Zhang et al., 2005, 2017; Zheng et al., 2015]. These uraniferous basins have the features of varied sizes and shapes. Amongst them are a number of large-scale uraniferous basins (e.g., Ordos, Songliao basins), and several smaller uraniferous basins (e.g., Erlian, Ili, Turpan-Hami basins) (Fig. 1). Additionally, massive uranium anomalies have been discovered in the Tarim, Junggar, Qaidam, and Hailaer basins, and hence have significant outlooks for prospecting in these basins [Liu et al., 2007a]. Likewise, these uranium deposits found in North China had also normally been discovered in the coal bearing basins [Wu et al., 2007]. In turn, some uraniferous and proven abnormally radioactive basins, the large-scale basins like Ordos, Tarim, and Junggar basins, have annual output of hydrocarbons more than 10 Mt [Liu et al., 2007a]. And the outputs of the smaller basins of Turpan-Hami, Erlian, and Hailaer basins are over 1 Mt [Liu et al., 2007a]. However, minimal hydrocarbon is sporadically distributed in the Ili and Turpan-Hami basins, Xinjiang [Yue and Wang, 2011].

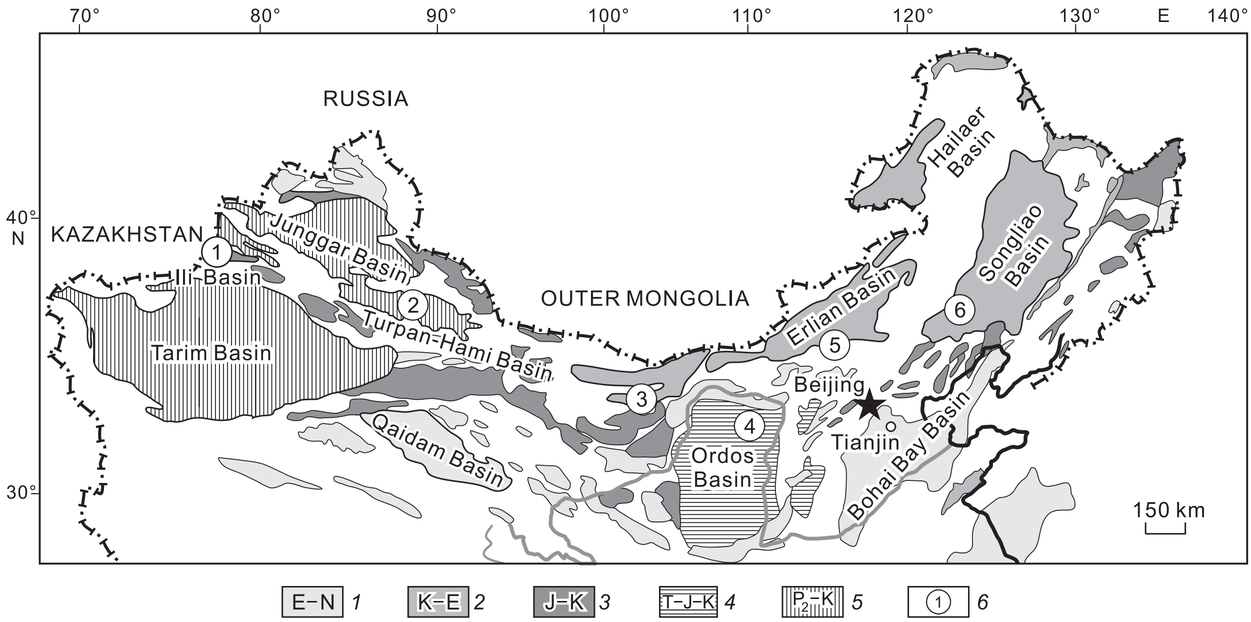


Fig. 1. Distribution map of the major Meso-Cenozoic uranium-bearing basins in North China. ***1*****, Paleogene-Neogene basins;** ***2*****, Mesozoic-Cenozoic basins;** ***3*****, Jurassic-Cretaceous basins;** ***4*****, Triassic-Cretaceous basins;** ***5*****, Late Permian-Cretaceous basins;** ***6*****, Sandstone-hosted uranium deposits. ①, Ili uranium deposits; ②, Shihongtan uranium deposit; ③, Tamusu uranium deposit; ④, Dongsheng uranium deposit;⑤, Bayanwula uranium deposit; ⑥, Qianjiadian-baixingtu uranium deposits.**

In general, uraniferous basins in North China underwent multiple phases of tectonic events [Chen et al., 2010]. However, there are differences in different parts of the same basin; hydrocarbon, coal, and uranium deposits have their own special features in the spatial distribution due to their difference of metallogenetic mechanisms. In most cases, uranium deposits are situated at the intrabasinal uplifts or the edge of these uraniferous basins (i.e., Ili Basin, Ordos Basin, Erlian Basin), while hydrocarbon fields are distributed within the basins, and coal mines are widespread throughout these basins. For example, a number of uranium deposits or anomalies are located in the Erlian Basin near the Bayanbolig uplift belt [Bonnetti, et al., 2014]. The Bayanwula uranium deposit is present in the vicinity of Manglai coal mine, and the Nuheting uranium deposit is also near the Gigsen oilfield [Fig. 2b; Li, et al., 2009]. In addition, in the Ordos Basin, natural gases are mainly distributed in the lower Paleozoic strata of the central basin, and the upper Paleozoic strata of northern basin, oil fields have been discovered in the southern basin [Chen, et al., 2013; Du at al., 2013], whereas uranium deposits are mainly located at the edge of the Ordos Basin [Li et al., 2011].

2.1.2. Vertical distribution

The distribution among uranium, coal and hydrocarbons has a close association with each other, especially in vertical direction.

The Bayanwula uranium deposit is situated at the western Tabei sag in Manite sub-basin, Erlian Basin [Li et al., 2009]. Through comprehensive analysis of geological and logging data, we found that in the Manite sub-basin of Erlian Basin, the major uranium mineralization occurs in the sandstone of Saihan Formation (K_1bs), whereas it is minor in the mudstone of the Yi'erdingmaha Formation (E_2y). Moreover, drill-core samples suggest that the mudstones of the lower member of the Saihan Formation (K_1s_1) are always rich in organic matter. Manglai coal mine is located to the east of Bayanwula uranium deposit [Fig. 2a, b; Li et al., 2009]. Indeed, the Nuheting uranium deposit is located on the roof of the Gigsen oilfield, formed in the upper Cretaceous Erlian Formation (K_2e) [Bonnetti et al., 2015]. The burial depth of uranium ore bodies is less than 100 m [Bonnetti et al., 2014], but for the major hydrocarbon bearing layers, the burial depth is deeper than 1 km [Fig. 2b; Li et al., 2009]. There is a large difference in the burial depth between the major ore-bearing uranium and coal layers (Fig. 2a). It is difficult for hydrocarbons from deep strata migrated upwards into the shallow host rocks, so we conclude that the magnitude of their influence was limited. In addition, Bonnetti et al. (2015) also reported that carbonaceous debris in host rocks, inherited from terrestrial plant material, was involved as reductants for uranium mineralization, rather than hydrocarbons.

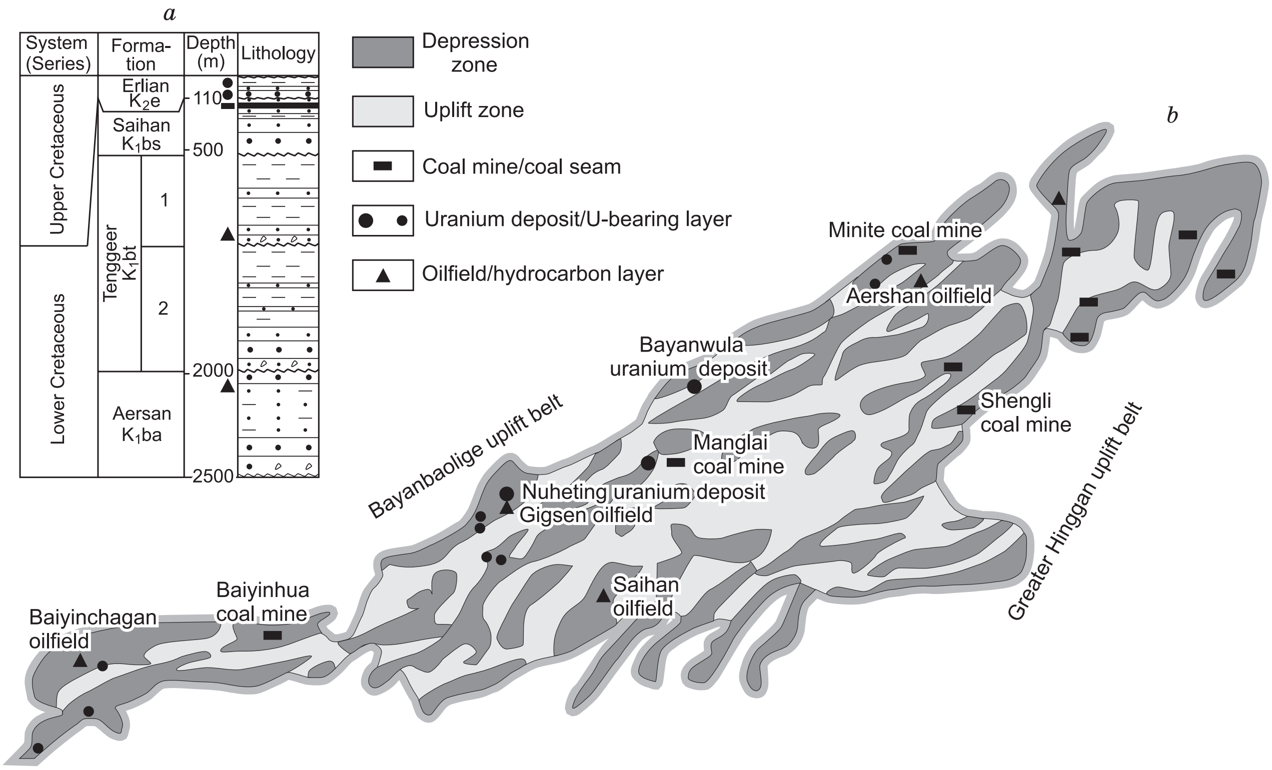


Fig. 2. *a*, Mineralized horizon and stratigraphic subdivision of Erlian Basin; *b*, Distribution map of hydrocarbon fields, coal mine and uranium deposits in the Erlian Basin (modified from Li et al., 2009).

2.2. Uranium metallogenic epochs

The formation of sandstone-hosted uranium deposit can be divided into two phases: a) the formation of the host rocks; and b) uranium mineralization [Taireth et al., 2015; Zhang et al., 2005]. The epochs of uranium mineralization are commonly simultaneous with and/or later than the formation of the host rocks [Liu et al., 2006]. The formation of uranium deposit needs a long term, and with multiple phases [Liu, et al., 2007a]. Additionally, in general, the uranium mineralization takes longer than the accumulation of the host rocks. To some extent, the polyphase metallogenesis was controlled by a complicated geological evolutionary history, which could cause uranium to re-migrate and re-concentrate in the same or other host rocks [Taireth et al., 2015]. In China, the formation epochs of the host rocks become younger from west to east in North China [Chen et al., 2010]. For the Ordos Basin and its western basins, the U-bearing strata mainly occurred in Jurassic, which is a result of the Himalayan movements [Chen et al., 2010]. A series of compressional basins were formed under its influence, which contains several small-sized intermontane basins, including the Ili and Turpan-Hami basins which host a significant portion of known uranium resources in northwest China [Ritts et al., 2004]. However, the eastern basins are younger where the U-bearing strata mainly occur in the Cretaceous, corresponding to the tectonic event of the subduction of the paleo-Pacific plate beneath the Eurasian plate [Yang et al., 2012]. Regional/local tectonics could have not only triggered the accumulation of the host rocks, but also created the landscape needed to generate the enrichment and occurrence of uranium mineralization.

Table 1. **Genetic association of uranium ore and hydrocarbon in Dongsheng area of Ordos Basin, China**

Event	Epochs(Ma)	Method	Data sources
Tectonic events	165~120± 65~45± 20~5±	Apatite fission-track dating	Wang et al (2014)
Hydrocarbon dissipation	134.5~121± 95.6~85.3±	K-Ar dating	Li et al (2006)
	32.4±	Thermoluminescence dating	
Uranium mineralization	124~107± 85~74± 20~8±	U-Pb isochron dating	Liu et al. (2007b)

Samples from the main target layers of the Dongsheng uranium deposit of the Ordos Basin were analyzed by using methods of K-Ar dating [Li et al., 2006; Liu et al., 2007b; Wang et al., 2014]. Hydrocarbon dissipation was initiated during the age spans of 134.5~121± Ma and 95.6~85.3± Ma. In addition, several samples also had been dated to 32.4± Ma using thermoluminescence dating by Li et al. (2006). These results lead us conclude that hydrocarbon dissipation events occurred in early Cretaceous and Miocene. Moreover, uranium ores also had been dated using U-Pb isochron dating by Liu et al. (2007c), and the ages of uranium mineralization are found to be: 124± to 107±, 85± to 74±, and 20± to 8± Ma. The apatite fission-track dating ages shown that in the Ordos Basin, the tectonic events happened in early Cretaceous (165± to 120± Ma), late Cretaceous (65± to 45± Ma), and Miocene (20± to 5± Ma) [Table 1; Wang, et al., 2014]. The metallogenic epochs are coincident with the epochs of hydrocarbon migration and tectonic events, suggesting that uranium accumulation and mineralization, and hydrocarbon migration in the Ordos Basin have a uniform geodynamic background (Table 1).

3. Relationship among uranium mineralization and coal, oil and gas

3.1. Major U-bearing layers and adjacent layers

The lateral distribution of the host rocks and the physico-chemical compositions control the occurrence of uranium in the host rocks [Taireth et al., 2015]. What's more, they also govern the size and distribution of the uranium ore-body [Taireth et al., 2015]. Likewise, ground water migration is controlled by the porosity and permeability of sandstone [Qidwai, et al., 1979]. Previous studies have shown that the host rocks are considered to be mid-fine sandstones, with high porosity and permeability [Liu et al., 2013]. These mid-fine grained sandstones frequently contain lots of organic matter and clay minerals [Liu et al., 2013]. The organic matter and clay minerals have strong abilities for adsorption of uranium minerals [Liu et al., 2013].

The host rocks were formed in a mild and humid paleo-climate so that they were rich in organic matter (pyrite, carbonaceous debris) [Bonnetti et al., 2014, 2015; Dai et al., 2015]. In addition, they are mainly composed of ancient braided channel and fan delta sedimentary sandstones [Table 2; Gao et al., 2008; Wu et al., 2009b; Yue and Wang, 2011]. The organic-rich sandy rocks can provide reductants for the formation of the transitional zone of redox. In addition, the assemblage of roof and floor aquifuges, comprised of lacustrine mud, forming in the mild and humid paleo-climate, will benefit the preservation of uranium ore [Xia et al., 2003].

3.2. Uranium transport and deposition

Uranium itself is a metallic element, which is vulnerable to oxidation and dissolution in O-bearing water [Dai et al., 2015]. The O-U-bearing water infiltrated into the porous sandstones by gravity-induced centripetal flows, and then migrated from the oxidized zone to the redox transition zone, which eventually led to the formation of uranium deposits [Taireth et al., 2015]. This process, to some extent, is similar to hydrocarbon accumulation, which in turn determines how hydrocarbons and uranium can respond together to some specific geological events [Liu, et al., 2007a].

Tectonic events (e.g., neo-tectonic movements) caused the differential uplift and subsidence of sedimentary basins [Sang et al., 2004], therefore giving rise to strong remigration of uranium element [Chen et al., 2010]. U-rich rocks from the edges and upwelling areas of these basins were denuded, atmospheric precipitation extracted uranium from U-rich rocks, and the O-U-bearing water infiltrated along with the faults or directly into the host rocks [Taireth et al., 2015]. Morevoer, tectonic events can also influence the size and distribution of uranium ore bodies, corresponding to those mineral deposits related to fluid mineral enrichment. In general, the epochs of primary uranium mineralization are young, but for oil, gas, and coal, the ore-forming epochs are older. Tectonic events are not only a driving factor for the occurrence of uranium, but also may lead to hydrocarbon migration, accumulation, and alteration of the coal quality of coalfields [Wu et al., 2007].

The O-U-bearing water infiltrated into porous sandstone and interacted with organic matter, forming the redox transition zone [Min et al., 2007]. At present, it has been discovered that reductants can be divided into two ingredients: a) inorganic mediums, such as pyrite; and b) organic mediums, such as carbonaceous debris [Liu et al., 2013]. Our study shows that these reductants play different roles in the occurrence of uranium in different regions:

a) The carbonaceous debris-based reductants mainly occur in the central-west of North China, such as uranium deposits in the Ili, Turpan-Hami, and Erlian basins. Both carbonaceous debris and sandstone migrated into the sedimentary field by water, and therefore formed the host rocks. Likewise, the mild and humid paleo-climate was favorable for plant growth. They are buried under the ground and formed the coal seams and the host rocks with organic matter.

b) The hydrocarbon-based reductants mainly occur in the central-east of North China. The Dongsheng uranium deposit in the Ordos Basin is a typical example [Cai et al., 2007]. Hydrocarbon migrated from the deep strata to the upper host rocks, then formed the reducing environment in the host rocks, which played a critical role in the formation of uranium deposits in the Ordos Basin [Cai et al., 2014; Xue et al., 2010]. A regional-scale alteration (e.g., green alteration, sandstone bleaching) formed in the host rocks and its adjacent strata by hydrocarbon reduction, suggesting that the uranium mineralization was govern by the reducing of hydrocarbon throughout the whole deposit region [Li et al., 2007; Wu et al., 2009a]. Previous studies show that epochs of the initial uranium mineralization are roughly the same as the epochs of the initial hydrocarbon migration and tectonic events, suggesting that uranium accumulation/mineralization and hydrocarbon migration in the Ordos Basin have the uniform geodynamic background. The interaction between O-U-bearing water and the reductants controls the size and distribution of the redox transition zone, and then determines the size and distribution of uranium ore bodies.

4. DETAILED DESCRIPTION OF TWO SELECTED URANIFEROUS BASINS

Uranium deposits in the Ordos Basin have been the focus of most studies in China [Cai et al., 2007; Fan et al., 2007; Li and Li., 2011; Li et al., 2006; Liu et al., 2007b; Sun et al., 2007; Tuo et al., 2010; Xue et al., 2010, 2011; Yang et al., 2009; Zhang et al., 2017], whereas other basins, such as the Ili and Songliao basins, have been discounted. Taking account of the differences between hydrocarbons and coal, in the following sections, uranium deposits in the southern margin area of Ili Basin and Qianjiadian-baixingtu uranium deposits in the Songliao Basin will be used as examples for evaluation and comparative analysis.

4.1. Ili Basin

Ili Basin, an intermontane superimposed basin, is located between the Tarim and Kazakhstan plates [Yue and Wang. 2011; Zheng, et al., 2015]. The basement strata are composed of Proterozoic and Palaeozoic crystalline rocks [Yue and Wang. 2011]. A series of uranium deposits have been discovered on the southern margin of Ili Basin [Dai, et al., 2015]. These ore-centralization areas contain the Kujieertai, Zajistan, Wukuerq, Mengqiguer, and Daladi uranium deposits and several uranium outliers (Fig. 3a), but there is minimal hydrocarbon formation in the southern margin area of Ili Basin.

Uranium ores mainly occur in the sandstones of dark terrestrial coal-bearing strata of the middle-lower Jurassic Shuixigou Group ($J_{1-2}sh$). Coal seams, thirteen layers in total, are also well developed in the Shuixigou strata, and are represented symbolically by M_1, M_2, M_3,…, M_{13} in turn, from the bottom to top (Fig. 3b). The layers M_5, M_8, and M_{10} are quite stable, and can be used as regional marker layers. Uranium ore-bodies (e.g., Kujieertai, Zajistan, Mengqiguer uranium deposits) are hosted between M_5 and M_8, but other uranium ore-bodies (e.g., Daladi uranium deposit) can be further divided into two segments (i.e., M_1-M_2, M_{10}-M_{11}). Sometimes, coal seams act as the roof and floor aquifuges. What's more, they also keep oxygen and water from seeping into the host rocks, thus maintaining the reduction environment for the preservation of the uranium ore [Yue and Wang, 2011].

The host rocks of the Shuixigou Group were deposited in a fan-delta environment, and were formed in a mild and humid paleo-climate so that they were rich in organic matter [Min, et al., 2005]. In addition, it features a complex lithology, such as glutenite, sandstone, mudstone, and coal (Fig. 3b). The host rocks are frequently interbedded with coal seams or mudstone. The basin is in a state of uplift influenced by the Himalaya movement since late Jurassic period [Fig. 3c; Table 3; Zheng, et al., 2015], the paleo-climate underwent a transition from mild and humid to arid during this time [Dai et al., 2015]. Many studies indicate that the uplift and denudation of strata at the edge of the Ili Basin can act as the source areas, atmospheric precipitation extracts uranium in

Table 2. **Features of ore-bearing layers of sandstone-hosted uranium deposits in North China. Geological information of Shihongtan, and Dongsheng deposits from Cai et al., (2007), Min et al., (2007), respectively**

Uranium deposit	Mengqiguer	Shihongtan	Dongsheng	Bayanwula	Qianjiadian
Basin	Ili Basin	Turpan-Hami Basin	Ordos Basin	Erlain Basin	Songliao Basin
Major ore-bearing layer	Shuixigou Group of the Middle-Lower Jurassic	Shuixigou Group of the Middle-Lower Jurassic	Zhiluo Formation of the Middle-Lower Jurassic	Upper member of Saihan Formation of the Lower Cretaceous	Yaojia Formation of the Upper Cretaceous
Lithology	Middle- to coarse-grained sandstone	Middle- to fine-grained sandstone	Middle- to coarse-grained sandstone	Middle- to fine-grained sandstone	Coarse-grained sandstone
Sedimentary system	Fan delta	Braided river	Braided river	Braided river (paleo-channels)	Braided river
Major reductants	Pyrite, Carbonaceous debris	Pyrite, Carbonaceous debris	Pyrite, Carbonaceous debris, Oil-gas	Pyrite, Carbonaceous debris	Pyrite, Oil-gas

U-rich rocks from these areas, and O-U-bearing water infiltrates along the faults or directly into the host rocks [Chen et al., 2013; Min et al., 2005; Yue and Wang, 2012]. The faults can also act as conduits for water drainage or hydrocarbon migration into the host rocks from deep strata. Reductants (i.e., pyrite, carbonaceous debris, hydrocarbons) interact with O-U-bearing water, forming the redox transition zone, and then uranium concentration and mineralization occurs in this zone [Fig. 4a, Min et al., 2005].

In order to date the metallogenic periods of uranium deposits in the Ili Basin, previous researchers used the U-Pb isochron dating method to measure the uranium ore samples [Table 4; Chen et al., 2010]. Results indicated that the epochs of primary uranium mineralization were Miocene and Pliocene, suggesting that the epochs of primary uranium mineralization in the Ili Basin were young, which are obviously younger than the

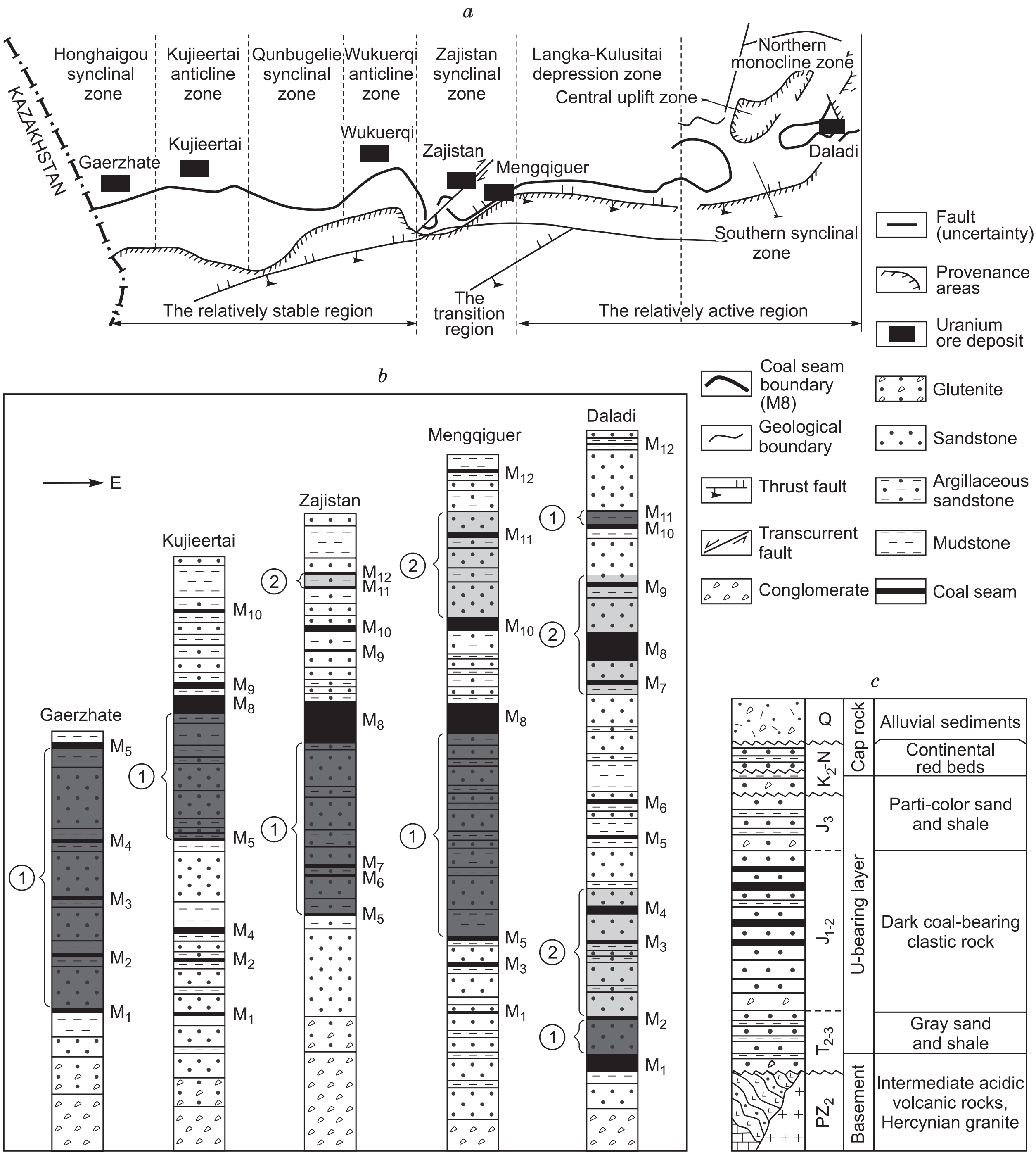


Fig. 3. *a*, Schemtic map showing the tectonic division of the southern margin of Ili Basin (modified from Yue and Wang, 2011); *b*, Stratigraphic column of the southern margin of Ili Basin; *c*, Mineralized horizon and stratigraphic of the southern margin Ili Basin. ①, U-bearing layer; ②, Mineralized layer.

Table 3. **Division of stratigraphic and structural stages in the southern part of Ili Basin**

Age	Stratigraphic units (Formation)		Tectonic events	Tentonic characteristics
Quaternary	Q		Himalayan movement	Overall uplift, but subsidence relative to Tianshan mountains
Neogene	N_2			Rift, rift-depression and tectonic deformation
Cretaceous	Donggou (K_2d)		Yanshan movement	Compression uplift
Jurassic	Qigu (J_3q)			Rift, rift-depression and tectonic deformation
	Shuixigou Group ($J_{1-2}sh$)	Xishanyao (J_2x)		
		Sangonghe (J_1s)		
		Badaowan (J_1b)		
Triassic	Xiaoquangou Group ($T_{2-3}xq$)		Indosinian movement	Depression

formation epochs of the U-bearing strata; therefore the sandstone-hosted uranium deposit is epigenetic. These epochs are consistent with the periods of the uplift and denudation of strata in the edge of Ili Basin, at that time, which was in an arid paleo-climate.

4.2. Songliao Basin

Songliao Basin is a petroliferous basin developed in northeast China [Xin et al., 2009]. This basin can further be subdivided into a series of sub-basins and depressions [Fig. 5a; Xin et al., 2009]. The Qianjiadian-Baixingtu uranium deposits are situated in the southwest of the Kailu sub-basin of the Songliao Basin [Gao et

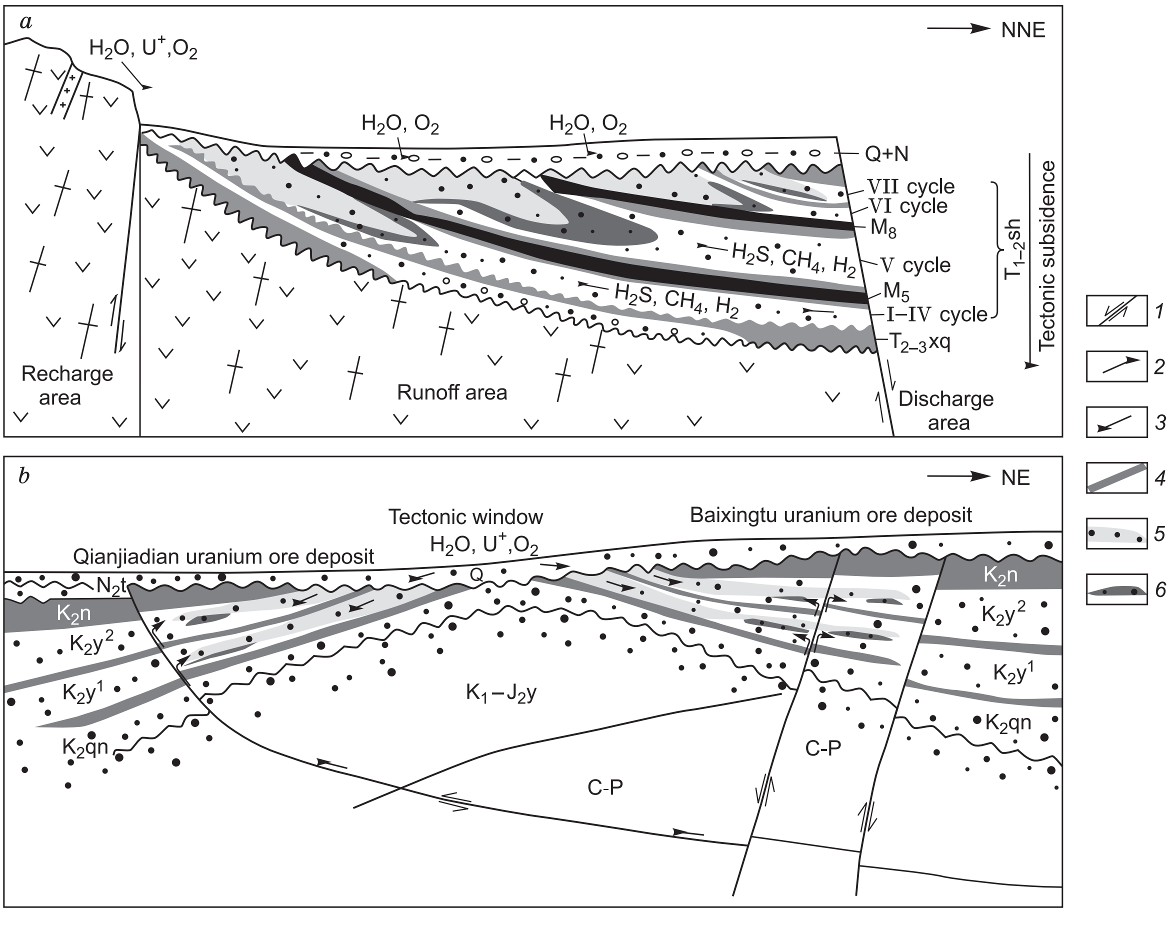


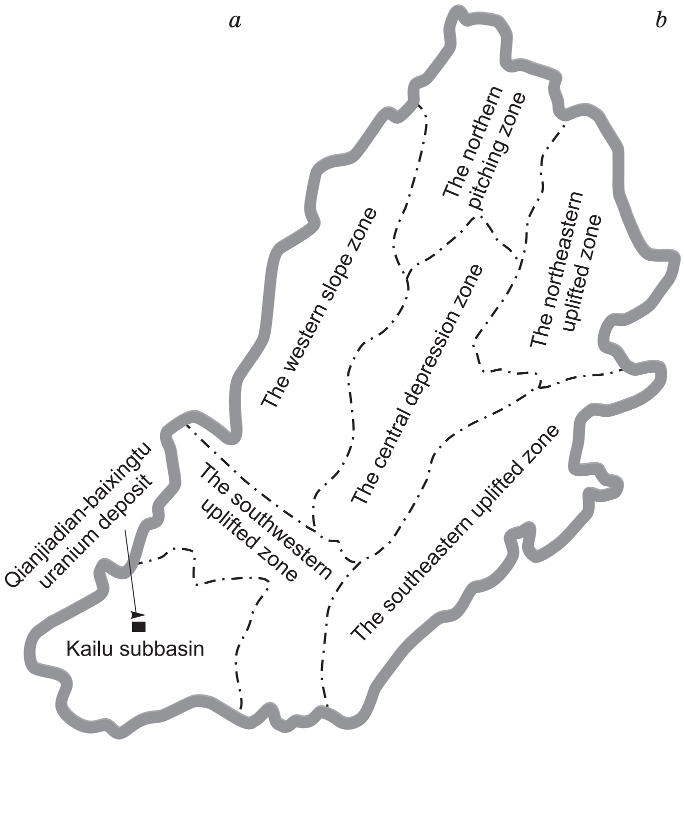
Fig. 4. ***a*, The metallogenetic model of uranium deposits in the southern margin Ili Basin (modified from Zhang et al., (2005)); *b*, The metallogenetic model of Qianjiadian-baixingtu uranium deposits in Songliao Basin (modified from Gao et al., (2008)). *1*, Faults; *2*, The flow direction of hydrocarbon; *3*, The flow direction of O-U-bearing; *4*, Mudstone; *5*, Interlayer oxidation zone; *6*, Uranium ore-body.**

Table 4. **Mineralization epochs of uranium deposits in the southern margin of Ili Basin**

Uranium deposit	Formation	Metallogenic epochs（Ma）	Method	Data sources
Kujieertai		38, 25		
Zajistan		12±4, 19		Chen et al., (2010)
Wukuerq	J_{1-2}	7, 5±1, 2, 1	U-Pb isochron dating	
Mengqiguer		4.1, 11.5		This study
Daladi		6.5		Xia et al., (2003)

al., 2008]. These deposits occur in the limb of a fold of the Songliao Basin, but farther from the edge of the basin [Gao et al., 2008]. Although there are several hydrocarbon outliers in and adjacent to the uranium ore areas, a hydrocarbon field has not been proven. The major uranium mineralization occurred in the sandstones of the Yaojia Formation (K_2y) of the Cretaceous. These host rocks consist of a series of coarse-grained sandstones deposited in braided river sedimentary environments (Fig. 5b). The assemblage of roof and floor aquifuges is mainly comprised of lacustrine mud, but coal seams have not been found. Sang et al. (2004) suggested that the uranium ores of the Qianjiadian deposit were formed in Cenozoic. The compression and uplifting of Songliao Basin are related to the Pacific Plate subduction beneath the Eurasian Plate that began in the late Cretaceous [Sang et al., 2004]. Based on the above analysis, we suggest that tectonic events caused the differential uplift and subsidence of Songliao Basin, which led to the occurrence of uranium (Fig. 4b).

Large quantities of carbonaceous debris have been found in the host rocks from the Baixingtu uranium deposit [Figs. 6a and b; Xia et al., 2003]. In addition, authigenic pyrite also existed in the host rocks [Gao et al., 2008]. Likewise, the microscopy images show that there is hydrocarbon in the host rocks (Figs. 6c and d). Through comprehensive analysis based on related work, we argue that the main reductants are from carbonaceous debris, rather than from hydrocarbon.



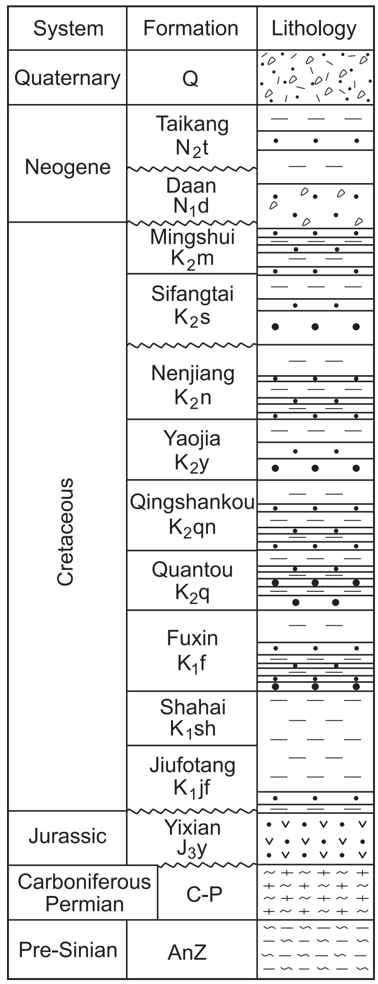


Fig. 5. ***a*, Sketch map showing tectonic division of the Songliao Basin (modified from Gao et al., (2004)); *b*, Comprehensive stratigraphic subdivision of the Kailu sub-basin, Songliao Basin.**

Lots of hydrocarbon resources occur in the shallow and deep strata of the Daqing placanticline and the western slope of the Songliao Basin (Fig. 5a). Uranium anomalies have been found adjacent to the hydrocarbon bearing area, however, the uranium ore bodies of economic size have not been discovered in these regions [Feng et al., 2013]. The Daqing placanticline is located in the center of the northern Songliao Basin [Xin et al., 2009]. Influenced by the tectonic movement, tectonic windows on top of the anticline axis are formed [Yang et al., 2012]. The western slope of Songliao Basin, a monocline with a gentle dipping angle, is similar to the southern margin area of Ili Basin. The monocline and tectonic windows provide favorable structural units for the occurrence of uranium. Massive hydrocarbon from deep strata migrated through faults into the shallow strata, forming new hydrocarbon reservoirs or were dispersed [Yang et al., 2012]. At this time, hydrocarbons could also infiltrate into the host rocks. As the reducing "force" is stronger, the oxidized sand-body is reduced, and the redox transition zones are pushed closer to the uranium source rocks, forming large-scale uranium mineralization but without economic concentrations.

4.3. Comparative analysis

Uranium deposits have been found in both Songliao and Ili basins, located in Northeast China and Northwest China, respectively. Songliao Basin is an important petroliferous basin, whereas extensive coal deposits were discovered in Ili Basin [Dai et al., 2015; Xin et al., 2009]. These uranium deposits can act as the ideal comparison objects to study the relationship of uranium mineralization with coal and hydrocarbons. Uranium deposits occur mainly in the southern margin region of Ili Basin [Yue and Wang, 2011]. However, the Qianjiadian-Baixingtu uranium deposits in the Songliao Basin were found in the intrabasinal uplifts [Gao et al., 2008]. The occurrence of uranium in the southern margin region of Ili Basin and in Songliao Basin are related to Himalayan movement and the subduction of the Pacific Plate beneath the Eurasian Plate, respectively [Chen et al., 2010; Xia et al., 2003]. Both occurrences indicate that uranium mineralization has a close relation with tectonic events. As mentioned above, there is a close spatial location relation between uranium and coal in the southern margin region of Ili Basin. Although hydrocarbon may benefit the formation of uranium deposits in the Songliao Basin to some extent, in reality, we found that the host rocks with carbonates are the main reductants. Additionally, we have done extensive studies in the western slope zone of Songliao Basin. Uranium anomalies have been found adjacent to the hydrocarbon-bearing area, whereas the uranium ore bodies with economic concentrations have not been discovered in these regions. In view of these points, we don't conclude that hydrocarbon is only favorable for the formation of uranium ore deposit. In contrast, hydrocarbon may curb the formation of uranium deposit.

5. DISCUSSION

5.1. Relationship among uranium, coal and hydrocarbons

5.1.1. Relationship between uranium mineralization and coal

China has long been famous for the largest coal resource reserves in the world [Liu et al., 2007a]. The Meso-Cenozoic sedimentary basins in North China host more than 80 percent of coal resources in China [Liu et al., 2007a]. The host rocks in the central-west of North China mainly occur in the Jurassic, whereas the Jurassic coal seams are widespread throughout these basins [Liu et al., 2007a]. Thus, the coal seams are closely related with the host rocks, especially in Northwest China. The ore-bearing uranium and coal layers within the same basins are commonly interbedded or adjacent to each other. In addition, coal seams and mudstones can act as the roof and floor aquifuges for uranium precipitation within the host rocks. The coal seams or mudstones were formed in mild and humid paleo-climates ([Yue and Wang, 2011]. Likewise, the host rocks generally contain abundant reductants (i.e., pyrite, carbonaceous debris) [Dai et al., 2015]. Previous studies suggested that the host rocks also accumulated in relatively humid paleo-climates, consistent with the coal seam and mudstones [Yue and Wang, 2011]. Thus, the host rocks and coal seems come to be interlinked in time as well as in space. Regardless of the infiltration of coalbed methane and hydrocarbon, let us assume that the amount of organic matter and its location are fixed. Large amounts of O-U-bearing water passed through the host rocks because of continuous infiltration, and the organic matter within the host rocks was gradually washed out, which made the redox transition zone move away from the source areas. The early precipitation of uranium was reactivated because of the input of the O-U-bearing water, and was transported and accumulated in the distal redox transition zone. In this way, the longer the process occurred, the more the uranium-bearing material tended to be concentrated, and the larger ore-body scale became in the host rocks.

5.1.2. Relationship between uranium mineralization and hydrocarbons

The hydrocarbon triggering of uranium mineralization has been widely recognized, which had also been shown by a number of research results from the Dongsheng and Nuheting uranium deposits of the Ordos and

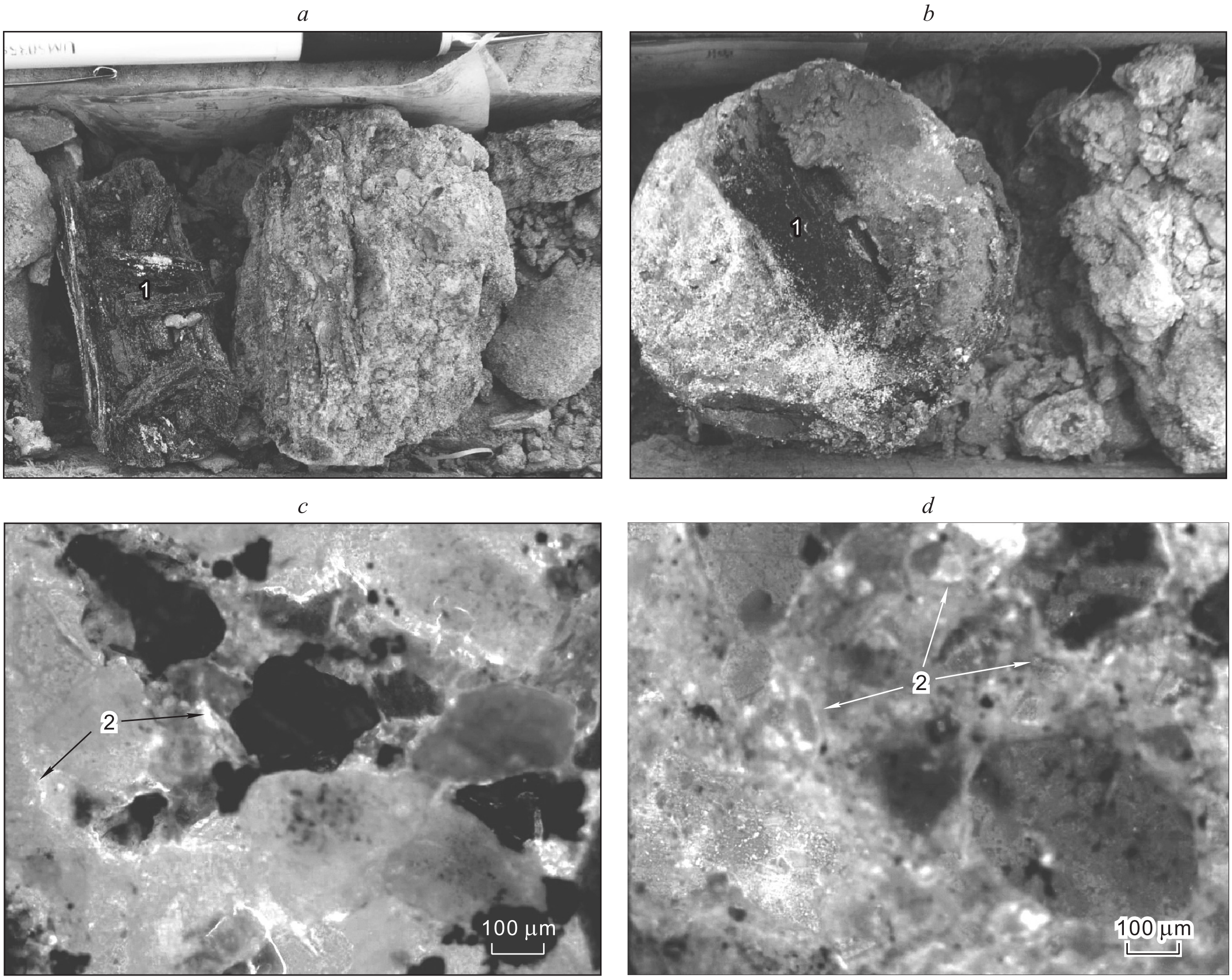


Fig. 6. ***a*** **and** ***b*****, Carbonaceous debris in the host sandstone from the Baixingtu uranium deposit;** ***c*** **and** ***d*****, Hydrocarbon in the host sandstone from the Baixingtu uranium deposit identified by Microscopy images. 1, Carbonaceous debris; 2, hydrocarbon.**

Erlian basins, respectively [Cai et al., 2007; Deng et al., 2005; Fan et al., 2007; Li et al., 2007, 2009]. However, we found that hydrocarbon had a limited impact on uranium mineralization within the Ili and Turpan-Hami basins. Recently Bonnetti et al. (2015) suggested that carbonaceous debris were involved as reductants for uranium mineralization, but hydrocarbons had not been found. In addition, uranium deposits are generally spatially distant from oilfields. For example, while the Nuheting uranium deposit in the Erlian Basin is developed on the roof of Gigsen oilfield, there is a large difference in the burial depth between the major ore layers of uranium and oil (Li et al., 2009), and the hydrocarbon fields have not been found near the Dongsheng uranium ore deposit in the Ordos Basin, where minimal hydrocarbon formation has been found. However, as mentioned above, the western slope of Songliao Basin is an area with lots of hydrocarbon resources hosted in the shallow strata [Fig. 5a; Xia et al., 2003]. Numerous uranium anomalies can be identified in radioactivity logging on and adjacent to hydrocarbon-bearing areas, but uranium ore bodies with economic concentrations have not been discovered in these regions. These facts reveal that there are some limitations of uranium mineralization related to hydrocarbons.

Through comprehensive analysis and comparison of the relationship between sandstone-hosted uranium ore and hydrocarbons, a rough model that accounts for the interplay of uranium ore and hydrocarbons is proposed here (Fig. 7).

Most sedimentary basins located in the North of China had experienced a series of tectonic events since the Mesozoic-Cenozoic era [Deng et al., 2005]. There are several new tectonic fractures and reactivation of faults in the basin under the regional tectonic evolution. These faults can act as migration pathways for groundwater discharge and upward, lateral migration of hydrocarbons from deep strata [Abzalov and Paulson,

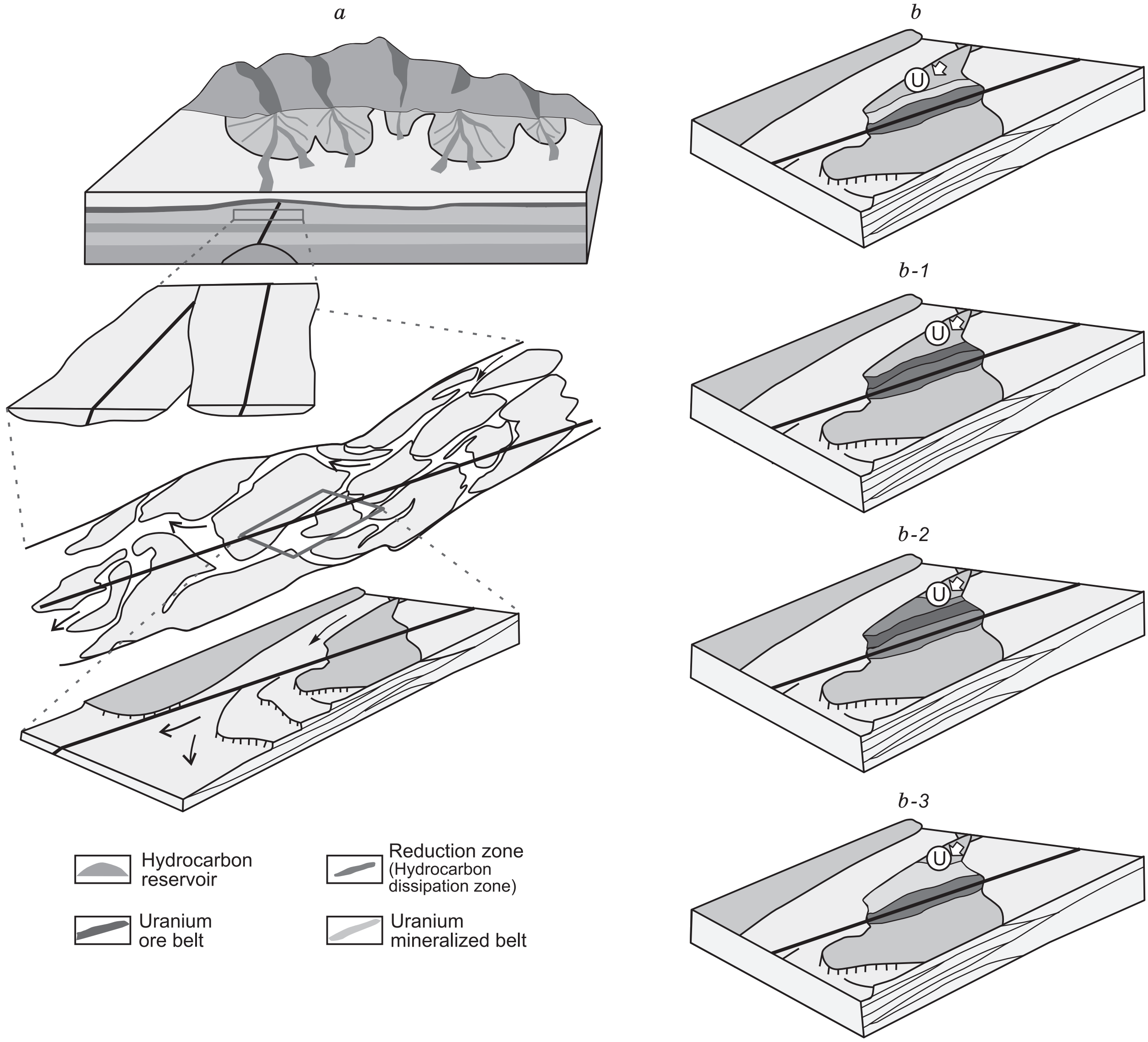


Fig. 7. The process and result of uranium mineralization affected by hydrocarbon. *a*, Spatial location relationship between the host rocks and hydrocarbon; *b*, Initiate interaction between hydrocarbon and O-U-water; *b-1*, Moderate dissipation of hydrocarbon: from uranium ore-body; *b-2*, Excess dissipation of hydrocarbon: preservation of uranium ore; *b-3*, Excess dissipation of hydrocarbon: curb uranium mineralization.

2012]. Hydrocarbons and O-U-bearing water migrate into the host rocks, forming two "forces": the oxidation "forces" from O-U-bearing water, and the reducing "forces" from hydrocarbons. They interact and are mutually restricted in the host rocks so that the redox transition zone is able to move, which leads to some results as follows:

a) When the oxidation "force" is stronger, uranium-bearing material can be accumulated in the redox transition zone. The longer the process goes on, the more concentrated the uranium-bearing materials become, and the bigger the ore-body scale is in the host rocks (e.g., uranium deposits in the Ili basin), as shown in Fig. 7b-1.

b) When the reducing "force" is stronger, they may lead to two consequences. On the one hand, hydrocarbon could continually consume O_2 in sandstone, forming secondary reduction such as green alteration and sandstone bleaching. This may then prevent uranium mineralization, and maintaining the reduction environment for the preservation of uranium ore (e.g., Dongsheng uranium deposit; Ordos Basin, Fig. 7b-2). On the other hand, while uranium mineralization was in the stage of pre-enrichment of uranium ore, the oxidized sand-body had already been reduced by reductants, which made the redox transition zone closer to the uranium source area. In this case, uranium-bearing materials cannot continue to be accumulated at the location of pre-enrichment of uranium ores, but are accumulated instead in the new redox transition zone, thereby forming a large-scale uranium mineralization without economic concentrations (e.g., numerous uranium anomalies occurred in the western slope of Songliao Basin; Fig. 7b-3).

This rough model as discussed is based on the synthesis of numerous field surveys and a few test analyses, but correlation lab analysis has not been studied in detail. Clearly, this model deserves closer scrutiny in the future.

5.2. Exploration significance

The rich organic matter in the host rocks is a critical factor for uranium enrichment and mineralization. Coal seams are believed to have formed in mild and humid paleo-climates, similar to that of the host rocks. The host rocks and coal seams are commonly interbedded or adjacent to each other. Given that coal mines often exhibit a close relation with uranium, we suggest that these coal mining areas which occur at the edges of basins deserve to be studied in detail. The existing data from coal exploration can be used to unravel the paleo-climate, environment, and sedimentation changes which are significantly beneficial for uranium exploration. However, the uranium metallogenic epochs coincide well with the epochs of hydrocarbon migration and tectonic events. Hydrocarbon migration and uranium mineralization underwent a unified tectonic setting. Thus, studies of regional and local tectonic evolutions of the basin based on these existing data from hydrocarbon exploration are favorable for deepening our knowledge of the tectonic settings related to uranium mineralization.

6. CONCLUSIONS

(1) The host rocks are generally known be rich in organic material (mostly carbonaceous debris), which accumulate in relatively mild and humid paleo-climates and are consistent with coal seam formation.

(2) The ore-bearing uranium and coal layers coexistent in the same basin are commonly interbedded or adjacent to each other, suggesting coal mines have a close association with uranium deposits in spatial distribution. It is noted that these coal mining areas occurring at the edges of basins deserve to be studied in detail for uranium exploration.

(3) Tectonic events caused uranium re-activation and re-migration and hydrocarbon dissipation. Studies of regional and local tectonic evolutions of the basin through these existing data from hydrocarbon exploration are crucial for us to have a knowledge of the tectonic settings related to uranium mineralization.

(4) Uranium deposits are normally spatially distant from oilfields. We argue that hydrocarbon is not just beneficial for the formation of uranium deposits, but may inhibit the transportation and mineralization of uranium-bearing material. Regions with shallow hydrocarbon fields or large quantities of hydrocarbon dissipation are not the ideal exploration locations for uranium.

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REFERENCES

Abzalov M.Z., Paulson O., 2012. Sandstone hosted uranium deposits of the Great Divide Basin, Wyoming, USA. Appl. Earth Sci. 121(2), 76–83.

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.

Bonnetti C., Malartre F., Huault V., Cuney M., Bourlange S., Liu X.D., Peng Y.B., 2014. Sedimentology, stratigraphy and palynological occurrences of the late Cretaceous Erlian Formation, Erlian Basin, Inner Mongolia, People's Republic of China. Cretaceous Res. 48, 177–192.

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.

Chen G., Li S.H., Zhang H.R., Yang F., Ding C., Lei P.P., Hu Y.X., 2013. Fluid inclusion analysis for constraining the hydrocarbon accumulation periods of the Permian reservoirs in Northeast Ordos Basin. J. Earth Sci. 24, 589–598.

Chen Z.Y., Chen D.S., Gu K.H., Wang Y.J., 2010. The regional distribution regularities of ore-hosting horizon, deposit type and mineralization age of China's sandstone-hosted uranium deposits [in Chinese with English Abstract]. Uranium Geol. 26, 321–330.

Chi G.X., Xue C.J., 2011. An overview of hydrodynamic studies of mineralization. Geosci. Front. 2 (3), 423–438.

Chi G.X., Xue C.J., 2014. Hydrodynamic regime as a major control on localization of uranium mineralization in sedimentary basins. Sci. China, Ser. D: Earth Sci. 57 (12), 2928–2933.

Dai S.F., Yang J.Y., Ward C.R., Hower J.C., Liu H.D., Garrision T.M., O'Keefe J.M., 2015. Geochemical and mineralogical evidence for a coal-hosted uranium deposit in the Yili Basin, Xinjiang, northwestern China. Ore Geol. Rev. 70, 1–30.

Deng J., Wang Q.F., Gao B.F., 2005. Evolution of Ordos Basin and its distribution of various energy resources [in Chinese with English Abstract]. Geoscience 19, 538–545.

Du W., Jiang Z.X., Zhang Y., Xu, J., 2013. Sequence stratigraphy and sedimentary facies in the lower member of the Permian Shanxi formation, northeastern Ordos Basin, China. J. Earth Sci. 24, 75–88.

Fan A.P., Liu Y.Q., Yang R.C., Feng Q., Zhang F.X., Han Z.Z., 2007. Research on diagenesis of the sandstone-type uranium deposits in Dongsheng area, Ordos basin. Sci. China, Ser. D: Earth Sci. 50 (S1), 195–202.

Feng Z.B., Nie F.J., Yan Z.B., Zhong Y.Q., Gu S.F., Li J., 2013. Mineralizing conditions and metallogenic model of uranium in west slope of Songliao Basin [in Chinese with English Abstract]. Petrol. Geol. Oilfield Dev. Daqing 32 (4), 36–41.

Gao Y.Y., Yu B.L., Yu W.B., Li Z.C., Zhang Q.X., Miao A.Z., 2008, Analysis on uranium metallogenic conditions and ore-controlling factors of Qianjiadian–Jiamatu area, southwest of Songliao Basin [in Chinese with English Abstract]. World Nucl. Geosci. 25, 150–156.

Jaireth S., Roach I.C., Bastrakov E., Liu S.F., 2015. Basin-related uranium mineral systems in Australia: A review of critical features. Ore Geol. Rev. 76, 360–394.

Kislyakov Ya.M., Shchetochkin V.N., 2000. Hydrogenic ore formation [in Russian]. Geoinformmark, Moscow, 608 pp.

Li R.X., Li Y.Z., 2011. The geologic features of mineralization at the Dongsheng uranium deposit in the northern Ordos Basin (Central China). Russian Geology and Geophysics (Geologiya i Geofizika) 52 (6), 593–602 (763–774).

Li R.X., He Y., Li J.B., Li J.H., Li X., 2006. Isotope composition of fluid inclusion and tracing to the source of mineralization fluid in Dongsheng uranium deposit, North Ordos Basin [in Chinese with English Abstract]. Acta Geol. Sinica 80, 753–760.

Li Y.X, Qin M.K., He Z.B., 2009. Spatio-temporal distribution of uranium,oil and coal, and uranium metallogenic processes in Erlian Basin, Inner Mongolia [in Chinese with English Abstract]. World Nucl. Geosci. 26, 25–30.

Li Z.Y., Fang X.H., Chen A.P., Ou G.X., Xiao X.J., Sun Y., Liu C.Y., Wang Y., 2007. Origin of gray-green sandstone in ore bed of sandstone type uranium deposit in North Ordos Basin. Sci. China, Ser. D: Earth Sci. 50 (2), 165–173.

Liu C.Y., Zhao H.G., Tan C.Q., 2006. Occurrences of multiple energy mineral deposits and mineralization/reservoiring system in the basin [in Chinese with English Abstract]. Oil Gas Geol. 27, 131–142.

Liu C.Y., Qiu X.W., Wu B.L., Zhao H.G., 2007a. Characteristics and dynamic settings of the Central–East Asia multi-energy minerals metallogenetic domain. Sci. China, Ser. D: Earth Sci. 50 (S2), 1–18.

Liu C.Y., Zhao H.G., Zhao J.F., Wang J.Q., Zhang D.D., Yang M.H., 2008. Temporo-spatial coordinates of evolution of the Ordos basin and its mineralization responses. Acta Geol. Sinica 82 (6), 1229–1243.

Liu H.B., Xia Y.L., Tian S.F., 2007b. Study on geochronology and uranium source of sandstone-type uranium deposit in Dongsheng area [in Chinese with English Abstract]. Uranium Geol. 23, 23–29.

Liu J., Nie F.J., Hou S.R., Chen L.L., Wang J.L., 2013. Types of uraniam minerial and its occurrence state of the sandstone-type uranium deposits in the Meso-Cenozoic basin [in Chinese with English Abstract]. J. East China Inst. Technol. (Nat. Sci.) 36 (2), 107–112.

Mikake S., Yoshida H., Koide K., Maekawa K., Ogata N., Yanagizawa K., 2000. Methodology development for modeling heterogeneous conductivity fields for a sandstone type uranium deposit, Central Japan. Eng. Geol. 56 (1–2), 185–195.

Min M.Z., Chen J., Wang J.P., Wei G., Fayek M., 2005. Mineral paragenesis and textures associated with sandstone-hosted roll-front uranium deposits, NW China. Ore Geol. Rev. 26, 51–69.

Min M.Z., Peng X.J., Zhou X.L., Qiao H.M., Wang J.P., Zhang L., 2007. Hydrochemistry and isotope compositions of groundwater from the Shihongtan sandstone-hosted uranium deposit, Xinjiang, NW China. J. Geochem. Explor. 93 (2), 91–108.

OECD-NEA/IAEA, 2014. Uranium 2014: Resources, Production and Demand.

Qidwai H.A., Jensen M.L., 1979. Methodology and exploration for sandstone-type uranium deposits. Miner. Deposita 14, 137–152.

Ritts B.D., Hanson A.D., Darby B.J., Nanson L., Berry A., 2004. Sedimentary record of Triassic intraplate extension in North China: Evidence from the nonmarine NW Ordos Basin, Helan Shan and Zhuozi Shan. Tectonophysics 386, 177–202.

Sang J.S., Zhang Y.B., Chen W.Y., 2004. Neotectonic movement and its relation to uranium metallogenesis in central southern Songliao basin and its adjacent areas [in Chinese with English Abstract]. Uranium Geol. 24, 219–224.

Seredin V., Finkelman R.B., 2008. Metalliferous coals: a review of the main genetic and geochemical types. Int. J. Coal Geol. 76, 253–289.

Sun Y.Z., Liu C.Y., Dai S.F., Qin P., 2007. Geochemical characteristics of Dongsheng sandstone-type uranium deposit, Ordos Basin. Chinese J. Geochem. 26 (3), 5–243.

Tuo J.C., Chen R., Zhang M.F, Wang X.B., 2010. Occurrences and distributions of branched alkylbenzenes in the Dongsheng sedimentary uranium ore deposits, China. J. Asian Earth Sci. 39 (6), 770–785.

Wang Y., Yang W.L., Deng J., Wu B.L., Li Z.Y., Wang M.Z., 2014. Accumulation system of cohabitating multi-energy minerals and their comprehensive exploration in sedimentary basin [in Chinese with English Abstract]. Acta Geol. Sinica 88, 815–824.

Wu B.L., Liu C.Y., Wang J.Q., 2007. Basical characteristics of fluid geologic process of interlayer oxidation zone sandstone-type uranium deposit. Sci. China, Ser. D: Earth Sci. 50, 185–194.

Wu B.L., Zheng G., Zhang A.J., Wang W.Y., Qiu X.W., Wang J.Q., Hu L., Zhang B.H., 2009a. The different characteristics and geological significance of reduction alteration of sandstone-type uranium deposits in northwest region of China. Energy Explor. Exploit. 27(4), 261–275.

Wu L.Q., Jiao Y.Q., Roger M., Yang S.K., 2009b. 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 (2), 223–237.

Xia Y.L., Lin J.R., Liu H.B., 2003. Analysis on metallogenic conditions and prospect prognosis for interlayer oxidation zone sandstone-type uranium deposit at western slope of Songliao Basin [in Chinese with English Abstract]. Uranium Geol. 19, 129–136.

Xin R.C., Li G.F., Feng Z.Q., Liang J., Lin C., 2009. Depositional characteristics of lake-floor fan of Cretaceous lower Yaojia Formation in western part of Central depression region, Songliao basin. J. Earth Sci. 20, 731–745.

Xue C.J., Chi G.X., Xue W., 2010. Interaction of two fluid systems in the formation of sandstone-hosted uranium deposits in the Ordos Basin: Geochemical evidence and hydrodynamic modeling. J. Geochem. Explor. 106, 226–235.

Xue C.J, Chi G.X, Xue W., 2011. Effects of hydrocarbon generation on fluid flow in the Ordos Basin and its relationship to uranium mineralization. Geosci. Front. 2 (3), 439–447.

Yang H.B., Zhu Y.P., Gu S.F., 2012. Reversal tectonic characteristics and their contribution to mineralizing uranium in North Songliao Basin [in Chinese with English Abstract]. Petrol. Geol. Oilfield Dev. Daqing 31, 7–11.

Yang W.X., Zhang L.P., 2007. Distinguishing signs of fluids in a basin where multifarious minerals deposit together [in Chinese with English Abstract]. Acta Geol. Sinica 18, 176–180.

Yang X.Y., Ling M.X., Sun W.D., 2009. The genesis of sandstone-type uranium deposits in the Ordos Basin, NW China: Constraints provided by fluid inclusions and stable isotopes. Int. Geol. Rev. 51, 422?455.

Yudovich Ya.E., Ketri, M.P., 2001. Uranium in coals [in Russian]. Komi Science Centre, Syktyvkar, 84 pp.

Yudovich, Ya.E., Ketris, M.P., 2006. Selenium in coal: a review. Int. J. Coal Geol. 67, 112–126.

Yue S.J., Wang G.C., 2011. Relationship between the hydrogeochemical environment and sandstone-type uranium mineralization in the Ili basin, China. Appl. Geochem. 26, 133–139.

Zhang J.D., Xu G.Z., Chen A.P., 2005. Preliminary discussion on uranium metallogenic models of China's in-situ leachable sandstone-type uranium deposits [in Chinese with English Abstract]. Uranium Geol. 21, 139–145.

Zhang L., Liu C.Y., Fayek M., Wu B.L., Lei K.Y., Cun X.N., Sun L., 2017. Hydrothermal mineralization in the sandstone-hosted Hangjinqi uranium deposit, North Ordos Basin, China. Ore Geol. Rev. 80, 103–115.

Zheng J.H., Mao J.W., Yang F.Q., Zhu Y., 2015. The post-collisional Cihai iron skarn deposit, eastern Tianshan, Xinjiang, China. Ore Geol. Rev. 67, 244–254.

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