



Influence mechanism of palaeoclimate of uranium-bearing strata on mineralization: A case study from the Qianjiadian sandstone-hosted uranium deposit, Songliao Basin, China

Hui Rong^{a,*}, Yangquan Jiao^{a,*}, Weihong Liu^b, Minqiang Cao^c, Jianxin Yu^d, Liquan Wu^a, Qingchun Li^c

^a Key Laboratory of Tectonics and Petroleum Resources (China University of Geosciences), Ministry of Education, Wuhan 430074, China

^b Development of New Energy Research Institute of Petroleum Exploration and Development, PetroChina, Langfang 065007, Hebei, China

^c Development Company of New Energy Sources of Liaohe Petroleum Exploration Bureau, CNPC, Panjin 124010, China

^d School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

ARTICLE INFO

Keywords:

Sandstone-hosted uranium deposit
Palaeoclimate
Uranium mineralization
Songliao Basin

ABSTRACT

Paleoclimate, uranium reservoirs, interlayer oxidized zones and ore bodies of the Upper Cretaceous Yaojia Formation in the Qianjiadian uranium deposit are illustrated in order to reveal effects of palaeoclimate on uranium mineralization. The Yaojia Formation is divided into six units: SQ_{K2y}-LST, SQ_{K2y}-EST (Pss1), SQ_{K2y}-EST (Pss2), SQ_{K2y}-EST (Pss3), SQ_{K2y}-HST (Pss1) and SQ_{K2y}-HST (Pss2). Paleoclimate of the SQ_{K2y}-LST, SQ_{K2y}-EST (Pss1), SQ_{K2y}-EST (Pss2), SQ_{K2y}-EST (Pss3), SQ_{K2y}-HST (Pss1) and SQ_{K2y}-HST (Pss2) is south subtropical semi-arid and sub-humid, tropical sub-humid, south subtropical semi-arid, central subtropical semi-arid and sub-humid, south subtropical semi-arid, and south subtropical semi-arid, respectively. In the same temperate zones, thickness and TOC contents of the uranium reservoirs in the humid climates are larger and higher respectively, thickness and area of the corresponding interlayer oxidized zones are both larger, and thickness, uranium amount per square meter and area of the corresponding ore bodies are all larger than those in the arid climates. In the same humidity zones, thickness and TOC contents of the uranium reservoirs in the warm climates are larger and higher respectively, thickness and area of the corresponding interlayer oxidized zones are both larger, and thickness, uranium amount per square meter and area of the corresponding ore bodies are all larger than those in the cold climates. This study reveals that hot and humid paleoclimate is favorable for mineralization of sandstone-hosted uranium deposits, and paleoclimate has a restriction on geometry and composition of uranium reservoirs, which may affect scales and distribution of interlayer oxidized zones and uranium ore bodies.

1. Introduction

Sandstone-hosted uranium deposits are considered to be formed by migration of oxygen-bearing U⁶⁺ groundwater to oxidized-reduced transition zones where U⁶⁺ is reduced to U⁴⁺, leading to enrichment of uranium (Granger and Warren, 1974; Lehmann, 2008; Mudd, 2014; Zammit et al., 2014). These deposits are typically epigenetic, and their mineralization frequently occurs after formation of uranium-bearing strata (Reynolds and Goldhaber, 1978, 1983; Xue et al., 2010; Hall et al., 2017). Many studies have shown that palaeoclimate of uranium-bearing strata has significant effects on mineralization of sandstone-

hosted uranium deposits, and is an important indicator for evaluation of uranium metallogenic potentials since it dominates formation of favorable uranium-bearing strata (Jiang, 1983; Wang, 1988; Meunier, et al., 1989; Zhou and Quan, 1991; Liu, 1998; Jiao et al., 2004; Wang and Guan, 2004; Cheng et al., 2011; Xu et al., 2019). However, studies on influence mechanism of palaeoclimate of uranium-bearing strata on mineralization of sandstone-hosted uranium deposits are scarce.

The Songliao Basin recording successive Cretaceous sediments has been considered as a typical region for studying greenhouse climate in the Cretaceous (Li et al., 2009; Du et al., 2011; Wang et al., 2013). The Qianjiadian uranium deposit as a large interlayer oxidized-zone

* Corresponding authors.

E-mail addresses: ronghui0411@163.com (H. Rong), yqjiao@cug.edu.cn (Y. Jiao).

<https://doi.org/10.1016/j.oregeorev.2021.104336>

Received 28 December 2020; Received in revised form 14 June 2021; Accepted 26 June 2021

Available online 2 July 2021

0169-1368/© 2021 Elsevier B.V. All rights reserved.

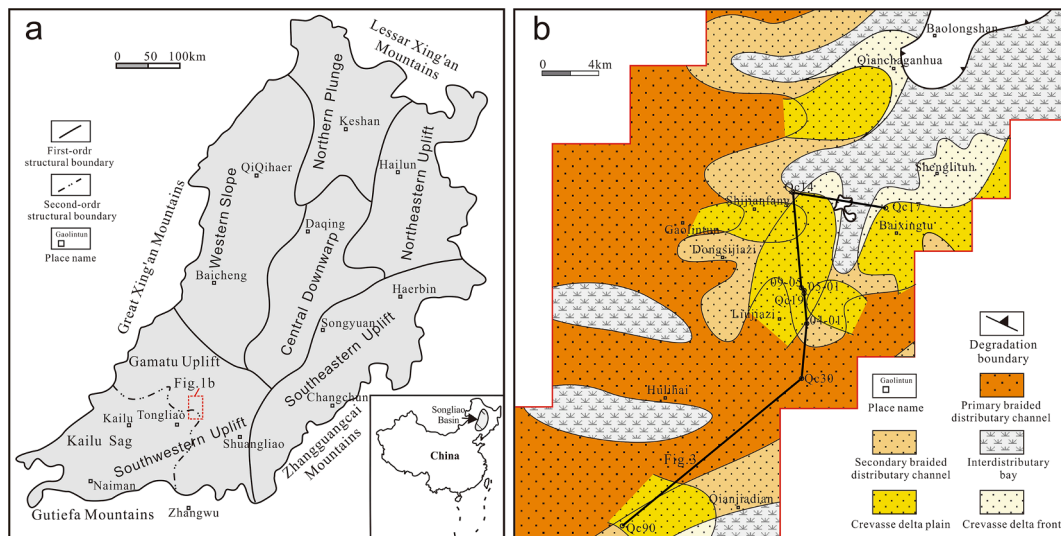


Fig. 1. (a) Tectonic units of the Songliao Basin (modified from Feng et al., 2010). (b) Sedimentary microfacies of the lower part of the Yaojia Formation in the Qianjiadian uranium deposit (modified from Jiao et al., 2015).

sandstone-hosted type has been found in the Upper Cretaceous Yaojia Formation in the southern Songliao Basin (Fig. 1; Xia et al., 2003; Chen et al., 2008; Pang et al., 2010; Jiao et al., 2015; Rong et al., 2016, 2019; Cheng et al., 2018, 2020; Zhao et al., 2018). The Yaojia Formation widely distributed in Songliao Basin is a set of continental red beds, and generally formed in the subtropical semi-arid climates (Xi et al., 2008; Zhang, 2008; Du et al., 2011). Mineralization characteristics and metallogenetic regularities of the Qianjiadian uranium deposit have extensively been studied (Xia et al., 2003, 2010; Luo et al., 2007, 2012; Jiao et al., 2015; Zhao et al., 2018; Jia et al., 2020). The complete cores from the drill holes in the Qianjiadian uranium deposit have been preserved, providing a good chance to evaluate effects of palaeoclimate of uranium-bearing strata on mineralization of sandstone-hosted uranium deposits.

The purpose of this study is to reconstruct paleoclimate of the Yaojia Formation in the Qianjiadian uranium deposit, and characterize geometry and distribution of uranium reservoirs, interlayer oxidized zones and ore bodies in different climates. According to these data, influence mechanism of palaeoclimate of uranium-bearing strata on uranium mineralization will be revealed.

2. Geological background

The Songliao Basin in northeastern China is one of the largest petroliferous basins in the world (Du et al., 2011; Wang et al., 2013). It has been divided into six first-order structural units: northern plunge, central downwarp, northeastern uplift, southeastern uplift, southwestern uplift, and western slope (Fig. 1; Feng et al., 2010). The Qianjiadian uranium deposit spans the Kailu Sag and Gamatu Uplift within the southeastern uplift of the Songliao Basin (Fig. 1).

The southern Songliao Basin is filled by the Cretaceous, Paleogene and Neogene clastic deposits, which are underlain by the Palaeozoic metamorphic and magmatic rocks (Xu and Li, 1995; Fig. 2). The Lower Cretaceous deposits developed in the tectonic setting of *syn*-rifting include the Yixian Formation (K_1y), Jiufotang Formation (K_1jf), Shahai Formation (K_1sh) and Fuxin Formation (K_1f). The Yixian Formation is characterized by volcanic and volcanoclastic rocks, whereas the others are composed of deltaic and lacustrine sediments. The Upper Cretaceous deposits formed in the tectonic setting of post-rift thermal subsidence

comprise of the Quantou Formation (K_2q), Qingshankou Formation (K_2qn), Yaojia Formation (K_2y), Nenjiang Formation (K_2n), Sifangtai Formation (K_2s) and Mingshui Formation (K_2m) (Xu and Li, 1995; Fig. 2). The Quantou Formation and Yaojia Formation primarily consist of fluvial and deltaic coarse-grained deposits, whereas the Qingshankou Formation and Nenjiang Formation contain majority of lacustrine and deltaic fine-grained deposits. The Sifangtai Formation and Mingshui Formation developed during the basin inversion are mainly composed of alluvial and fluvial coarse-grained deposits (Xu and Li, 1995; Fig. 2). Paleogene deposits including the Yi'an Formation are lost in the southern Songliao Basin (Xu and Li, 1995; Fig. 2). The upper part of the basin comprises of Neogene fluvial deposits (Xu and Li, 1995; Fig. 2).

The Yaojia Formation in the Qianjiadian uranium deposit has been served as a third-order sequence (SQ_{K_2y}) including three systems tracts: SQ_{K_2y} -LST, SQ_{K_2y} -EST and SQ_{K_2y} -HST (Figs. 2, 3; Rong et al., 2016). The SQ_{K_2y} -EST comprises of three parasequence sets: SQ_{K_2y} -EST (Pss1), SQ_{K_2y} -EST (Pss2) and SQ_{K_2y} -EST (Pss3), and the SQ_{K_2y} -HST includes two parasequence sets: SQ_{K_2y} -HST (Pss1) and SQ_{K_2y} -HST (Pss2) (Figs. 2, 3; Rong et al., 2016). The Yaojia Formation is mainly composed of braided river and braided river delta sedimentary systems in the Qianjiadian uranium deposit (Jiao et al., 2015; Fig. 1b). The sandstone of the Yaojia Formation comprises of red sandstone, yellow sandstone, non-mineralized grey sandstone, mineralized grey sandstone and primary grey sandstone (Rong et al., 2016, 2019). Uranium ore bodies occur near the pinch out zones of the oxidized sandstone (red and yellow sandstone) and have a tabular or lenticular shape with an average thickness of about 3 m (Rong et al., 2016, 2019; Zhao et al., 2018; Jia et al., 2020). Uranium minerals are primarily composed of pitchblende, coffinite and brannerite (Xia et al., 2003, 2010; Luo et al., 2007, 2012; Zhao et al., 2018; Rong et al., 2019; Jia et al., 2020). The Songliao Basin was lifted because of the regional structural inversion during the last deposition of the Nenjiang Formation (Chen et al., 2010; Song et al., 2010; Li et al., 2012), and then the Yaojia Formation was denuded at the northeast of the Qianjiadian uranium deposit, providing a discharge passage of confined groundwater (Jiao et al., 2015; Rong et al., 2016). Ore-forming fluids from mountains around the Songliao Basin permeated into sandstone of the Yaojia Formation, resulting in formation of interlayer oxidation and uranium mineralization (Jiao et al., 2015; Rong et al.,

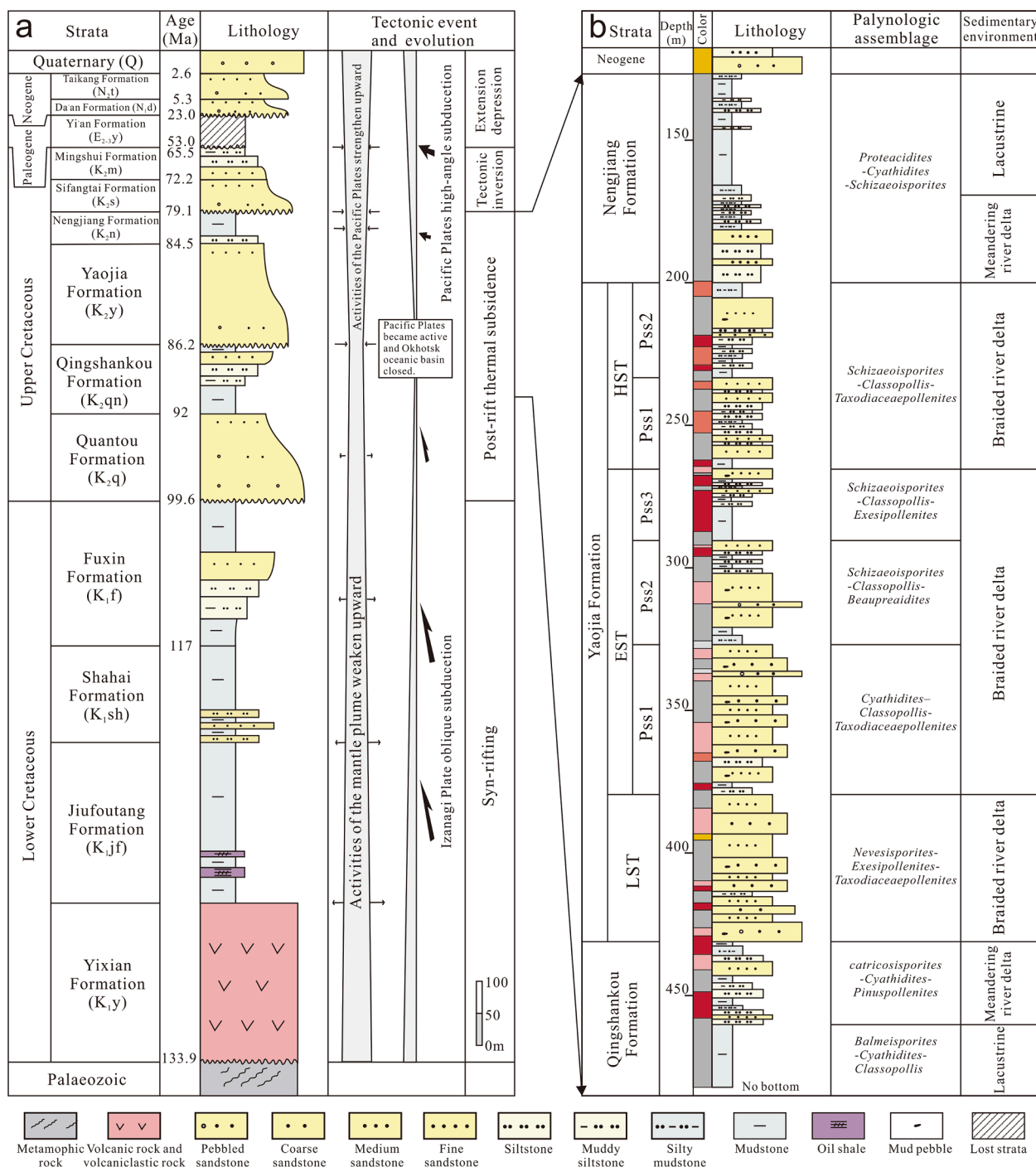


Fig. 2. (a) Stratigraphic column illustrating the stratigraphic architecture, lithologies and structure phase of the southern Songliao Basin (modified from Xu and Li, 1995; Du et al., 2011). The Cretaceous and Cenozoic ages are cited from Huang et al. (2011) and Wan et al. (2013). The Yi'an Formation primarily distributed in the northwestern Songliao Basin is lost in the southern Songliao Basin (Fang et al., 2007). (b) Stratigraphic units of the Yaojia Formation in the Qianjiadian uranium deposit (Rong et al., 2016).

2016).

3. Material and methods

Distribution and spatial arrangement of the lithologic units of the Yaojia Formation have been illustrated by lateral tracing and correlation of lithological assemblages within the stratigraphic sections of the

Yaojia Formation and plane mapping at the scale of 1:100000 based on more than 800 drill holes in the Qianjiadian area (Rong et al., 2019, 2020, 2021). Samples were examined using a combination of thin-section petrographic characterization, sporopollen analysis, and bulk-rock total organic carbon (TOC), U and Th analysis (Fig. 3). Samples for sporopollen analysis are all of grey mudstone, and samples for thin-section petrographic characterization and bulk-rock total organic

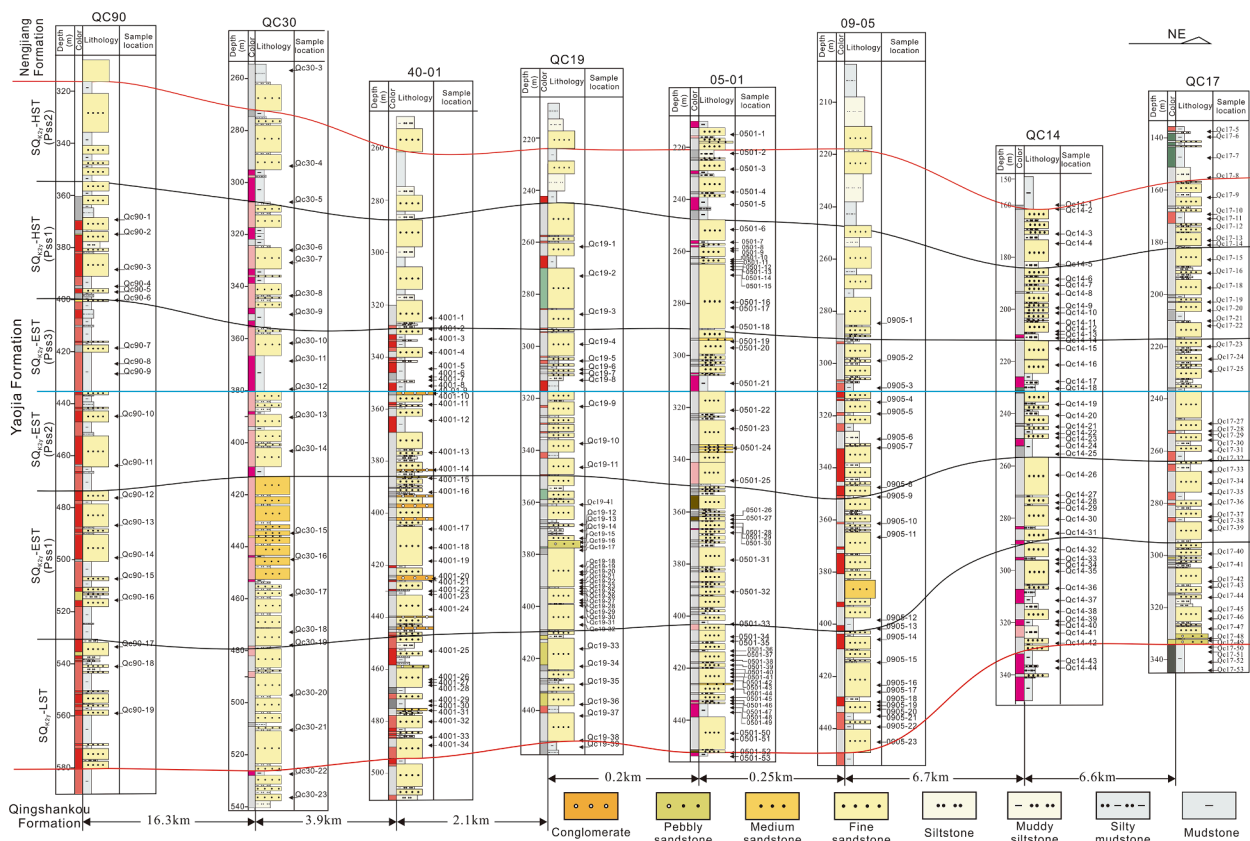


Fig. 3. Sample locations and lithologic characters from typical drill holes in the Qianjiadian uranium deposit. Locations of the drill holes was shown in Fig. 1b.

carbon (TOC), U and Th analysis are all of grey sandstone far away from the oxidized sandstone and diabase dikes in order to characterize mineral compositions and geochemical characteristics of the primary grey sandstone since the sandstone of the Yaojia Formation in the Qianjiadian uranium deposit is mainly altered by the interlayer oxidation and basic intrusions (Xia et al., 2003; Chen et al., 2008; Pang et al., 2010; Jiao et al., 2015; Rong et al., 2019, 2020, 2021).

29 samples were selected for sporopollen analysis in the Department of Stratigraphic Biology, China University of Geosciences (Wuhan). The sporopollen analysis was carried out as follows: (1) Fresh rock with a weight of about 200 g was crushing into small particles with a diameter of about 2 mm, and the powders with a weight of about 50 g were moved out for use. (2) Each sample was immersed in 20% HCl with a volume of 150 ml for 12 h in plastic beaker, and the beaker should be shook. (3) Mixture was diluted several times with distilled water until pH = 6–7, and then pour out the last diluted water, leaving only the residue. (4) The residue of each sample was immersed in 47% HF a volume of 100 ml for 48 h in plastic beaker, and the beaker should be shook at least one time. (5) Mixture was diluted several times with distilled water until pH = 6–7, and then pour out the last diluted water, leaving only the residue. (6) The residue was moved to glass beaker in which 10% HCl was added, and then heated in water bath with a temperature of 60 °C for 1 h. (7) Mixture was diluted several times with distilled water until pH = 6–7, and then pour out the last diluted water, leaving only the residue. (8) Dilution dispersant was added into the beaker, and then settle it. (9) Mixture was diluted several times with distilled water until pH = 6–7. (10) Heavy liquids (ZnCl₂) were used for flotation. (11) The residues were check under microscope, permanent slides were prepared for

observation, and spore morphology was identified and calculated. A total of 95 samples were selected for thin-section petrographic characterization by using a microscope in the Key Laboratory of Tectonics and Petroleum Resources (China University of Geosciences), Ministry of Education. For whole-rock geochemical analysis, all samples were crushed and ground to less than 200-mesh using an agate mill. Total organic carbon (TOC) of selected sandstone was tested according to DZG20.01–1991 (Testing standard for rock and mineral analysis). Bulk-rock U and Th were analyzed at the Institute of Oceanology, Chinese Academy of Sciences, by ICP-MS ELAN DRC II.

4. Palaeoclimate of the uranium-bearing strata

4.1. Paleoclimate recorded by the sporopollen

4.1.1. Sporopollen of the typical ecological groups

Contents of *Classopollis* ranges from 5.8% to 50.4% with an average value of 18.7% (Table 1; Fig. 4), and its parent plants are *Coniferales* which is considered to live in tropical or subtropical arid climates (Gao et al., 1994, 1999; Huang et al., 1999). *Schizaeisporites* has a content of 3.2–31.9% with an average value of 13.1% (Table 1; Fig. 4), and its parent plants often appear in arid climates (Gao et al., 1994, 1999; Huang et al., 1999). Contents of *Exesipollenites* are in the range of 0–16.5% with an average value of 5.2% (Table 1; Fig. 4), and its parent plants have a genetic relationship with *Cupressaceae* which is primarily distributed in subtropical climates (Gao et al., 1994, 1999; Huang et al., 1999). Contents of *Taxodiaceapollenites* range from 2.1% to 19.8% with an average value of 8.9% (Table 1; Fig. 4), and its parent plants are

Table 1
Results of sporopollen identification.

Sample No.	17–1	17–2	30–6	30–9	90–4	14–11	17–19	19–5	19–7	17–26	4001–2	4001–10	14–22	14–23	17–28	17–29
Buried depth (m)	126.4	128	326.5	351.1	396.7	205.2	203.2	305.7	311	235.1	329.3	353.1	247.6	248.6	252.6	253
Strata	Nengjiang Formation		SQ _{K2y} -HST(Pss2)		SQ _{K2y} -HST(Pss1)		SQ _{K2y} -EST(Pss3)		SQ _{K2y} -EST(Pss2)							
<i>Leiotriletes</i> (%)	1.2	0.0	0.0	7.1	1.7	0.8	0.7	0.7	0.0	0.7	0.0	0.8	0.6	0.0	0.0	0.0
<i>Osmudacidites</i> (%)	0.0	1.1	0.0	0.0	0.0	0.8	0.7	0.7	0.8	1.4	0.8	1.5	0.0	0.0	0.0	0.0
<i>Cyathidites</i> (%)	5.8	4.6	8.3	7.1	2.6	1.6	2.1	5.1	6.2	3.5	4.7	3.8	1.9	2.6	1.8	1.7
<i>Dictyotriletes</i> (%)	2.3	2.3	0.0	0.0	0.9	0.0	1.4	0.7	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0
<i>Lygodiumsporites</i> (%)	0.0	0.0	0.0	0.0	0.9	0.8	1.4	0.7	0.8	0.7	2.4	1.5	0.6	0.0	0.0	0.0
<i>Toroisporis</i> (%)	1.2	0.0	0.0	0.0	1.7	0.0	0.7	0.7	0.8	0.7	0.8	0.8	0.0	0.0	0.0	0.0
<i>Klukisporites</i> (%)	0.0	1.1	0.0	0.0	0.9	0.8	1.4	0.7	1.5	0.0	0.0	0.0	1.3	0.7	0.0	0.0
<i>Cicatricosisporites</i> (%)	1.2	0.0	0.0	0.0	0.0	0.8	0.7	2.2	2.3	2.1	3.1	3.8	1.3	0.0	0.0	0.0
<i>Schizaeisporites</i> (%)	9.3	10.3	16.9	21.6	31.9	14.0	15.5	15.2	15.4	17.0	19.7	19.5	16.0	14.5	22.0	17.1
<i>Pterisporites</i> (%)	0.0	1.1	0.0	0.0	0.9	0.0	0.7	0.7	2.3	0.7	0.8	1.5	0.0	0.0	0.0	0.0
<i>Undulatisporites</i> (%)	2.3	1.1	8.3	0.0	0.9	0.0	0.7	0.0	0.8	2.1	1.6	0.8	0.6	0.0	0.0	0.0
<i>Deltoidospora</i> (%)	3.5	2.3	0.0	7.1	0.0	0.8	1.4	1.4	1.5	1.4	2.4	0.0	1.3	1.3	0.0	0.0
<i>Punctatisporites</i> (%)	0.0	1.1	0.0	0.0	0.9	0.0	0.7	0.7	1.5	2.1	1.6	2.3	0.6	0.0	0.0	0.0
<i>Granulatisporites</i> (%)	1.2	0.0	8.3	0.0	0.0	0.8	0.7	0.7	0.8	0.7	1.6	0.8	0.0	0.0	0.0	0.0
<i>Verrucosisporites</i> (%)	0.0	0.0	0.0	0.0	0.0	1.6	1.4	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0
<i>Lycopodiumsporites</i> (%)	0.0	1.1	0.0	0.0	1.7	2.3	2.1	0.7	0.8	0.0	0.0	0.0	1.3	0.0	0.0	0.0
<i>Baculatisporites</i> (%)	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0
<i>Radiorugosporites</i> (%)	0.0	2.3	0.0	0.0	0.9	0.0	0.7	0.7	0.8	0.0	0.0	0.0	0.6	0.0	0.0	0.0
<i>Gabonisoris</i> (%)	0.0	0.0	0.0	0.0	0.9	0.0	0.7	2.2	1.5	1.4	1.6	2.3	0.6	0.0	0.0	0.0
<i>Polycingulatisporites</i> (%)	1.2	1.1	0.0	7.1	1.7	1.6	1.4	0.7	0.8	1.4	0.8	0.8	0.6	0.7	0.9	0.9
<i>Ceratosporites</i> (%)	0.0	0.0	0.0	0.0	0.0	0.8	0.7	0.7	0.8	0.7	0.8	0.8	0.0	0.0	0.0	0.0
<i>Triporoletes</i> (%)	0.0	1.1	0.0	0.0	0.9	0.0	0.0	0.7	0.8	1.4	0.8	0.8	0.0	0.7	0.0	0.0
<i>Nevesisporites</i> (%)	2.3	0.0	8.3	0.0	0.9	0.8	0.7	0.7	0.0	2.1	0.8	0.8	1.3	0.0	0.0	0.0
<i>Balmeisporites</i> (%)	0.0	0.0	0.0	0.0	0.9	1.6	1.4	2.9	2.3	2.1	1.6	1.5	1.9	0.0	0.0	0.0
<i>Neoraistrickia</i> (%)	0.0	1.1	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.7	0.8	0.0	0.0	0.0	0.0	0.0
<i>Laevigatosporites</i> (%)	1.2	1.1	0.0	0.0	0.0	0.0	0.7	2.2	2.3	1.4	0.8	0.8	0.6	0.0	0.0	0.0
<i>Cycadopites</i> (%)	2.3	1.1	8.3	7.1	1.7	0.8	1.4	2.2	1.5	2.1	1.6	2.3	1.3	2.0	3.7	0.9
<i>Monosulcites</i> (%)	0.0	1.1	0.0	0.0	1.7	0.8	1.4	1.4	0.8	1.4	2.4	0.8	1.9	3.3	3.7	0.9
<i>Bennettites</i> (%)	1.2	1.1	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.7	1.6	1.5	0.0	0.0	0.0	0.0
<i>Araucariacites</i> (%)	0.0	2.3	0.0	0.0	0.9	0.0	0.7	0.7	0.8	0.7	0.0	0.8	1.3	1.3	0.0	0.0
<i>Classopollis</i> (%)	5.8	6.9	25	14.5	28.4	50.4	38.7	8.7	8.5	7.1	8.7	9.8	32.1	42.8	8.3	30.8
<i>Pinuspollenites</i> (%)	2.3	1.1	0.0	0.0	0.0	0.0	0.7	2.9	3.8	2.8	2.4	1.5	1.3	0.7	1.8	1.7
<i>Abietinaepollenites</i> (%)	1.2	2.3	0.0	0.0	0.9	0.0	1.4	4.3	3.8	2.1	0.8	0.8	0.6	1.3	0.0	0.0
<i>Cedripites</i> (%)	2.3	2.3	0.0	0.0	0.9	0.8	1.4	0.7	0.8	1.4	0.8	0.8	0.0	0.7	0.0	0.0
<i>Piceapollenites</i> (%)	2.3	2.3	0.0	7.1	0.0	0.0	0.0	0.0	0.8	0.0	0.8	0.0	0.6	0.0	0.9	1.7
<i>Podocarpidites</i> (%)	1.2	0.0	0.0	0.0	1.7	0.8	0.7	2.2	3.1	0.7	0.8	0.8	0.6	0.7	0.9	0.9
<i>Parvisaccites</i> (%)	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.7	0.8	0.8	0.0	0.0	0.0	0.0
<i>Taxodiaceapollenites</i> (%)	2.3	3.4	8.3	7.1	2.6	3.1	2.1	10.9	10.8	10.6	7.9	8.3	3.8	3.3	11.0	4.3
<i>Ephedripites</i> (%)	3.5	3.4	0.0	0.0	0.9	0.8	1.4	1.4	1.5	2.1	2.4	3.0	1.3	2.0	6.4	3.4
<i>Psophosphaera</i> (%)	1.2	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.8	1.4	1.6	1.5	0.0	0.7	0.0	0.0
<i>Inaperturopollenites</i> (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	1.4	0.8	2.3	0.6	0.0	3.7	0.0
<i>Exesipollenites</i> (%)	2.3	3.4	0.0	7.1	0.9	0.8	1.4	5.1	2.3	5.7	1.6	1.5	7.7	6.6	16.5	14.5
<i>Magnolipollis</i> (%)	1.2	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.8	0.7	0.8	0.8	0.6	0.7	0.9	0.9
<i>Quercoidites</i> (%)	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Cupuliferoidaepollenites</i> (%)	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.8	0.7	0.8	0.8	0.6	0.7	0.9	0.9
<i>Ulmipollenites</i> (%)	1.2	1.1	0.0	0.0	0.0	0.0	0.0	0.7	0.8	0.7	0.8	0.0	0.0	0.7	0.0	0.0
<i>Betulaepollenites</i> (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Momipites</i> (%)	1.2	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Aquilapollenites</i> (%)	2.3	2.3	0.0	0.0	0.9	0.0	0.0	0.7	0.8	1.4	0.8	0.8	0.6	0.7	0.9	0.9
<i>Nyssopollenites</i> (%)	0.0	1.1	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.6	0.7	0.0	0.9
<i>Myrtacidites</i> (%)	2.3	1.1	0.0	0.0	0.0	0.8	0.7	0.7	0.0	0.0	0.8	0.0	0.0	0.7	0.9	0.0
<i>Proteacidites</i> (%)	3.5	2.3	0.0	0.0	0.0	0.8	0.0	0.0	0.8	0.0	0.0	0.0	0.6	0.7	0.9	0.9
<i>Xinjiangpollis</i> (%)	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.7	0.0	0.0	0.8	8.3	0.6	0.7	0.0	0.9
<i>Cranwellia</i> (%)	2.3	2.3	0.0	0.0	0.0	0.8	0.7	0.7	0.8	0.0	0.8	0.8	0.6	0.7	0.9	0.9
<i>Beaupreaidites</i> (%)	1.2	2.3	0.0	0.0	1.7	2.3	1.4	1.4	0.8	2.1	0.8	1.5	1.3	1.3	0.9	2.6
<i>Gothanipollis</i> (%)	2.3	2.3	0.0	0.0	0.9	0.8	0.0	0.7	0.0	0.0	0.0	0.8	0.0	0.7	0.9	1.7
<i>Callistopollenites</i> (%)	1.2	1.1	0.0	0.0	0.0	0.8	0.7	0.7	0.8	0.7	1.6	1.5	0.6	0.7	1.8	1.7
<i>Lythraites</i> (%)	3.5	4.6	0.0	0.0	0.9	0.0	0.7	0.0	0.8	0.7	0.8	0.8	1.3	1.3	0.9	1.7
<i>Sporopollis</i> (%)	2.3	1.1	0.0	0.0	0.0	0.8	0.0	0.0	0.8	0.0	0.8	0.8	0.0	0.7	0.9	1.7
<i>Chenopodipollis</i> (%)	0.0	1.1	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Orbiculapollis</i> (%)	1.2	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.8	0.0	0.8	0.0	0.6	0.0	0.9	0.0
<i>Tripoporipollenites</i> (%)	2.3	2.3	0.0	0.0	0.9	0.0	0.7	0.7	0.0	1.4	0.8	0.0	0.6	0.0	0.9	0.9
<i>Tricolpopollenites</i> (%)	3.5	2.3	8.3	7.1	1.7	0.8	1.4	2.2	1.5	1.4	2.4	2.3	1.3	1.3	2.8	0.9
<i>Tricolpites</i> (%)	2.3	2.3	0.0	0.0	0.0	0.0	0.0	1.4	1.5	2.1	1.6	1.5	0.6	0.7	0.9	1.7
<i>Tetracolpites</i> (%)	1.2	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0
<i>Tricolporopollenites</i> (%)	3.5	1.1	0.0	0.0	0.0	0.8	0.7	2.9	3.8	2.1	3.1	3.8	1.9	1.3	1.8	2.6
Total (%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Sample No.	0905–10	0905–12	0501–33	4001–19	0905–21	0501–50	4001–28	4001–29	90–22	0905–28	0501–57	19–39	Humidity	Temperature
Buried depth (m)	361.4	399	403	418.3	433.8	445	465.4	472.1	642.5	483	503.3	454	/	/
Strata	SQ _{K2y} -EST(Pss1)				SQ _{K2y} -LST				Qingshankou Formation				/	/
<i>Leiotriletes</i> (%)	0.9	0.9	1.7	0.9	1.0	0.9	0.0	0.8	1.9	2.1	1.1	0.0	Hydrophyte	

(continued on next page)

Table 1 (continued)

Sample No.	0905-10	0905-12	0501-33	4001-19	0905-21	0501-50	4001-28	4001-29	90-22	0905-28	0501-57	19-39	Humidity	Temperature
														Tropical-subtropical
<i>Osmudacidites</i> (%)	0.0	0.0	0.0	0.9	0.0	0.9	0.0	0.0	0.9	0.0	1.1	1.1	Helophyte	Tropical-warm
<i>Cyathidites</i> (%)	11.0	8.7	9.3	8.0	3.1	1.8	2.5	3.4	16.0	10.0	8.5	8.7	Hydrophyte	Tropical
<i>Dictyotrilites</i> (%)	0.0	0.9	0.0	1.8	0.0	1.8	0.0	0.8	1.9	0.0	1.1	0.0	/	/
<i>Lygodiumsporites</i> (%)	1.8	1.7	0.8	1.8	1.0	0.9	1.7	0.0	0.9	1.0	2.1	0.0	Hydrophyte	Tropical
<i>Toroisporis</i> (%)	1.8	0.0	1.7	0.0	1.0	0.9	0.8	0.8	1.9	0.0	0.0	1.1	Hydrophyte	Tropical-subtropical
<i>Klukisporites</i> (%)	0.9	0.9	1.7	0.9	0.0	1.8	1.7	1.7	0.9	1.0	0.0	2.2	Hydrophyte	Subtropical
<i>Cicatricosisporites</i> (%)	0.0	0.9	0.8	0.9	0.0	1.8	0.8	0.0	1.9	0.0	1.1	2.2	Hydrophyte	Tropical
<i>Schizaeisporites</i> (%)	9.2	4.3	5.1	3.6	10.4	7.0	8.4	7.6	9.5	15.1	3.2	6.5	Xerophyte	Tropical-subtropical
<i>Pterisporites</i> (%)	0.0	0.9	0.8	0.0	1.0	0.9	0.0	1.7	0.9	0.0	2.1	1.1	Xerophyte	Tropical
<i>Undulatisporites</i> (%)	0.0	0.9	0.8	1.8	0.0	0.9	0.8	0.0	0.9	0.0	1.1	1.1	/	/
<i>Deltoidospora</i> (%)	1.8	1.7	0.0	0.9	0.0	0.9	0.0	0.8	0.9	2.1	0.0	5.4	Hydrophyte	Tropical-subtropical
<i>Punctatisporites</i> (%)	0.9	0.9	0.8	0.0	0.0	0.9	0.0	0.8	0.0	1.0	0.0	0.0	/	/
<i>Granulatisporites</i> (%)	0.9	0.9	0.8	0.9	1.0	0.9	0.8	0.0	0.9	0.0	1.1	0.0	/	/
<i>Verrucosisporites</i> (%)	0.0	0.0	0.0	0.9	1.0	1.8	0.0	0.8	0.0	1.0	2.1	1.1	Xerophyte	/
<i>Lycopodiumsporites</i> (%)	1.8	0.9	0.8	1.8	1.0	1.8	0.8	1.7	0.9	1.0	0.0	1.1	Mesophyte	Tropical-warm
<i>Baculatisporites</i> (%)	0.0	0.0	0.0	0.0	1.0	0.0	0.8	0.0	0.0	0.0	1.1	0.0	Helophyte	Tropical-warm
<i>Radiorugosporites</i> (%)	0.9	0.9	0.8	0.9	0.0	0.9	0.8	0.8	0.9	1.0	0.0	1.1	/	/
<i>Gabonispors</i> (%)	1.8	0.9	1.7	0.9	1.0	0.9	1.7	2.5	0.9	1.0	1.1	0.0	/	/
<i>Polycingulatisporites</i> (%)	2.8	3.5	1.7	2.7	2.1	2.6	2.5	2.5	0.9	2.1	2.1	1.1	Macrophyte	Tropical-warm
<i>Ceratosporites</i> (%)	0.9	0.0	0.8	0.0	0.0	0.9	1.7	0.0	0.9	0.0	1.1	1.1	Hydrophyte	Tropical-subtropical
<i>Triporoletes</i> (%)	0.0	0.9	0.8	0.9	0.0	1.8	0.8	1.7	0.0	1.0	0.0	1.1	Hydrophyte	Tropical
<i>Nevesporites</i> (%)	5.5	6.1	5.1	8.0	5.2	5.3	6.7	5.9	1.9	1.0	1.1	0.0	/	/
<i>Balmeisporites</i> (%)	0.9	1.7	0.8	0.9	1.0	0.9	2.5	1.7	2.8	3.1	3.2	2.2	Macrophyte	Warm
<i>Neoraistrickia</i> (%)	0.9	0.9	0.8	0.0	0.0	1.8	0.8	0.0	0.9	0.0	0.0	0.0	/	Tropical-subtropical
<i>Laevigatosporites</i> (%)	0.0	0.9	0.8	0.0	0.0	0.9	0.0	1.7	0.9	1.0	1.1	2.2	Helophyte	Tropical-warm
<i>Cycodopites</i> (%)	0.9	1.7	0.8	0.9	1.0	1.8	1.7	1.7	1.9	1.0	3.2	2.2	Mesophyte	Tropical
<i>Monosulcites</i> (%)	0.9	0.9	0.0	0.9	2.1	0.9	0.8	2.5	0.9	2.1	2.1	1.1	Mesophyte	Tropical-subtropical
<i>Bennettites</i> (%)	0.9	0.0	0.8	0.0	0.0	0.0	1.7	0.8	0.9	0.0	1.1	1.1	Mesophyte	Tropical
<i>Araucariacites</i> (%)	0.0	0.9	0.0	0.9	0.0	0.9	0.0	0.0	0.9	0.0	0.0	0.0	Mesophyte	Tropical
<i>Classopollis</i> (%)	20.2	21.7	19.5	21.4	15.6	8.8	16.0	15.1	16.0	22.9	10.6	9.8	Xerophyte	Tropical-subtropical
<i>Pinuspollenites</i> (%)	0.0	0.9	2.5	2.7	0.0	0.9	0.0	0.8	1.9	1.0	0.0	0.0	Mesophyte	Tropical-warm
<i>Abietinaepollenites</i> (%)	0.0	0.0	1.7	1.8	1.0	1.8	0.8	0.8	1.9	1.0	1.1	0.0	Mesophyte	Tropical-warm
<i>Cedripites</i> (%)	0.9	0.0	0.8	1.8	0.0	0.9	0.0	0.8	0.9	0.0	1.1	1.1	Mesophyte	Subtropical
<i>Piceapollenites</i> (%)	0.0	0.9	1.7	0.9	0.0	0.0	0.8	0.0	0.0	0.0	2.1	0.0	Hydrophyte	Warm
<i>Podocarpidites</i> (%)	0.0	0.0	1.7	1.8	1.0	0.9	1.7	1.7	0.9	0.0	1.1	2.2	Hydrophyte	Tropical
<i>Parvisaccites</i> (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	1.0	0.0	1.1	Mesophyte	Tropical-warm
<i>Taxodiaceapollenites</i> (%)	16.5	16.5	14.4	10.7	19.8	9.6	11.8	10.9	5.7	6.3	16.0	10.9	Helophyte	Subtropical
<i>Ephedripites</i> (%)	1.8	0.9	1.7	0.9	0.0	1.8	1.7	2.5	0.9	1.0	1.1	0.0	Xerophyte	Warm
<i>Psophosphaera</i> (%)	0.0	0.9	0.0	0.0	0.0	0.0	2.5	0.0	0.0	0.0	1.1	1.1	Mesophyte	Tropical-warm
<i>Inaperturopollenites</i> (%)	0.9	0.0	0.8	0.0	0.0	0.9	0.0	0.0	0.0	0.0	1.1	0.0	Mesophyte	Warm
<i>Exesipollenites</i> (%)	2.8	3.5	2.5	7.1	9.4	10.5	6.7	8.4	2.8	2.1	3.2	8.7	Helophyte	Subtropical
<i>Magnoliipollis</i> (%)	0.0	0.0	0.8	0.9	3.1	0.0	0.8	0.8	0.0	0.0	0.0	0.0	Mesophyte	Tropical-subtropical
<i>Quercoidites</i> (%)	0.0	0.9	0.0	0.0	0.0	0.9	0.0	0.0	0.9	0.0	1.1	1.1	Mesophyte	Subtropical
<i>Cupuliferoidapollenites</i> (%)	0.9	0.0	0.0	0.9	0.0	0.0	0.8	0.0	1.9	1.0	2.1	1.1	Mesophyte	Subtropical
<i>Ulmipollenites</i> (%)	0.0	0.9	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	1.1	0.0	Mesophyte	Warm
<i>Betulaepollenites</i> (%)	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.8	0.9	1.0	0.0	0.0	Mesophyte	Warm
<i>Momipites</i> (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Mesophyte	Warm
<i>Aquilapollenites</i> (%)	0.9	0.9	0.8	0.0	1.0	1.8	0.0	1.7	0.0	0.0	0.0	0.0	Hydrophyte	Tropical-subtropical
<i>Nyssopollenites</i> (%)	0.9	0.0	0.0	0.0	0.0	0.9	1.7	0.0	0.9	0.0	1.1	1.1	Mesophyte	Tropical-subtropical
<i>Myrtaceidites</i> (%)	0.0	0.0	0.8	0.9	1.0	0.9	0.0	0.8	0.0	1.0	0.0	1.1	Mesophyte	Tropical
<i>Proteacidites</i> (%)	0.9	0.0	1.7	0.0	0.0	0.0	0.8	0.0	0.9	0.0	1.1	0.0	Hydrophyte	Tropical
<i>Xinjiangpollis</i> (%)	0.0	0.9	0.0	0.9	0.0	0.0	0.0	0.8	0.0	1.0	0.0	1.1	/	/
<i>Cranwellia</i> (%)	0.9	0.0	0.8	0.0	2.1	1.8	1.7	2.5	1.9	2.1	1.1	2.2	/	/
<i>Beaupreaidites</i> (%)	1.8	1.7	0.0	0.9	1.0	1.8	1.7	0.8	0.9	1.0	1.1	1.1	Hydrophyte	Tropical
<i>Gothanipollis</i> (%)	0.0	0.9	0.0	0.0	2.1	0.9	0.0	0.8	0.9	0.0	2.1	1.1	Mesophyte	Tropical
<i>Callistopollenites</i> (%)	0.0	0.0	0.8	0.9	1.0	1.8	1.7	0.8	0.9	2.1	2.1	2.2	Xerophyte	/
<i>Lythraites</i> (%)	0.0	1.7	0.8	0.0	0.0	1.8	0.8	1.7	0.0	0.0	0.0	1.1	/	/
<i>Sporopollis</i> (%)	0.9	0.0	0.8	0.9	1.0	1.8	0.8	0.8	0.0	1.0	1.1	0.0	/	/
<i>Chenopodipollis</i> (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	1.1	1.1	Xerophyte	Tropical-warm
<i>Orbiculapollis</i> (%)	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.9	1.0	0.0	0.0	/	Tropical-subtropical
<i>Triporopollenites</i> (%)	0.0	0.9	0.0	0.0	1.0	1.8	0.0	1.7	0.0	2.1	0.0	2.2	Mesophyte	Warm

(continued on next page)

Table 1 (continued)

Sample No.	0905-10	0905-12	0501-33	4001-19	0905-21	0501-50	4001-28	4001-29	90-22	0905-28	0501-57	19-39	Humidity	Temperature
<i>Tricolpopollenites</i> (%)	0.9	0.9	1.7	1.8	1.0	0.0	1.7	0.8	0.9	2.1	3.2	2.2	Mesophyte	Tropical-subtropical
<i>Tricolpites</i> (%)	0.0	0.0	1.7	0.0	0.0	0.9	0.0	0.0	0.0	1.0	1.1	1.2	Mesophyte	Tropical-subtropical
<i>Tetracolpites</i> (%)	0.0	0.0	0.0	0.0	1.0	0.0	0.8	0.0	0.9	0.0	1.1	1.1	/	/
<i>Tricolporopollenites</i> (%)	0.9	1.7	0.0	0.9	2.1	1.8	1.7	0.8	0.0	0.0	0.0	0.0	Xerophyte	Subtropical
Total (%)	100	100	100	100	100	100	100	100	100	100	100	100	/	/

Texodiaceae which mainly occurs in subtropical climates (Gao et al., 1994, 1999; Huang et al., 1999). Contents of *Ephedripites* are in the range of 0–6.4 % with an average value of 1.7% (Table 1; Fig. 4), and it always lives in arid regions such as deserts, arid grasslands or saline alkali lands (Gao et al., 1994, 1999; Huang et al., 1999). *Lygodiumsporites* and *Pterisporites* have a content of 0–2.4% with an average value of 0.8% and a content of 0–2.3% with an average value of 0.6% respectively (Table 1; Fig. 4), and they both tend to occur in tropical or subtropical arid climates (Gao et al., 1994, 1999; Huang et al., 1999).

4.1.2. Classification of the temperature zones

Species of the sporopollen in this study can be classified into tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants (Tables 1, 2; Gao et al., 1999; Huang et al., 1999). Average contents of the sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the Qingshankou Formation are 23.0%, 34.3%, 17.0%, 8.0% and 6.2% respectively (Table 2). The sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the SQ_{K2y}-LST have average contents of 14.4%, 31.2%, 24.3%, 7.7%, and 5.2% respectively (Table 2). The sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the SQ_{K2y}-EST (Pss1) account for 18.9%, 34.4%, 21.0%, 7.3%, and 4.2% on average respectively (Table 2). Average contents of the sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the SQ_{K2y}-EST (Pss2) are 10.1%, 54.1%, 19.8%, 3.6%, and 6.4% respectively (Table 2). The sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the SQ_{K2y}-EST (Pss3) have average contents of 18.1%, 36.4%, 17.7%, 10.4% and 7.0% respectively (Table 2). Average contents of the sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the SQ_{K2y}-HST (Pss1) are 11.7%, 66.3%, 5.1%, 6.4%, and 2.8% respectively (Table 2). The sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the SQ_{K2y}-HST (Pss2) account for 15.5%, 53.6%, 11.3%, 3.6%, and 3.6% on average respectively (Table 2). The sporopollen of tropical plants, tropical-subtropical plants, subtropical plants, tropical-warm plants, and warm plants in the Nengjiang Formation have average contents of 20.8%, 30.6%, 12.1%, 8.1%, and 11.0% respectively (Table 2). So, it can be inferred that palaeoclimate of the Qingshankou Formation, SQ_{K2y}-LST, SQ_{K2y}-EST (Pss1), SQ_{K2y}-EST (Pss2), SQ_{K2y}-EST (Pss3), SQ_{K2y}-HST (Pss1), SQ_{K2y}-HST (Pss2) and Nengjiang Formation is tropical, south subtropical, tropical, south subtropical, central subtropical, south subtropical, south subtropical and central subtropical climates respectively (Table 2).

4.1.3. Classification of the humidity zones

Species of the sporopollen in this study are primarily composed by xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte (Tables 1, 3; Gao et al., 1999; Huang et al., 1999). Average contents of the

sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the Qingshankou Formation are 28.7%, 18.7%, 22.7%, 16.2%, and 4.4% respectively (Table 3). The sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the SQ_{K2y}-LST have average contents of 28.7%, 15.2%, 13.4%, 23.1%, and 4.0% respectively (Table 3). The sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the SQ_{K2y}-EST (Pss1) account for 29.6%, 12.1%, 20.9%, 19.2%, and 3.8% on average respectively (Table 3). Average contents of the sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the SQ_{K2y}-EST (Pss2) are 52.4%, 15.2%, 8.6%, 17.4%, and 1.3% respectively (Table 3). The sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the SQ_{K2y}-EST (Pss3) have average contents of 33.4%, 20.9%, 17.4%, 15.4%, and 3.0% respectively (Table 3). The sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the SQ_{K2y}-HST (Pss1) account for 63.4%, 11.3%, 11.4%, 4.6%, and 2.8% on average respectively (Table 3). Average contents of the sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the SQ_{K2y}-HST (Pss2) are 38.7%, 15.5%, 18.5%, 11.3%, and 3.6% respectively (Table 3). The sporopollen of xerophyte, mesophyte, hydrophyte, helophyte, and macrophyte in the Nengjiang Formation have average contents of 24.3%, 28.9%, 20.8%, 7.5%, and 1.2% respectively (Table 3). So, it can be inferred that palaeoclimate of the Qingshankou Formation, SQ_{K2y}-LST, SQ_{K2y}-EST (Pss1), SQ_{K2y}-EST (Pss2), SQ_{K2y}-EST (Pss3), SQ_{K2y}-HST (Pss1), SQ_{K2y}-HST (Pss2) and Nengjiang Formation is semi-arid and sub-humid, semi-arid and sub-humid, sub-humid, semi-arid, semi-arid and sub-humid, semi-arid, semi-arid, and sub-humid respectively.

4.2. Paleoclimate recorded by the sandstone composition

Sandstone of the Qingshankou Formation, Yaojia Formation and Nengjiang Formation is mainly composed of feldspar lithic sandstone and lithic sandstone (Table 4). Detrital grains of the sandstone dominated by quartz, feldspar, and debris are moderately to poorly sorted. The quartz with a percentages of 30–50% includes single crystal quartz and polymorphic quartz (Table 4). The feldspar with a percentages of 10–30% primarily comprise of alkali feldspar and plagioclase (Table 4). The debris a percentages of 25–30% is mainly composed of volcanic rocks, granite, and carbonate rocks (Table 4). Due to the long-term erosion and long-distance transportation of the parent rocks in relatively stable tectonic conditions, arid climates are required for preservation of feldspar (Suttner and Dutta, 1986; Liu and Chen, 1994). So, ratio of feldspar content to quartz content (F/Q) in sandstone is always used as a parameter to predict climates: climates are relatively arid when F/Q is large (Suttner and Dutta, 1986; Liu and Chen, 1994).

In this study, F/Q of the sandstone in the Qingshankou Formation ranges from 0.36 to 0.43 with an average value of 0.385 (Fig. 5; Table 4). The sandstone in the SQ_{K2y}-LST has F/Q of 0.20–0.38 with an average value of 0.346 (Fig. 5; Table 4). F/Q of the sandstone in the SQ_{K2y}-EST (Pss1) is in the range of 0.28–0.48 with an average value of 0.334 (Fig. 5; Table 4). F/Q of the sandstone in the SQ_{K2y}-EST (Pss2) ranges from 0.25



Fig. 4. Sporopollen of typical ecological groups in the Upper Cretaceous in the Qianjiadian uranium deposit. (1) *Classopollis minus*, Qc90-4, 396.7 m. (2) *Classopollis minus*, Qc90-4, 396.7 m. (3) *Classopollis annulatus*, Qc17-19, 203.2 m. (4) *Classopollis annulatus*, 4001-10, 353.1 m. (5) *Classopollis annulatus*, Qc90-22, 642.5 m. (6) *Classopollis annulatus*, Qc19-39, 454 m. (7) *Classopollis annulatus*, Qc17-19, 203.2 m. (8) *Schizaeoisporites* spp., Qc17-29, 253 m. (9) *Schizaeoisporites* spp., Qc90-4, 396.7 m. (10) *Schizaeoisporites* spp., Qc90-4, 396.7 m. (11) *Schizaeoisporites* spp., Qc17-19, 203.2 m. (12) *Schizaeoisporites* spp., Qc14-23, 248.6 m. (13) *Schizaeoisporites* spp., Qc90-22, 642.5 m. (14) *Schizaeoisporites* spp., 0905-21, 433.8 m. (15) *Exesipollenites tumulus* subsp *pseudotriletus*, 4001-19, 418.3 m. (16) *Exesipollenites tumulus* subsp *pseudotriletus*, Qc90-22, 642.5 m. (17) *Exesipollenites tumulus* subsp *pseudotriletus*, 0501-33, 403 m. (18) *Exesipollenites Laevigatus*, 0905-12, 399 m. (19) *Exesipollenites Laevigatus*, 4001-10, 353.1 m. (20) *Exesipollenites tumulus* Balme subsp *triangulus*, Qc19-39, 454 m. (21) *Exesipollenites tumulus* subsp *pseudotriletus*, Qc17-29, 253 m. (22) *Exesipollenites Laevigatus*, 0905-21, 433.8 m. (23) *Taxodiaceapollenites hiatus*, Qc90-22, 642.5 m. (24) *Taxodiaceapollenites hiatus*, 0905-21, 433.8 m. (25) *Taxodiaceapollenites hiatus*, 0905-10, 361.4 m. (26) *Taxodiaceapollenites hiatus*, Qc14-23, 248.6 m. (27) *Ephedripites* spp., 0905-21, 433.8 m. (28) *Ephedripites* spp., Qc17-29, 253 m. (29) *Ephedripites* spp., Qc17-29, 253 m. (30) *Ephedripites* spp., Qc17-26, 235.1 m. (31) *Ephedripites* spp., 4001-10, 353.1 m. (32) *Lygodiumsporites microadriensis*, 0905-12, 399 m. (33) *Pterisporites nanhaiensis*, 0905-12, 399 m. All photomicrographs in Fig. 4 were enlarged 800 times. Fossils were preserved in the Department of Stratigraphic Biology, China University of Geosciences (Wuhan).

Table 2
Classification of temperature zones.

Strata	Sporopollen of tropical plants (%)	Sporopollen of tropical-subtropical plants (%)	Sporopollen of subtropical plants (%)	Sporopollen of tropical-warm plants (%)	Sporopollen of warm plants (%)	Others (%)	Temperature zones
Nengjiang Formation	20.8	30.6	12.1	8.1	11.0	17.4	Central subtropics
SQ _{K2y} -HST(Pss2)	15.5	53.6	11.3	3.6	3.6	12.5	South subtropics
SQ _{K2y} -HST(Pss1)	11.7	66.3	5.1	6.4	2.8	7.8	South subtropics
SQ _{K2y} -EST(Pss3)	18.1	36.4	17.7	10.4	7.0	10.3	Central subtropics
SQ _{K2y} -EST(Pss2)	10.1	54.1	19.8	3.6	6.4	6.0	South subtropics
SQ _{K2y} -EST(Pss1)	18.9	34.4	21.0	7.3	4.2	14.3	Tropics
SQ _{K2y} -LST	14.4	31.2	24.3	7.7	5.2	17.3	South subtropics
Qingshankou Formation	23.0	34.3	17.0	8.0	6.2	11.6	Tropics

Table 3
Classification of humidity zones.

Strata	Sporopollen of xerophyte (%)	Sporopollen of mesophyte (%)	Sporopollen of hydrophyte (%)	Sporopollen of helophyte (%)	Sporopollen of macrophyte (%)	Other (%)	Humidity zones
Nengjiang Formation	24.3	28.9	20.8	7.5	1.2	17.4	Sub-humid
SQ _{K2y} -HST(Pss2)	38.7	15.5	18.5	11.3	3.6	12.4	Semi-arid
SQ _{K2y} -HST(Pss1)	63.4	11.3	11.4	4.6	2.8	6.4	Semi-arid
SQ _{K2y} -EST(Pss3)	33.4	20.9	17.4	15.4	3.0	9.9	Semi-arid and sub-humid
SQ _{K2y} -EST(Pss2)	52.4	15.2	8.6	17.4	1.3	5.1	Semi-arid
SQ _{K2y} -EST(Pss1)	29.6	12.1	20.9	19.2	3.8	14.4	Sub-humid
SQ _{K2y} -LST	28.7	15.2	13.4	23.1	4.0	15.7	Semi-arid and sub-humid
Qingshankou Formation	28.7	18.7	22.7	16.2	4.4	9.4	Semi-arid and sub-humid

to 0.38 with an average value of 0.379 (Fig. 5; Table 4). The sandstone in the SQ_{K2y}-EST (Pss3) has F/Q of 0.36–0.39 with an average value of 0.376 (Fig. 5; Table 4). F/Q of the sandstone in the SQ_{K2y}-HST (Pss1) is in the range of 0.36–0.51 with an average value of 0.402 (Fig. 5; Table 4). F/Q of the sandstone in the SQ_{K2y}-HST (Pss2) ranges from 0.39 to 0.50 with an average value of 0.432 (Fig. 5; Table 4). The sandstone of the Nengjiang Formation has F/Q of 0.36–0.40 with an average value of 0.385 (Fig. 5; Table 4). So, it can be inferred that paleoclimate of the SQ_{K2y}-EST (Pss1) is relatively humid, followed by that of the SQ_{K2y}-LST, SQ_{K2y}-EST (Pss3), SQ_{K2y}-EST (Pss2), Qingshankou formation and Nengjiang Formation, and paleoclimate of the SQ_{K2y}-HST (Pss1) and SQ_{K2y}-HST (Pss2) are relatively arid.

In summary, paleoclimate of the Qingshankou Formation, SQ_{K2y}-LST, SQ_{K2y}-EST (Pss1), SQ_{K2y}-EST (Pss2), SQ_{K2y}-EST (Pss3), SQ_{K2y}-HST (Pss1), SQ_{K2y}-HST (Pss2) and Nengjiang Formation is tropical semi-arid and sub-humid, south subtropical semi-arid and sub-humid, tropical sub-humid, south subtropical semi-arid, central subtropical semi-arid and sub-humid, south subtropical semi-arid, south subtropical semi-arid, and central subtropical sub-humid respectively. Previous studies have shown that the Yaojia formation in Songliao Basin was formed in the tropical-subtropical semi-arid and arid climates, and the climates were hot and humid in the early stage of deposition of the Yaojia formation and cold and dry in the late stage (Zhang and Wang, 1994; Huang et al., 1999; Du et al., 2011; Xu et al., 2019). The result of this study on paleoclimate change trends of the uranium-bearing strata is generally consistent with that of the previous studies, but the difference

is that this study has revealed paleoclimate of the six sequence stratigraphic units of the Yaojia Formation, providing a prerequisite for studying influence of palaeoclimate of uranium-bearing strata on uranium mineralization.

5. Uranium reservoirs in different climates

Uranium reservoirs in the SQ_{K2y}-LST, SQ_{K2y}-EST (Pss2) and SQ_{K2y}-EST (Pss3) are selected as examples in order to compare geometry and composition of uranium reservoirs formed in different climates.

5.1. Uranium reservoirs in south subtropical semi-arid and sub-humid climates

The uranium reservoirs in the SQ_{K2y}-LST are formed in the south subtropical semi-arid and sub-humid climates, and are widely distributed in the Qianjiadian area (Fig. 6a, b). The primary gray sandstone in the south subtropical semi-arid and sub-humid climates has TOC contents of 0.10–0.29% with an average of 0.22%, U contents of 5.92–10.20 ppm with an average of 7.29 ppm, and Th/U of 0.80–1.88 with an average of 1.42 respectively (Tables 5, 6). Thickness of the uranium reservoirs is 4.1–61 m with an average of 34.2 m, and is concentrated in the range of 30–40 m (Fig. 7a; Table 6). Ratio of the sandstone and strata ranges from 12.8% to 100% with an average of 81.4%, and is mainly distributed in the range of 80–100 % (Fig. 7b; Table 6).

Table 4

Contents of detrital minerals of the Upper Cretaceous sandstone in the Qianjiadian uranium deposit.

Serial No.	Sample No.	Depth (m)	Strata	Qp (%)	Qm (%)	F (%)	R (%)	F/Q
1	0905-24	462.5	Qingshankou Formation	33	18	22	27	0.43
2	0905-25	466.3		30	23	20	27	0.38
3	0905-27	479.1		30	23	20	28	0.38
4	0905-30	508.8		30	23	20	28	0.38
5	0905-34	546.4		30	23	20	27	0.38
6	Qc19-41	460.2		35	20	20	25	0.36
7	0905-14	405.5		40	16	20	24	0.36
8	0905-15	414.3		30	25	20	25	0.36
9	0905-16	423.1		30	24	20	25	0.37
10	0905-18	429.7		30	23	20	28	0.38
11	0905-19	431	SQ _{K2y} -LST	30	24	20	25	0.37
12	0905-20	431.7		30	24	20	25	0.37
13	Qc14-41	324		35	21	18	26	0.32
14	Qc14-42	327.9		35	18	20	27	0.38
15	Qc17-47	328.2		30	23	20	27	0.38
16	Qc19-34	423		30	24	20	27	0.37
17	Qc19-35	430		30	23	20	28	0.38
18	Qc19-36	437.8		30	23	20	28	0.38
19	0501-39	417.8		35	24	15	26	0.25
20	0501-40	419		30	24	20	27	0.37
21	0501-41	420	SQ _{K2y} -EST(Pss1)	35	18	20	27	0.38
22	0501-42	421.4		35	24	15	26	0.25
23	0501-45	431.4		30	23	20	28	0.38
24	0501-46	432.5		35	20	18	27	0.33
25	0501-47	433.5		40	14	20	26	0.37
26	0501-48	434		30	23	20	28	0.38
27	0501-52	452.5		30	23	20	28	0.38
28	4001-24	437		40	18	15	27	0.26
29	4001-26	464		30	22	15	32	0.29
30	4001-27	465		35	20	20	25	0.36
31	4001-30	473.8	SQ _{K2y} -EST(Pss2)	35	25	12	28	0.20
32	4001-31	475.8		30	24	18	28	0.33
33	4001-32	480		30	23	20	28	0.38
34	0905-11	366.4		45	16	15	24	0.25
35	Qc14-30	280.4		40	13	20	27	0.38
36	qc14-31	285.7		35	18	20	27	0.38
37	Qc17-34	272.3		30	24	20	27	0.37
38	Qc19-11	346.6		45	11	15	29	0.27
39	Qc19-12	368.5		45	12	20	23	0.35
40	Qc19-15	374.6		45	15	18	22	0.30
41	Qc19-16	375.6	SQ _{K2y} -EST(Pss3)	45	16	15	24	0.25
42	Qc19-19	385.5		35	18	20	27	0.38
43	Qc19-20	387		32	23	18	28	0.33
44	Qc19-21	390		30	23	20	25	0.38
45	Qc19-22	391		30	24	20	25	0.37
46	Qc19-24	392		32	25	18	25	0.32
47	Qc19-25	393		30	24	20	25	0.37
48	Qc19-26	394		30	23	20	28	0.38
49	Qc19-27	395		30	23	20	28	0.38
50	Qc19-28	397.7		30	24	20	25	0.37
51	Qc19-29	398.9	SQ _{K2y} -EST(Pss3)	30	25	20	25	0.36
52	Qc19-30	399.2		40	15	20	25	0.36
53	Qc90-14	499.7		40	18	15	27	0.26
54	Qc90-15	507		45	15	20	20	0.33
55	0501-27	362		32	24	20	23	0.36
56	0501-32	390.6		35	25	20	20	0.33
57	4001-20	425.2		43	20	17	20	0.27
58	4001-23	431		40	24	16	20	0.25
59	0905-4	314.4		30	23	20	27	0.38
60	0905-8	347		30	24	20	25	0.37
61	Qc19-9	323.2	SQ _{K2y} -EST(Pss3)	30	24	20	25	0.37
62	Qc62-2	359.4		40	14	20	26	0.37
63	Qc62-3	370.6		40	14	20	26	0.37
64	Qc80-2	214.8		30	16	20	24	0.43
65	Qc90-10	445		30	24	20	25	0.37
66	Qc90-11	464.4		40	15	20	25	0.36
67	0905-7	329.4		34	23	16	28	0.28
68	2401-5	342.9		35	16	20	27	0.39
69	2401-5	342.9		40	13	25	23	0.48
70	Qc62-1	305.4		42	14	21	23	0.38
71	Qc90-6	398.5	SQ _{K2y} -EST(Pss3)	30	25	20	25	0.36
72	Qc90-7	419.5		35	18	20	27	0.38
73	4001-8	351		30	24	20	27	0.37
74	4001-9	353		37	15	20	28	0.39

(continued on next page)

Table 4 (continued)

Serial No.	Sample No.	Depth (m)	Strata	Qp (%)	Qm (%)	F (%)	R (%)	F/Q
75	Qc38-24	247.2	SQ _{K2y} -HST(Pss1)	35	20	20	25	0.36
76	Qc38-25	261.6		30	23	20	28	0.38
77	Qc38-26	268.3		40	10	20	30	0.40
78	Qc38-27	269.3		30	20	20	30	0.40
79	Qc43-10	357.5		30	20	20	30	0.40
80	Qc43-2	324.1	SQ _{K2y} -HST(Pss2)	35	14	25	26	0.51
81	Qc43-3	334		45	8	22	26	0.42
82	Qc43-5	345.3		40	14	20	26	0.37
83	0501-09	259.8		30	23	20	28	0.38
84	Qc122-3	388.6		43	8	22	27	0.43
85	Qc122-4	408.2	Nengjiang Formation	40	10	20	30	0.40
86	Qc110-23	158		30	10	20	40	0.50
87	Qc110-5	147.5		30	15	20	35	0.44
88	Qc38-20	205.9		40	11	20	29	0.39
89	Qc38-46	144		30	20	20	30	0.40
90	Qc38-53	158.1		45	10	20	25	0.36
91	Qc38-56	191		45	8	20	27	0.38
92	Qc38-7	135.1		30	20	20	30	0.40

Note: Qp = Single crystal quartz; Qm = Polycrystalline quartz; Q = Qp + Qm; F = Feldspar; R = Debris.

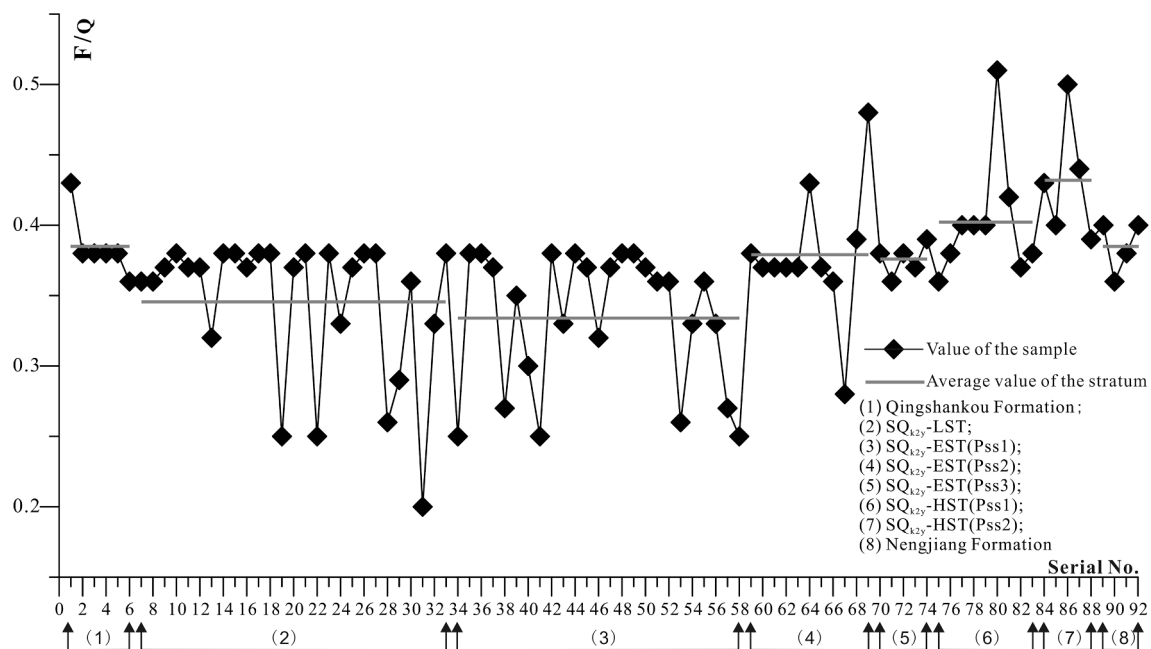


Fig. 5. Ratio of feldspar content to quartz content (F/Q) in the sandstone from the Qianjiadian uranium deposit. Refer to Table 4 for detailed data.

5.2. Uranium reservoirs in south subtropical semi-arid climates

The uranium reservoirs in the SQ_{K2y}-EST (Pss2) occur in the south subtropical semi-arid climates, and have a relatively smaller scale than those in the SQ_{K2y}-LST (Fig. 6c, d). TOC contents of the primary gray sandstone in the south subtropical semi-arid and sub-humid climates range from 0.06% to 0.31% with an average of 0.12%, corresponding U contents are in the range of 3.87–8.24 ppm with an average of 6.19 ppm, and corresponding Th/U ranges from 1.23 to 2.59 with an average of 1.79 (Tables 5, 6). Thickness of the uranium reservoirs is in the range of 1.6–53.2 m with an average of 22.6 m, and is mainly distributed in 20–30 m (Fig. 7c; Table 6). Ratio of the sandstone and strata is 8.0–100% with an average of 80.5%, and is concentrated in the range of 80–100 % (Fig. 7d; Table 6).

5.3. Uranium reservoirs in central subtropical semi-arid and sub-humid climates

The uranium reservoirs in the SQ_{K2y}-EST (Pss3) are developed in the central subtropical semi-arid and sub-humid climates, and also had a relatively smaller scale than those in the SQ_{K2y}-LST (Fig. 6e, f). The primary gray sandstone in the central subtropical semi-arid and sub-humid climates has TOC contents of 0.08–0.13% with an average of 0.11%, U contents of 5.27–8.87 ppm with an average of 7.32 ppm, and Th/U of 1.06–1.52 with an average of 1.39 respectively (Tables 5, 6). Thickness of the uranium reservoirs is between 0 and 58.12 m with an average of 17.73 m, which is mainly concentrated in 10–20 m (Fig. 7e; Table 6). Ratio of the sandstone and strata is 0–100% with an average of 65.7%, and is primarily distributed in 60–80% (Fig. 7f; Table 6).

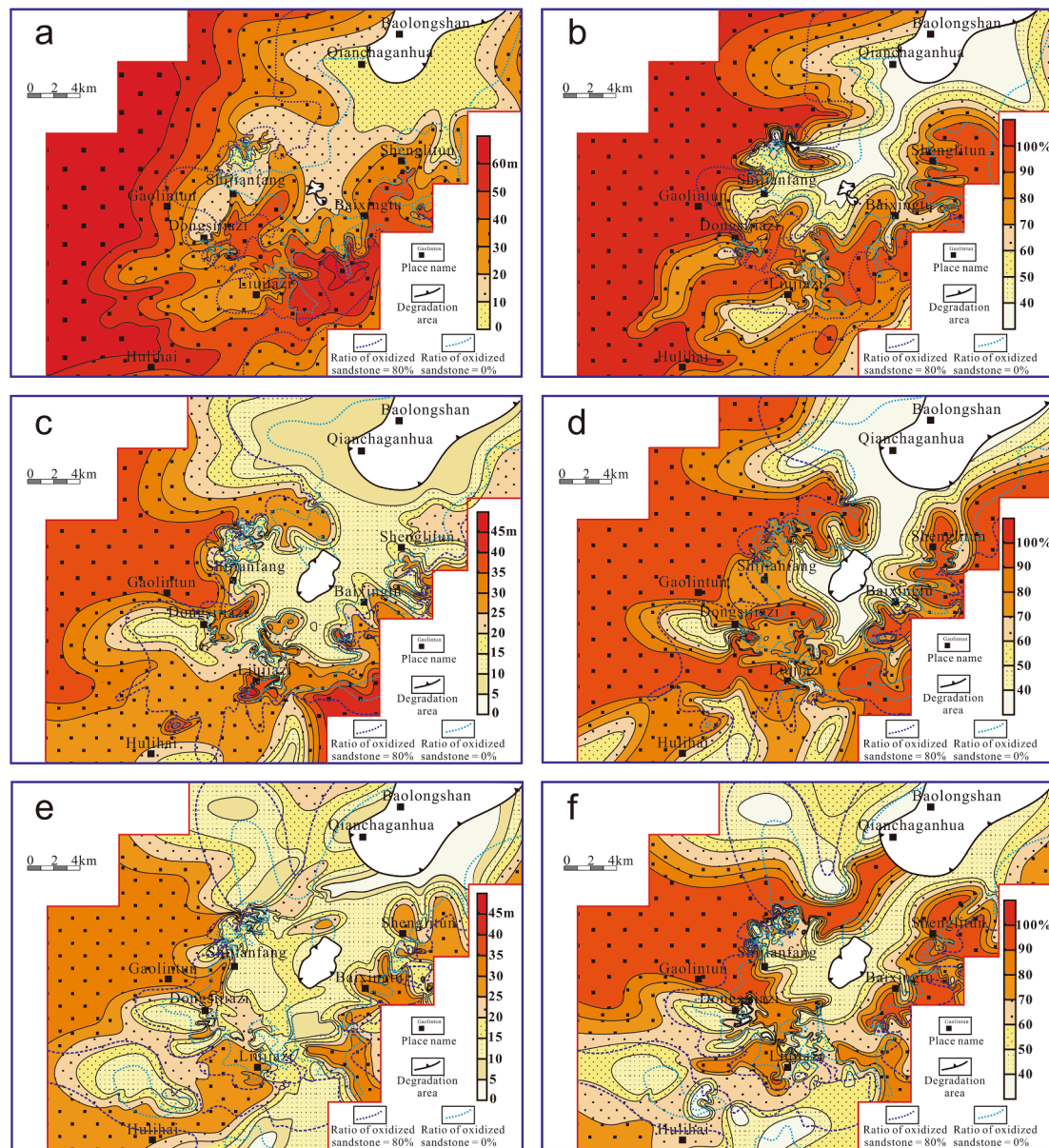


Fig. 6. (a) Spatial arrangement of thickness of the uranium reservoirs and distribution of interlayer oxidized zones in the SQ_{K2y}-LST. (b) Spatial arrangement of ratio of the sandstone and strata and distribution of interlayer oxidized zones in the SQ_{K2y}-LST. (c) Spatial arrangement of thickness of the uranium reservoirs and distribution of interlayer oxidized zones in the SQ_{K2y}-EST (Pss2). (d) Spatial arrangement of ratio of the sandstone and strata and distribution of interlayer oxidized zones in the SQ_{K2y}-EST (Pss2). (e) Spatial arrangement of thickness of the uranium reservoirs and distribution of interlayer oxidized zones in the SQ_{K2y}-EST (Pss3). (f) Spatial arrangement of ratio of the sandstone and strata and distribution of interlayer oxidized zones in the SQ_{K2y}-EST (Pss3).

6. Interlayer oxidized zones in different climates

Interlayer oxidized zones in the SQ_{K2y}-LST, SQ_{K2y}-EST (Pss2) and SQ_{K2y}-EST (Pss3) are selected as examples in order to compare geometry and distribution of interlayer oxidized zones within uranium reservoirs formed in different climates. Oxidized sandstone is primarily composed of red sandstone and yellow sandstone in the Qianjadian uranium deposit, and ratio of oxidized sandstone has been defined as (thickness of red sandstone and yellow sandstone / cumulative thickness of sandstone) * 100% (Rong et al., 2019).

6.1. Interlayer oxidized zones in south subtropical semi-arid and sub-humid climates

Thickness of oxidized sandstone is 0–63.1 m with an average of 12.0 m, and ratio of oxidized sandstone is 0–100% with an average of 36.8% in the uranium reservoirs formed in the south subtropical semi-arid and sub-humid climates (Table 7). Oxidized zones (regions where ratio of oxidized sandstone is over 80%) are distributed along NE with obvious branches, transition zones (regions where ratio of oxidized sandstone is between 0 and 80 %) are distributed in belts, and reduction zones (regions where ratio of oxidized sandstone is 0%) are mainly distributed in

Table 5

Geochemical compositions of the primary gray sandstone of the Yaojia Formation.

Sample No.	Depth (m)	Strata	U (ppm)	TOC (%)	Th (ppm)	Th/U
Qc17-47	328.2	SQ _{K2y} -LST	5.92	0.29	11.16	1.88
Qc17-40	299.4		6.91	/	10.91	1.58
0905-14	405.5		6.11	0.26	8.68	1.42
Qc19-16A	399.3		10.20	0.10	8.21	0.80
Qc19-94A	364.3	SQ _{K2y} -EST	8.42	0.08	7.89	0.94
Qc19-99A	362.4	(Pss1)	7.58	0.10	7.68	1.01
Qc19-16	375.6		6.42	/	8.00	1.25
Qc19-19	385.5		7.66	/	5.58	0.73
2320-4	353.5		/	0.23	/	/
2401-18	375.7		/	0.15	/	/
0905-4	314.4	SQ _{K2y} -EST	3.87	0.31	10.01	2.59
Qc14	265	(Pss2)	6.66	/	8.20	1.23
Qc10	273.5		/	/	5.60	/
Qc12	274.4		/	/	12.00	/
Qc15	217.83		/	0.06	/	/
Qc16	218.49		/	0.06	/	/
0905-7	329.4		8.24	/	12.85	1.56
4509-1	334.60		6.00	0.03	/	/
0401-10	231.75	SQ _{K2y} -EST	8.87	0.13	13.40	1.51
0401-12	232.5	(Pss3)	8.66	0.08	9.20	1.06
0401-25	258.8		6.46	0.13	9.50	1.47
Qc17-24	224.8		5.27	/	8.03	1.52
Qc17-12	174.8	SQ _{K2y} -HST	1.08	0.07	4.83	4.49
Qc5	260.86	(Pss1)	3.30	0.07	10.50	3.18
Qc6	273		3.30	0.14	5.80	1.76
0401-6	230.25		6.54	0.13	12.00	1.83
Qc17-16	191.8		8.46	/	9.84	1.16
Qc90-1	369		3.20	/	14.03	4.38
0905-1	284.6		8.47	/	12.49	1.48
Qc2	234.85	SQ _{K2y} -HST	4.71	0.05	9.30	1.97
Qc3	244.47	(Pss2)	2.02	0.07	11.60	5.74
Qc17-9	162.7		8.80	/	11.02	1.25

the northeast of the Qianjiadian area (Fig. 8a, b). Area of the oxidized sandstone is 1135.1 km² (Table 7).

6.2. Interlayer oxidized zones in south subtropical semi-arid climates

Thickness of oxidized sandstone ranges from 0 m to 38.3 m with an average of 5.9 m, and ratio of oxidized sandstone is in the range of 0–100 % with an average of 24.8% in the uranium reservoirs formed in the

Table 6

Thickness of uranium reservoirs, ratio of sandstone and strata, and geochemical compositions of sandstone in the Yaojia Formation.

Palaeoclimate		Strata	Average thickness of uranium reservoirs (m)	Average ratio of sandstone and strata (%)	U (%)	TOC (%)	Th/U
Tropics	Sub-humid	SQ _{K2y} -EST (Pss1)	28.9	79.6	7.52	0.14	0.98
South subtropics	Semi-arid and sub-humid	SQ _{K2y} -LST	34.2	81.4	7.29	0.22	1.42
	Semi-arid	SQ _{K2y} -EST (Pss2)	22.6	80.5	6.19	0.12	1.79
	Semi-arid	SQ _{K2y} -HST (Pss1)	24.8	70.9	5.95	0.10	2.37
	Semi-arid	SQ _{K2y} -HST (Pss2)	16.3	58.7	5.18	0.06	2.99
Central subtropics	Semi-arid and sub-humid	SQ _{K2y} -EST (Pss3)	17.7	65.7	7.32	0.11	1.39

Refer to Table 6 for detailed data.

south subtropical semi-arid climates (Table 7). Oxidized zones occur along NE with obvious branches, transition zones transition zones surrounding oxidized zones are distributed in the south, middle and northeast of the Qianjiadian area, and reduction zones are mainly located in the northeast of the Qianjiadian area (Fig. 8c, d). Area of the oxidized sandstone is 1000.9 km² (Table 7).

6.3. Interlayer oxidized zones in central subtropical semi-arid and sub-humid climates

Thickness of oxidized sandstone is in the range of 0–40.1 m with an average of 4.3 m, and ratio of oxidized sandstone ranges from 0% to 100% with an average of 23.6% in the uranium reservoirs formed in the central subtropical semi-arid and sub-humid climates (Table 7). Oxidized zones with obvious branches are mainly distributed in the west of the Qianjiadian area, transition zones are mainly distributed in the south, middle and northeast of the Qianjiadian area, and reduction zones are mainly distributed in the northeast and south of the Qianjiadian area (Fig. 8e, f). Area of the oxidized sandstone is 756.4 km² (Table 7).

7. Ore bodies within uranium reservoirs in different climates

Uranium ore bodies are primarily tabular or lenticular (Fig. 9), and uranium mineralization is primarily hosted in fine-grained sandstone (Xia et al., 2003, 2010; Luo et al., 2007, 2012; Zhao et al., 2018; Rong et al., 2019; Jia et al., 2020). Ore bodies in the SQ_{K2y}-LST, SQ_{K2y}-EST (Pss2) and SQ_{K2y}-EST (Pss3) are selected as examples in order to compare geometry and distribution of ore bodies within uranium reservoirs formed in different climates. The ore bodies in the uranium reservoirs formed in the south subtropical semi-arid and sub-humid climates have an average thickness of 3.3 m, average uranium amount per square meter of 1.19 kg/m², and area of 51.97 km² respectively (Fig. 8b; Table 7). An average thickness, average uranium amount per square meter and area of the ore bodies in the uranium reservoirs formed in the south subtropical semi-arid climates are 3.0 m, 0.82 kg/m², and 37.90 km² respectively (Fig. 8d; Table 7). The ore bodies in the uranium reservoirs formed in central subtropical semi-arid and sub-humid climate have an average thickness of 1.9 m, average uranium amount per square meter of 0.50 kg/m², and area of 20.47 km² (Fig. 8e; Table 7).

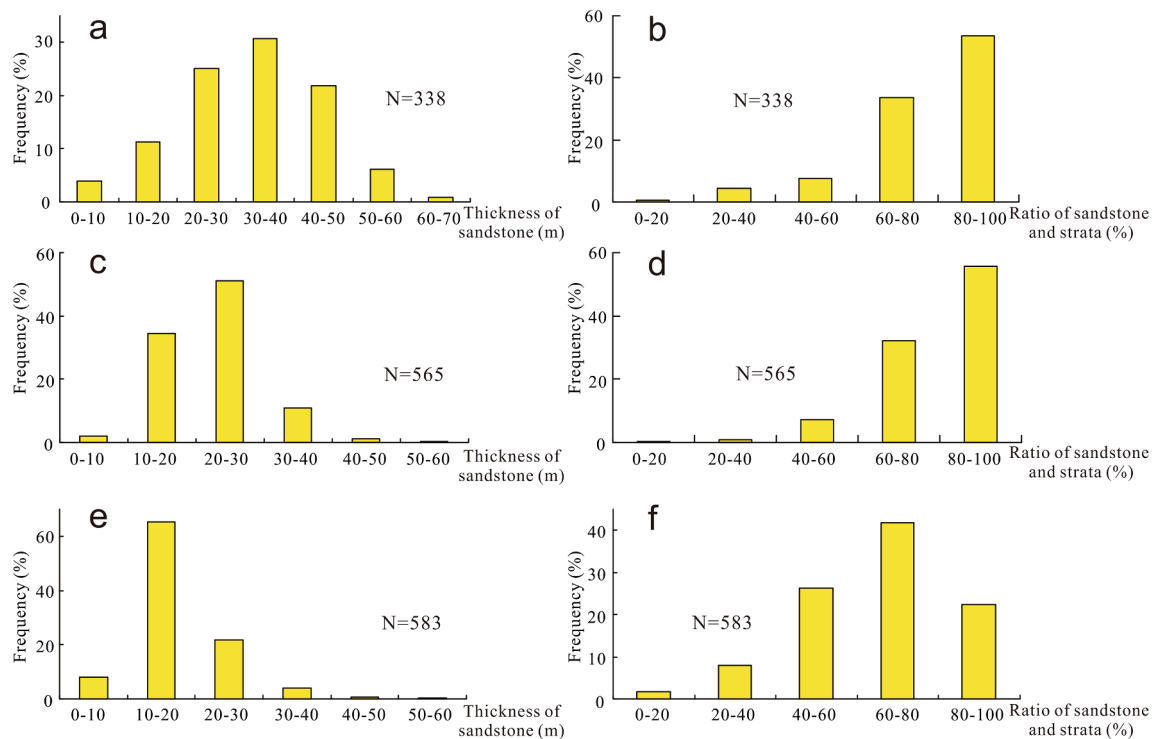


Fig. 7. (a) Probability distribution of thickness of the uranium reservoirs in the SQ_{K2Y}-LST. (b) Probability distribution of ratio of the sandstone and strata in the SQ_{K2Y}-LST. (c) Probability distribution of thickness of the uranium reservoirs in the SQ_{K2Y}-EST (Pss2). (d) Probability distribution of ratio of the sandstone and strata in the SQ_{K2Y}-EST (Pss2). (e) Probability distribution of thickness of the uranium reservoirs in the SQ_{K2Y}-EST (Pss3). (f) Probability distribution of ratio of the sandstone and strata in the SQ_{K2Y}-EST (Pss3).

Table 7

Thickness, ratio and area of oxidized sandstone, and thickness, uranium amount per square meter and area of ore bodies in the Yaojia Formation.

Palaeoclimate	Sub-humid	Strata	ATOS (m)	AROS (%)	AOS (km ²)	ATOB (m)	UASM (kg/m ²)	AOB (km ²)
Tropics		SQ _{K2Y} -EST(Pss1)	9.4	31.6	1014.7	3.1	1.35	
South subtropics	Semi-arid and sub-humid	SQ _{K2Y} -LST	12.0	36.8	1135.1	3.3	1.19	51.97
	Semi-arid	SQ _{K2Y} -EST(Pss2)	5.9	24.8	1000.9	3.0	0.82	37.90
	Semi-arid	SQ _{K2Y} -HST(Pss1)	4.1	15.6	743.1	1.9	0.50	20.47
	Semi-arid	SQ _{K2Y} -HST(Pss2)	1.6	11.1	339.3	1.1	0.18	10.11
Central subtropics	Semi-arid and sub-humid	SQ _{K2Y} -EST(Pss3)	4.3	23.6	756.4	2.6	0.79	26.83

Note: ATOS = Average thickness of oxidized sandstone; AROS = Average ratio of oxidized sandstone; AOS = Area of oxidized sandstone; ATOB = Average thickness of ore bodies; UASM = Uranium amount per square meter; AOB = Area of ore bodies.

8. Discussion

8.1. Effects of palaeoclimate on uranium reservoirs

Climates have been considered to be a key factor controlling accumulation of sandstone bodies in sedimentary basins (Lavie et al., 2001; Tian, 2001; Wellner and Bartek, 2003; Jiao et al., 2006, 2015; Allen, 2008; Lin et al., 2015; Yang and Ma, 2017). Significant attention has been paid to influences of climate changes on accumulation of sandstone bodies in deep water sedimentary environment (Ruddiman, 2001; Hessler et al., 2018; Jia et al., 2019; Gong et al., 2021; Wang et al., 2021). However, studies on effects of climate changes on deposition of sandstone bodies in shallow water sedimentary environment are relatively scarce. Braided river and braided river delta sedimentary systems occurred during the deposition of the Yaojia Formation in the Qiaojadian

uranium deposit (Jiao et al., 2015; Rong et al., 2019; Fig. 1b), providing a good case for studying influences of climate changes on deposition of sandstone bodies in shallow water sedimentary environment.

In the south subtropical climates, thickness, TOC and U contents of the uranium reservoirs in the semi-arid and sub-humid conditions are larger and higher than those in the semi-arid conditions (Figs. 6, 7, 10; Table 6). In the semi-arid and sub humid climates, thickness and TOC contents of the uranium reservoirs in the south subtropical conditions are larger and higher than those in central subtropical conditions (Figs. 6, 7, 10; Table 6). So, in the same temperature zones, the uranium reservoirs formed in the humid climates have larger scales and higher TOC and U contents than those formed in the arid climates, whereas in the same humidity zones, the uranium reservoirs formed in the hot climates have larger scales and higher TOC contents than those formed in the cold climates (Figs. 6, 7, 10; Table 6). Therefore, it is suggested that

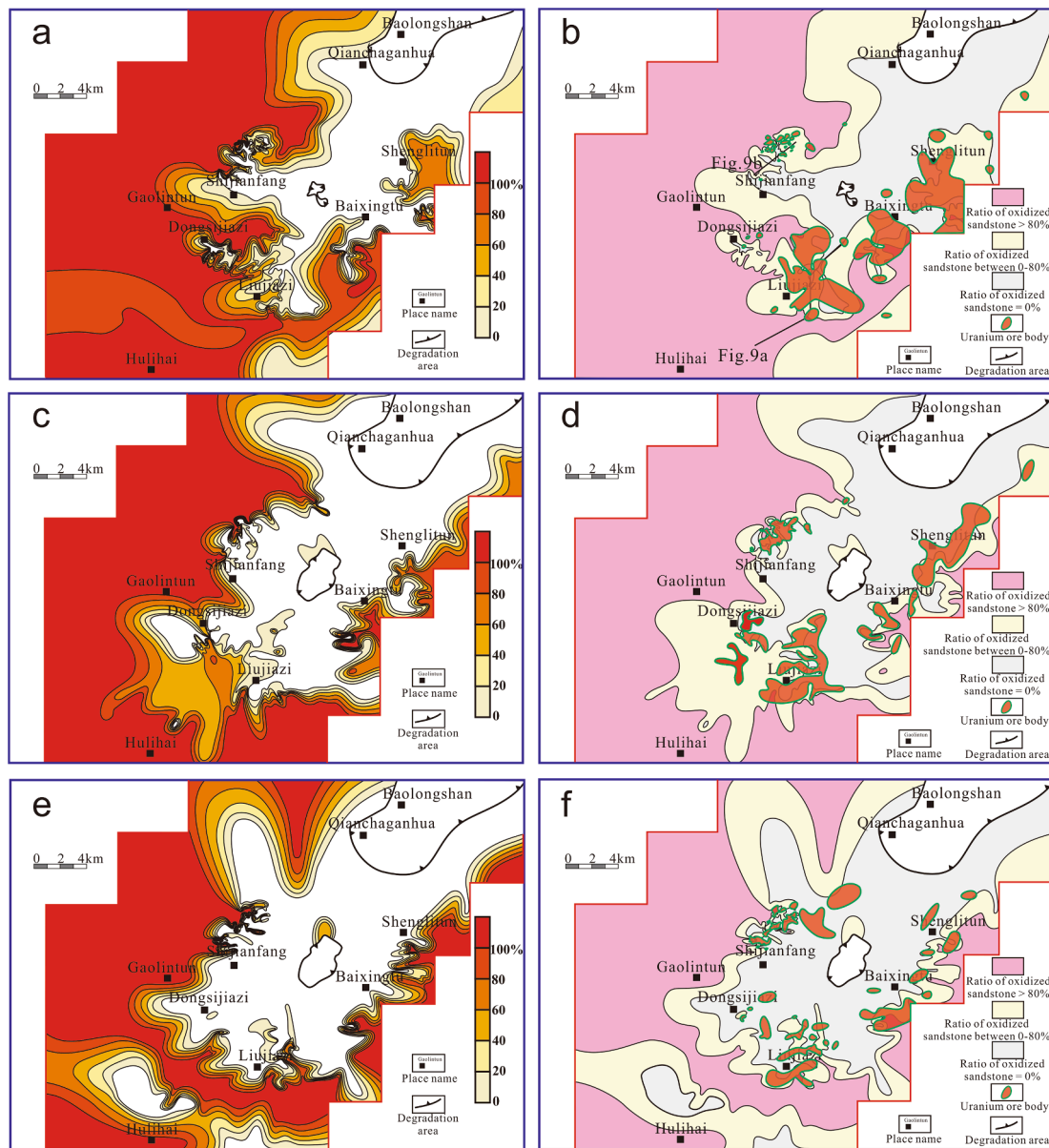


Fig. 8. (a) Contour map of ratio of oxidized sandstone in the SQ_{k2y}-LST. (b) Distribution of interlayer oxidized zones and uranium ore bodies in the SQ_{k2y}-LST. (c) Contour map of ratio of oxidized sandstone in the SQ_{k2y}-EST (Pss2). (d) Distribution of interlayer oxidized zones and uranium ore bodies in the SQ_{k2y}-EST (Pss2). (e) Contour map of ratio of oxidized sandstone in the SQ_{k2y}-EST (Pss3). (f) Distribution of interlayer oxidized zones and uranium ore bodies in the SQ_{k2y}-EST (Pss3).

influences of climate changes on deposition of uranium reservoirs appear in two aspects. Firstly, geometry of uranium reservoirs is affected by climate changes. Weathering and erosion of provenance are more intense, rainfall is larger, and river system is more developed in humid and hot climates than those in arid and cold climates (Lavie et al., 2001; Tian, 2001; Allen, 2008; Yang and Ma, 2017). So, supplies of materials from provenance in humid and hot climates are more sufficient than those in arid and cold climates, leading to larger scales of uranium reservoirs in humid and hot climates (Fig. 11). Secondly, composition of uranium reservoirs is constrained by climate changes. Animals and plants are more developed, and organic matter is more easily preserved in humid and hot climates than those in arid and cold climates (Yudovich, 2003; Ielpi et al., 2015), resulting in higher TOC contents of

uranium reservoirs in humid and hot climates (Fig. 11).

8.2. Effects of uranium reservoirs on interlayer oxidation

Interlayer oxidized zones of sandstone-hosted uranium deposits have been considered to be related with architecture and composition of uranium reservoirs (Galloway, 1978; Reynolds and Goldhaber, 1978, 1983; Jiao et al., 2006, 2015; Hall et al., 2017). Large-scale frame sandstone bodies with good connectivity have often been served as migration channels of ore-forming fluids and favorable places where interlayer oxidized zones occurred (Galloway, 1978; Jiao et al., 2005, 2006). However, when the sandstone bodies tend to frequently bifurcate or their thickness rapidly becomes thinner, the ore-forming fluids

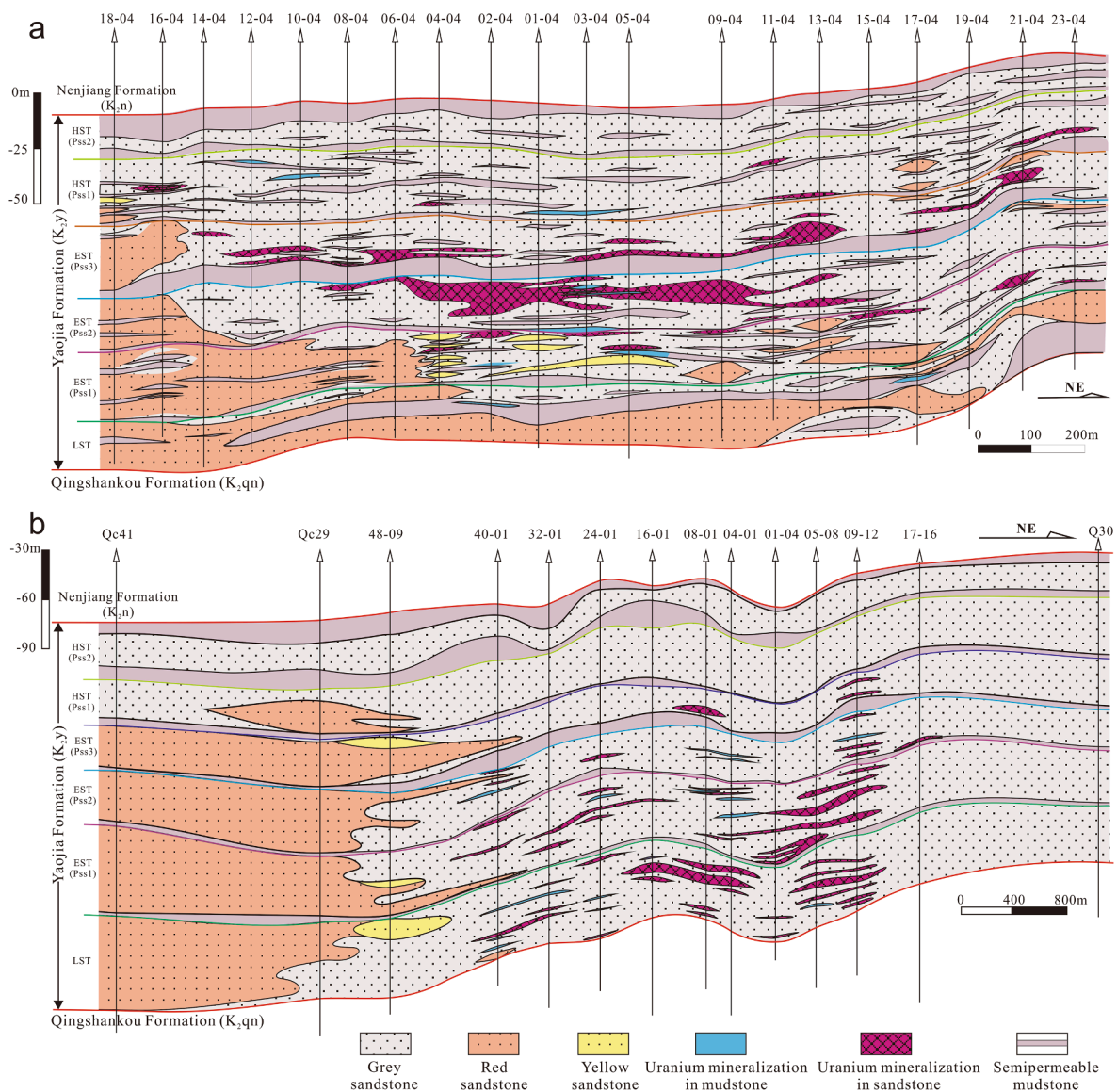


Fig. 9. Geological cross-sections of the Qianjiadian uranium deposit (the location is shown in Fig. 8b). Two figures illustrate the red sandstone, yellow sandstone, non-mineralized grey sandstone, mineralized grey sandstone and primary grey sandstone successively occur along the orientation of interlayer oxidation (NE), and the uranium ore bodies are primarily tabular or lenticular. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

infiltrating into these sandstone bodies will dispersedly flow and their flow velocities will decrease, resulting in inhibition of formation of interlayer oxidized zones (Galloway, 1978; Jiao et al., 2005, 2006). In addition, TOC contents of uranium reservoirs may inhibit development of interlayer oxidized zones: higher TOC contents of uranium reservoirs, smaller scales of interlayer oxidized zones (Jiao et al., 2015).

In this study, the interlayer oxidation mainly occurs in the regions where the thickness of the uranium reservoirs and ratio of sandstone and strata are both larger and higher, and tend to pinch out at the positions where the uranium reservoirs frequently bifurcate or rapidly thin (Figs. 6, 8), indicating that thicker uranium reservoirs and higher ratio of sandstone and strata are favorable for occurrence of interlayer oxidation. From the SQ_{k2y}-LST to SQ_{k2y}-HST (Pss2), the thickness of the uranium reservoirs and ratio of sandstone and strata generally decrease,

while the corresponding thickness, ratio and area of oxidized sandstone successively decrease (Fig. 10). The thickness of the uranium reservoirs and ratio of sandstone and strata are both positively correlated with thickness or area of oxidized sandstone, and the general trend observed is as expected an increase of thickness or area of oxidized sandstone as the thickness of the uranium reservoirs or ratio of sandstone and strata increases (Fig. 12a, b, c, d). So, the study shows that development of interlayer oxidized zones is controlled by geometry of uranium reservoirs. The TOC contents of uranium reservoirs decrease with a decrease of thickness or area of oxidized sandstone in this study (Figs. 10, 12e, f), which differs significantly from the traditional changing trend: higher TOC contents of uranium reservoirs, smaller scales of interlayer oxidized zones (Jiao et al., 2015). This phenomenon may be related to generally low TOC contents of the uranium reservoirs and a little difference in

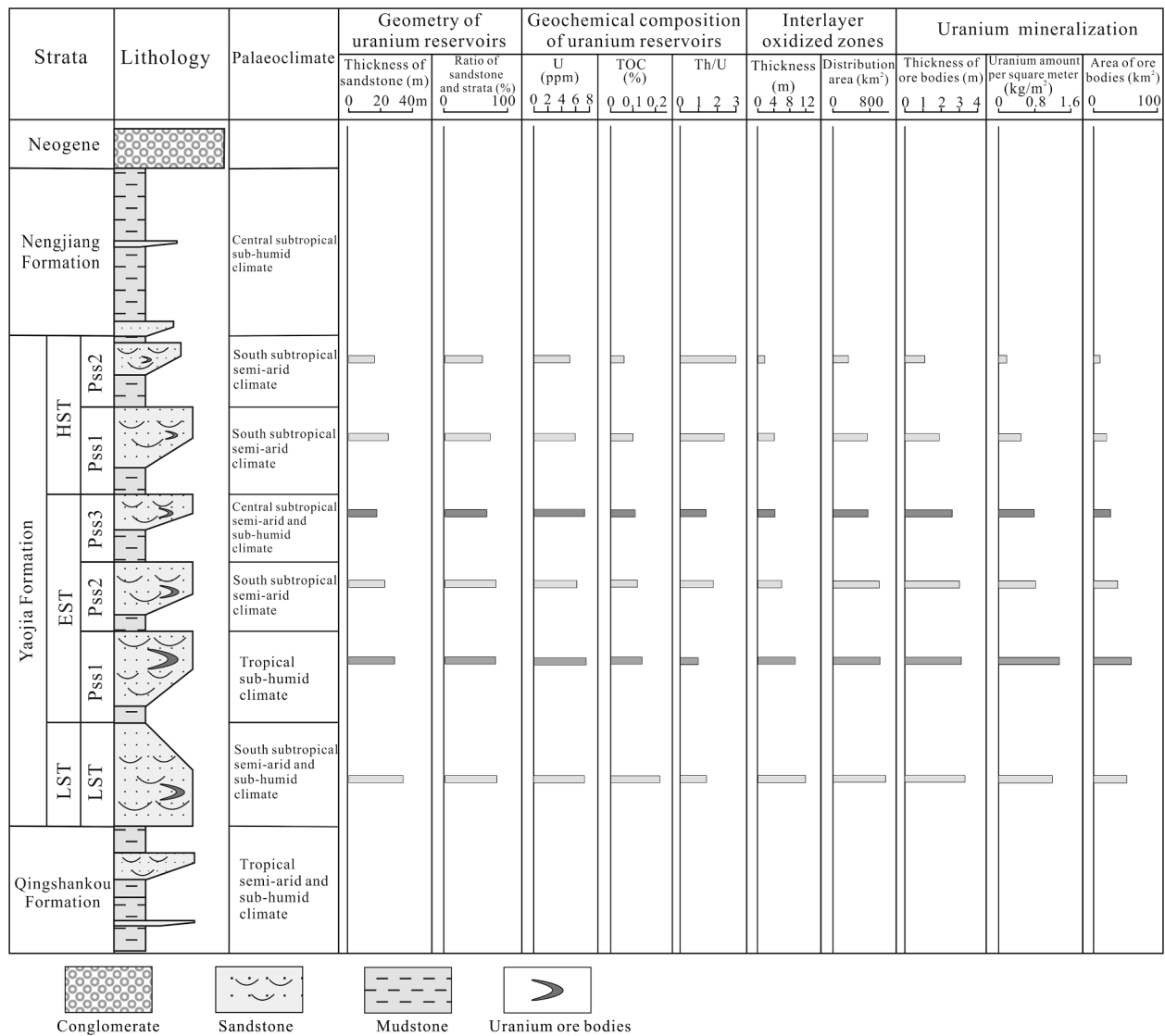


Fig. 10. Palaeoclimate, uranium reservoirs, interlayer oxidized zones, and uranium ore bodies of the Yaojia Formation in the Qianjiadian uranium deposit. Refer to Tables 6, 7 for detailed data.

TOC contents among the uranium reservoirs in different climates (Fig. 10; Tables 5, 6). Therefore, influences of geometry of uranium reservoirs on interlayer oxidation may be more obvious when TOC contents of uranium reservoir are relatively low.

8.3. Effects of interlayer oxidation on uranium mineralization

Interlayer oxidized zones caused by oxygen-bearing U^{6+} groundwater in uranium reservoirs are generally divided into oxidized zones, oxidized-reduced transition zones and reduced zones (Granger and Warren, 1969, 1974; Reynolds and Goldhaber, 1978; Hall et al., 2017). The oxidized zones are mainly composed of red, brown or yellow sandstone; the reduced zones primarily comprise of gray and dark gray sandstone; the oxidized-reduced transition zones occurring at the pinch out of the oxidized zones are locations where uranium ores are formed (Granger and Warren, 1969, 1974; Reynolds and Goldhaber, 1978; Lehmann, 2008; Zammit et al., 2014; Jiao et al., 2015; Rong et al., 2016; Hall et al., 2017). So, the interlayer oxidized zones regarded as an

important prospecting indicator control formation and distribution of uranium ores of sandstone-hosted uranium deposits.

In this study, the uranium ores of the Qianjiadian uranium deposit are formed near pinchout line of the oxidized sandstone (Figs. 8, 9). From the SQ_{k2y} -LST to SQ_{k2y} -HST (Pss2), the thickness and area of oxidized sandstone generally decrease, while the thickness, uranium amount per square meter and area of uranium bodies correspondingly decrease (Fig. 10; Table 7). The thickness and area of oxidized sandstone are both positively correlated with thickness, uranium amount per square meter or area of uranium bodies, and the general trend observed is as expected an increase of thickness, uranium amount per square meter or area of uranium bodies as the thickness of uranium reservoirs or area of oxidized sandstone increases (Fig. 12g, h, i, j, k, l). So, the study indicate that scales and distribution of uranium ore bodies are restricted by those of oxidized sandstone.

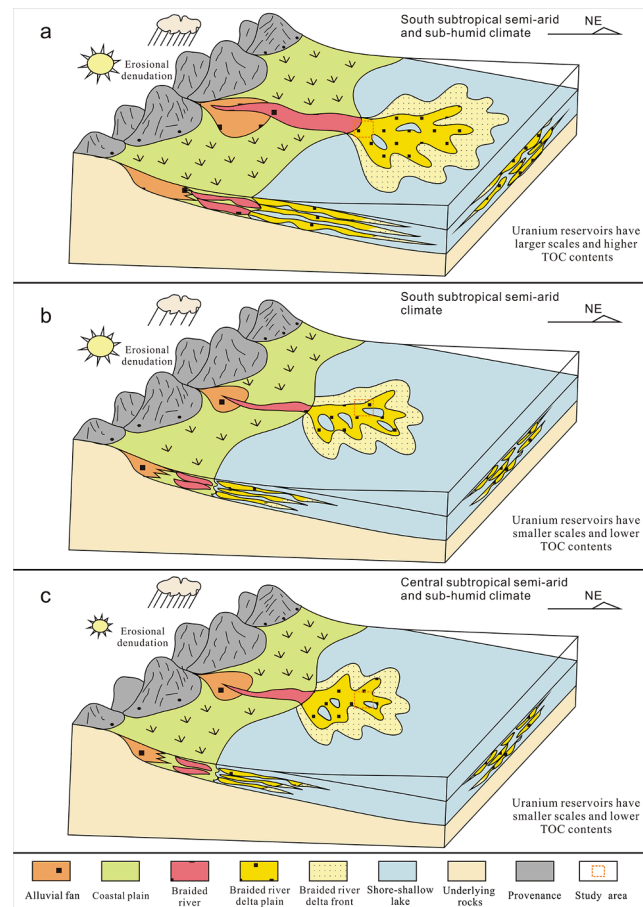


Fig. 11. Depositional models of the uranium reservoirs formed in different climates. (a) Depositional model of the uranium reservoirs formed in the south subtropical semi-arid and sub-humid climates. (b) Depositional model of the uranium reservoirs formed in the south subtropical semi-arid climates. (c) Depositional model of the uranium reservoirs formed in the central subtropical semi-arid and sub-humid climates.

8.4. Influence mechanism of palaeoclimate on uranium mineralization

In the south subtropical climates, thickness, uranium amount per square meter and area of the ore bodies within the uranium reservoirs in the semi-arid and sub-humid conditions are all larger than those in the semi-arid conditions respectively (Figs. 8, 10, 12g, h, i, j, k, l; Table 7). In the semi-arid and semi humid climates, thickness, uranium amount per square meter and area of the ore bodies within the uranium reservoir in the subtropical conditions are all larger than those in central subtropical conditions respectively (Figs. 8, 10, 12g, h, i, j, k, l; Table 7). So, the study reveals that uranium mineralization became worse from humid to arid climates in the same temperate zones, while it also became worse from hot to cold climates in the same humidity zones. It can also be inferred that hot and humid paleoclimate is favorable for mineralization of sandstone-hosted uranium deposits.

The study indicates that in the same temperature zones, the uranium reservoirs formed in the humid conditions have larger scales than those formed in the arid conditions, resulting in larger scales of the interlayer oxidized zones and uranium ore bodies, whereas in the same humidity

zones, the uranium reservoirs formed in the hot conditions have larger scales than those formed in the cold climates, resulting in larger scales of the interlayer oxidized zones and uranium ore bodies (Figs. 10, 12, 13). So, it suggests that paleoclimate has a restriction on geometry and composition of uranium reservoirs, which may affect scales and distribution of interlayer oxidized zones and uranium ore bodies.

9. Conclusion

- (1) The Upper Cretaceous Yaojia Formation was divided into six units: SQ_{K2y}-LST, SQ_{K2y}-EST (Pss1), SQ_{K2y}-EST (Pss2), SQ_{K2y}-EST (Pss3), SQ_{K2y}-HST (Pss1) and SQ_{K2y}-HST (Pss2). Paleoclimate of the SQ_{K2y}-LST, SQ_{K2y}-EST (Pss1), SQ_{K2y}-EST (Pss2), SQ_{K2y}-EST (Pss3), SQ_{K2y}-HST (Pss1) and SQ_{K2y}-HST (Pss2) is south subtropical semi-arid and sub-humid, tropical sub-humid, south subtropical semi-arid, central subtropical semi-arid and sub-humid, south subtropical semi-arid, and south subtropical semi-arid, respectively.

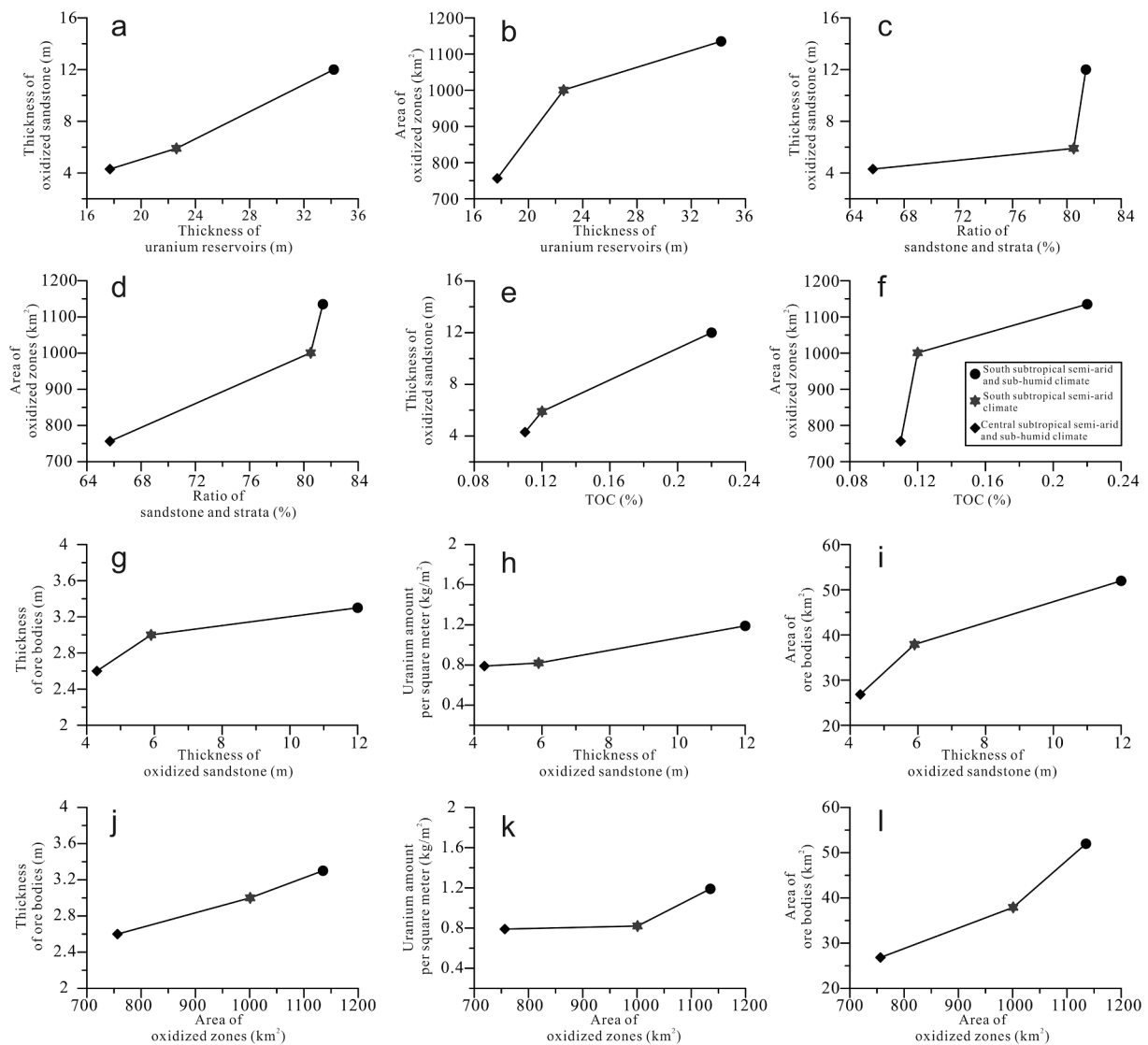


Fig. 12. (a) Cross-plot of thickness of uranium reservoirs against thickness of oxidized sandstone. (b) Cross-plot of thickness of uranium reservoirs against area of oxidized zones. (c) Cross-plot of ratio of sandstone and strata against thickness of oxidized sandstone. (d) Cross-plot of ratio of sandstone and strata against area of oxidized zones. (e) Cross-plot of TOC against thickness of oxidized sandstone. (f) Cross-plot of TOC against area of oxidized zones. (g) Cross-plot of thickness of oxidized sandstone against thickness of ore bodies. (h) Cross-plot of thickness of oxidized sandstone against uranium amount per square meter. (i) Cross-plot of thickness of oxidized sandstone against area of ore bodies. (j) Cross-plot of area of oxidized zones against thickness of ore bodies. (k) Cross-plot of area of oxidized zones against uranium amount per square meter. (l) Cross-plot of area of oxidized zones against area of ore bodies. See the same legend in Fig. 12f. Refer to Tables 6, 7 for detailed data.

(2) In the same temperate zones, thickness and TOC of the uranium reservoirs in the humid climates are larger and higher respectively, thickness and distribution area of the corresponding interlayer oxidized zones are both larger, and thickness, uranium amount per square meter and area of the corresponding ore bodies are all larger than those in the arid climates. In the same humidity zones, thickness and TOC of the uranium reservoirs in the warm climates are larger and higher respectively, thickness and distribution area of the corresponding interlayer oxidized zones are both larger, and thickness, uranium amount per square meter and area of the corresponding ore bodies are all larger than those in the cold climates.

(3) Hot and humid paleoclimate is favorable for mineralization of sandstone-hosted uranium deposits. Paleoclimate has a restriction on geometry and composition of uranium reservoirs, which may affect scales and distribution of interlayer oxidized zones and uranium ore bodies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

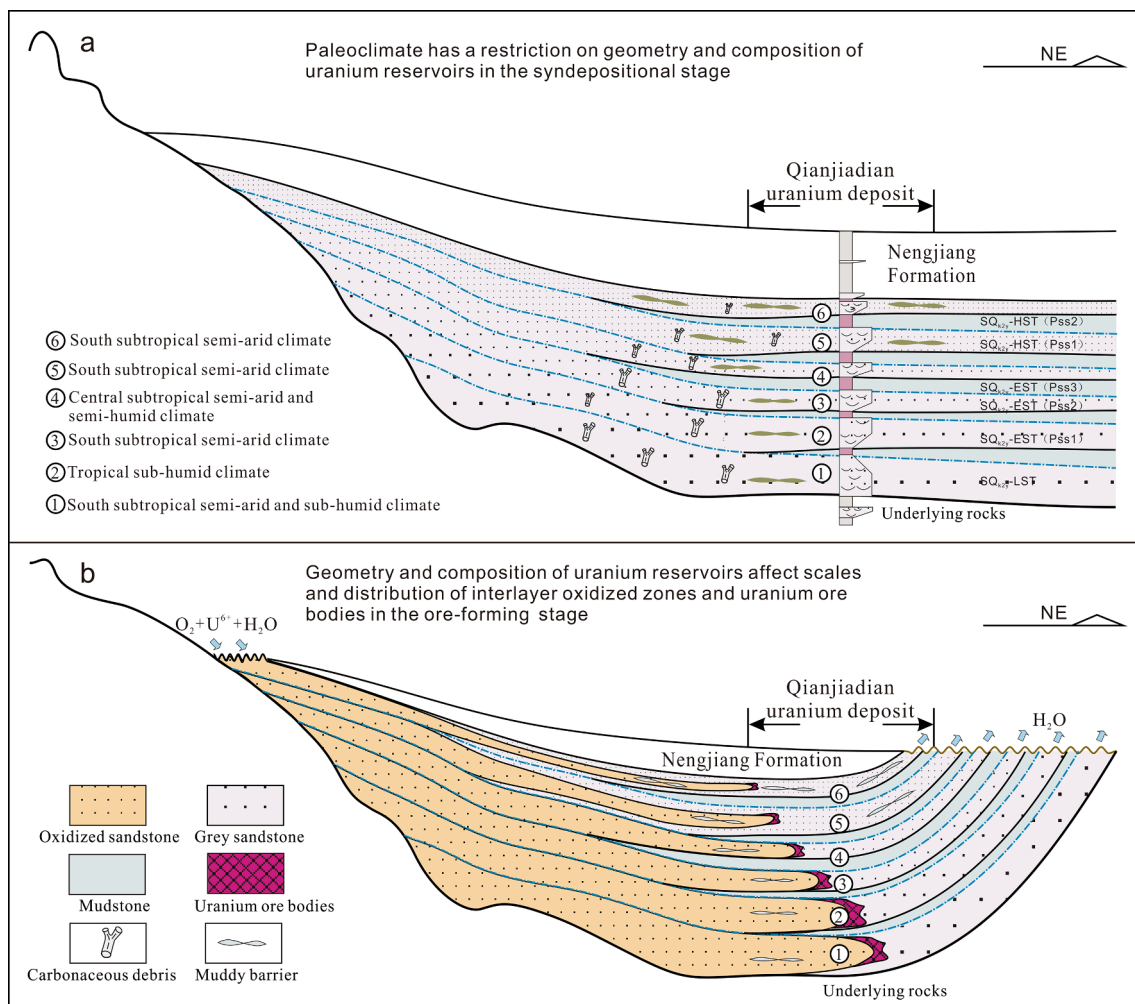


Fig. 13. Influence mechanism of the palaeoclimate on mineralization of the Qianjiadian uranium deposit. (a) Paleoclimate has a restriction on geometry and composition of uranium reservoirs in the syndepositional stage. (b) Geometry and composition of uranium reservoirs may affect scales and distribution of interlayer oxidized zones and uranium ore bodies in the ore-forming stage.

Acknowledgments

This research is sponsored by the National Key Research and Development Program of China (No. 2018YFC0604202), National Natural Science Foundation of China (No. 41502105), Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan) (No. G1323511660), and Fund of Outstanding Talents in Discipline of China University of Geosciences (Wuhan) (102-162301192664). We sincerely thank Dongmin Ji, Hongliang Li and Lei Zhang in the Development Company of New Energy Sources of Liaohe Petroleum Exploration Bureau for their guidance and selfless help. Xiaojin Wang is thanked for useful discussion and language polishing.

References

- Allen, P.A., 2008. From landscapes into geological history. *Nature* 451, 274–276.
- Chen, X., Li, Z., Chen, J., Li, H., Zhang, T., 2010. Determination of the reverse period of Songliao Basin, China. *Geol. Bull. China* 29, 305–311 (in Chinese with English abstract).
- Chen, X., Fang, X., Guo, Q., Xia, Y., Pang, Y., Sun, Y., 2008. Re-discussion on uranium metallogenesis in Qianjiadian Sag, Songliao Basin. *Acta Geol. Sin.* 82, 553–561 (in Chinese with English abstract).
- Cheng, D., Liu, W., Jia, L., 2011. Paleo-climate evolution in China and its control on the metallization of sandstone type uranium deposit of Meso-Cenozoic basins. *Uranium Geology* 27, 321–344 (in Chinese with English abstract).
- Cheng, Y., Wang, S., Li, Y., Ao, C., Li, Y., Li, J., Li, H., Zhang, T., 2018. Late Cretaceous–Cenozoic thermochronology in the southern Songliao Basin, NE China: New insights from apatite and zircon fission track analysis. *J. Asian Earth Sci.* 160, 95–106.
- Cheng, Y., Wang, S., Zhang, T., Teng, X., Ao, C., Jin, R., Li, H., 2020. Regional sandstone-type uranium mineralization rooted in Oligo-Miocene tectonic inversion in the Songliao Basin, NE China. *Gondwana Res.* 88, 88–105.
- Du, X., Xie, X., Lu, Y., Ren, J., Zhang, S., Lang, P., Cheng, T., Su, M., Zhang, C., 2011. Distribution of continental red paleosols and their forming mechanisms in the Late Cretaceous Yaojia Formation of the Songliao Basin, NE China. *Cretac. Res.* 32, 244–257.
- Fang, S., Zhang, Z., Liu, Z., Dong, Q., Wan, J., Du, J., 2007. Hydrothermal history and stratum age in the Cenozoic of the Songliao Basin, NE China. *Journal of Jilin University (Earth Science Edition)* 37, 923–928.
- Feng, Z., Jia, C., Xie, X., Zhang, S., Feng, Z., Cross, T.A., 2010. Tectonostratigraphic units and stratigraphic sequences of the nonmarine Songliao basin, northeast China. *Basin Res.* 22, 79–95.
- Galloway, W.E., 1978. Uranium mineralization in a coastal-plain fluvial aquifer system. *Catahoula Formation, Texas. Economic Geology* 73, 1655–1676.
- Gao, R., Zhang, Y., Cui, T., 1994. Cretaceous Petroleum strata in the Songliao Basin. China Petroleum Industry Press, Beijing, 333p (in Chinese).
- Gao, R., Zhu, Z., Zheng, G., Zhao, Z., 1999. Palynology of the petroliferous basins in China. China Petroleum Industry Press, Beijing, 251p (in Chinese).
- Gong, C., Qi, K., Xu, J., Liu, X., Wang, Y., 2021. Process-product linkages and feedback mechanisms of deepwater source-to-sink responses to multi-scale climate changes. *Acta Sedimentol. Sin.* 39, 231–252 (in Chinese with English abstract).
- Granger, H.C., Warren, C.G., 1969. Unstable sulfur compound and the origin of roll-type uranium deposits. *Econ. Geol.* 64, 160–171.
- Granger, H. C., Warren, C. G., 1974. Zoning in the altered tongue associated with roll-type uranium deposits. In: Symposium on the formation of uranium ore deposits. IAEA, Vienna, 185–199.
- Hall, S.M., Mihalasky, M.J., Tureck, K.R., Hammarstrom, J.M., Hannon, M.T., 2017. Genetic and grade and tonnage models for sandstone-hosted roll-type uranium deposits, Texas Coastal Plain, USA. *Ore Geol. Rev.* 80, 716–753.
- Hessler, A.M., Covault, J.A., Stockli, D.F., Fildani, A., 2018. Late Cenozoic cooling favored glacial over tectonic controls on sediment supply to the western Gulf of Mexico. *Geology* 46, 995–998.

- Huang, Q., Wu, H., Wan, X., He, H., Deng, C., 2011. New progress of integrated chronostratigraphy of the Cretaceous in Songliao Basin. *J. Stratigr.* 35, 250–257 (in Chinese with English abstract).
- Huang, Q., Zheng, Y., Yang, M., Li, X., Han, M., Chen, C., 1999. Study on Cretaceous paleoclimate in the Songliao Basin. *Acta Micropalaeontol. Sin.* 16, 95–103 (in Chinese with English abstract).
- Ielpi, A., Gibling, M.R., Bashforth, A.R., Dennar, C.I., 2015. Impact of vegetation on Early Pennsylvanian fluvial channels: Insight from the Joggins Formation of Atlantic Canada. *J. Sediment. Res.* 85, 999–1018.
- Jia, J., Kang, H., Liu, X., Li, D., Feng, X., 2019. Climate events and their bearing on turbidite channels of the Congo Fan. *Marine Geology Frontiers* 35, 2–10 (in Chinese with English abstract).
- Jia, J., Rong, H., Jiao, Y., Wu, L., Wang, Y., Li, H., Cao, M., 2020. Mineralogy and geochemistry of carbonate cement in sandstone and implications for mineralization of the Qianjiadian sandstone-hosted uranium deposit, southern Songliao Basin. *China. Ore Geology Reviews* 123, 103590.
- Jiang, Y., 1983. Discussion on the metallogenic conditions of exogenetic uranium deposits: Paleoclimatic conditions. *Radioactive geology* 2, 9–13 (in Chinese with English abstract).
- Jiao, Y., Lv, X., Wang, Z., Wang, M., 2004. Two Distinct Geological Environments from Sedimentary to Diagenesis Stages: Examples from Sandstone-Type Uranium Deposits, Turpan-Hami Basin. *Earth Sci.* 29, 615–620 (in Chinese with English abstract).
- Jiao, Y., Wu, L., Peng, Y., Rong, H., Ji, D., Miao, A., Li, H., 2015. Sedimentary-tectonic setting of the deposition-type uranium deposits forming in the Paleo-Asian tectonic domain, North China. *Earth Sci. Front.* 22, 189–205 (in Chinese with English abstract).
- Jiao, Y., Wu, L., Yang, S., Lv, X., 2006. Uranium reservoir sedimentology: The basis of exploration and development of sandstone-type uranium deposits. Geological Publishing House, Beijing (in Chinese).
- Jiao, Y., Yan, J., Li, S., Yang, R., Lang, F., Yang, S., 2005. Architectural units and heterogeneity of channel reservoirs in the Karamay Formation, outcrop area of Karamay Oil Field, Junggar Basin, Northwest China. *AAPG Bull.* 89, 529–545.
- Lavier, L., Steckler, M., Brigand, F., 2001. Climatic and tectonic control on the Cenozoic evolution of the West African margin. *Mar. Geol.* 178, 63–80.
- Lehmann, B., 2008. Uranium ore deposits. *Econ. Geol.* 2, 16–26.
- Li, G., Wan, X., Batten, D., Bengtson, P., Xi, D., Wang, P., 2009. Spinicaudatans from the upper Cretaceous Nenjiang formation of the Songliao basin, northeast China: Taxonomy and biostratigraphy. *Cretac. Res.* 30, 687–698.
- Li, S., Chen, F., Siebel, W., Wu, J., Zhu, X., Shan, X., Sun, X., 2012. Late Mesozoic tectonic evolution of the Songliao basin, NE China: Evidence from detrital zircon ages and Sr–Nd isotopes. *Gondwana Res.* 22, 943–955.
- Lin, C., Xia, Q., Shi, H., Zhou, X., 2015. Geomorphological evolution, source to sink system and basin analysis. *Earth Sci. Front.* 22, 9–20 (in Chinese with English abstract).
- Liu, L., Chen, J., 1994. The application of sand-sandstone compositions to research on the paleoclimate. *Jilin Geol.* 13, 25–31 (in Chinese with English abstract).
- Liu, X., 1998. Metallogenic conditions and prospecting criteria of sandstone type uranium deposits in regional interlayer oxidation zones in Central Asia. *Overseas Uranium Gold Geol.* 15, 368–375 (in Chinese with English abstract).
- Luo, Y., He, Z., Ma, H., Sun, X., 2012. Metallogenic characteristics of Qianjiadian sandstone uranium deposit in Songliao basin. *Mineral Deposits* 31, 391–400 (in Chinese with English abstract).
- Luo, Y., Ma, H., Xia, Y., Zhang, Z., 2007. Geologic characteristics and metallogenic model of Qianjiadian uranium deposit in Songliao basin. *Uranium Geology* 23, 193–199 (in Chinese with English abstract).
- Meunier, J.D., Trouiller, A., Brulhet, J., Pagel, M., 1989. Uranium and organic matter in a paleodeltaic environment: the Coutras Deposit (Gironde, France). *Econ. Geol.* 84, 1541–1556.
- Mudd, G.M., 2014. The future of Yellowcake: A global assessment of uranium resources and mining. *Sci. Total Environ.* 472, 590–607.
- Pang, Y., Chen, X., Fang, X., Sun, Y., 2010. Discussion on the interlayer oxidation and uranium metallogenesis in Qianjiadian uranium deposit, Songliao Basin. *Uranium Geol.* 26, 9–23 (in Chinese with English abstract).
- Reynolds, R.L., Goldhaber, M.B., 1978. Origin of a south Texas roll-type uranium deposit: I. Alteration of iron-titanium oxide minerals. *Econ. Geol.* 73, 1677–1689.
- Reynolds, R.L., Goldhaber, M.B., 1983. Iron disulfide minerals and the genesis of roll-type uranium deposits. *Econ. Geol.* 78, 105–120.
- Rong, H., Jiao, Y.Q., Wu, L.Q., Wan, D., Cui, Z.J., Guo, X.J., Jia, J.M., 2019. Origin of the carbonaceous debris and its implication for mineralization within the Qianjiadian uranium deposit, southern Songliao Basin. *Ore Geol. Rev.* 107, 336–352.
- Rong, H., Jiao, Y., Liu, X., Wu, L., Jia, J., Cao, M., 2020. Effects of basic intrusions on REE mobility of sandstones and their geological significance: A case study from the Qianjiadian sandstone-hosted uranium deposit in the Songliao Basin. *Appl. Geochem.* 120, 104665.
- Rong, H., Jiao, Y., Wu, L., Ji, D., Li, H., Zhu, Q., Cao, M., Wang, X., Li, Q., Xie, H., 2016. Epigenetic alteration and its constraint on uranium mineralization from the Qianjiadian uranium deposit, southern Songliao Basin. *Earth Sci.* 41, 153–166 (in Chinese with English abstract).
- Rong, H., Jiao, Y., Wu, L., Zhao, X., Cao, M., Liu, W., 2021. Effects of igneous intrusions on diagenesis and reservoir quality of sandstone in the Songliao Basin, China. *Marine Petrol. Geol.* 127, 104980.
- Ruddiman, W.F., 2001. *Earth's climate: Past and future*. W.H. Freeman & Sons, New York, p. 576p.
- Song, Y., Ren, J., Yang, H., Tong, D., Lei, C., 2010. Characteristics and dynamic background of bottom boundary in Yaojia Formation of the northern Songliao Basin. *Acta Petrolei Sinica* 31, 187–195 (in Chinese with English abstract).
- Suttner, L.J., Dutta, P.K., 1986. Alluvial sandstone composition and paleoclimate, I. framework mineralogy. *J. Sediment. Petrol.* 56, 329–345.
- Tian, J., 2001. The feature, evolution and controlling factors of terrigenous clastic reservoir sandbodies on the steep slope zone in the halfgraben-like rift lake basin. *J. Mineral. Petrol.* 21, 56–63 (in Chinese with English abstract).
- Wan, X., Zhao, J., Scott, R.W., Wang, P., Feng, Z., Huang, Q., Xi, D., 2013. Late Cretaceous stratigraphy, Songliao Basin, NE China: SK1 cores. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 385, 31–43.
- Wang, C., Scott, R.W., Wan, X., Graham, S.A., Huang, Y., Wang, P., Wu, H., Dean, W.E., Zhang, L., 2013. Late Cretaceous climate changes recorded in Eastern Asian lacustrine deposits and North American Epiherc sea strata. *Earth-Sci. Rev.* 126, 275–299.
- Wang, T., Zhu, X., Dong, Y., Yang, D., Su, B., Tan, M., Liu, Y., Wu, W., Zhang, Y., 2021. Signals of depositional response to Deep Time paleoclimate in continental depression lake: a case study of Anjihaihe Formation in northwestern Junggar Basin. *Earth Sci. Front.* 28, 60–76 (in Chinese with English abstract).
- Wang, Z., 1988. The red bed-type and sandstone-type uranium deposits in the inland basins, Northwest China. *Uranium Geology* 4, 193–198 (in Chinese with English abstract).
- Wang, Z., Guan, T., 2004. Uranium pre-concentration in Miaogou Formation, Lower Cretaceous and its prospecting significance in Chaoshui Basin. *Uranium Geol.* 20, 279–285 (in Chinese with English abstract).
- Wellner, R.W., Bartek, L.R., 2003. The effect of sea level, climate, and shelf physiography on the development of incised valley complexes: A modern example from the East China Sea. *J. Sediment. Res.* 73, 926–940.
- Xi, D., Yin, X., Cui, Y., Jing, X., Wan, X., 2008. Paleolimnology and paleoclimate from the Upper Qingshankou to the Lower Yaojia Formations in central Songliao Basin. *Acta Micropalaeontol. Sin.* 25, 266–274 (in Chinese with English abstract).
- Xia, Y., Lin, J., Li, Z., Li, S., Liu, H., Wang, Z., Fan, G., Zheng, J., Li, Z., Zhang, M., 2003. Perspective and resource evaluation and metallogenic studies on sandstone-type uranium deposit in Qianjiadian depression of Songliao Basin. *China Nucl. Sci. Technol. Report* 3, 105–117 (in Chinese).
- Xia, Y., Zheng, J., Li, Z., Li, L., Tian, S., 2010. Metallogenic characteristics and model of the Qianjiadian uranium deposit in the Songliao basin. *Mineral Deposits* 29, 154–155 (in Chinese with English abstract).
- Xu, K., Li, Y., 1995. Late Mesozoic strata of the Kailu Basin. *J. Stratigr.* 19, 88–95 (in Chinese with English abstract).
- Xu, Z., Li, J., Zhu, Q., Wei, J., Li, H., Zhang, B., 2019. Late Cretaceous paleoclimate change and its impact on uranium mineralization in the Kailu Depression, southwest Songliao Basin. *Ore Geol. Rev.* 104, 403–421.
- 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.
- Yang, J., Ma, Y., 2017. Paleoclimate perspectives of source-to-sink sedimentary processes. *Earth Sci.* 42, 1910–1921 (in Chinese with English abstract).
- Yudovich, Y.E., 2003. Coal inclusions in sedimentary rocks: a geochemical phenomenon. A review. *Int. J. Coal Geol.* 56, 203–222.
- Zammit, C.M., Brugger, J., Southam, G., Reith, F., 2014. In-situ recovery of uranium—the microbial influence. *Hydrometallurgy* 150, 236–244.
- Zhang, J., 2008. Molecular microbiology research in black and red mudstones of Cretaceous Continental Scientific Drilling, Master's dissertation, China University of Geosciences (Beijing). 68p (in Chinese with English abstract).
- Zhang, L., Wang, D., 1994. Palaeoclimatic characteristics and the mechanism for climatic changes in the Songliao Basin during the Cretaceous. *Sediment. Facies Palaeogeogr.* 14, 11–15 (in Chinese with English abstract).
- Zhao, L., Cai, C., Jin, R., Li, J., Li, H., Wei, J., Guo, H., Zhang, B., 2018. Mineralogical and geochemical evidence for biogenic and petroleum-related uranium mineralization in the Qianjiadian deposit, NE China. *Ore Geol. Rev.* 101, 273–292.
- Zhou, Q., Quan, Z., 1991. Relations of red bed periods to uranium mineralization in northwest China, Shanxi and Inner Mongolia. *Mineral Deposits* 10, 161–169 (in Chinese with English abstract).