CNIC-01778
BRIUG-0070

产铀盆地的形成演化模式及其鉴别标志[①]

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摘　要

根据国内外现有重要产铀盆地地质构造背景及其动力学演化，划分出六类产铀盆地，并以每类盆地中的类型代表命名，即楚·萨雷苏-锡尔河式、中央克兹勒库姆式、外乌拉尔-西西伯利亚式、外贝加尔式、波希米亚式和南得克萨斯式。对每类产铀盆地的形成演化模式进行了界定并归纳出其鉴别标志。最后，分析了各类产铀盆地的区别。提出中国寻找产铀盆地的设想。

关键词：砂岩型铀矿　容矿岩系　产铀盆地　演化模式

① 本文系核工业地质局"全国新一轮可地浸砂岩铀矿勘查战略选区"项目的部分内容总结。参加这一项目的还有范立亭、李建红、蔡煜琦、冯明月、李胜祥、金明、祝民强、张树明和黄解军。

Formation-evolution Model of Uranium-productive Basin and Its Recognition Criteria[①]

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ABSTRACT

Based on geologic-tectonic setting and dynamic evolution of important U-productive basins both at home and abroad, authors distinguish six types of U-productive basins, and nominate each type by typical representative of this type, namely Chu-Sarysu and Syr-Darya type, Central Kyzylkum type, Zaural and West-Siberia type, Zabaikal type, Bohemia type, and South Texas type. The formation-evolution model of each type of U-productive basin has been established and recognition criteria have been proposed. Finally, the difference between each type U-productive basin is discussed and some assumption on prospecting for U-productive basins is proposed.

Key words: Sandstone-hosted uranium deposit, Ore-hosting rock series, U-productive basin, Evolutional model

① This paper is a part of the summary of a Research Project (A new round of strategic target area selection for ISL-amenable sandstone-hosted uranium deposits in China), 2002. Besides authors of this paper, Pan Liting, Li Jianhong, Cai Yuqi, Peng Mingyue, Li Wuwei, Jin Ming, Zhu Minqiang, Zhang Shuming, Huang Jiejun participated the project too

INTRODUCTION

Though sandstone-hosted uranium deposits are extensively distributed in Meso-Cenozoic sedimentary basins all over the world, the total number of U-productive basins where sandstone-hosted uranium deposits occur, is not big. For example, uranium resources (RAR+EAR−I, ≤ $80/kgU) in Chu-Sarysu and Syr-Darya basin, Kazakhstan reach 590 000 tU (Red Book, 2001), but some basins are lacking of any sandstone-hosted uranium deposit totally. So, authors nominate those basins where a lot of sandstone-hosted uranium deposits are located, as uranium productive basins; and those where no important uranium deposit occurs—non-uranium productive basins.

According to necessary ore-forming conditions for sandstone-hosted uranium deposit, to become a U-productive basin depends on the geologic background where the basin is located, and geologic events the basin experienced. Of those events, the tectonic movement the basin experienced is the most important. So, by recognizing favorable geologic background the basin is located in, and by analyzing the formational and evolutional history of the basin, the potential of the basin for locating sandstone-hosted uranium deposit can generally be determined.

At present, known commercial sandstone-hosted uranium deposits in the world include two major types, i. e. interlayer oxidation sandstone-hosted uranium deposits and paleovalley sandstone-hosted uranium deposits. Those stratiform deposits formed during syn-sedimentary (or diagenetic) stage, and those U-coal deposits formed by epigenetic infiltration can not be mined by ISL technology, are excluded from prospecting targets of most countries in the world.

Though attributed to the same type of interlayer oxidation origin, sandstone-hosted uranium deposits, as well as the initial basin type, the geologic structure, the dynamic evolution of the basin where these uranium deposits occur are different from each other (Chen Zhao-bo, et al., 2003). Therefore, it is difficult to establish a universal formation-evolution model to characterize geologic features of all U-productive basins. In the mean time, it is impossible to set up an individual formation-evolution model for each U-productive basin. So, on the basis of summarizing the formation-evolution model of most known U-productive basins in the world, authors propose six formation-evolution models of U-productive basins.

The necessary constituents that must be considered in establishing the formation-evolution model of U-productive basin are: the geotectonic position where the basin is located, the nature of the basin basement, local structure where the basin is emplaced, the dynamic character and mechanism during the formation and the evolution of the basin, as well as the genesis and the type of uranium mineralizations that occur in the basin. Authors nominate each type of U-productive basin by the name of representative typical U-productive basin or the name of the area where the basin is located. Totally, six types of U-productive basins are distinguished.

(1) Chu-Sarysu and Syr-Darya type

(2) Central Kyzylkum type

(3) Zaural and West-Siberia type

(4) Zabaikal type

(5) Bohemia type

(6) South Texas type

1 FORMATION-EVOLUTION MODEL OF U-PRODUCTIVE BASIN AND ITS RECOGNITION CRITERIA

As compared to the original research project this paper omitted the Colorado type, because uranium deposits occurring in Colorado basin mostly are of syn-sedimentary-diagenetic origin and of plate form, and cannot be mined by ISL technology. At present, they have been excluded from main prospecting targets in most countries in the world. The Wyoming and Yili types of U-productive basins are attributed to Central Kyzylkum type, because sandstone-hosted uranium deposits in these basins are similar in genesis and ore-forming mechanism, as well as in the evolution of U-productive basin.

1.1 Chu-Sarysu and Syr-Darya type

The Chu-Sarysu and Syr-Darya basin in Kazakhstan is the largest sandstone uranium metallogenetic province in the world. Several tens of sandstone-hosted uranium deposits have been revealed in the province with the total uranium resources over 1 000 000 tU. Data of main sandstone-hosted deposits are listed in Table 1.

Table 1 Data of main uranium deposits in Chu-Sarysu and Syr-Darya uranium province

Uranium Sub-province	Deposit	Main ore-hosting horizon	Range of ore grade and average grade %U	Uranium resources 10^3tU
Chu-Sarysu	Inkay	K_2t, E_3^1	0.03~0.1 (0.046)	293.0
	Bujonov	K_2t, K_2st	0.05~0.1 (0.056)	300.0
	Mynkuduk	K_2t, E_3^1	0.015~0.15 (0.045)	76.0
	Moynkum	E_1^2	0.03~0.1 (0.062)	59.0
	Kanshugan	E_1^2, E_2^1	0.03~0.07 (0.033)	20.0
	Uvanas	E_1^2	0.02~0.1 (0.028)	10.0
	Zhalpak	K_2km, E_3^1	0.01~0.4 (0.035)	16.0
	Sholak-Espe	K_2st, E_3^1	0.01~0.1	5.0~20.0
Syr-Darya	South & North Karamurun	K_2t, K_2kn, K_2km, K_2m	0.03~0.1 (0.086)	41.0
	Harasan	K_2st, K_2km, K_2m	0.03~0.2 (0.107)	70.0
	Irkol	K_2t, K_2kn, K_2st	0.01~0.1 (0.042)	38.0
	Zarechn	K_2km, K_2m	0.03~0.60 (0.056)	42.0
	Kyzylkol	E_2^1, E_3^1	0.016~0.115	3.0~5.0
	Chayan	E_2^1, E_2^1	0.016~0.125	3.0~5.0
	Lunnoe	E_2^1, E_3^1	0.02~0.30	0.5~1.5

Data in Table 1 are taken from *Uranium Deposits of Kazakhstan* (1996); Guidebook to accompany IAEA map: World Distribution of Uranium Deposits (IAEA, 1996), "Situation of world uranium industry", Tarhanov, 2002

All sandstone-hosted uranium deposits in the uranium province are of interlayer oxidation genesis. The redox front trends towards S-N and extends over 400 km, and is located 150～200 km from the basin margin (Fig 1) Geologists of the former Soviet Union call it regional interlayer oxidation zone. Individual uranium deposits are emplaced just near the redox front, and the place where uranium mineralization at the redox front is broken, is regarded as the boundary between two adjacent uranium deposits. The Big Karatau uplift, which intersects the regional redox front, and is considered to be the post-ore uplifted structural element, divides Chu-Sarysu and Syr-Darya uranium sub-provinces.

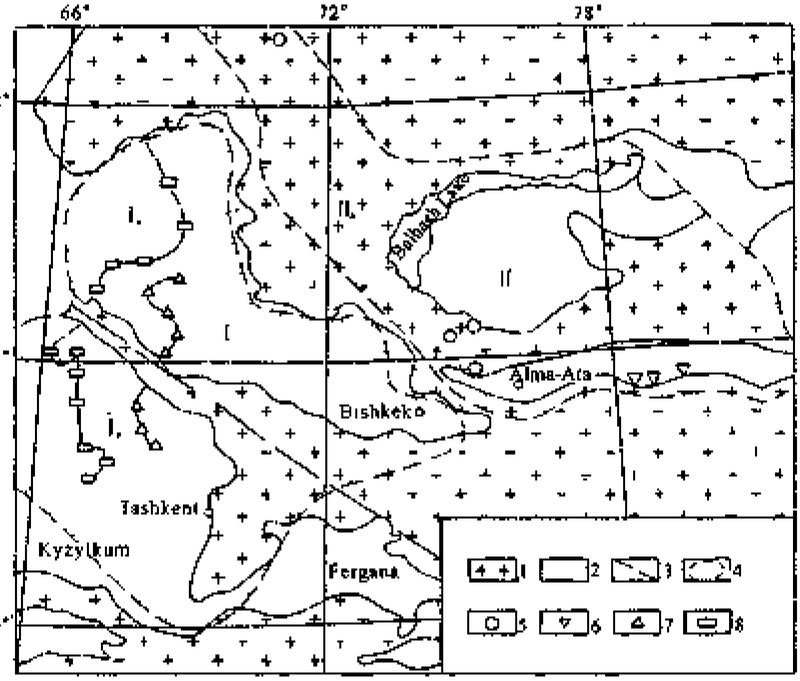

Fig 1 Map showing the distribution of uranium deposits in Chu-Sarysu—Syr-Darya basins and adjacent areas

1 Basement rocks; 2 Meso-Cenozoic basin; 3 Fault; 4 Boundary of uranium province; 5 Volcanics type uranium deposit; 6 Sandstone-hosted uranium deposit in Jurassic; 7 Sandstone-hosted uranium deposit in Upper Cretaceous; 8 Sandstone-hosted uranium deposit in Paleocene

Uranium province: I_a——Chu-Sarysu; I_b——Syr-Darya; II_a——Kundiktas-Chuyili; II_b——Yili

1.1.1 The formation-evolution model of Chu-Sarysu and Syr-Darya U-productive basin (Table 2)

Authors suggest that following points in the model must be emphasized:

(1) The Chu-Sarysu and Syr-Darya type U-productive basin was founded on the basement of a consolidated young platform (Caledonian folded belt). Between the cover and the basement there exists a "transitional layer" showing that the region enters a rather

Table 2 The formation-evolution model of Chu-Sarysu and Syr-Darya type U-productive basin

Tectonic attribute of strata	Tectono-stratigraphic pattern and its age		Tectono-geologic event and its description	Uranium ore-formation and associated events
Cover	Oligocene-Quaternary compressional tectonic regime	Late Pliocene-Quaternary intensely compressional sequence	Strong uplift of Tianshan Mountain led to the appearance of compressional basins (Fergana, Afganistan, Tadzhikistan) and extremely thick red molasse formation was accumulated Uplifting of Big Karatau separated the Chu-Sarysu and Syr-Darya basins Deposition of yellow gravel-sand-clay formation	Dynamics of groundwater was intensified, and the previously-formed U-mineralization was reworked, depleted or locally redistributed
		Oligocene-Pliocene weakly compressional sequence	The collision of Indian-Arabian plate and Eurasian plate at 50Ma resulted in the extrusion of the Pamirs-Tibet terrain to the east and its extension towards the north. The region was extensively uplifted without deposition. Upper Cretaceous-Paleogene gently tilted, and aquifers were outcropping. E_3^1~N_1^1 composed of red gravel-sand-clay sequence, and N_1^2~N_2^1 composed of mottled gypsum-bearing calcareous sand-clay sequence were deposited	The paleo-hydrodynamic system was established with the recharge area of northern Kazakhstan, and the discharge area of Aral sea. It is the main period of sandstone-hosted uranium ore-formation
	Cretaceous-Eocene weakly extensional tectonic regime	Cretaceous-Eocene heat-sinking sequence	Regional compression and uplifting at the end of Jurassic resulted in Cretaceous-Paleogene heat-sinking, and the deposition of continental mottled clay-sand-gravel formation (K_2 ore-hosting series) and marine gravel-sand-clay formation (E) In Cretaceous and Paleogene time, the region was located in semiarid and semiarid-semihumid subtropical zone respectively, and ore-hosting series were deposited in stream-lacustrine, delta and shallow marine environments	The main period for the formation of ore-hosting sequence. The total thickness of ore-hosting Cretaceous-Paleogene sequence is 300~600m
	Triassic-Jurassic compressional-extensional tectonic regime	Jurassic extension	Deposition of coal-bearing clastic formation in Early-Middle Jurassic and carbonate formation in Late Jurassic	
		Triassic compression	Without deposition	
Transitional layer	Late Paleozoic extension	Late Paleozoic	Sub-active sedimentary layer on folded basement	
Basement	Folded basement	Early Paleozoic	Pre-Cambrian terrains were welded into the Caledonian folded belt forming the Kazakhstan intercontinental plate	The formation of favourable regional geological background and geochemical field for uranium ore-formation
	Crystalline basement	Pre-Cambrian	Crystalline terrains composed of gneiss, schist with some uranium-enriched ones	

※ The tectono-geologic events in the table are described from the older to the younger (from the bottom to the top). The same for other tables.

stable tectonic environment. For this reason, the cover sediments overlying the transitional layer are characterized by large area of distribution, relatively complete and well differential depositional facies, creating large and better "ore-storing space" (ore-hosting series) for uranium ore-formation.

(2) The evolution of tectonic environments for the cover deposition shows a general tendency from the extensional to the compressional ones, i. e. it starts with the extensional environment, then it changes into weakly extensional (heat-sinking) one, and finally turns to the compressional (even strongly compressional) one. Of them, the heat-sinking stage corresponds to the depositional period of ore-hosting sequence, and weakly compressional environment is closely related to the formation of interlayer oxidation and associated sandstone-hosted uranium ore-formation

(3) Each tectonic evolution stage is accompanied by its "diagnostic" sedimentary formation. For example, in case of Chu-Sarysu and Syr-Darya U-productive basin, coal-bearing clastic formation or carbonate formation are developed in taphrogenic extensional stage; the weakly extensional stage is characterized by continental (or littoral) stream-lacustrine, delta facies sedimentary formations; and compressional stage is marked by molasse (or submolasse) formation

1 1. 2 Recognition criteria of Chu-Sarysu and Syr-Darya type U-productive basin

(1) These basins are located within the intercontinental Kazakhstan plate. Besides sandstone-hosted uranium deposits, a number of other uranium deposits occur in the plate. The pre-Cambrian rocks in the basement are U-enriched (uranium content is $3.2\times10^{6}\sim7.2\times10^{6}$) All above data indicate that the Kazakhstan plate is a U-rich geochemical province.

(2) The most important feature of the cover sediments is: the area of sedimentation is quite large, but the total thickness is relatively small. Taking the Chu-Sarysu and Syr-Darya basin as an example, the total area of the basin is 200 000~250 000 km^2, and the total thickness of Meso-Cenozoic cover is only 400~2 000 m. The ratio of area to thickness reaches 125. In order to have a concept, the Turpan-Hami basin is taken as another example The Turpan-Hami basin covers 52 800 km^2 with the total thickness of Meso-Cenozoic sediments being about 9 000 m The ratio of area to thickness is only 6! Authors suggest that the ratio value of area to thickness could be regarded as a reference value to assess the uranium potential in U-productive basin. Generally speaking, the larger the ratio, the more favorable the development of interlayer oxidation in cover sediments, and the more scale of uranium mineralization associated with the interlayer oxidation. Of course, there is no direct proportion between the above value and sandstone-hosted uranium resources.

(3) The sequence structure and lithofacies of the cover sediments are favorable. The typical sequence of cover sediment is: the lower transitional layer (the mottled continental clastic formation and gray carbonate formation), the middle ore-hosting rock series (grey

continental, littoral clastic formation), and the upper overlying sequence (mottled gypsum-bearing calcareous sand-clay formation and red molasse formation). Such a sequence order approximately indicates the tectonic evolution of the U-productive basin. The lower sequence corresponds to the pre-cover sub-platform regime. The middle sequence — the heat-sinking subsidence (weak extension), and the upper sequence reflects the tectonic reversion—from weakly extensional tectonic regime to compressional one, being its "sedimentary response", and indicating the sub-orogenic regime. This sequence shows also the change of paleoclimate—from semi humid-humid to arid climatic condition. So, the period of interlayer oxidation U-mineralization is characterized by "double reversion" — tectonic and climatic reversions.

The lithofacies of uranium-hosting series is quite unique. The redox front that extends over 100 km (from the northeastern end — Mynkuduk deposit to the southwestern end-Bujonov deposit, Fig. 2) with a width of 7～17 km is developed in a delta sand body

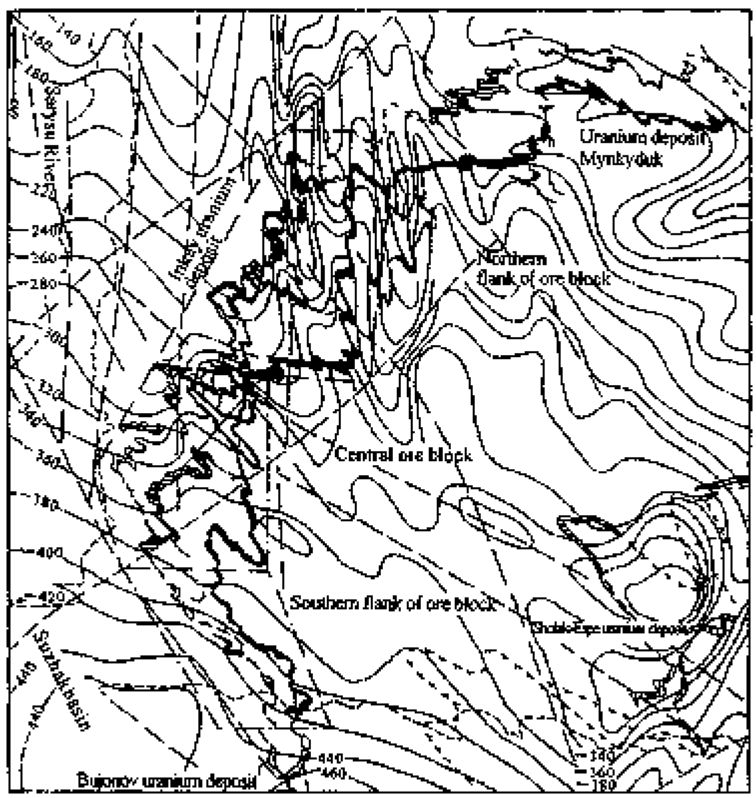

Fig. 2 Map showing the distribution of Mynkuduk — Bujonov uranium deposits

1. Isoheight of top surface of pre-Mesozoic formation; 2. Fault; 3～5. Boundary of ore-controlling interlayer oxidation zone and related uranium mineralization, 3. in Mynkuduk Formation (K_2t_1); 4. in Inkuduk Formation (K_2t_2-st_1); 5. in Zhalpak Formation (K_2st_1-E_1^1); 6. Boundary of exploration area

(or several sand bodies). At the time of the deposition of ore-hosting series, there existed a huge gently dipping slope zone between the western end of Tianshan and the Aral Sea. The slight variation of Aral sea level would result in transgression or regression of the Aral sea, and the lithofacies would change from stream-lacustrine to submarine delta lithofacies, and vice versa. It is the huge sand body that provides a huge ore-storing space for subsequently emerging U-mineralizations, and the formation of super-large sandstone-hosted uranium deposit becomes possible.

Based on the above characteristics, this type of U-productive basins is nominated by authors as U-productive basin on weakly activated areas of young platform. At present, in other regions of the world no similar U-productive basin has been found.

1.2 Central Kyzylkum type

The Central Kyzylkum uranium province, Uzbekistan together with the Chu-Sarysu and Syr-Darya uranium province construct the Mid-Asian Turonian uranium mega-province.

The U-productive basin model is based on a basin group developed on Central Kyzylkum uplift, Uzbekistan. The region covers a series of medium-small sized basins, such as Djamankum, Karakadzin, and Eastern Kyzylkum depressions being artesian basins of horst-graben origin(Fig. 3).

Tens of sandstone-hosted uranium deposits have been discovered in the province. Data of the most important deposits are listed in Table 3.

1.2.1 The formation-evolution model of Central Kyzylkum type U-productive basin

The model is illustrated in Table 4.

As it is seen from the Table 4, no obvious difference in the tectonic evolution of the two above U-productive basins, and the most important difference between the two basins is the scale of basin where the ore-hosting series occur. Basins in Central Kyzylkum located between local uplifts and of small-medium size with an area of hundreds to thousands of square kilometers in general. However, the Chu-Sarysu basin covers an area of 200 000 ~250 000 km^2. Subsequently, there appears series of difference in uranium metallogenesis: the size of interlayer oxidation zone in Central Kyzylkum is relatively small with the length and the width of several kilometers to tens of kilometers; the redox front is located near the basin margin (several kilometers to 20 km). The size of interlayer oxidation zone in Chu-Sarysu and Syr-Darya province is large reaching tens even one hundred kilometers in length and width, the redox front is far (150~200 km) from the basin margin. Therefore, reserves of individual deposit may be quite different, in Central Kyzylkum—several thousands to 30 thousand tonnes of uranium, but in Chu-Sarysu and Syr-Darya——up to 300 thousand tonnes of uranium (Table 1, 3).

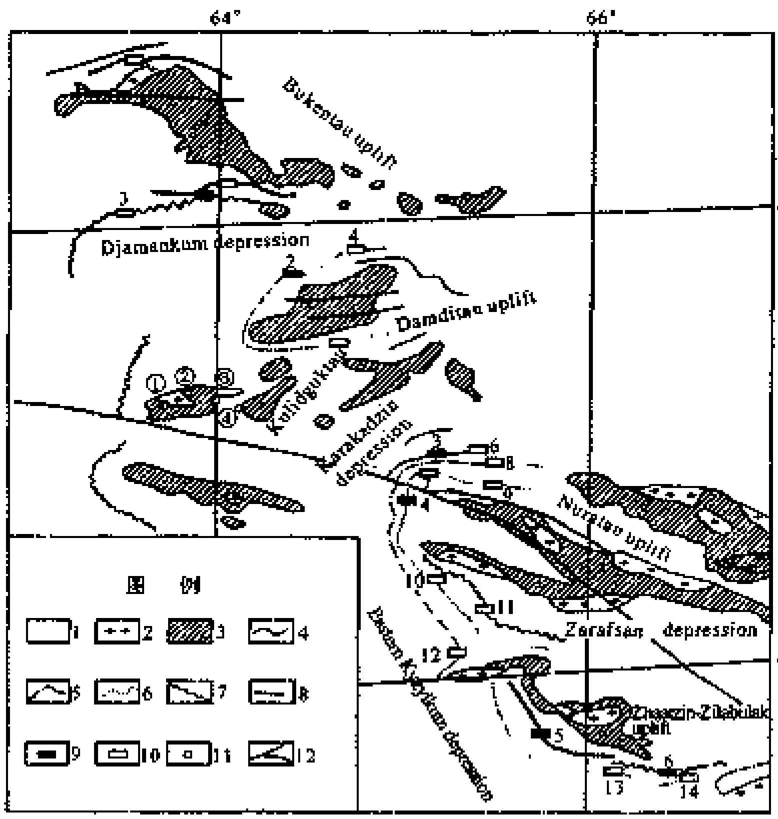

Fig. 3 Geologic sketch of Central Kyzylkum uranium province

1. Cover sediments; 2 Hercynian granitoid; 3 Paleozoic folded basement;
4~8 Redox fronts in different stratigraphic horizons, 4. in Eocene, 5. in Campanian-Maastrichtian;
6 in Coniacian-Satonian, 7 in Upper Turonian; 8. in Lower Turonian;
9 Represantative sandstone-hosted deposits: (1) Uchkuduk, (2) Sugraly, (3) Beshkak, (4) North Bukinai; (5) Kermenchi; (6) Sabyrsai; 10 Other sandstone-hosted uranium deposits: (1) Bakhaly; (2) Kendykijube; (3) Meylisai; (4) Aktau, (5) Amantau; (6) Liavliakan, (7) Alendy, (8) Terekuduk, (9) Varadzhan; (10) South Bukinai, (11) Kanimekh, (12) Maizak, (13) Agron; 11. Vein uranium deposits in basement black shales, (1) Djantuar, (2) Rudnoye, (3) Koscheka, (4) Voshod; 12. Fault

Main points of the formation-evolution model of Central Kyzylkum type U-productive basin are:

(1) The formation of sedimentary basins in Central Kyzylkum resulted from the regional compression during Triassic-Jurassic time leading to the emergence of the alternate pattern of uplifts and local depressions. These depressions are of compressional dynamic nature different from those of Chu-Sarysu and Syr-Darya which are originated from extension. It might be the important reason leading subsequently to the distinction of two kind basins in lithofacies, sand bodies of ore-hosting series, as well as in features of interlayer oxidization zone.

Table 3 Major sandstone-hosted uranium deposits and their ore grade and explored reverses in Central Kyzylkum uranium province

Uranium Deposit	Determined reserves, 10^3tU	Range of ore grade and average grade, %U
Uchkuduk	100.0	0.03~0.4
Kandykijube	22.0	0.01~0.09
Bakhaly	2.2	
Sugraly	43.0	0.03~0.3
Bukinai	19.6	0.02~0.08
Beshkak		0.02~0.20
Sabyrsai	20.6	0.05~0.32 (0.115)
North Kanimekh	16.0	0.02~0.8 (0.09)
Tohombet	7.0	0.03
Ketmenchi	16.0	0.07~0.3
Shark	4.0	0.015~0.432 (0.08)
Total	240.4	

(2) The basement of basins in Central Kyzylkum is composed of Paleozoic folded belt, somewhat different from that in Chu-Sarysu and Syr-Darya basins where the basement consists of pre-Cambrian crystalline rocks. So, the basement in Central Kyzylkum shows relatively plastic character. It must be the main reason that in the Central Kyzylkum region there emerged alternate pattern of uplifts and depressions under the Triassic-Jurassic compressional stress, and that there exists obvious distinction in the distribution area of cover, in the size of interlayer oxidation and uranium mineralization, though two uranium provinces are located nearby.

(3) The subsequent evolution of Central Kyzylkum type U-productive basins is similar to that of Chu-Sarysu and Syr-Darya type i. e. the continental and littoral ore-hosting series was formed under heat-sinking regime, the pre-existing series tilted by regional weak compression, and during the latest geologic time (10 Ma ago to the present) uranium ore-formation is accompanied by red molasse formation as the sedimentary response of the latest tectonic compression.

Basins in Wyoming, USA are similar to those in Central Kyzylkum region. More than 250 000 tU has been determined. As the calculation of reserves in USA is performed without strict limitation of cut-off grade, real reserves of uranium in Wyoming basins might be much greater than the above data. Taking the Gas Hills uranium district (west to Shirley basin, in an area of 50 km×50 km) as an example, the average grade of ores and uranium reserves in the dependence upon the cut-off grade are listed in Table 5.

Table 4 The formation-evolution model of Central Kyzylkum type U-productive basin

Tectonic attribute of strata	Tectono-stratigraphic pattern and its age		Tectono-geologic event and its description	Uranium ore-formation and associated events
Cover	Oligocene-Quaternary compressional tectonic regime	N_2-Q intensely compressional sequence	Intense uplifting of Tianshan Mountain and intramontane basins withered away in the latest 1 Ma Range of basins shrinked and N_2-Q red coarse clastics were deposited	Interlayer oxidation occurred along titled primary (secondary) gray permeable beds and U-mineralization appeared
		E_3-N_1 weakly compressional sequence	Tianshan and Pamirs began to rise, and red mottled fine-clastics, mudstone were deposited Mountain areas extended, deposition areas gradually withered. Pre-Oligocene sediments tilted and were faulted	
	Cretaceous-Eocene weakly extensional tectonic regime	Late Paleocene-Eocene heat-sinking extensional sequence	Transgression led to extension of basin areas, and basins in Central Kyzylkum were connected with each other and with those of Syr-Darya Fine-grained sediments of marine facies were predominant	The marine facies ore-hosting series was formed
		Cretaceous heat-sinking sequence	Re-subsidence occurred in Coniacian and proluvial-allvial sediments appeared in Coniacian-Satonian stage Regression occurred in Campanian and littoral sediments were deposited Intense subsidence occurred in Senomanian forming proluvial sediments Overall subsidence in Early Turonian led to accumulation of littoral delta sediments, and regression in Late Turonian resulted in proluvial- alluvial sediments again	The continental and littoral (delta and submarine delta) ore-hosting series was formed
	Triassic-Jurassic compressional tectonic regime	Triassic-Jurassic compressional sequence	Regional uplifting resulted in the structural pattern of alternate arrangement of anticline-uplifting and depression	The characteristic structural pattern of medium-small intramontane basins was formed
Basement	Folded basement	Late Paleozoic	Deposition of carbonate formation, intense folding accompanied by intrusion of granitoid magma	Favorable regional background and geochemical field for uranium ore-formation were formed
		Early Paleozoic	Clastic series is dominant, of them Ordovician-Silurian are U-rich black shales	
	Crystalline basement	Pre-Cambrian	The Central Kyzylkum block composed of schist and gneiss (some of them are U-enriched) was formed	

Table 5 Dependence of average grade and uranium reserves upon cut-off grade in Gas Hills

Cut-off grade, %U	Average grade in ores, %U	Total reserves lbU_3O_8, 10^3tU
0.01	0.06	1 000 000 000 (384 500)
0.03	0.10	600 000 000 (234 700)
0.05	0.16	400 000 000 (153 800)
0.10	0.21	200 000 000 (76 900)

After David R Miller, 2003

At present, the grade of uranium ores that are being mined in USA ranges from 0.10% to 0.20%. If the cut-off grade of 0.01%U were adopted, the reserves of uranium in Wyoming and in USA would be, at least, doubled.

Most basins in Wyoming are medium to small in size. The Shirley basin in USA famous for its abundant uranium resources has the area of only 350 km^2. The largest basin in Wyoming—Powder River basin has the area of 31 200 km^2 (Fig. 4). The distribution of basins is generally similar to that in Central Kyzylkum—alternate arrangement of uplifts and basins (depressions). So, the concept that deposits with large uranium reserves can be found only in large basins must be changed.

However, basins in Central Kyzylkum, Uzbekistan and Wyoming, USA are somewhat different in some aspects: (1) the basement of Wyoming's basins is composed of pre-Cambrian metamorphic rocks being a part of North America plate. The alternate distribution pattern of uplifts resulted from the block faulting rather than differential subsidence; (2) Wyoming's basins have been being under compressional tectonic regime since Triassic by the collision of Cordillera Mountains, having the nature of foreland basin; (3) main Wyoming's ore-hosting series was deposited in compressional tectonic environment rather than in extensional one as in Central Kyzylkum. However, uranium ore-formation occurred in regionally weakly compressional stage (Late Miocene), similar to that of most U-productive provinces.

The Yili and Turpan-Hami basins in China can be attributed to this type of U-productive basin. Authors nominate such type of U-productive basin as intramontane U-productive basin at the margin or the periphery of young (old) platform.

1.2.2 Recognition criteria of Central Kyzylkum type U-productive basin

(1) Medium-small sized intramontane basin located in the region of alternate distribution of uplifts and depressions with the basement of Hercynian Fold belt at the margin of intercontinental plate.

(2) Ore-hosting series is attributed to $K_2 \sim E$ heat-sinking sequence.

(3) During the weakly compressional tectonic regime after Oligocene, the pre-Oligocene sequence tilted, and the primary and secondary oxidized red and mottled rocks were secondary reduced by oil-gas products and changed into potential ore-hosting series. This

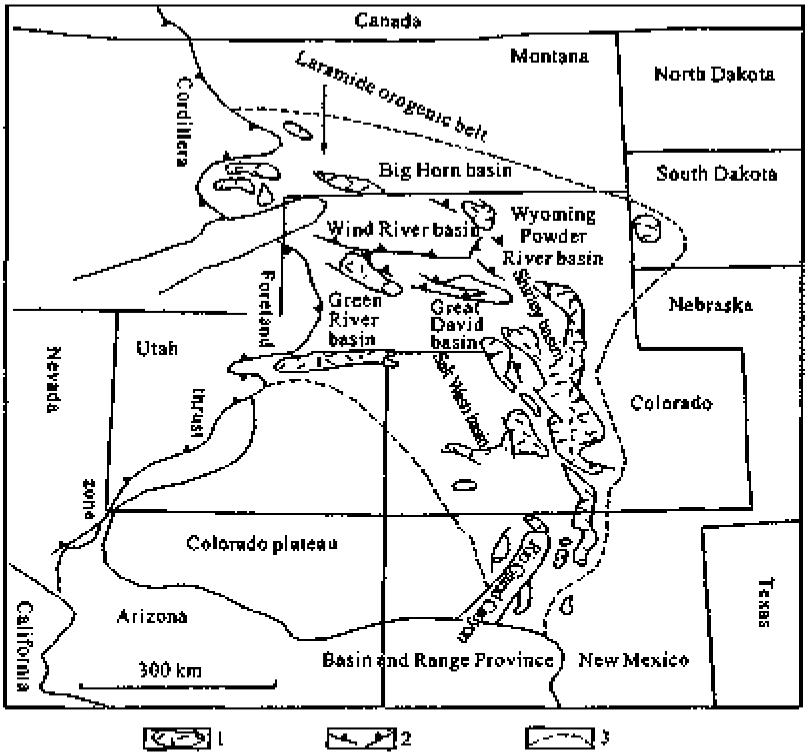

Fig. 4 Map showing the location of Wyoming-Colorado uranium province and Laramide oregenic belt, Western USA

1. Outcrop of pre-Cambrian basement; 2. Thrust zone; 3. Boundary of Wyoming uranium province.

is one of the important "diagnostic" features of this type U-productive basin.

(4) The geotectonic movement starting since Oligocene is the main factor leading to the uranium ore-formation in the region. According to data of Central Kyzylkum uranium province, all ages of uranium ores in sandstone-hosted uranium deposits are quite young, less than 10 Ma (oral communication of Korsakov Y. F. 2003). The latest intense tectonic movement (1 Ma to the present) results in the disappearance of Meso-Cenozoic basins and the reworking and reprecipitation of pre-existing uranium mineralization.

The formation-evolution model of Central Kyzylkum type U-productive basins may be of more important significance in guiding uranium prospecting and exploration in China. Moreover, it may give more confidence to find large sandstone-hosted uranium deposits in similar medium-small sized intramontane basins in northern China.

1.3 Zaural-West Siberia type

The Zaural and West Siberia uranium provinces are located at the southwestern and southeastern parts of West Siberian basin respectively (Fig. 5). They are two important uranium ore-field of paleovalley type discovered recently.

Three uranium deposits have been found in Zaural uranium ore-field with total reserves of 38 000 tU, and total potential resources of 100 000 tU. Six uranium deposits

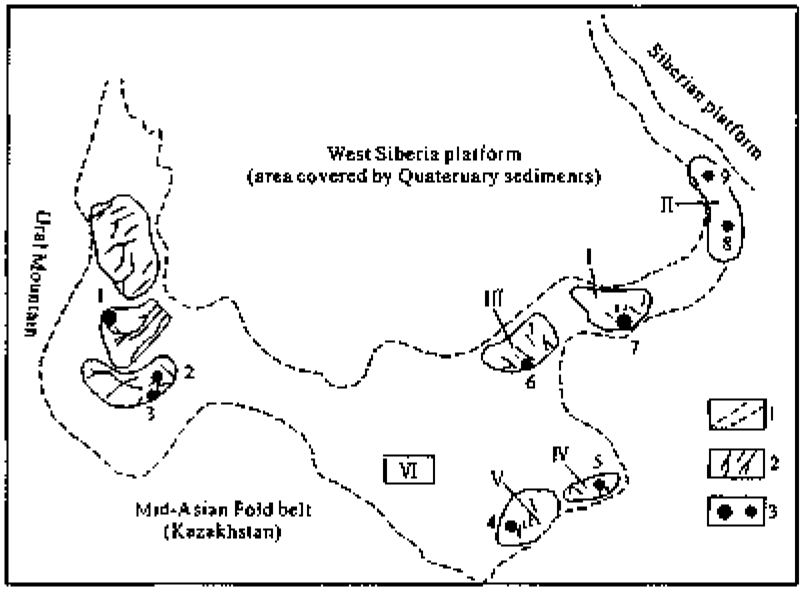

Fig. 5 Sketch showing the distribution of paleovalley type sandstone-hosted uranium deposits in Zaural and West Siberia

1. Boundary of area where paleovalleys occur; 2 Recent river stream;
3. Uranium deposit: Uranium deposit in Zaural ore areas: (1) Dalmatov; (2) Dobrovol; (3) Hohlov.
Uranium ore areas: in West Siberia, Ⅰ——Malinov; Ⅱ——Kazadjin; Ⅲ——Novosiberia;
Ⅳ——Smolensk; Ⅴ——Mihailov; Ⅵ——Kulundjin.
Uranium deposits in West Siberia: 4 Mihailov; 5. Smolensk; 6. Prigorod; 7. Malinov; 8 Bestri; 9. Kostiliov

have been explored with total reserves of 4 000 tU and potential resources of 500 000 tU in total (Table 6).

Table 6 Uranium reserves and resources in West-Siberian and Zaural uranium ore-fields

Uranium province	Potential metallogenetic area	Deposit	Determined reserves, 10^3tU	Potential resources, 10^3tU
West Siberian	Kulundjin			150.0
	Mihailov	Mihailov	0.60	4.0
	Smolensk	Smolensk	2.5~3.0	5.4
	Novosiberia	Prigorod	2.5~3.0	21.0
	Malin	Malinov	20.0	190.0
	Kazachin	Bestri	1.6	
		Kostiliov		120.0
	Total		27.2~28.2	490.4
Zaural		Dalmatov	13.0	49.0~50.0
		Dobrovol	13.1	
		Hohlov	12.0	45.0
	Total		38.1	94.0~95.0

1.3.1 The formation-evolution model of Zaural and West Siberian type U-productive basin-

The model is illustrated in Table 7.

(1) The region where the basin is located represents a large-young platform composed of numerous mid-massifs welded by fold belt of different periods (Salairian, Caledonian, and Hercynian).

(2) The sedimentary cover was accumulated during weakly extensional regime being a heat-sinking (or the eutectic fluctuation of the Arctic Ocean) resulting in multiple transgression and regression forming the interbedding of continental and littoral sandstone-mudstone sediments.

(3) Weak regional uplifting (or the lowering of the sea level) resulting in the incision of stream channel at the margin of the West Siberia platform, and the subsequent weak regional subsidence (or the rising of the sea level) led to the accumulation of coarse clastics in incised stream channel. Then the phreatic oxidation caused the uranium ore-formation in above sediments of paleochannels.

(4) In the southwestern and southern parts of the West Siberia plate (including the Semizbai uranium district), the main uplifting occurred in Late Jurassic to Early Cretaceous ($J_3 \sim K_1$ Badjenov period), and in the eastern part it appeared in Oligocene to Miocene ($E_3 \sim N_1$ Znamen period). Though the age of main ore-hosting series is different in the western and eastern parts of the platform, the uranium ore-formation is similar in features, i. e. it occurred both in sediments of paleochannels incised basement rocks, and the phreatic oxidation was the dominant ore-forming process.

(5) The ore-hosting series is usually overlain by impermeable layers. It is not the necessary ore-forming condition, but an important ore-preserving factor protecting the earlier-formed U-mineralization from erosion. This kind of U-productive basin is nominated by authors as U-productive basin of subsidiary valley net at the periphery of large young platform.

1.3.2 Recognition criteria of Zaural and West Siberian type U-productive basin

(1) It is the large oil- and gas-containing basin with the basement composed of numerous old blocks welded by Paleozoic magmatic massifs thought to be possible uranium source for uranium ore-formation in paleochannels.

(2) The marginal area of the basin represents a large gently-dipping slope towards the central depression of the basin.

(3) In the basement where paleovalley-type uranium deposit occurs, a lot of U-rich rocks, such as U-rich volcanics, granitoids and black shales exist. Locally, thick weathering crust in basement rocks is developed.

(4) At the base of stratigraphic section of the cover, there exist stream channels that incised the basement. Sediments filling the channel usually are coarse-grained, cemented by clay materials, and contain abundant organic remains.

Table 7 The formation-evolution model of Zaural and West Siberia type U-productive basin

Tectonic type of basin	Tectonic attribute of strata	Tectono-stratigraphic pattern and its age			Tectonic-geologic event and its description	Uranium ore-formation and associated events
Young craton subsidence basin	Cover	Weakly extensional-weakly compressional tectonic regime	Weakly extensional (heat-sinking) sequence	Oligocene to Quaternary	$N_1 \sim Q$ continental stream-lacustrine alluvial sediments were deposited with intercalations of glacial sediments E_3 continental sand-stone-mudstone sediments were deposited with intercalations of coal seams	Uranium ore-formation in paleochannels occurred Minor ore-hosting series was formed
				Cretaceous to Eocene	Regression-transgression in Maastrichtian (K_2 m) to Middle Eocene (E_2) Regression-transgression in Hauterivian (K_1 h) to Campanian (K_1 cm)	
				Late Jurassic	Compression was relaxed and J_3 organic-rich coarse clastics were deposited in stream channels Weak compression-uplifting in early stage of J_3 led to the incision of stream channel into basement	The main ore-hosting series was formed, subsequently the phreatic oxidation followed by uranium ore-formation occurred Uranium-rich rhyolite appeared
				Triassic	Compression-uplifting in $T_3 \sim J_2$ resulted in the break of sedimentation Volcanic eruption in T_1 and T_2 resulted in accumulation of sedimentary-volcanic clastic series	
		Intensely compressional tectonic regime		Late Permian	Basement blocks were welded by Hercynian magma into relatively united block Hercynian folding and reversion occurred	Uranium-rich granitoid appeared
	Basement	Folded basement	Late Proterozoic to Middle Permian		Geosyncline-type formation of Late Paleozoic was accumulated Salair orogeny occurred Clastic-carbonate formation was deposited	
		Crystalline basement	Archean to Middle Proterozoic		Folding and metamorphism of Baikal orogeny (600 Ma) occurred Folding and metamorphism of Karelian orogeny (800 Ma) occurred Deposition of flysch formation and eruption of basic magma	

(5) The ore-hosting paleochannel sediments are usually overlain by a sedimentary hiatus, followed by an impermeable layer.

As the metallogenic conditions for paleochannel type uranium mineralizations are different from those of interlayer oxidation type, authors would like to once again emphasize following points:

(1) Most paleochannel type sandstone-hosted uranium deposits are sourced by adjacent U-rich rocks. So, the uranium content, especially its mobile (easily leachable) constituent in basement and provenance rocks becomes an important criterion for the assessment of U-productive basin.

(2) Paleochannel type uranium mineralization is mostly of phreatic oxidation origin (may be subsequently superimposed by interlayer oxidation mineralization). The process of ore-formation basically begins in the period of sedimentation breaking that follows the accumulation of ore-hosting series, and principally ends when the overlying impermeable layer is settled. The ore-forming process lasts more shortly as compared to that for interlayer oxidation sandstone-hosted uranium deposit.

(3) The ore-hosting sandstones are high-energy coarse-grained channel-filling clastics with high content of coalfield organic carbon (usually 0.5%~1.5%) of plant series. Because the time that paleochannel type sandstone-hosted uranium ore-formation process lasts is quite short, and the amount of uranium- and oxygen-bearing water that infiltrates through host rocks is limited, so, it is necessary for host rocks to possess high-effective uranium-unloading mechanism that could unload most uranium in groundwater in a relatively short time to form uranium deposit.

(4) The tectonic environments under which the ore-hosting series of paleochannel sandstone-hosted uranium deposit exists, and the ore-formation process occurs, differ from those for interlayer oxidation sandstone-hosted uranium deposits. The ore-hosting series of the former one is deposited in an environment with alternate weakly extensional-weakly compressional regime, and the ore-formation process occurs in the same environment. As mentioned above, the ore-hosting series of the latter one is definitely formed in the weakly extensional (heat-sinking) environment, and the ore-formation occurs in the period of "double change"—the tectonic regime changes from the weakly extensional to weakly compressional one, and the paleoclimate conditions change from semihumid to semiarid ones. Besides, the climate change for some paleochannel sandstone-hosted uranium deposits is not necessary for uranium ore-formation.

The above differences between two major types (paleochannel and interlayer oxidation) sandstone-hosted uranium deposits must be the most important, and should be kept in mind when an assessment of uranium potential of a basin is made.

Such U-productive basins have not been found in other regions of the world.

1.4 Zabaikal type

The Zabaikal uranium province is located in the Far East region, Russia. Geotectonically, it is attributed to the reactivated periphery of Siberia platform, and then it experienced Baikal orogeny, and was consolidated into a young continental block.

Uranium deposits in the province are concentrated in Khiagda uranium ore-field (Fig. 6). Fifteen uranium deposits have been revealed with the total uranium reserves of 42 400 tU, and total uranium resources of 56 600 tU (Table 8) Besides, in the region there is another uranium deposit Yima with determined reserves of 2 000 tU and potential resources of 30 000 tU.

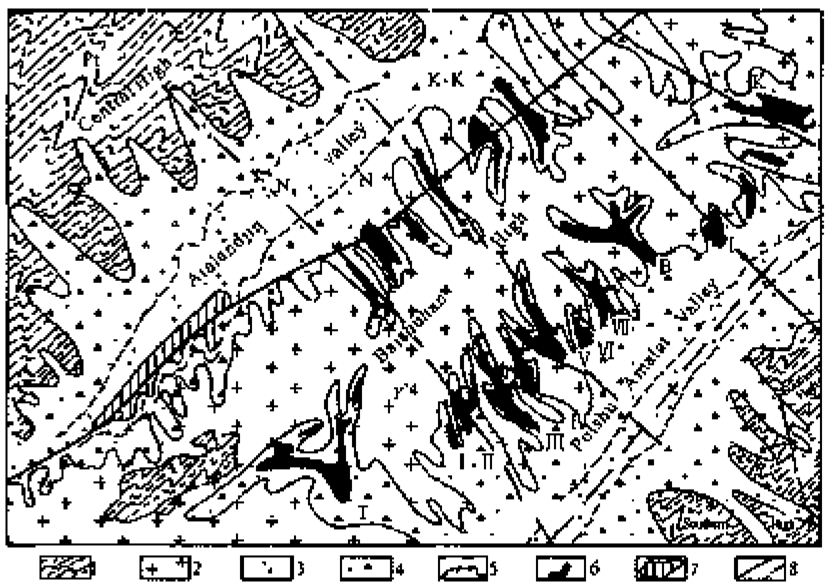

Fig 6 Geologic scheme of Khiagda uranium ore-field (N_1^3 ~ Q basalt is uncovered)
(Modified after Zhong Jiarong, 1995)

1 Proterozoic crystalline schist; 2 Hercynian granite; 3 Miocene alluvial sediments; 4 Miocene paleovalley sediments; 5 Boundary of paleovalley; 6 U-REE deposit; 7 Gold-containing U-REE deposit; 8 Fault (a—Determined; b—Speculative)

T, B, I, N, K~K, K-Symbol of Uranium deposit; Ⅰ-Ⅳ-Ore-hosting paleovalley and its number

The Khiagda uranium ore-field was discovered in 1970's. All uranium deposits in the field are paleochannel sandstone-hosted ones. Uranium ore-field represents a granite dome high sandwiched in between two NE-trending big valleys — the Atalanjin valley and the Polshu-Amalat valley. The subsidiary valleys originated from the high towards the main valley are main ore-hosting sites for uranium mineralization. Uranium ore bodies are strictly constrained by paleochannel possessing a banded form on plane. Mineralized host rocks (N_1^2) are channel-filling loose coarse sandstones that incised the basement granite. Lithologically, these are feldspar sandstone, sandy conglomerate rich in coalified organic remains (average content of organic carbon is 0.8%). Pliocene-Quaternary basalts often overlie ore-hosting series with a thickness of tens of meters to 150 m

Table 8 Determined reserves and potential resources of main uranium deposits in Khiagda uranium ore-field

Deposit	Symbol	Reserves, 10^3tU	Resources, 10^3tU
Khiagda	I—Ⅶ	13.5	14.0
Vershina	B	5.2	5.5
Tetlah	T	6.0	6.5
Kolechkon	K	6.2	7.0
Istochnik	I	0.9	2.0
Namalu	N	3.3	6.0
Koletkonjin	K—K	3.1	5.0
Djelinjin	D	1.0	2.0
Total		42.4	56.6

1.4.1 The formation-evolution model of Zabaikal type U-productive basin

The Zabaikal (Khiagda) model is illustrated in Table 9.

U-productive basin of this type is characterized by following specifics.

(1) The ore-hosting series are the sedimentary bodies filling individual stream channels of the erosional stream net. In fact, the region does not represent a basin in the traditional sense.

(2) The principal phase of uranium ore-formation occurs as soon as host rocks are settled, similar to that for most paleochannel sandstone-hosted uranium deposits. However, the extensive and intense eruption of basaltic magma in Pliocene-Quaternary time resulted in endogenic hydrothermal uranium mineralization and associated alteration. It made the genesis of uranium mineralization in sandstones more complicated, as well as the uranium prospecting in the region more difficult.

(3) The most obvious specific of the Khiagde uranium ore-field different from that for interlayer oxidation sandstone-hosted uranium deposits is: the region of Zabaikal (Khiagda) U-productive basin has been being in an environment of tectonic compression-uplifting. The region represented a granitic dome in Paleozoic period. Intermediate-acidic magma was erupted and intruded in Cretaceous time. The dome was continuously uplifted and became a high in Tertiary. At the time of basaltic magma eruption in Pliocene-Quaternary, the region still kept plateau geography. Such a geologic-tectonic setting is the unique specific for the U-productive "basin" of this type.

(4) The paleoclimate condition at the time of uranium ore-formation remained unchanged, i.e. the humid-cold climate always has dominanted in the region since the ore-hosting sediments are accumulated. The ore-formation does not need paleoclimate to change to semiarid regime.

Table 9 The formation-evolution model of Zabaikal (Khiagda) type U-productive basin

Tectonic attribute of strata	Tectono-stratigraphic pattern and its age			Tectonic environment where the basin is located and tectono-geologic events	Uranium ore-formation and associated events
Reactivated cover	Intensely extensional tectonic regime	Intensely extensional sequence	Pliocene to Quaternary	Extensive eruption of basaltic magma	Hydrothermal and phreatic oxidation uranium ore-formation
	Compressional to weakly compressional tectonic regime	Compressional to weakly compressional sequence	Late Miocene	Compressional stress was released, coarse clastics were accumulated in incised stream channels	Main ore-hosting series was formed
			Cretaceous to Early Miocene	Compession-uplifting resulted in the development of stream net and incision of stream channels into basement Intermediate-acidic magma was erupted and intruded forming high-radioactive granites	Second stage U-rich granite appeared
Folded basement	Intensely compressional tectonic regime		Paleozoic	Late Paleozoic tectono-magmatic reactivation led to the appearance of high-radioactive granites Early Paleozoic tectono-magmatic reactivation	First stage U-rich granite appeared
			Early Cambrian	Clastics of continental margin were deposited, intermediate-acidic magma eruption occurred The cratonic marginal depression was formed	
Crystalline basement			Late Proterozoic	The folding, metamorphism, reversion of pre-Late Proterozoic occurred, and the region was consolidated into Baikal fold system Flysch formation was accumulated	
			Archean to Middle Proterozoic	Archean-Middle Proterozoic high-metamorphic rock series were formed The marginal periphery of Siberian continental block	

The Longchuanjing uranium ore-field in the southwest of China may be attributed to this type of U-productive basin.

Based on the above characteristics, such U-productive basin is nominated as stream valley net U-productive "basin" at the uplifted periphery of platform, mid-massif or mobile belt.

1.4.2 Recognition criteria of Zabaikal type U-productive basin

(1) Reactivated marginal fold zone of craton (Zabaikal type) or young mobile belt with uranium-rich granites (Longchuanjiang type).

(2) The basement of the basin consists of a rock block casted by multiple tectono-magmatic reactivation, or magmatic reactivation, or the eruption and intrusion of intermediate-acidic magmatic rocks.

(3) Uplifted Meso-Cenozoic block with primary stream valley net that incised the U-rich basement, or down-faulted intramontane basin constrained by fault structures.

(4) Sediments filling the stream valley are loose, coarse-grained and rich in coalified organic remnants.

(5) Area with extensive Cenozoic basaltic magma eruption.

1.5 Bohemia type

The Bohemia block at the boundary of Germany and Czech Republic is an important uranium province with determined reserves more than 500 000 tU. Besides vein uranium deposits in metamorphic rock domain (represented by the Pribram deposit in Czech), and polygenetic uranium deposits in black shales (represented by the Ronneburg deposit in Germany), there exist a series of sandston-hosted uranium deposits. Of them, the most famous ones are the Koenigstein in Germany, and the Hamr in Czech. The total sandstone-hosted uranium resources in Bohemia block must be over 100 000 tU (Table 10).

Table 10 Main Meso-Cenozoic sandstone-hosted uranium deposits and uranium resources in Bohemia block

Country	Uranium deposit	Age of host rocks	Grade, %U	Resources, 10^3 tU
Germany	Koenigstein	K_1	0.06	30
Czech Republic	Hamr	K_2	0.03~0.1	20~50
	Osecna-Kotel	K	0.03~0.1	20~50
	Stras	K	0.03~0.1	20~50
	Brevniste	K	0.03~0.1	5.0~2.0
	Hvezdov	K	0.03~0.1	5.0~2.0
	Mimon	K	0.03~0.1	5.0~2.0

After《Guidebook to accompany IAEA Map: World distribution of uranium deposits》IAEA, 1996

Sandstone-hosted uranium deposits occurring in Bohemia mid-massif are somewhat different from ordinary ones.

First, sedimentary basins where sandstone-hosted uranium deposits occur are typical down-faulted ones with the length much more longer than the width, and are constrained by boundary (usually, normal) faults For example, the Koenigstein deposit occurs in local Pirna depression in the Elbtal continental down-faulted tectonic belt, and the Straz and Hamr uranium deposits are located in North-Bohemia down-faulted basin.

Second, though uranium mineralizations occur in sedimentary rocks, evidence of hydrothermal activity can always be found in mineralized sandstones. Fissure is extensively developed in ore-hosting sandstones, and uranium mineralization occurs often in structural fissures, and is associated with sulfide minerals and barite etc. Hydrothermal alteration (silicification, argillitizalion etc) usually exists in wall rocks. Sometimes, other metallic mineralizations (Cu, Ba, Pb, Zn, seldom Co and Ag) exist around the uranium mineralization.

Moreover, uranium ore body is usually of plate form, located not far (several meters to tens of meters) from basement granite (Fig 7). The basement granite is U-enriched, and its mobile constituent is relatively high (up to 32%) Basaltic magma eruption emerged and basalts overlie the cover sediments. Lithologically, basic lava represents biotite-rich olivine basalt, obviously showing its mantle origin.

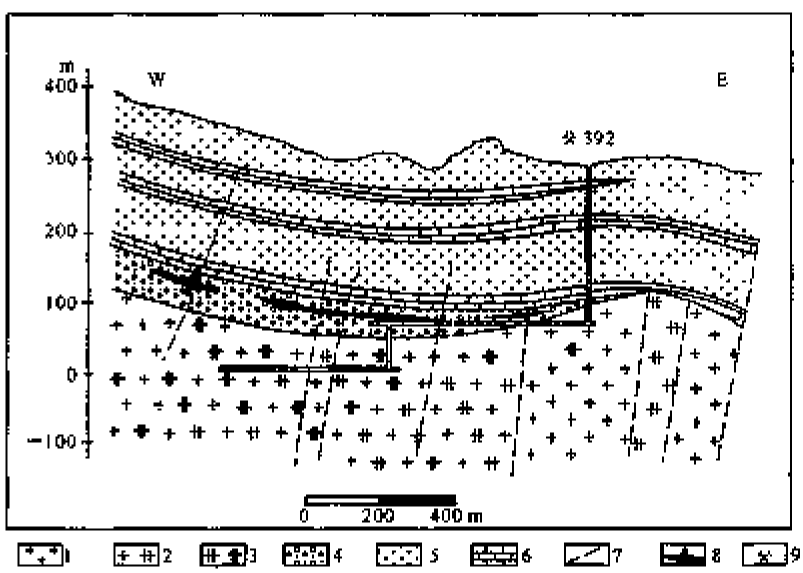

Fig 7 Schematic lateral section of Koenigstein uranium deposit

1 Maksbah granite; 2 Lauses granodiorite; 3 Porphyry; 4 Senomanian, sandstone and mudstone; 5 Turonian, sandstone; 6 Calcareous, sandstone and clay; 7 Fault; 8 Uranium ore body; 9 Uranium mine

Taking the example of Koenigstein, uranium mineralization occurs mainly in three lower well-permeable horizons from Senomanian (K_2cm) to Turonian (K_2t), Upper Cretaceous. Uranium ore bodies are of plate and lense-like forms in accordance with the attitude of ore-hosting series. Three ages of uranium mineralization have been obtained The lense-like, stratiform uranium mineralization is the earliest with the age of 74 Ma. The uranium mineralization with complicated lense-like form in fissures is the second having the age of 49 5 Ma The fissure-form uranium mineralization is the latest with the age of 24 Ma. Obviously, uranium mineralizations in Bohemia type U-productive basin are of polygenetic origin. The early stratiform mineralization might be of syn-sedimentary-diagenic origin superimposed by subsequent interlayer oxidation/phreatic oxidation uranium ore-formation process. The mineralization in fissures is apparently of hydrothermal genesis. Moreover, hydrothermal mineralization is generally predominant in such U-productive basins

1.5.1 The formation-evolution model of Bohemia type U-productive basin

As mentioned above, the role of endogenic uranium ore-formation is more important than that of exogenic one in such U-productive "basin" So, the significance of formation-evolution of sedimentary basin in the process of uranium metallogenesis is not as important as the magmatic-tectonic reactivation of the region However, for the uniformity of the description, authors still illustrate the formation-evolution model of Bohemia type U-productive basin (Table 11).

The uranium mineralizations in Bohemia type U-productive basin are characterized by polygenetic origin Initially, syn-sedimentary-diagenetic and phreatic oxidation uranium ore-formation might occur in Upper Cretaceous (Senomanian and Turonian). At the time of sedimentation hiatus (between Late Cretaceous and Early Tertiary) interlayer oxidation might exist leading to uranium ore-formation. Finally, the eruption of basaltic magma and associated hydrothermal processes might hide, even completely destroy, or rework pre-existing exogenic uranium mineralization to form polygenetic reprecipitated one At the same time, the reprecipitated and late hydrothermal mineralizations may occur both in cover sediments and in basement and overlying basalt (reactivated cover).

According to above characteristics, authors suggest to nominate such U-productive basins as down-faulted basins on mid-massifs with polygenetic sandstone-hosted uranium deposits.

1.5.2 Recognition criteria of Bohemia type U-productive basin

(1) The existence of mid-massif with favourable uranium source, i. e. the uranium content in the geologic body (for example, granite) is high, and the mobile constituent of uranium is high as well.

(2) Long-term peneplaination occurred before the accumulation of the cover. So, a thick weathering crust was formed making the uranium in it mobile (easily extractable) for the transformation of uranium in basement (weathering crust) into basin area.

Table 11 The formation-evolution model of Bohemia type U-productive basin

Tectonic attribute of strata	Tectono-stratigraphic pattern and its age			Tectono-geologic event and its description	Uranium ore-formation and associated events
Cover	Weakly compressional tectonic regime		Quaternay	Stream and glacial sediments were deposited	
	Intensely extensional tectonic regime		Paleogene	Eruption of olivine basalt occurred	Hydrothermal uranium ore-formation and alteration Tectonic fissuring
	Extensional-weakly extensional tedtonic regime	Heat-sinking sequence	Turonian and Senomanian, Late Cretaceous	Sand, sandy clay and chert were deposited and lithological interbedding of permeable and inermeable layers was formed Regional subsidence, transgression led to the deposition of fine-grained sandstone, clay and marl	Interlayer oxidation uranium ore-formation Syn-sedimentary dia- genesis and phreatic oxidation uranium ore-formation Main ore-hosting series were formed
			Late stage of Early Cretaceous	The taphrogenic depression withered and alluvial fan stream-lacustrine sediments and littoral clastic formations were deposited Tectonic stability led to the formation of thick (up to 50 m) weathering crust Regional taphrogenesis resulted in the appearance of Elbtal continental down-faulted zone	
Basement	Intensely compressional tectonic regime			Multiple tectonic-magmatic reactivation resulted in the formation of numerous intermediate-acidic and alkaline intrusive massifs The folding and reversion of Pre-Mesozoic series occurred	Uranium-rich intrusive rocks appeared

(3) Weak extension-taphrogenesis occurred on the basement and down-faulted basin appeared.

(4) The lithological combination of impermeable-permeable-impermeable layers (mudstone-sandstone-mudstone) is formed with high content of coalified organic matters existing in cover sedimentary section.

(5) The tectonic fissuring derived by weak tectonic movement occurred at the contact between the cover and basement which provided important emplacement site for subsequent uranium mineralizations.

(6) Intense magmatic activity and volcanic hydrothermal ore-formation process occurred after the deposition of sedimentary cover. The features of magmatic activity indicate that the uranium ore-field experienced intense extension-taphrogenesis associated with extensive hydrothermal alteration and metallogenesis.

1.6 South Texas type

The South Texas uranium province is located in marginal sedimentary basin of North America. Uranium deposits are distributed in the south of Texas coastal plain with an area of 160 000 km^2. The sandstone-hosted uranium mineralization was first discovered in 1954 by radioactive logging of prospecting drill hole for petroleum. In 1971, uranium reserves with grade over 0 16%U were determined as 8 140 tU. By the end of 1981 there still remained 34 500 tU with the cut-off grade of 0.06% in the region.

During 1970's to 1980's, these sandstone-hosted uranium deposits were intensely studied, and the research results indicated that sandstone-hosted uranium deposits in the region differ from those in Wyoming and Colorado uranium provinces. The heavy fraction of ore-hosting series in South Texas consists of Fe-Ti oxides, a series of titano-magnetite These minerals are stable in oxidation environments at ground surface or in groundwater and keep unoxidized making the host sandstone still grey (primary colour). However, in uranium ore-district, because of the introduction of H_2S gas into ore-hosting horizon, the titano-magnetite was first altered and changed into iron sulfides. Then, when the iron sulfide encounters the oxygen-bearing groundwater, it is easily oxidized. Later, the process progresses just like that in case of interlayer oxidation at many sandstone-hosted uranium deposits, and uranium is reduced and precipitated at the redox front (Fig. 8). These deposits are nominated by American geologists as non-organic roll-type sandstone-hosted uranium deposits

1.6.1 The formation-evolution model of South Texas type U-productive basin

The South Texas model is illustrated in Table 12.

As followed by the table, such U-productive basin is characterized by:

(1) Though the uranium mineralization occurs in sedimentary cover, it is located far (hundreds, even one thousand meters) away from the basement Apparently, the basement does not control the mineralizations In other words, the mineralizations have no relationship with the uranium content in basement rocks.

Table 12 The formation-evolution model of South Texas type U-productive basin

Tectonic attribute of strata	Tectono-stratigraphic pattern and its age			Tectono-geologic event and its description	Uranium ore-formation and associated events
Cover	Weakly compressional tectonic regime	Weakly compressional sequence	Pleistocene to Holocene	Climate aridization Tectonic fracturing, introduction of H_2S into host rocks resulted in sulfidization of Fe-Ti oxides Q_1 stream sandstone, conglomerate were deposited in the lower part, and glacial sediments in the upper one.	Interlayer oxidation uranium ore-formation—the main ore-formation stage of uranium Q_1 ore-hosting series was formed
	Weakly extensional tectonic regime intermitted by weakly compressional one	Heat-sinking sequence	Late Miocene to Pliocene	Volcanic pyroclastics were accumulated Stream facies clastics were deposited	N_2 ore-hosting series was formed
			Early Miocene	Flood plain, swamp facies mudstone, siltstone and stream coarse-grained clastics were deposited	N_1^1 ore-hosting series was formed
			Late Eocene to Oligocene	E_3 large amount of volcanic ash from the west was accumulated E_2^3 delta lagoon mudstone, sandstone containing volcanic ash and tuff malterial were deposited E_2^2 marine, littoral, delta facies sandstone, mudstone, interbedding of sandstone and mudstone with siderite, limonite concretions, glauconite mudstone, lignite etc. were settled	E_3, E_2^3 and E_2^2 ore-hosting series were formed
			Paleocene to Early Eocene	E_2^1 lagoon facies coal-bearing series, marine shale, delta facies sandstone were deposited E_1 marine mudstone, siltstone were deposited	
			Cretaceous	Clastics and carbonates were deposited	
Basement				Proterozoic granite, gneiss, schist and Paleozoic clastics	

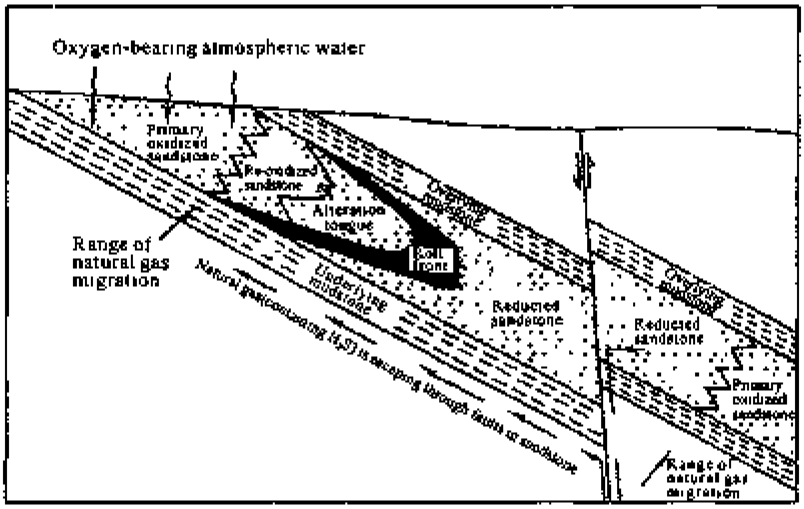

Fig 8 Schematic section showing the relation of re-reduction, partial re-oxidation of alteration tongue and uranium mineralization

(2) Age of uranium mineralization is quite young, because it has been encountered in lower Houston Group (Pleistocene Qp). Obviously, the interlayer oxidation ore-formation is associated with the climate aridization after the deposition of Pleistocene. As uranium mineralizations are observed in a wide range of stratigraphic interval (from Eocene to Pleistocene), and in places where Fe-Ti oxides were first altered into sulfides, it is assumed that regional fracturing and the introduction of H_2S into ore-hosting horizon have occurred since Pleistocene. In other words, the unconformity between Pleistocene and underlying Pliocene that resulted in structural fracturing and the subsequent latest tilting are extremely important in uranium ore-formation and its emplacement The dynamics was possibly derived from the collision of Cordillera Mountains towards North American continent, and the south Texas plain was changed into a foreland basin

(3) As different from that of other types of sandstone-hosted uranium deposits, the ore-forming material—uranium, appears to be derived from ore-hosting series itself rather than from the basement or provenance area. American geologists suggest that the tuff material that exists widely in cover sediments is the main supplier of uranium for ore-formation It is in accordance with the geology of the region. The average uranium content in Catahoula Formation is 10×10^{-6}.

(4) Similarily, the reductant and precipitant of uranium in such U-productive basin are secondary iron sulfides transformed from titano-magnetite rather than primary coalified organic remains and associated sulfides as in other sandstone-hosted uranium deposits. It is the "diagnostic" specific of South Texas U-productive basin.

Authors suggest nominating the above basin as marginal basin of reactivated old platform with non-organic roll-type sandstone-hosted uranium deposits

1.6.2 Recognition criteria of South Texas type U-productive basin

(1) Large coastal plain basin in marginal mobile zone of craton which subsequently experienced compression and turned into foreland basin.

(2) Large stream channel sand bodies or littoral, delta sand bodies with abundant U-rich volcanic pyroclastics exist in cover section.

(3) The basin is an oil-gas containg one with the wide development of growth faults allowing the migration of reducing gas from oil-gas field to enter host sandstones resulting in the sulfidization of iron minerals.

(4) Regional climate aridization following the formation of ore-hosting series resulted in the further concentration of oxygen and uranium in groundwater, the infiltration of which caused interlayer oxidation of host rocks and associated uranium mineralization.

2 MAIN CONCLUSIONS

Summarizing the formation-evolution model and its recognition criteria of six main U-productive basins, authors come to following main conclusions.

(1) The first order control of U-productive basin is the geotectonic factor. The geotectonic evolution history of the region where the basin is located determines if the basin could be a U-productive one. According to present data, in the Kazakhstan plate that is of intercontinental nature there occur the most sandstone-hosted uranium resources in the world. Obviously, the Junggar, Yili, Turpan-Hami basins etc. in China located in the same Kazakhstan plate should possess great prospecting potential of sandstone-hosted uranium deposits. Recently, some Russian and Chinese geologists have extended the intercontinental Kazakhstan plate towards east, and nominated it as the "Central-Asian Mobile belt" or the "Mongolian Arc". Many Meso-Cenozoic basins in the north of China are just situated in this tectonic unit. To locate large sandstone-hosted uranium deposit in Meso-Cenozoic basins of this tectonic belt should be an important prospecting target in the near future.

(2) Genetically, uranium mineralizations occurring in above six U-productive basins may be classified into: interlayer oxidation sandstone-hosted, paleochannel (phreatic oxidation or phreatic oxidation superimposed by interlayer oxidation) sandstone-hosted and polygenic sandstone-hosted. U-productive basins with these three kind uranium mineralizations are obviously different from each other in prospecting potential evaluation and recognition criteria. Moreover, U-productive basins with uranium deposits of similar genesis sometimes differ from each other too in their formation-evolution history. So, it is impossible and unsuitable to establish a universal model to assess and recognize U-productive basin. Using one model and same recognition criteria we might miss important U-productive basin, or make mistakes in the assessment. For example, a well-developed recharge-run-off-discharge groundwater system is an important criterion for judging U-productive basin with interlayer oxidation sandstone-hosted U-deposits. However, this criterion, obviously, is

not necessary for the identification of U-productive basins with paleochannel and polygenic uranium mineralizations.

(3) Based on analyzing the formation-evolution model of U-productive basin authors roughly imagine the further prospecting targets in China. Main prospecting target in northwestern China should be the Central Kyzylkum type U-productive basin with interlayer oxidation uranium ore-formation. Attention should be paid to locate Zabaikal type U-productive basin in southwestern China and some regions of northern and northeastern China. Many down-faulted Meso-Cenozoic basins in the south of China are similar to those on Bohemia mid-massif. The potential expects to be enlarged if more attention is to be paid to look for polygenic sandstone-hosted uranium deposits in southern China. In coastal plains of the eastern and southern China, the possibility of discovering South Texas type U-productive basin should be taken into consideration By using various formation-evolution models of U-productive basins, the field of uranium prospecting can be extended and expected type of uranium mineralization may be roughly determined.

(4) Most uranium ore-hosting series in U-productive basins abroad are concentrated in stratigraphic horizons younger than Cretaceous. Only a few sandstone-hosted uranium deposits (for example, Dalmatov in Russia) occur in Upper Jurassic. However, most known uranium deposits in China occur in Lower-Middle Jurassic. Perhaps, this is the specific of China's geology. Recent research results of authors show that the age of uranium ore-hosting series is getting younger from the west to the east of northern China. In addition, young ore-hosting rocks are more advantageous to ISL-mining than older ones in aspects of consolidation, permeability and buried depth. So, attention must be paid to younger rock series (younger than Jurassic) in the central north and northeast of China to check its ore-hosting possibility. It is better to select certain area for detailed study to expect new progresses.

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