ISL-amenable sandstone-type uranium deposit: Global aspects and recent developments in China

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Abstract. It is concluded that most of known ISL-amenable uranium deposits are attributed to roll sub-type, a minority to basal-channel sub-type, and a few to tabular in case that redistribution of U occurred. Such a classification and related explanation are beneficial to exploration in China. However, there exist significant differences between deposits in Central Asia and those in Wyoming in aspects of tectonic background, scale and shape of host sandbodies, and attitude of ore bodies though all are attributed to the same roll sub-type. Similar situation is presented for deposits of basal channel sub-type. So, it is proposed to establish deposit model and model series, providing guidelines for exploration. Four model series and eleven models have been tentatively formulated, including: 1) Central Asia-South Texas series (Chu Sarysu-Syr Darya, Central Kyzylkum, Yili and South Texas models) where hosts are large-scale tabular sandbodies, usually developed on the slope parallel to the long axis of the basin and orebodies have a "C" shape with convex surfaces perpendicular to the long axis of the basin; 2) Wyoming series (Shirley-Wind River-Powder River and Great Divide models) where hosts are moderate/small sandbodies forming a wide ribbon, deposited in compressive foreland basins while ore bodies occur on both margins of ribbon-shaped sandbodies with the convex surfaces directed outwards; 3) Grants series (Grants-primary and Grants re-distributed models) where host sandstones were deposited as channel fill within a large-scale humid alluvial fan, containing plenty of organic matter, and orebodies are mostly tabular in shape, transformed locally into roll form; and 4) Siberia-Bohemia series (West Siberia, Trans-baikal-West Yunnan and North Bohemia models) where U concentrations occur in, on, and/or adjacent to detrital plant debris within the channel sandstone, filling incised valley. Besides, recognition criteria are briefly explained. On the other hand, the sandstone-type uranium metallogenetic prospect of China is discussed with special attention to the Northwest Territory of China that could be considered as the east extension of a giant uranium super-province, stretching from Central Asia eastwards. The territory includes four domains and thirteen sub-domains different in uranium endowment. Meanwhile, the features of six selected deposits/mineralized areas are described in brief, including the Kujie'ertai, roll sub-type, hosted in tabular sand-bodies (J_{1-2sh}); the Shihongtan, roll sub-type, hosted in ribbon-shaped sand-bodies (J_{2x}); the Dongsheng, tabular sub-type with local U redistribution, hosted in ribbon-shaped sand-bodies (J_{2z}); the Nuheting, tabular sub-type, hosted in ribbon-shaped sand-bodies (K_{2e}); the Bayantala, basal channel sub-type of Mesozoic (K_{1bs}) age; and the Chenzishan, basal channel sub-type of Cenozoic (N_{2m} age). Finally, it is emphasized that China, especially the Northwest Territory of China, remains highly perspective, having only minor exploration in the past.

Key words: Sandstone-type uranium deposit; ISL-amenable; Deposit model and model series; Recent developments in China.

1. Introduction

First report on sandstone-hosted uranium mineralization came from the Colorado Plateau, USA [3], where carnotite-type sandstone deposits were discovered prior to 1880 in what later became known as the Uravan Mineral Belt, Colorado-Utah. Since then, sandstone-type uranium deposits have become one of the most important types of uranium deposits in the world. However, most conventional mines working sandstone-type U deposits were closed since the mid 1980 (the last US conventional mine in 1992) in response to declining uranium prices while in-situ leach (ISL) U extraction from suitable sandstone-type U deposits remained competitive. It is predicted that ISL output is expected to increase remarkably during 2000-2015, accounting for 15% in 2000 and 21% in 2015 of the world annual production [6,10,7,13].

In China, exploration for sandstone-type uranium deposits began in 1950s and became the major target for exploration by the end of last century when ISL mining technology has been successfully introduced. So far, a series of uranium ore deposits have been discovered in Yili, Turfan-Hami, Ordos, Eren, and other basins.

2. Distribution of sandstone-type uranium deposits and identification of mineral deposit models/model series [1]

2.1. Time and spatial distribution

Sandstone-type uranium deposits can be timely divided into pre-Mesozoic and Mesozoic-Cenozoic with respect to ISL amenability. ISL-amenable deposits occur especially in post-Triassic basins where host sandstones are non-deformed and permeable. Pre-Mesozoic uraniferous basins mainly occur in Africa. The Mesozoic-Cenozoic sandstone-type uranium deposits or showings are widespread all over the world. However, those of commercial significance are restricted to distinct geological regions: the West of U.S., including Wyoming Basins, Colorado Plateau and South Texas coastal plain; the North Bohemia of Czech Republic, extending into Germany; the Central Asian basins, including Chu Sarysu-Syr Darya Basin in South Kazakhstan, Central Kyzylkum basins in Uzbekistan [8,11], Junggar, Turfan-Hami and Tianshan intermountain basins (such as Yili and Kumishi basins) in northwestern China; the southwestern margin and southeastern margin of West Siberian Basin; the Trans-Baikal, including a series of valley basins in Vitim area. Among them, the Central Asian basins and the West U.S. are of more importance. Besides, there may exist a sandstone-type uranium super-province, which extends from Trans-Ural eastwards, passing through Central Asia and Mongolia-Inner Mongolia into Trans-Baikal, having a geographical coordinate scope of N56º-39ºand E63º-113º (Fig. 1). This is a giant arcuate tectonic belt with a southward arc apex and frontal arc in Mongolia and Inner Mongolia of China, termed “Mongolia Arc”. The Belt was formed from the end of Late Paleozoic to Triassic Period, covering the southern margin of the Siberia Continental Block (platform) as its northern part, the northern margin of the Tarim Continental Block and the northern margin of the Sino-Korean Continental Block as its southern part and Paleozoic fold belts between these blocks.

The uraniferous basins display some similarities elsewhere in the world. On the other hand, some differences in tectonic evolution have been revealed (Table I). In Central Asia, host sediments were deposited under an intracratonic subsidence or post-orogenic strike-slip mild-extensional regime while ore was formed in association with mild compression (so-called sub-orogenic event). It means that a tectonic reversion happened between the sedimentation of host rocks and the ore formation. However, such reversion is absent in South Texas, Wyoming and West Siberia. The tectonic evolutionary pattern of uraniferous basins, the scale and the shape of host sand-bodies exert an obvious influence on the attitude of ore deposits and the mode of ore-forming process.

FIG. 1. Generalized map showing Central Asian sandstone-type uranium super-province (Modified after Li Shuqing et al, 1998; Chen Zuyi, 2002).
1) Basal channel sandstone-type, 2) Tabular sandstone-type, 3) Roll sandstone-type, 4) Volcanic-type, 5) Vein-type (in metamorphosed rock), 6) Peralkalic intrusive-type.

Table I. Evolutionary pattern of basins and lithology of host sediments in selected regions.

Region/Basin	Underlying rocks	Tectonic regime during		Lithology of host rocks
		Deposition of host rocks	Ore formation	
Chu Sarysu-Syr Darya	Late Paleozoic passage layer	K_2-E_{1-2}, intracratonic subsidence	E_3^2-N_1, mild compression	Gray clastic rock series with low content of carbon debris
Central Kyzylkum	Late Paleozoic foldbelt	K_2-E_{1-2} , mild extension	N_1-N_2, mild compression	Gray (locally red) clastic rock series
Yili	Late Paleozoic foldbelt	J_{1-2}, post-ogogenic mild strike-slip extension	N_1-N_2 , mild compression	Melanocratic coal-bearing rock series
South Texas	Paleozoic passage layer	E_3-N_1, mild extension, along passive continental margin	N_2-Q_1 ,mild extension	Grayish clastic rock series, poor in carbon
Wyoming	Paleozoic passage layer	E_2^{1-2}, compression	E_3, compression	Gray clastic rock series with carbon debris
San Juan basin, Colorado Plateau	Paleozoic passage layer	J_3, intracratonic subsidence	J_3, cratonic subsidence for primary ore; N_1^2-N_2, regional uplift for re-distributed roll ore	Melanocratic clastic rock series, enriched in extrinsic carbon
Trans-Ural/West Siberia	Late Paleozoic foldbelt	J_3-K_1, intracratonic subsidence	J_3-K_1, mild compression after intracratonic subsidence	Melanocratic clastic rock series with carbon debris
Trans-Baikal	Paleozoic granitoid	N_1^2, compression	N_2-Q_1, mild extension after compression	Melanocratic clastic rock series with carbon debris
North Bohemia	Pre-Cambrian crystalline rocks	K_2^1, mild extension after uplifting	E, extension	Gray carbonaceous clastic rock series of alluvial fan/bog/delta/ littoral facies

2.2. Ore deposit modeling and ore formation mechanism

Ore deposit model is a standard form to characterize similar ore deposits on realistic description with subsidiary inference. Meanwhile, similar ore deposit models can be incorporated into an ore deposit model series. In such a way, twelve models and four model series have been tentatively established on the essential features of a number of known sandstone-type uranium deposits (Table II). Most of above-mentioned deposits are of exogenous-epigenetic origin. However, ore formation mechanism is not all the same:

(1) The deposits of Central Asia-South Texas series [14] are characterized by that mineralising solutions (oxygenated uraniferous water) flowed down the regional dip of large- to moderate-size tabular sand bodies and crescent-shaped U deposits occur along the boundary between unaltered sandstone and altered sandstone. Germanov [4], as early as in 1960, firstly described ore bodies at the deposits of this series that are irregularly scattered along a wide regional redox front (Fig. 2). Curving parts of the front seem to be more favourable sites for the deposition of ore than straight parts, but ore does not occur on all curves and it does occur on some straight parts. Within the Central Asia-South Texas series, the Yili and South Texas models are characteristic of self-reducing barrier (carbon debris) and allogenic reducing barrier (extrinsic sulphide) prior to ore-forming intra-layer oxidation respectively. It is not clear whether the allogenic reduction is also typical for the Chu Sarysu–Syr Darya and Central Kyzylkum models.

(2) The movement of mineralising solutions along the strike of a ribbon-like sandstone body is typical for the deposits of the Wyoming series. As pointed out by Frank C. Armstrong (1960) that “ore bodies might approximate mirror images of one another and would lie along opposite margins of the flow path” with outwards-directed convex surfaces (Fig. 3). Sweetwater Mine Area, central Great Divide Basin [12], provides an example where ore bodies lie along two opposite margins. However, in most cases ore bodies are predominantly developed along one margin, as shown in Shirley Basin where sandstone bodies strike NNW-ward and ore bodies occur mainly on their western edges with westwards-directed convex margins.

(3) In the deposits of Grants series, uranium was concentrated together with humate during diagenesis to form blanket and elongated tabular ore bodies. Early interlayer oxidation and late interlayer oxidation is locally characteristic for this series. The Crownpoint and Churchrock deposits are the examples where tabular ore-deposits were subsequently transformed into roll type by the early interlayer and the late interlayer reduction. It is reported that both deposits will be developed, using ISL mining techniques (McCarn, 2001) [9].

(4) Within the Siberia–Bohemia series, the deposits of Siberia and Trans-Baikal-West Yunnan models [2] were firstly formed as the product of phreatic oxidation. Then, they were possibly superimposed by interlayer oxidation immediately after the host sandstone was covered by a confining bed and the oxygenated water could flow inwards to form roll-shaped ore-bodies with inward convex margins facing one group to another. Tertiary magmatism might be involved in the ore-forming process as a heat source for the North Bohemian model.

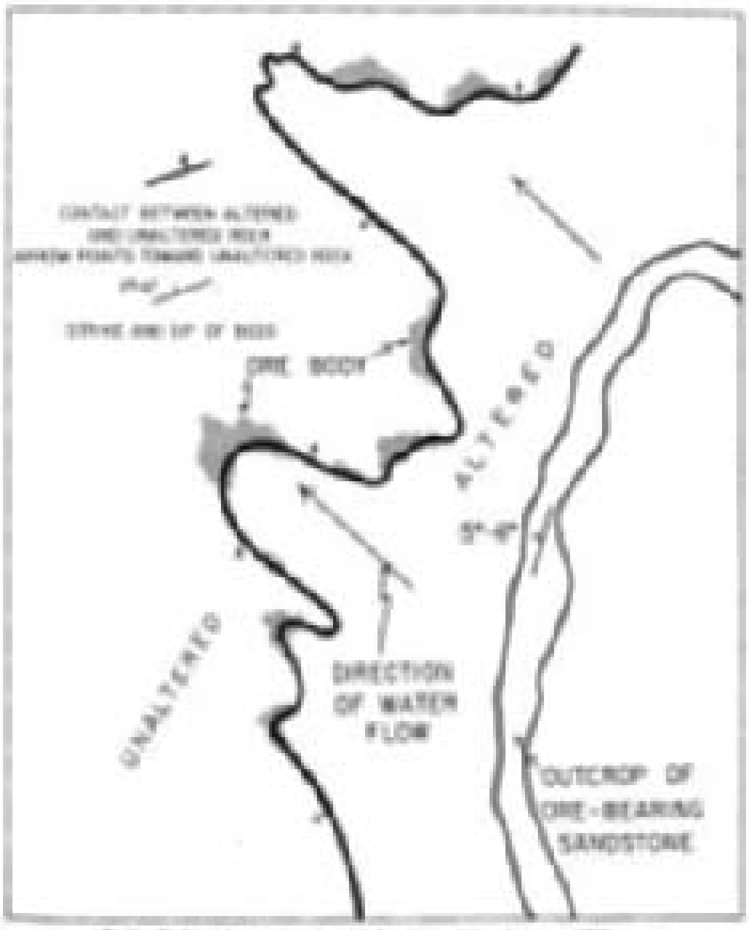

FIG. 2. Sandstone type uranium deposit in former USSR (After Germanov, 1960; No scale given).

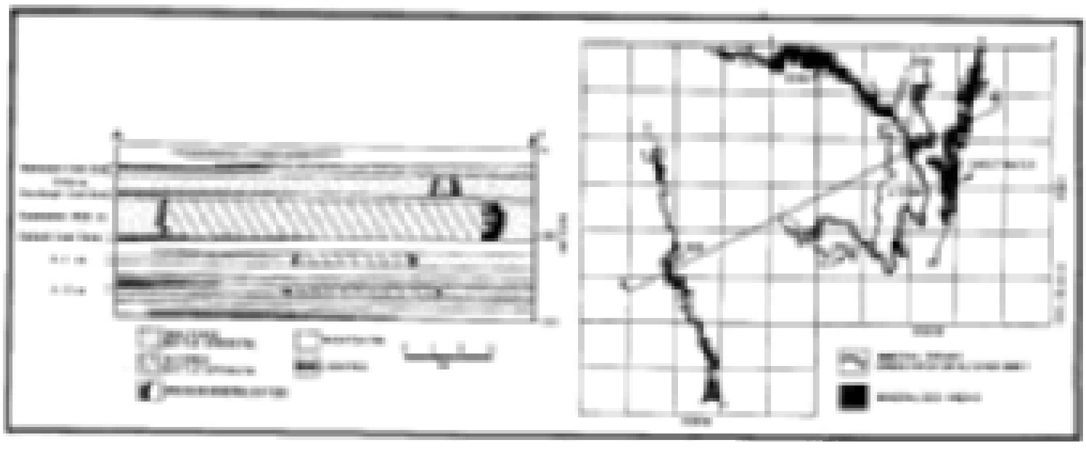

FIG. 3. Generalized uranium trend map, with associated stratigraphic section (A-A') of the Sweetwater Mine area, central Great Divide Basin, Wyoming (After Sherborne et al., 1980).

3. Tectonic delimitation of Mesozoic-cenozoic basins and their exploration perspective

The tectonic framework of China exhibits a pre-Mesozoic basement divided by meridional lineaments into several blocks and three Mesozoic-Cenozoic structural regions of latitudinal direction; the three regions correspond to both the recent landform and the morphology of mantle top surface identified by various geophysical measurements. Furthermore, eight structural sub-regions could be divided in three regions by the limits of pre-Mesozoic blocks (Fig. 4). The evolutionary patterns vary in certain extent between the Mesozoic-Cenozoic basins located in different regions and even between those in different sub-regions of the same region. In China, above-mentioned Mongolia Arc occupies northern sub-region of the north region, northern and middle sub-regions of the middle region, named also as "Northwest Territory of China". This territory, north to the Kunlunshan-Qinling Mountains and west to Daxing'anling-Taihangshan Mountains, hosts most of known sandstone-type deposits in China except Qinglong ore-field and Chengzishan deposit. It could be divided into 4 domains and 13 sub-domains (Fig. 5). In the territory, known productive layers are attributed to $J_{1\text{-}2}$, J_2 and K_1.

FIG. 4. Distribution of tectonic elements in China (Compiled with references to Li Chunyu, et al., 1982; Cheng Yuqi, et al., 1994; Wang Hongzren and Mo Xuanxue, 1996).
1) Siberian Plate, 2) Kazakhstan Plate, 3) Northeast Asian Plate, 4) Karakum-Tarim Plate, 5) Sinokorean Plate, 6) Yangtze-Qangtang Plate, 7) Turkey-Central Iran-Gondise Plate, 8) Southeast Asian Plate, 9) Indian Plate, 10) West Tectonic Domain, 11) Middle Tectonic Domain, 12) East Tectonic Domain, 13) Boundary between Plates, 14) Boundary between Tectonic Regions, 15) Strike-Slip Fault.

Table II. Tentative ore deposit models and model series for sandstone-type U deposits.

Model Series/Model	Principal Recognition Criteria	Examples
1. Central Asia-South Texas Series: Hosts are large-scale tabular sandbodies, usually developed on the slope parallel to the long axis of the basin. Orebodies have a "C" shape with convex margin perpendicular to the long axis of the basin.		
1.1 Chu Sarysu-Syr Darya	Host sandstones were deposited in intracratonic basins poor in organic matter. Ore formation is closely related to the regional redox interface with a length of >200 km	Inkay, Uvanas and other deposits in South Kazakhstan
1.2 Central Kyzylkum	The same as 1.1 with the exception that the ore formation is related to small-size local redox interface	Uchkuduk, Sugraly, Kyzylkum, Uzbekistan
1.3 Yili	Host sandstones were deposited in post-orogenic strike-slip extension basins, enriched in organic matter. Ore formation is related to local redox interface	Kuji'ertai, Zajistan, North Xinjiang, China
1.4 South Texas	Host sandstones were deposited in continental marginal environments with lack of organic matter and syn- and dia-genetic pyrite. Ore formation occurred after the introduction of extrinsic sulphide	Rosita, Rhode, Ranch, Texas, USA
2.Wyoming Series: Hosts are moderate/small sandbodies forming a wide ribbon, deposited in compressive foreland intermontane basins. They are distributed from the basin margin inwards perpendicular to its long axis. Ore bodies occur discontinuous along curvilinear redox interfaces at the front end of alteration (oxidation) tongues developed on both margins of ribbon-shaped sand bodies.		
2.1 Shirley	U-bearing basins are the so-called "arid" basins, lacking lacustrine and deltaic deposits with a few turfs at the bottom of the basin filling sequence	Deposits in Shirley Basin and Wind River Basin, Wyoming, USA
2.2 Powder River	The same as 2. 1 with the exception that the deposits occur not only in Paleocene (in the southern part) but also in Eocene (in the northern part)	Highland and Smith Ranch in southern part, and Christensen Ranch in northern part, Powder River Basin, Wyoming, USA
2.3 Great Divide-Turfan	U-bearing basins are well-developed "humid" continental basins. U concentrations occur within the transitional areas between alluvial-fan and fluvial system where uraniferous sandstone is intercalated with discontinuous coal, mudstone or siltstone	Crooks Gap, Sweetwater, Great Divide Basin, Wyoming, USA. Shihongtan, Turfan-Hami Basin, N.Xinjiang, China
3. Grants series: Host sandstones were deposited as channel fills within a large-scale humid alluvial fan, containing plenty of organic matter. Uranium is primarily closely connected predominantly with humate		
3.1 Grants-Primary ore	Ore colour is of dark grey to black. U was concentrated together with carbon during diagenesis to form blanket and elongated tabular ore bodies, and during early (pre-fault) oxidation to form roll-like ore bodies with quite wide limbs.	Most deposits in the Grants Uranium Region, Colorado Plateau, USA. Kharat, Mongolia. Nuheting, Inner Mongolia, China
3.2 Grants-Redistributed ore	Ore colour varies from dark brownish grey to light grey. U was redistributed, separated from carbon on the basis of pre-existing ore during later (post-fault) oxidation. Ore bodies have the form of a roll or occur stacked along faults.	Church Rock, Crownpoint, Grants Uranium Region, Colorado Plateau, USA. Dongsheng Area, Ordos, China
4. Siberia-Bohemia Series: U concentrations occur in, on, and/or adjacent to, detrital plant debris within channel sandstone. The sandstones were deposited under low-stand conditions, located at the bottom of the basin fill. Ore bodies are lens-like or tabular, less frequently having a form of an elongated roll. The roll-shaped ore bodies were developed from both flanks of the belt-like sandbodies with the convex margins directing inwards, seldom forming X-shape as a twin combination.		
4.1 West Siberia	U-hosting sandstones are distributed within incised valleys, developed on a plain. The sandstones eroded into either basement or underlying depositional sequences. Ore bodies are n km long, 50 m to n×100 m wide and 1-10 m thick	Dalmatovskoye, Trans-uralsk; Malinovskoye, SE part of W Siberia, Russia.
4.2 Trans-baikal-West Yunnan	U-hosting rocks are distributed in tributary valleys, converging into valley basins that are formed on uplifting highland. The sandstones are confined to Neogene-Quaternary age due to erosion, underlain unconformably by the basement (granitic rocks). Ore bodies are a few km long, n×10 m to 400 m wide and up to 20 m thick.	Khiagda, Trans-baikal, Russia. Ningyto-Toge, Japan. Chenzishan, W Yunnan and other deposits and occurrences in Inner Mongolia, China
4.3 North Bohemia	U-hosting rocks are distributed in the lower parts of Mesozoic marine sequences, consisting of alluvial-fan-fluvial-lacustrine conglomerates, sandstones, siltstones, mudstones and littoral quartzose sandstone containing rutile, monazite, zircon. Ore bodies have the shape of a lens and a flat flag. The mineralization age of 24 Ma to 74 Ma roughly corresponds to the age of Tertiary basaltic magmatism.	Hamr, Straz, Czech Republic. Koenigstein, Germany

FIG. 5. Tectonic delimitation of Mesozoic-Cenozoic basins in Northwest Territory of China (Compiled with references to He Dengfa, et al., 1999; Ji Rangshou, et al., 2000; Ren Jishun, et al., 2000).
1) Sedimentary basin, 2) Caledonian suture zone, 3) Hercynian suture zone, 4) Indo-Sinian suture zone, 5) Yenshanian suture zone, 6. Thrust zone, 7) Basin domains and their number.
I. Junggar-Tarim Domain: I_1: Junggar Sub-domain; I_2: Tienshan Sub-domain; I_3: Tarim Sub-domain;
II. Altun Domain: II_1: Badain Jaran Sub-domain; II_2: Beishan Sub-domain;III_3: Dunhuan Sub-domain;
III. Alxa–Qaidam Domain: III_1: Alxa Sub-domain; III_2: Corridor Sub-domain; III_3: Central Qilian Sub-domain; III_4: Qaidam Sub-domain;
IV. Eren-Ordos Domain: IV_1: Eren-Hailar Sub-domain; IV_2 Yingshan Sub-domain; IV_3: Ordos Sub-domain.

The Junggar-Tarim Domain borders on the east of Chu Syr Darya-Kyzylkum Domain of Middle Asia and on the west of Altun strike-slip fault system, having a relative high uranium endowment. The domain is composed of 3 sub-domains as shown in Figure 5. The Tianshan Sub-domain includes the Yili Basin that is well known for the discovery of the Kuji'ertai and Zajistan deposits. The sub-domain was involved by post-orogenic strike-slip extension and consists of a group of intermountain basins. Recently, exploration was also implemented at Kumishi Basin situated to the east of the Yili Basin. The Junggar Sub-domain includes the Junggar, Turfan-Hami, Buerjin and other relatively small basins around the Junggar Basin. Shihongtan is a newly discovered deposit located at the southwestern margin of the Turfan-Hami Basin. A certain amount exploration work has been done in the Junggar Basin with attention to J_{1-2} and K strata but no commercial deposit has been found so far. It is supposed that Paleogene sediments may be more promising than J_{1-2} in the northern Junggar Basin (Dingshan Area) and the Buerjin Basin where a low-angle southwards-dipping slope was developed during Paleogene period from the Altay Mountains (northern boundary mountain for the Junggar Basin), upon which favorable, alternating sand-pelitic sediments were deposited. The Tarim Sub-domain contains the only basin of the same name that covers an area of 560,000 km^2. This is a hydrocarbon-bearing basin and U-promising areas are known in its northern part where Bashibulak deposit was found in K_1 melanocratic bituminized sandstone-conglomerate, and in its northeastern part where Kongque River low-angle slope as a target area developed on the south edge of Kuluketak Precambrian massif. The Altun Domain has its name from Altun sinistral strike-slip fault system. This fault system was active since the Jurassic with highest intensity in Early Cretaceous. No drilling program has been conducted specially for uranium there. The domain consists of 3 sub-domains (Fig. 5). The Dunhuan Sub-domain, NE-striking, comprises the Dunhuang and two other basins. The Dunhuan Basin is developed on a stable Precambrian massif and is filled with Jurassic coal-bearing clastic rocks. The sediments are less deformed and show a certain potential for uranium exploration on its northern low-angle slope. The Beishan and the Badain Jaran sub-domains occur within a Late Palaeozoic fold belt that was intensely overprinted by early Yanshan orogenic movements so that the Jurassic coal-bearing clastic rocks are deformed and lost exploration value. The Beishan sub-domain is located at the site where the Altun fault system turns from NE- to EW-trending. It includes 8 small-sized intermountain basins, such as the Gongpoquan, the Zongkezi, and so on. The sub-domain was uplifted for a quite long time since the end of K_1 with omission of K_2-N_1 deposition so that Lower Cretaceous productive layers are relatively shallow-buried. A testing drilling program for uranium will be conducted soon in the Gongpoquan Basin where drilling for coal revealed several sections of U-mineralised sandstone. The Badain Jaran Sub-domain, generally EW-striking, is presented by a medium-sized basin filled with J-E sediments of more than 4000m in thickness, covered mostly by desert deposits. This sub-domain is considered to be relatively less productive. The Alxa-Qaidam Domain consists of 4 EW-trending sub-domains from north to south: the Alxa, the Corridor, the Central Qilian and the Qaidam. It is indicated that the deformation of J_2 and K_1 productive layers is getting more intense southwards due to northward push of Indian Plate. The Alxa Sub-domain includes the Huahai-Jinta, Chaoshui and Yabulai basins that were developed on the basis of Alxa Precambrian massif (a western extension of Sino-Korean Continental Block). The Chaoshui Basin has been selected for prospecting with special attention to the north monocline (Taobei Slope) where several low-grade sandstone- and coal-type U deposits/occurrences were discovered in J_2 and K_1 clastic rock formations during the 1950s-1980s. The Corridor Sub-domain, a lowland corridor between the Longshoushan-Alagushan Mountains and the Qilianshan Mountains, is a transitional element between Sino-Korean Continental Block (platform) and Qilian Fold System. This sub-domain includes the West Jiuquan, East Jiuquan and Minle basins. A preliminary study shows that Tertiary tectonism is relatively intense but heterogeneously developed (milder in the East Jiuquan and Minle basins, especially at their northern slopes). Of them, the East Jiuquan shows certain perspective for U exploration in the Hongyaogou depression at its northern margin where K_1 sandstone is distributed within an incised valley. The Central Qilian Sub-domain includes a series of medium/small intermountain basins that were formed during the Tertiary. No systematic reconnaissance has been done in this sub-domain. The Qaidam Basin, the only basin in the Qaidam Sub-domain, is oil-bearing, but not favourable for uranium exploration due to a thickness of more than 10,000m in response to a marked subsidence during the Tertiary and Quaternary. The Eren-Ordos Domain was developed on different pre-Mesozoic tectonic elements, the Eren-Hailar Sub-domain on Hercynian fold-belts of the Kazakhstan Plate, the Yingshan Sub-domain on the marginal Hercynian fold-belt (Inner Mongolian Axis) of the Sino-Korean Plate, and the Ordos Sub-domain on the Sino-Korean Continental Block of the Sino-Korean Plate. The Mesozoic sedimentary history is similar for the Eren and Yingshan sub-domains; it is characterized by folded J_{1-2} coal-bearing clastic rock series, appearance of volcano-clastic rocks in J_3, and well-developed K_1 coal-bearing clastic rock series. The evolution is different, however, during the Tertiary since the Yingshan basins are a group of intermountain basins essentially formed during the Tertiary. Some sandstone-type U deposits are known in Cretaceous sediments of the Eren Basin, such as Nuheting and Subeng (K_2, tabular), and Bayantala (K_1, basal-channel), while the Yingshan basins contain uranium occurrences and showings mainly in Tertiary channel-filling sandstones. Therefore, the productive host sandstones are different in ages in the above-mentioned two sub-domains. The Ordos Sub-domain includes the Ordos Basin covering about 250,000 km^2 and a series of "satellite" basins around it. Continental sedimentation started in the Ordos Basin at the end of the Permian. The Ordos Basin was an intracratonic basin, and became a foreland basin during T_3 with foredeep at the west margin. During J_{1-2}, tectonic activity weakened and the basin was turned into successive subsidence with development of incised valleys between T_3 and J_1^1, J_1^1 and J_1^2, J_1^2 and J_2^1. The Early Yanshanian orogeny caused a large-scale uplift by the end of Middle Jurassic. Afterwards, extension occurred in Early Cretaceous associated with widespread alluvial fan, fluvial and lacustrine, and locally eolian deposits. At the end of Cretaceous, the basin was completely uplifted as a plateau followed by the formation of several Miocene grabens on its north, west and south edges. Obviously, the Mesozoic-Cenozoic evolution of the Ordos Plateau in many respects is similar to the Colorado Plateau. A few productive strata were identified, including Triassic (T_1 and T_3), Middle Jurassic (Zhiluo Fm.) and Lower Cretaceous strata. It is reported that the Dongsheng U-mineralised area was discovered at its northern margin in 1999. The host rocks are channel-filling sandstones of Zhiluo Fm. that forms a large-scale alluvial fan. A certain perspective is also indicated in the north-western Ordos Basin where Lower Cretaceous alternating sandstone-mudstone beds occur in an optimal ratio and contain radioactive anomalies.

4. Simplified description of selected ore deposits [15]

4.1. Kuji'ertai Deposit: roll sub-type, hosted in tabular sandbodies of J_{1-2} coal-bearing clastic sediments [5]

The deposit lies in the territory of Yining City, Xinjiang Autonomous Region. It occurs at the southern margin of the Yili Mesozoic- Cenozoic Basin that was developed on a Carboniferous-Permian folded basement. The deposit covers about 60km^2, 12km in length and 5 km in width, and consists of a north, middle, and south ore (U-mineralized) zone (Fig. 6). The basin fill comprises Middle-Upper Triassic, Lower-Middle Jurassic (Shuixigou Group), Cretaceous, Tertiary, and Quaternary sediments. Host sediments are attributed to the Shuixigou Group that forms a northward inclined monocline with dip angles of 5º-7º and contains 8 depositional cycles. Roll ore bodies are discovered in the 5th cycle of a braided delta system characterized by reverse graded bedding. The cycle obtains a sand-mud ratio of about 1-2 and has an organic carbon content of 1.12%. Host sand bodies are 20km long, more than 2km wide and 10-25m thick. Roll head of ore bodies is about 50-150m wide and 5-10m thick, and averages 0.05% U. Two wings of the roll are 200-400m wide from the south to north and 1-2m thick and grade 0.05-0.1% U in average. A few tabular-shaped ore-bodies occur in the 1st-3rd cycles of an alluvial fan-braided fluvial system with sand-mud ratios of 2-3 and an organic carbon content of 0.29%. Tabular ore bodies have a thickness of about 1-2m and a uranium content of 0.05%-0.1% U. Ore-hosting rocks are quartzose sandstone, feldspar (kaolin) sandstone with some volcanic debris, sandy conglomerate, etc. Alteration is well developed and shows a down dip zoning from intensely altered sandstone, brown yellow-colored, with high hydro-goethite content; to weakly altered sandstone, yellow/light yellow-colored with hydro-goethite content of about 6.5%; to the redox front where ore bodies are located, gray colored, with the association of hydro-goethite and pyrite; and to dark gray-colored unaltered sandstone. Uranium occurs as uranium minerals as well as adsorption in the cement of sandstone and sandy conglomerate. Uranium minerals include pitchblende (about 80%) and coffinite (about 20%), seldom brannerite, and U-Ti-bearing magnetite. Pitchblende is associated with pyrite. Adsorbed uranium is associated with coal debris and pyrite. There are a series of associated elements, such as Se, Ga, Sc, Re, V, etc., in ore bodies. Se is mainly distributed in weakly altered sandstone while the others are concentrated together with uranium in the redox front.

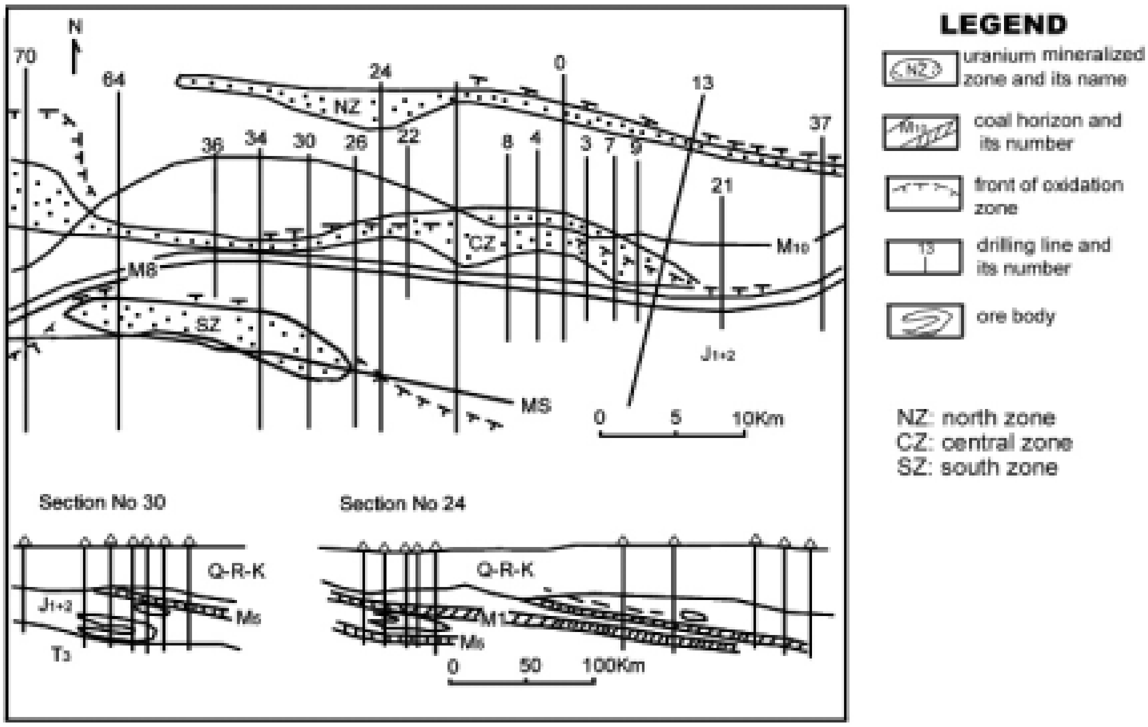

FIG. 6. Sketch geological plane and sections showing the distribution of uranium mineralized zones and ore bodies in Kujie'ertai Deposit (After Gu Kengheng, et al., 1996).

4.2. Shihongtan Deposit: roll sub-type, hosted in wide ribbon-shaped sandbodies of J_{2x} coal-bearing fragmental sediments

The deposit is situated in the territory of Turpan City, Xinjiang Autonomous Region, and occurs at the SW margin of the Turfan-Hami Basin. This is an EW-striking intermontane basin in a lowland with the elevation of -154.5m at Aiding Lake. It is the second lowest lowland in the world. The basin, developed on Late Carboniferous-Early Permian transitional structural layer, started as a foreland basin during P_2-T time. Shuixigou Gr. (J_{1-2}) was deposited under a post-compression relax regime. The deposit is located in the west section of Aiding Slope, and covers about $120km^2$, 20km in length and 6km in width (Fig. 7). The strata form a shallow -dipping monocline with a dip angle of 4º-10º, locally with a NNE-NE-trending nose-shaped swell where the Shuixigou Gr. is exposed on the surface (Fig. 8). The Shuixigou Gr. is divided into 3 formations, from the bottom to the top: the Badaowan Fm. (J_{1b}), the Sangonghe Fm.(J_{1s}), and the Xishanyao Fm.(J_{2x}). Host sediments are mainly attributed to J_{2x} that is further subdivided into three members from the bottom to the top: the lower (J_{2x}^1) of braided fluvial system, the intermediate (J_{2x}^2) of meandering fluvial-delta system, and the upper (J_{2x}^3) of rejuvenated braided fluvial system. Firstly discovered ore bodies are hosted in a J_{2x}^1 proximal braided fluvial zone, that trends northwards perpendicular to the long axis of the basin. U-mineralized holes are mostly distributed along the east flank of the Shihongtan nose-formed swell. Ore bodies are of roll shape with a NE-ward-directed convex margin. Roll head is about 4-8m thick and 50-150m in length. Tabular ore bodies have a thickness of about 2-6m and a length of 100-500m.

Host rocks are mostly arkose, minor lithic sandstone. Similar to Kuji'ertai Deposit, hydrogoethitization alteration zoning is also down dip well developed as:

(a) Brown-yellowish–colored, intensely altered sandstone with Fe^{3+}/Fe^{2+} >3.0 and $C_{org.}$ = 0.08%;
(b) Light yellow and variegated red-colored, weakly altered sandstone with Fe^{3+}/Fe^{2+} = 1.5-3.0 and $C_{org.}$ = 0.08%-0.72%;
(c) Deeply gray/gray/grayish white-colored mineralized sandstone at redox front with $Fe^{3+}/Fe^{2+} \cong 0.50$ and $C_{org.} \cong 57\%$;
(d) Gray/light gray-colored unaltered sandstone with $Fe^{3+}/Fe \cong 0.34$ and $C_{org.} \cong 0.26\%$. Uranium is present in both uranium minerals (about 50%) and adsorption (about 50%).

Uranium minerals include mainly pitchblende, and minor coffinite and uraniferous Ti-Fe oxide. Pitchblende is usually associated with pyrite while coffinite occurs either on the surface of pyrite or in association with pitchblende and quartz. Uraniferous Ti-Fe oxide seems to be an alteration product of leucoxene or ilmenite. Absorbed uranium is closely related to clay minerals, powdery pyrite and carbon debris. Ore grade is 0.035%U in average. Associated elements include Mo, Se, Re, Ga, and Se. Based on whole rock Pb-isotopic analysis of 14 ore and rock samples, U-Pb isochron ages have been obtained as 104Ma, 24Ma and 7Ma, corresponding to late Early Cretaceous, the end of Oligocene and late Miocene respectively.

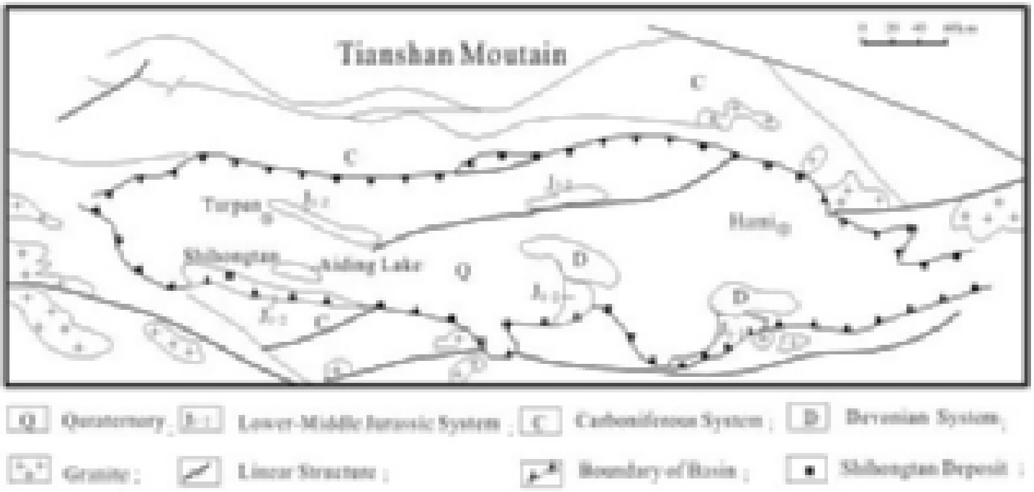

FIG. 7. Schematic geological map of Turfan-Hami Basin (After Wang Jinping, et al., 2002).

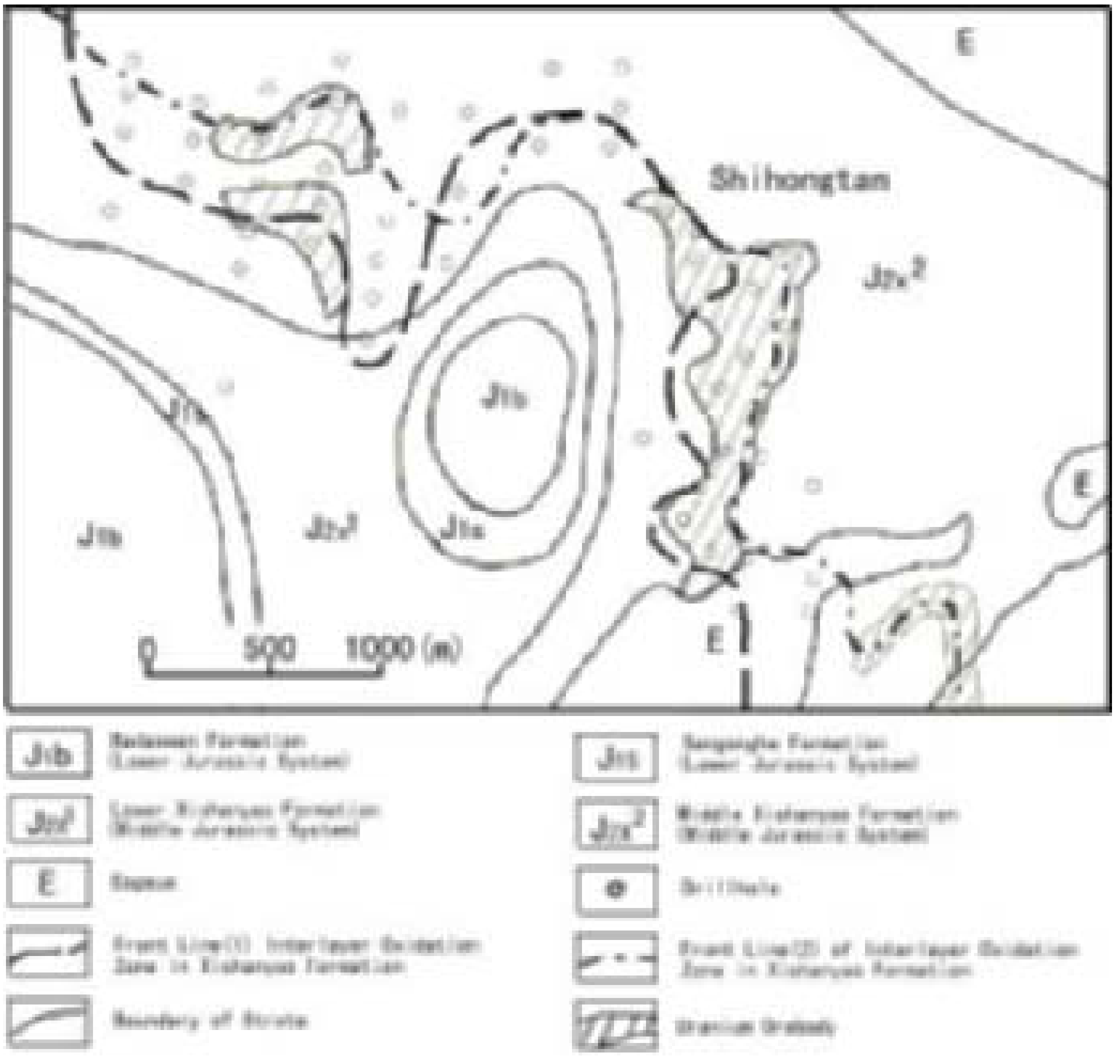

FIG. 8. Schematic map of Shihongtan uranium deposit (After Wang Jinping, et al., 2002).

4.3. *Dongsheng uranium–mineralized Area: tabular sub-type, locally with re-distribution of uranium, hosted in ribbon-shaped sand bodies of J_{2z} gray fragmental sediments*

This area is situated at the northern margin of Ordos Basin, in the territory of Ordos City, Inner Mongolian Autonomous Region. The U-mineralized area covers an area of more than $200km^2$. Mesozoic-Cenozoic Erathem includes Upper Triassic Yanchang Fm. (T_{3y}), Lower Jurassic Fuxian Fm. (J_{1f}) and Yan'an Fm. (J_{1y}), Middle Jurassic Zhiluo Fm. (J_{2z}), Lower Cretaceous Dongsheng Fm. (K_{1d}), Pleistocene (N_2) and Quaternary (Q). The Zhiluo Fm. (J_{2z}) is further subdivided into 3 members, the lower (J_{2z}^1) of braided fluvial system, the intermediate (J_{2z}^2) of low sinuosity meandering fluvial system and the upper (J_{2z}^3) of high sinuosity meandering fluvial system. J_{2z}^1 is the host member that was formed in NNW-striking proximal braided fluvial zones, possibly within a large-scale humid alluvial fan when the northern part of the basin underwent regional uplifting. The zones were eroded into underlying coal-bearing fragmental rocks, filling a group of incised valleys. During J_{2z}^2 and J_{2z}^3, the uplifting of the northern part weakened and subsidence–sedimentation predominated. Meanwhile, NNW-ward valleys were turned into NE-ward sags due to compression from SE direction. It is indicated that waters of J_{2z}^1 sandbodies remained in hydrological connection with surface waters after covering of J_{2z}^2 and J_{2z}^3 because intercalated impermeable mudstone layers are discontinuous. As a result, the waters of J_{2z}^1 sandbodies were locally oxidizing and locally reducing, depending upon the distribution and influence of indigenous organic debris, and the fluctuation of water table. In such environment, first-stage uranium mineralization widely occurred with formation of tabular ore bodies at the bottom of sandbodies (Fig.9). At the end of Early Cretaceous, the area was uplifted again, even more intensely. The J_{2z}^1 sand bodies were denudated and exposed on the surface. In this time, a EW-striking redox front was formed with a length of 40km and pre-existing tabular ore bodies were locally reworked and turned into roll shape at a few sags (Fig.10). The ore-forming process ceased in late Early Cretaceous when K_{1d} was deposited and the hydrological connection between waters of J_{2z}^1 sandbodies and surface waters was cut. This inference is proved by a mineralization age of 107.14Ma.

Three U-mineralized sections have been discovered discontinuously along the EW-striking redox front by reconnaissance drilling so far. They are 15km long in total. Ore bodies are several tens to one hundred m long, 1-20m thick and have ore grades of 0.033%U in average. Host rocks consist mainly of altered, gray/light gray colored coarse/medium-grained feldspar-quartz sandstone, and minor fine-grained sandstone. Color of altered sandstone is quite variable. Yellow-colored rocks are widespread on the surface, being product of oxidation. However, only blue/dark green-colored altered sandstone occurs on the up-gradient sides of U-mineralized sandstone as observed in drill cores. The detailed investigation shows that blue/dark green–colored altered sandstone contains relic debris of red-colored altered sandstone indicating early-stage oxidation, and the green-coloration is possibly caused by the presence of Ni-bearing chlorite and/or clinochlore. Therefore, it is assumed that the blue/dark green–colored altered sandstone might reflect secondary reduction of red colored, early-stage oxidized sandstone due to introduction of hydrocarbon gas from underlying gas reservoir; the red colored, oxidized sandstone, located primarily on the up-sides of regional redox fronts, may be related to the ore-forming process. Of course, the absence of red-colored and/or yellow-colored sandstones in the drill cores may raise doubts about the reality of regional redox front and roll-shaped ore bodies. Much about mineralogy and geochemistry of alteration remains unknown and needs to be clarified in the future, nevertheless.

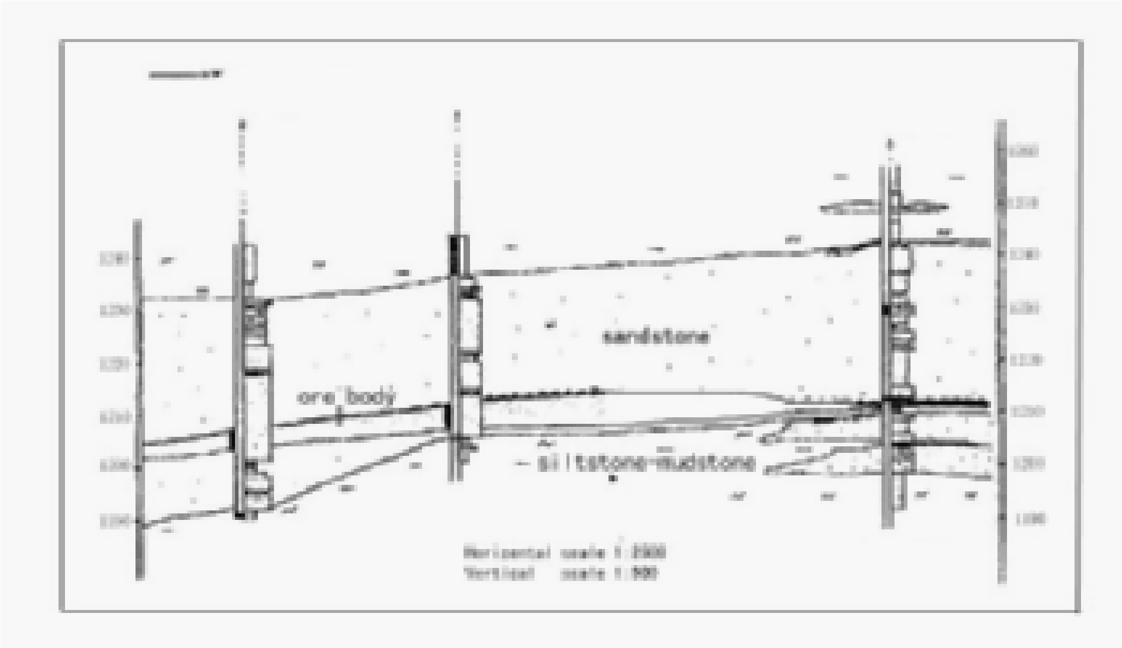

FIG. 9. Schematic profile showing tabular-shaped ore body in Zhiluo Fm. (J_{2z}) at Shashagetai Section, Dongsheng U-mineralized Area (Collected from Geological Team No. 208, 2001).

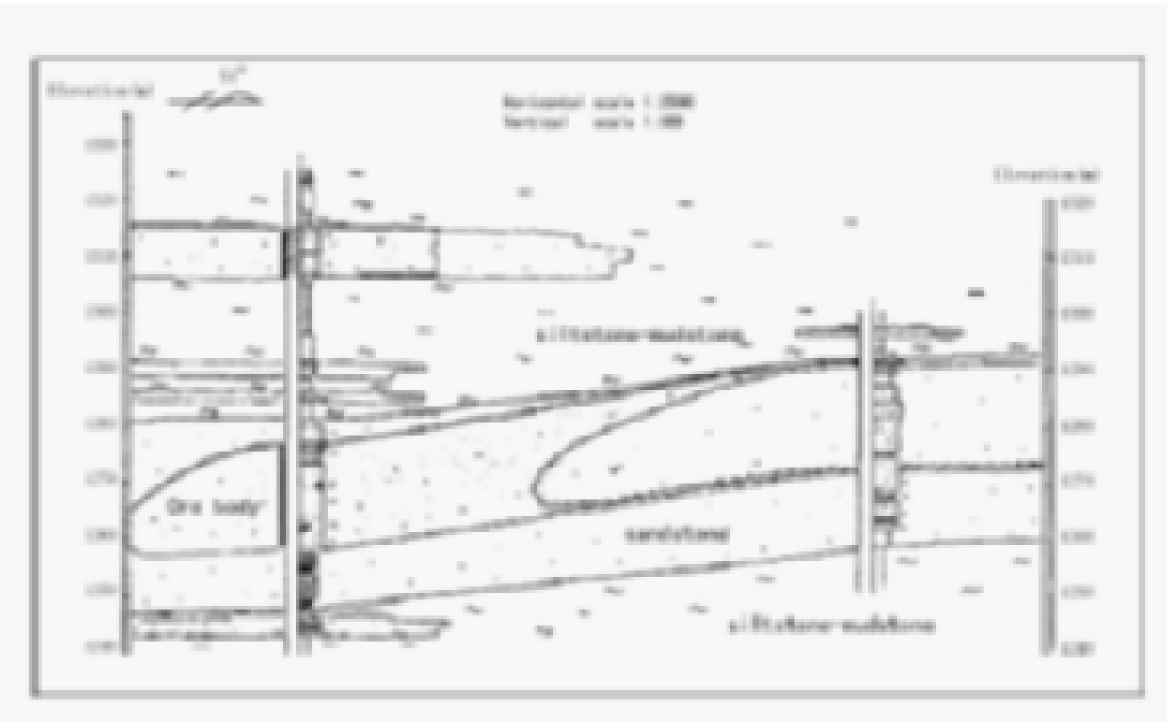

FIG. 10. Schematic profile showing roll-shaped ore body in Zhiluo Fm. (J_{2z}) at Sunjianliang Section, Dongsheng U-mineralized Area (Collected from Geological Team No. 208; 2001).

4.4. Nuheting Deposit: tabular sub-type, hosted in tabular-shaped sandbodies of K_{2e}^1 gypsum-bearing fragmental sediments

This deposit is located in the territory of Erenhot City, Inner Mongolian Autonomous Region and occurs in the Erennaoer depression at the northern margin of the Eren basin. The depression contains oil-source bed and reservoir in Lower Cretaceous sediments and uranium in the Upper Cretaceous Erendabusu Fm. (K_{2e}). At the deposit, the lower member of the upper Cretaceous is named sandstone member (K_{2e}^1), formed by a meandering fluvial system; and the Upper member is named mudstone member (K_{2e}^2), formed by a lacustrine system. Ore bodies are of lens and tabular shape. Ore grades range from 0.03%U to 0.1%U. The main ore body covers an area of 1.59-5.20km^2, and accounts for more than 90% of the total reserves. It is tabular-shaped and located at the topmost position of the deposit, 5-12m below the ground surface and 0.5-7m below the bottom of the mudstone member (Fig.11). The thickness of this ore body varies within the range of 0.7-1.3m. Below the main ore body there are more than 10 sporadically distributed small ore bodies. Host rocks consist of mudstone and siltstone that account for 80% and fine-grained sandstone for 20%. The ore, gray and grayish black-colored, contains considerable amount of pyrite, goethite, gypsum, carbonate minerals and carbonized plant debris. Uranium is mostly adsorbed in clay minerals.

4.5. Bayantala Deposit: basal-channel sub-type, hosted in belt-shaped sandbodies of K_{1bs}^1 variegated fragmental sediments

The deposit lies in the territory Xianghuangqi County, Inner Mongolian Autonomous Region, and occurs at the eastern edge of the Bayantala sag, Tengge'er Depression, Eren Basin. The sag is 64 km long in NS-direction, and 7-15Km wide, developed on a Hercynian Fold-Zone and Mesozoic granite. At the sag, the Lower Cretaceous Banyanhua Gr. (K_{1b}) is wide spread. It includes the A'ershan Fm. (K_{1ba}) of an alluvial fan system, the Tengge'er Fm. (K_{1bt}) of a fan delta system and the Saihantala Fm. (K_{1bs}) of a fluvial system. The K_{1bs} is further subdivided into 2 members: the lower (K_{1bs}^1) of a braided fluvial system, filling incised valleys; and the upper (K_{1bs}^2) of a meandering fluvial system. Host sediments are mostly attributed to the K_{1bs}^1 braided fluvial system (Fig.12). At Huhe Mineralized Section, lens-shaped ore bodies occur in K_{1bs}^1bluish gray or greenish gray pebbly sandstone, coarse- and medium-grained sandstone with intense smectitization and kaolinization. Ore bodies are 100-150m long and 6-12m thick (Fig.13). Ore grade is about 0.02%U in average. Besides, it is reported that uranium mineralization is discovered in sandbodies of the Tengge'er Fm. (K_{1bt}).

4.6. Chengzishan Deposit: basal-channel sub-type, hosted in ribbon-shaped sandbodies of Pliocene coal-bearing fragmental sediments

The deposit lies in the territory of Tengchong County, Yunnan Province, and occurs at the western edge of the Longchuanjiang Basin, close to the eroded outcrop of granitic basement. The basin covers an area of about 50km^2. The Middle Pliocene Mangbang Fm. (N_2m) includes 3 members, the lower (N_2m_1), middle (N_2m_2) and upper member (N_2m_3) (Fig.14). Host sediments are attributed to the middle member (N_2m_2) of an alluvial fan-braided fluvial–braided delta system. The member is sub-longitudinal- trending and dips eastwards with 5º-15º. Individual ore bodies are of tabular, lens and stacked shape (Fig.15). The lens-shaped ore bodies are hosted in deeply buried thin-bedded silty argillaceous beds enriched in organic matter and pyrite. The tabular and stacked-shaped ore bodies are 10m-160m long and 1- 8m thick and occur at shallow depth. Ore grade is 0.03%-0.1% U. Most ore bodies are hosted in sandstone, and uranium is mainly adsorbed on organic matter, pyrite and clay minerals, minor in form of pitchblende and secondary U minerals associated with pyrite, siderite and anatase. Isotopic determination of two pitchblende samples gave the ages of 4.4 Ma and 2.2 Ma.

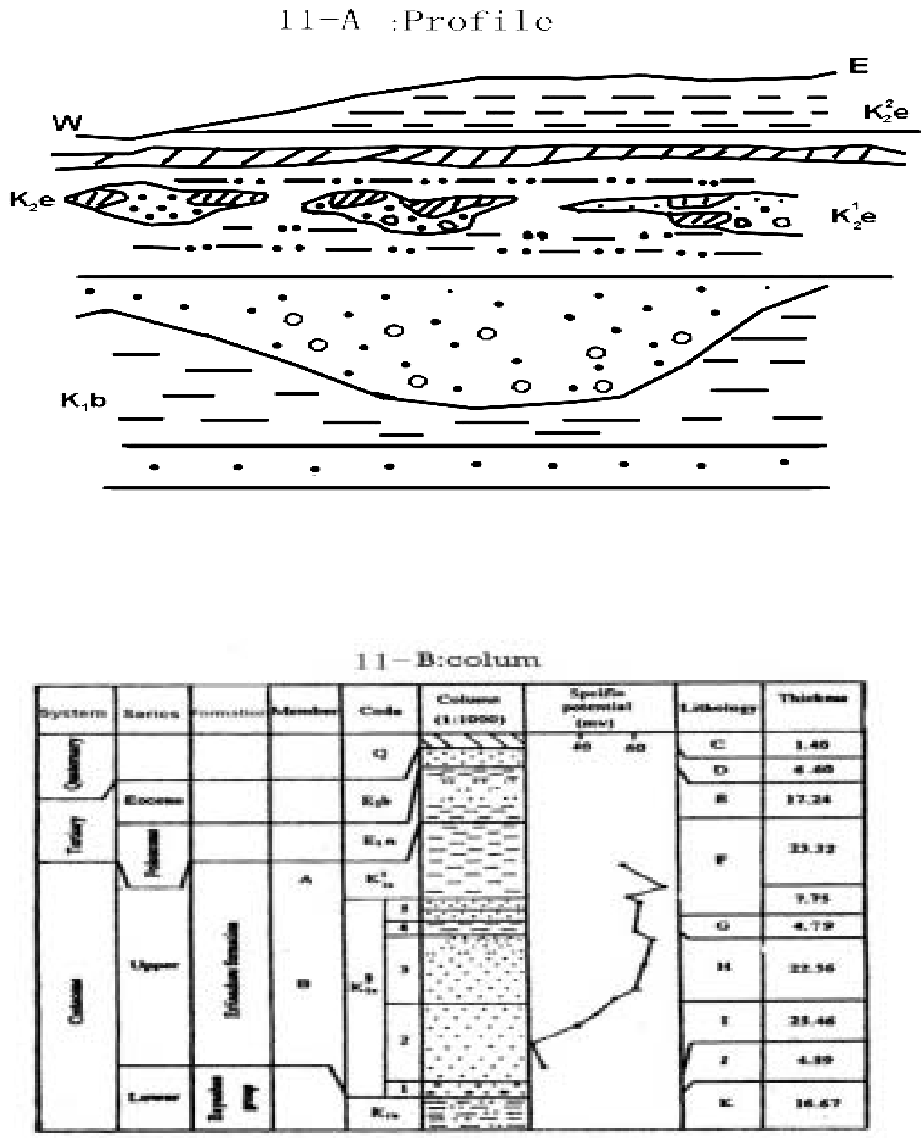

FIG. 11. Schematic geological section and stratigraphic column of Nuheting deposit.

A) Mudstone Member, B) Sandstone Member, C) Clay, D) Mottled sandstone, red sandstone, E) Brown mudstone, siltstone, F) Grey mudstone, calcareous mudstone, gray black sandstone, siltstone, G) Grey black mudstone, H) Grey fine-grained sandstone with intercalations of siltstone, I) Grey-yellow gravel-containing coarse-grained sandstone, grayish yellow gravel-containing medium-grained sandstone, J) Variegated sandy conglomerate, K) Brick-red sandy and silty mudstone, variegated sandy conglomerate.

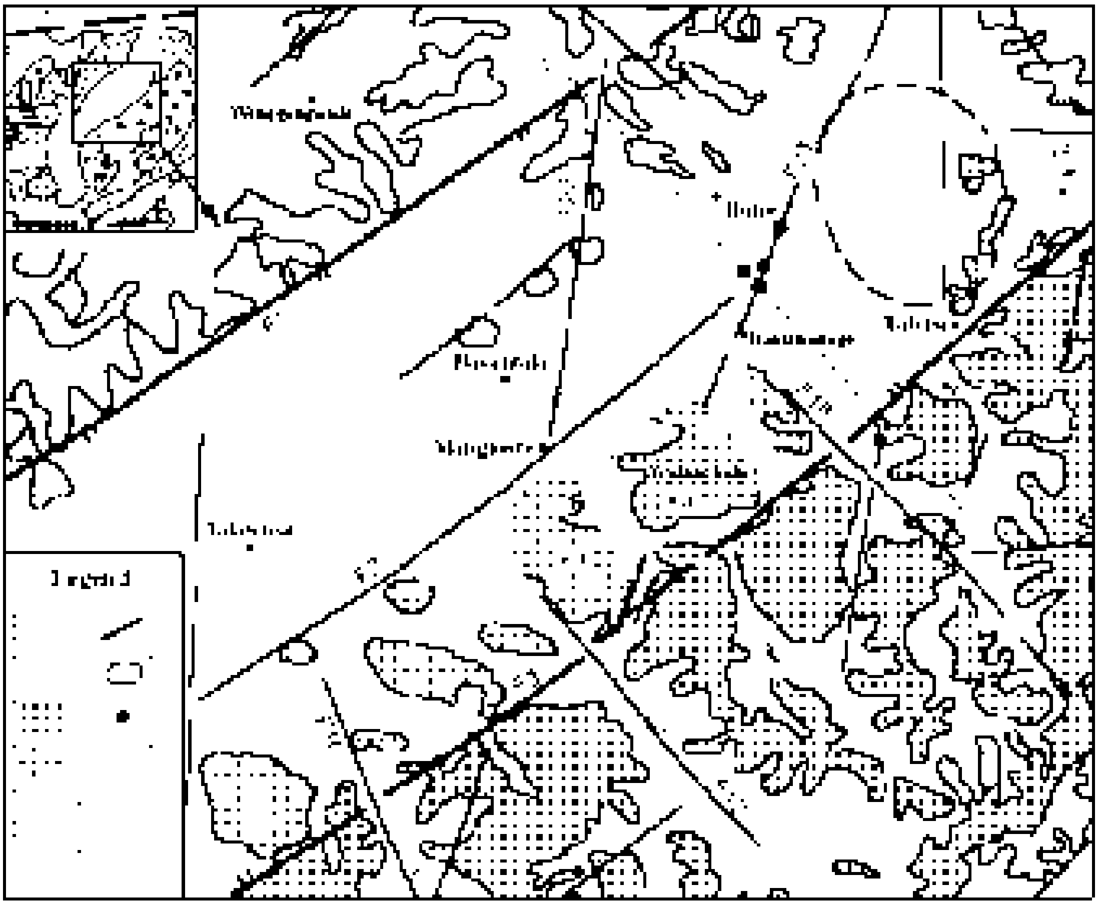

FIG. 12. Schematic map showing distribution of braided system in Saihantala, Fm., north-eastern Bayantala Sag (Collected from Geological Team No. 208; 2001).

1) Lower Permian, 2) Upper Jurassic, 3) Mesozoic granite, 4) Bayanhau Group (K_1b), 5) Baogedewula Fm. (N_2b), 6) Pleistocene, 7) Faults interpreted by TM imaging, 8) Ring structure, 9) Mineralized hole, 10) Braided fluvial sediments.

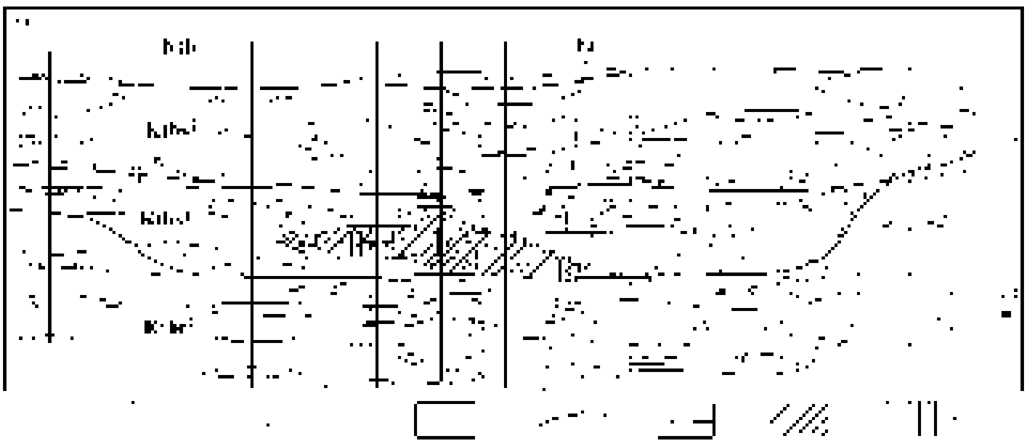

FIG. 13. Schematic profile showing lens-shaped ore body at Huhe Section, Bayantala Deposit (Collected from Geological Team No. 208; 2001).

1) Sandy conglomerate, 2) Sandstone, 3) Siltstone, 4) Mudstone, 5) Stratum boundary, 6) Boundary of redox front, 7) Blue-colored alteration, 8) Uranium ore body.

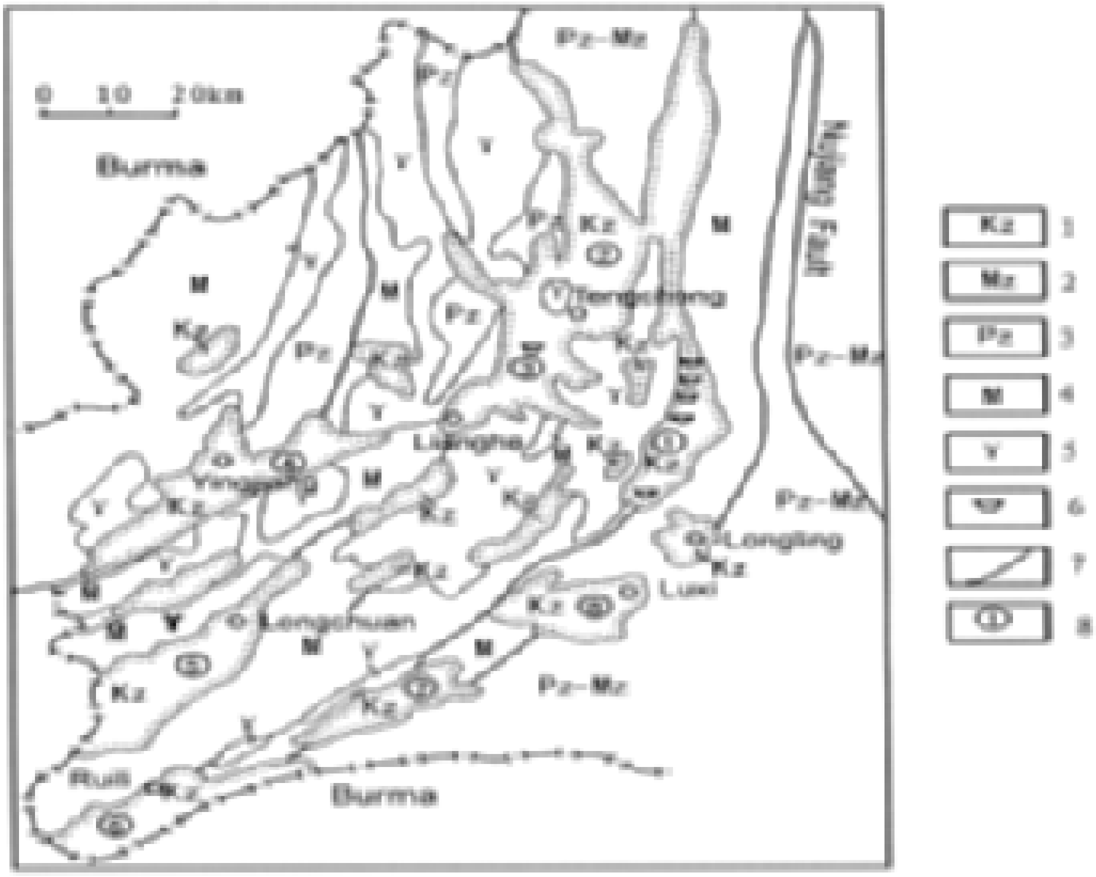

FIG. 14. Neogene basins and sandstone-type U deposits, Western Yunnan (After Chen Youliang et al., 2002).
1) Cenozoic Era, 2) Mesozoic Era, 3) Palacozolc Era, 4) Mid-proterozoic Era, 5) Granite, 6) Sandstone-type uranium deposit, 7) Fault,
8) Main basin and number: (1) Longchuanji-ang basin, (2) Tengchong basin, (3) Lianghe basin, (4) Yingjiang basin, (5) Longchuan basin, (6) Ruili basin, (7) Zhefang basin, (8) Nuxi Basin.

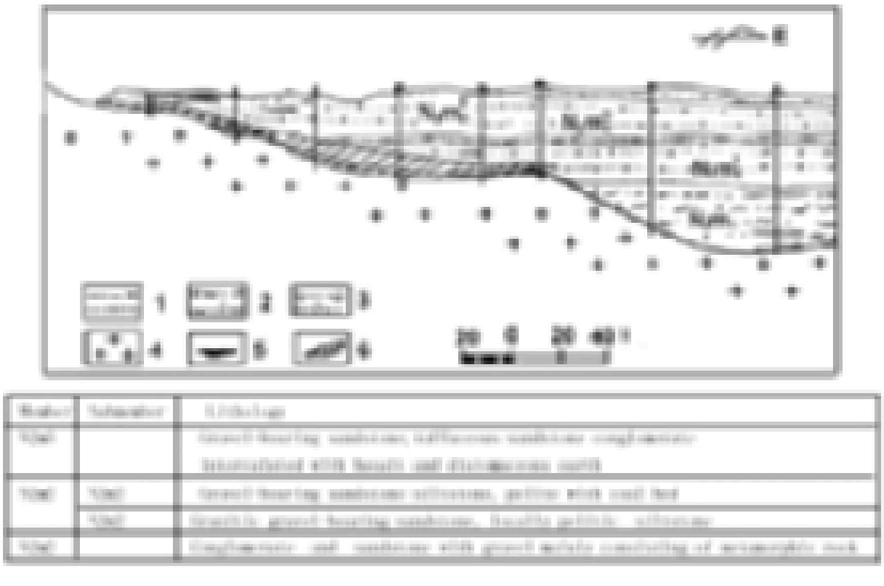

FIG. 15. Schematic Litho-stratigraphical section of Chengzishan Deposit, Western Yunnan (After Geological Team No. 209, 1985).

5. Conclusion and acknowledgments

ISL-amenable sandstone-type uranium deposits are actually an economic-technical type, established after successful mining by ISL technology in a series of countries rich in sandstone-type uranium resources. A considerable part of sandstone-type uranium deposits in southern Kazakhstan are known to contain "large tonnage-low grade ore reserves hosted in soft and water-saturated rocks" that are difficult and/or economically unavailable to mine by traditional underground extraction methods. In this field, ISL technology shows its particular vitality. The question is, how to recognize best deposits amenable to ISL mining in order to promote exploration and mining of sandstone-type U deposits. A logical approach would be to formulate an improved and comprehensive classification especially for sandstone type uranium deposits amenable to ISL mining. As known, most ISL-amenable deposits are of roll sub-type and as pointed out by Russian geologists, some of basal-channel (or valley) sub-type deposits might be amenable to ISL mining as well. Besides, the Crownpoint and Churchrock U deposits, New Mexico, which are considered for ISL mining indicate that a few of tabular sub-type deposits may also be feasible for ISL mining. On the other hand, there are some distinct differences between deposits of the same sub-type. For example, roll-sub-type deposits in Wyoming are obviously different from those in the Chu Sarysu-Syr Darya, Central Kyzylkum, and Yili basins in tectonic settings, scale and shape of host sandbodies and their depositional environment, as well as in the occurrence of ore bodies, including the direction of the convex margin of rolls and the relation to basin strike. A similar situation is valid for the basal-channel sub-type: deposits of Trans-Ural and West Siberia occur at the margin of a large-scale cratonic basin where the tectonic regime has been relatively stable with low-amplitude regional uplift since the deposition of host sediments. The host sediments are of Late Jurassic and younger age. In comparison, deposits of Vitimsk and western Yunnan are distributed in Cenozoic valley basins on a continuously uplifting plateau/highland where the tectonic regime is relatively mobile and host rocks are overlain by basalt or a similar competent cover. These host sediments are not older than Neogene as pre-Neogene sediments must have been denudated. So, it seems reasonable to establish ore deposit models and model series, providing guidelines for exploration.

As shown above, a series of ISL amenable sandstone type deposits have been discovered in China, especially in the Northwest Territory of China. This territory, which has seen only minor exploration in the past, remains highly perspective for the discovery of U deposits.

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REFERENCES

[1] DAHLKAMP, F.J., 1993. Uranium ore deposits. Springer-Verlag, Berlin/Heidelberg/New York/London/Paris/Tokyo/Hong Kong/ Barcelona/Budapest.

[2] DAI JIEMIN., Regional metallogenetic geological conditions and recognition criteria

of sandstone-hosted uranium deposit in western Yunnan. In: *Galaxy of research achievements of uranium geology of China,* Bureau of Geology, China National Nuclear Corporation, Beijing, 1996, pp. 112-121.

[3] FINCH, W., ed., (Finch, W., Davis, J.F., Barthel F., Phadke A.V., Golloway W.E., Cazoult, M.,). Geological environments of sandstone-type uranium deposits, IAEA-TECDOC-328, Vienna, 1985, pp. 1-408.

[4] GERMANOV, A.N., Main genetic features of some infiltration-type hydrothermal uranium deposits (English translation): Akad. Nauk SSSR Izv. Ser. Geol., No. 8, 1960, pp. 60-71.

[5] GU KANGHENG., WANG BAOQUN., Uranium metallogenetic geological characteristics of Deposit No.512 in interlayer oxidation zone in Yili Basin, In: *Galaxy of research achievements of uranium geology of China*, Bureau of Geology, China National Nuclear Corporation, Beijing, 1996, pp. 196–204.

[6] IAEA-TECDOC-961, Changes and events in uranium deposit development, exploration, resources, production and world supply-demand relationship, 1997, pp. 193-200.

[7] IAEA-TECDOC-1239, Manual of acid in situ leach uranium mining technology, 2001, pp. 51-104.

[8] KARIMOV, KH.K., BOBNOROV, N.S., BROVIN, K.G., GOLDSHTEIN, R.I., KORSAKOV, Yu.F., MAZURKEVICH., et al. Uchkuduk-type of uranium deposits in Uzbekistan, Tashkent, 1996, (in Russian).

[9] McCARN, D.W., The Crownpoint and Churchrock uranium deposits, San Juan Basin, New Mexico: An ISL mining perspective. In: *Assessment of uranium deposit types and resources-A worldwide perspective,* IAEA-TECDOC-1258, 2001, pp 171-184.

[10] Joint OECD/NEA-IAEA Publication. Uranium 2001: Resources, production and demand, (Redbook 2001) Paris, France, 2002.

[11] PETROV, N.N., YAZIKOV, V.G., AUBAKIROV, H.B., PLEKHNOV, V.N., VERSHKOV, A.F., LUKHTIN, V.F., Uranium deposits of Kazakhstan (exogenous), Almaty (in Russian), 1995.

[12] SHERBORNE, J.E. Jr., PAVLAK, S.J., PETERSON, C.H., BUCKOVIC, W.A., Uranium deposits of the Sweetwater Mine area, Great Divide Basin, Wyoming. In: Third Annual uranium seminar, New York, American Institute of Mining, Metallurgy, and Petroleum Engineers, 1980, pp. 27-37.

[13] UNDERHILL, D.H., Analysis of uranium to 2050. The uranium production cycle and the environment, IAEA-C&S Papers Series, 10/P, 2002, pp. 33-58.

[14] ZHANG RULIANG, DING WANLIE, Discussion on geologic characteristics NHT type uranium deposit and the relationship between oil and gas-bearing water and uranium metallogenesis. In: *Galaxy of research achievements of uranium geology of China*, Bureau of Geology, China National Nuclear Corporation, Beijing, 1996, pp. 205-214.

[15] ZHOU WEIXUN., CHEN ANPING., Sandstone-type uranium deposits and deposits amenable to in situ leach mining: Review and prospect, In: *The scientific and technical status at the turn of century*, Bureau of Geology, CNNC, Beijing, 2001, pp. 1-42 (in Chinese).