Geoscience and Remote Sensing (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/geors.2024.070107
ISSN 2523-2592 Vol. 7 Num. 1

Understanding and thinking about sandstone-type uranium sedimentary system

Gong Xianzhong[1], Wang Teng[2,*]

[1]*Institute of Resources & Environment, Henan Polytechnic University, Jiaozuo, 454000, China*
[2]*The Fifth Geological Brigade of the Tibet Bureau of Geology and Mineral Resources, Lasa, 850000, China*
[*]*Corresponding author*

Keywords: Uranium ore; sandstone-type uranium ore; sedimentary systems; Hypothesis

Abstract: *The* mission requirement of self-sufficiency in uranium resources has led to the rapid development of sandstone-type uranium exploration and development. In this paper, the relationship between uranium source, redox environment, sedimentary construction, transport medium, structural ore control and mineralization is studied by combing the literature and working examples related to sandstone-type uranium ore at home and abroad in recent years, and the hypothesis of sandstone-type uranium ore sedimentation system is preliminarily established. Focusing on the five links of the sandstone-type uranium sedimentation system hypothesis of "Raw, Accumulation, Deposition, Transport and Preserve", the research progress and results of each link of the existing sandstone-type uranium ore sedimentation were sorted out, the internal relationship and external evolution of each link were summarized, and his own insights and thoughts were put forward for the establishment of sandstone-type sedimentary system.

1. Introduction

Due to its own fission ability and ability to release a large amount of energy, uranium has an irreplaceable role in strategic deterrence and clean power generation, and has a strong strategic connotation and epochal significance since it was successfully used by human beings in the last century. Whether from the perspective of energy security or from the perspective of national security strategy, this radioactive element, uranium, will have an extraordinary mission. In 2021, the IAEA stated in the 26th session of the United Nations Framework Convention on Climate Change (COP26) that nuclear energy is part of the solution to global climate change and that nuclear energy will play an important role in addressing the challenges posed by climate change, which is expectedDemand for nuclear energy will increase sixfold by 2050[1,2]. In the same year, the global demand for uranium totaled 62,496 tons, and China's uranium demand was 9,563 tons, accounting for 15.3% of the total global uranium demand, ranking second in the world[3]. According to the reference scenario in the IAEA's Nuclear Fuel Report Global Demand and Availability Scenario 2021-2040, global reactor uranium demand is expected to be around 625 in 202100 tons, which will increase to 79,400 tons by 2030 and 112,300 tons in 2040. However, in 2016~2020, the world uranium production fell sharply from 63207 tons to 47731 tons, and it is predicted that uranium ore production will be reduced by more than half between 2030~2040[4]. According to relevant information and public materials of the World Nuclear Association, China's uranium resource production in 2020 was only 1885t, and the dependence of uranium resources on foreign sources has remained constant all year roundMore than 70%. In recent years, under the background of China's "dual carbon" goal, the construction of clean energy, especially nuclear energy, has rapidly expanded. In 2021, China's reactor capacity under construction was 20,600MWe, exceeding the second to sixth places with a total capacity of 1,268MWe under construction in the same period[5]. The demand for uranium, which is the main raw material for nuclear reactions, has correspondingly increased[6].

Because of its active chemical properties, uranium can interact with almost all non-metals (except inert gases), and can also form gold intercompounds with a variety of metals, and can also react with many acids, alkalis and salts. Various forms of existence form form a variety of complex types of deposits. From different research perspectives, relevant researchers propose different division schemes[7]. Among them, the most representative is the 15-category classification scheme of uranium deposits proposed by the International Atomic Energy Agency (1989), followed by a new classification proposed by Franz J. Dahlkamp in 1993 in 2013. The global Uranium Resources, Uranium Production and Uranium Demand published by the IAEA last year was adopted. According to the geological background of uranium resource production, the scheme is divided into sandstone type, non-integrated surface type, polymetallic iron oxide breccia type (IOCG type), quartz-pebble conglomerate type, vein type, intrusive rock type, volcanic rock type and calcanic rock type, metamorphic rock type, epigenetic type, collapsed breccia barrel type, etc. There are 13 categories, such as phosphorus rock type and other types. The above-mentioned "four types" of uranium ore account for 92.2% of China's proven resource reserves, of which sandstone-type uranium ore, as the main resource type produced in China, accounts for about 43% of China's uranium resources[8-14].

Subject to technological development, China only began large-scale sandstone-type uranium exploration and research in the 90s of the 20th century[15]. The study of the mineralization mechanism and model of sandstone-type uranium ore started later, and with the increase of exploration depth, the tectonic control of uranium mineralization under different geological backgrounds was important Pigment, redox environment, migration medium, sedimentary construction, mineralization mode and sedimentary system establishment are more complex and variable. Therefore, it is an urgent scientific problem to solve the current research on sandstone-type uranium ore by thoroughly sorting out the relevant literature and working examples at home and abroad, summarizing the general mineralization mechanism and law of typical sandstone-type uranium ore, systematically explaining the sedimentation enrichment mechanism and mineralization process of sandstone-type uranium ore, and establishing a theoretical system of sandstone-type uranium ore deposit. The sandstone-type uranium ore sedimentation system hypothesis enriches the theoretical system of sandstone-type uranium ore mineralization, which has guiding significance for the next step of prediction and prospecting of sandstone-type uranium ore, and can provide information support for the next step of uranium resource reserve research.

2. Previous research

Sedimentary system is a three-dimensional lithofacies assemblage that is causally related in sedimentary environment and sedimentary process. Sandstone-type uranium ore is located in the sedimentary basin, and there is a certain intrinsic relationship with coal, oil and gas in the temporal and spatial distribution, [16-17]and the mineralization is mainly affected by uranium source, redox environment, sedimentary construction, transport medium, and structural ore control elements and other factors control, covering the activation, migration[18-28], precipitation, enrichment and deposition of uranium elements in the process of mineralization.

2.1. Foreign research

Benefiting from the breakthrough of uranium fusion technology and the early mining of large-scale and extra-large sandstone-type uranium ore, the United States and the Soviet Union have conducted in-depth research on the theory of sandstone-type uranium ore mineralization. Shawe D.R.The term "roll-ore" was coined in 1959 [29]by Finch and Adleret al. conducted in-depth research on typical sandstone-type uranium deposits in the Midwestern region of the United States (South Texas, Colorado Plateau, Wyoming Basin, etc.), and summarized the famous "roll-type" sandstone uranium mineralization theory[30], Granger H.Cand Warren C.GIn 1974, the geochemical zoning model of the "coiled" uranium ore body that is considered to be more classic was first given(Fig. 1)[31]. The model is roughly described as: the "roll-type" ore body as a whole is produced in the altered sandstone tongue, and the cross-section is usually crescent-shaped or "C" shaped along the inclination direction of the main sandstone layer, and the front and rear can be divided into "curly head" and "curly tail", the "curly head" part is located at the front end of the oxidation-reduction transition zone of the cross-section, and the "curly tail" is also called the upper and lower wings of the "coiled" mine. The "roll-type" ore body is followed by a hematite core and an altered sandstone halo in front; The oxidation-reduction interface at the front of the altered sandstone halo meets the "curl front" ("curl head"), and then gradually transitions to the new pyrite and pyrite formation zone in the forward "coil zone", until the non-alteration sandstone. The formation mechanism can be explained as: the primary pyrite in groundwater and main sandstone will migrate sulfur at the oxidation-reduction interface and generate residual iron sulfide minerals, which are easily oxidized into limonite under the action of oxygenated water and easily soluble under weak acidic conditions, thus continuously promoting the formation of uranium mineralization in the "front zone" and constantly "rolling"Forward.

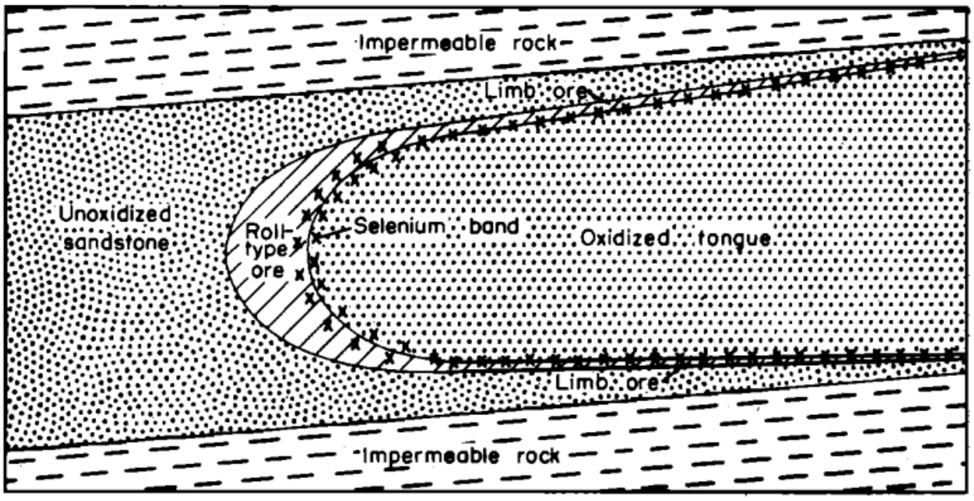
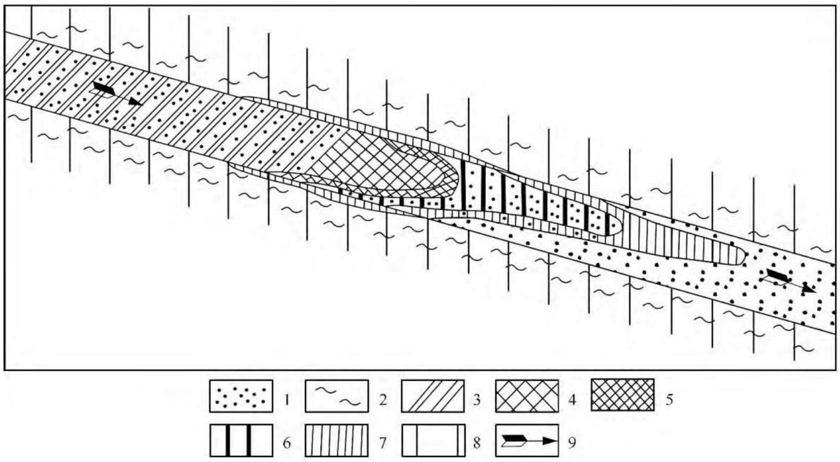


Figure 1: Geochemical zoning model of the U.S. "rolled" uranium ore body

Most of the precipitation mechanism of uranium in the United States advocate the "multiple migration-growth" theory, and uranium may undergo multiple cycles of oxidation, migration and reduction before mineralization[32-35]. All infiltrated deposits are controlled by oxidative metagenesis[36]. In the exogenous oxygenated groundwater migration path, a "geochemical barrier" is generated, that is, in the "geochemical barrier" section, the element migration intensity is sharply reduced, resulting in element precipitation enrichment. Then, the regional mineralization conditions of interbedded infiltration sandstone-type uranium ore were summarized: geotectonic conditions - weakly activated large platforms, platform edge platform slopes, marginal depressions of young orogenic belts, and intermountain basins (depressions) with strong depressions (or faults). Regional hydrodynamic conditions - pressurized sedimentary basins with changes from seepage hydrogeological dynamics to infiltration hydrogeological dynamics; Climatic conditions - the formation period of ore-bearing construction is warm and humid or semi-warm and humid paleoclimatic conditions, and the metaphytic transformation period is arid or semi-arid climate conditions. In addition, the theory of ancient valley (paleochannel) uranium ore mineralization was established according to the environment of paleoriver valley (paleochannel)[37], which belongs to the theory of the cause of infiltration submersion-interlaminar water oxidation. Since the overall geological background is in the platform area and is in a relatively stable tectonic environment, Russian scholars put forward the "theory of tectonic sea level lifting and control"[38] , as shown in Figure 2.

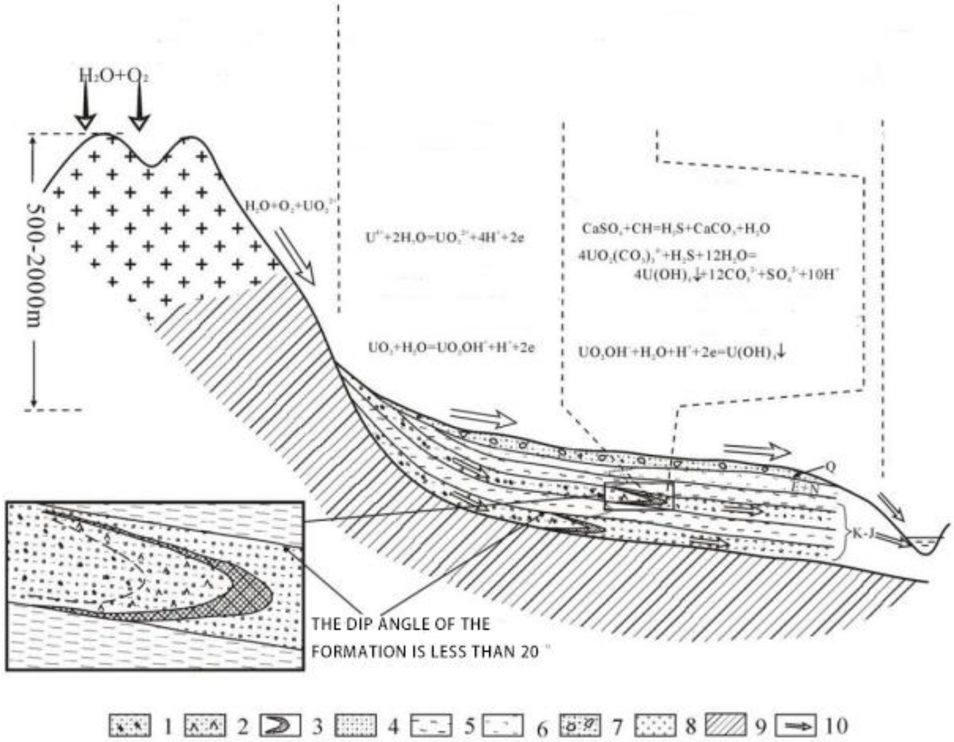


1-permeable sandstone; 2 - mudstone; 3- no interseam oxidation zone; 4- Limonite nuclei containing residual radium; 5- Unoxidized rock with leached uranium adjacent to the oxidation-reduction interface; 6- Uranium-bearing black-bitumen uranium mineralized part of the ore body; 7 - same as 6, but no significant uranium bituminous mineralization; 8- Ore-free unoxidized rock belt; 9- Interlayer water movement direction.

Figure 2: Schematic diagram of the inter-oxidation metagenesis zone of uranium deposits in the underwater delta and offshore sediments of the Lower Toulon Formation (Е.М.Шмариович) [39].

2.2. Domestic research

Influenced by Soviet researchers and limited by mining technology, some scholars believe that the uranium mineralization belt in Central Asia has a similar uranium mineralization geological background to northern China[40], and the mineral-rich strata generally have the characteristics of red layer ore control. On the basis of the superior mineralization geology and paleoclimatic conditions in the north, abundant uranium sources, large-scale sand bodies and tectonic activities triggered the migration of surface oxygen-containing uranium-containing fluids and deep hydrocarbon-containing fluids[41-42], and a supplement- diameter-drainage fluid mineralization system was constructedfracture) slope zone formed at the edge (top), fluid interaction, coupling mineralization, becoming a complete fluid mineralization system(Fig. 3)[43]. However, through the field work of sandstone-type uranium ore in the Ordos Basin, Li Weihong et al. believe that sandstone-type uranium ore also has the characteristics of epiphytic post-infiltration mineralization, and the late transformation of the basin is the most important control factor of uranium mineralization[44]. Relevant scholars introduced the dynamic concept of source-sink system on the earth's surface and constructed a complete source-sink system to explore the enrichment mechanism of [45]sandstone-type uranium ore. According to the three parts of denuded landform, sedimentary landform and sediment runoff associated with them[46-48], sandstone-type uranium ore is divided into physical and chemical processes in which uranium-rich substances are weathered and denuded from the erosion source area, transported through the confluence system, and then reduced to ore by the favorable ore sand body in the basin[49-50]. Compared with the complement-diameter-drainage system of typical interlayer oxidation zones, the source-sink system focuses more on the transport path of uranium-containing materials, focusing on clarifying the transport paths of uranium-source materials in the sedimentary and mineralization stages. It is a supplement to the sandstone-type uranium ore replenishment-diameter-drainage system[51].



1- strong oxide zone sandstone; 2-weak oxide zone sandstone; 3-redox sandstone-type uranium ore body; 4 - native band sandstone; 5 - argillaceous rocks; 6 - siltstone; 7 - conglomerate; 8- uranium-containing geological bodies (represented by granite); 9- uranium-containing basement rock; 10- Direction of groundwater movement

Figure 3: Formation pattern of sandstone-type uranium deposits in interlaminar oxide zone [52-53]

3. Development status

Thanks to the progress of science and technology and the in-depth research of sandstone-type uranium ore, the mineralization theory shows a diversified trend.

The core of the migration-precipitation mechanism of uranium in the early American "coiled uranium ore theory" and the Soviet "interlayer infiltration mineralization theory" is redox. Uranium migrates with uranium ions in the oxidation medium, and is brought to the geochemical reduction barrier along the interlayer oxidation barrier to be reduced, adsorbed and precipitated, which can be called "geochemical barrier mineralization". Ye Tianzhu's prospecting prediction theory calls it "physicochemical conversion structural surface mineralization"[54], which reflects not only the mineralization mechanism but also the spatial location of ore body.

As the basis for sandstone-type uranium ore mineralization, its source is generally considered to be the mountain erosion source zone around the prototype basin, and it is also controlled by the mountain erosion source zone around the residual basin during the mineralization process. In addition, Zhang Zilong, Lu Baolong [55-57] and others believe that metamorphic rocks such as magmatic rocks and mixed rocks can also provide uranium sources for sedimentation, and Li Qiang traces the uranium source at the western margin of the Qaidam Basin through the petrochemical method of elemental characteristics to verify this theory. The combination of abundant uranium sources increases the complexity of mineralization supply.

Low-temperature sandstone uranium mineralization is generally dynamic (semi-)open and continuous, the uranium content in the recharge oxidation water is usually not high, in order to mineralize, the underground fluid always maintains a perfect hydrodynamic system of continuous replenishment, seepage and excretion, so that the uranium source can be continuously replenished through the underground fluid, and redox enrichment occurs repeatedly in the redox transition site [58-65].

Similarly, uranium-rich ores have not remained constant over a long period of geological history. Active chemistry also allows uranium to re-enter an ionic state in an oxidizing environment. Uranium ore can also be dissipated by multiple transport processes, which requires the formation of delineated semi-open channels above and below the pre-enriched uranium as a guarantee condition for mineralization[66]. Otherwise, under the open dynamic system with shallow burial depth, the precipitation of uranium will be very scattered, and it will not be possible to form a stable uranium ore body on a large scale. In these semi-open channels with good upper and lower traps, due to the good impermeability of the top layer, the leaching and transformation of the ore body by atmospheric precipitation in the later stage is avoided[67], which is conducive to further stable mineralization.

The continuously replenished uranium source and reducing fluid need to be excreted for outlet to meet the cyclical enrichment effect, and the emergence of tectonically active faults forms a complete dynamic sedimentary system. Fracture structures need to cut through organic matter layers (including coal seams, oil and gas layers) or substrates to provide channels for deep uranium sources and oil and gas rise, and also excretion channels for epigenetic fluids. The intersection of multiple sets of faults developed around the fold belt of the western margin of the Ordos Basin and the oil and gas dome in the southwest margin is the upward drainage channel of the deep reducing fluid or the discharge area of groundwater[68]. Coincidentally, the hidden fault structure in the sandstone-type uranium mine in the Zongkouzi Basin in the southern Beishan Province of Gansu Province is also conducive to ore formation and enrichment as a drainage source in the runoff area[69].

The information contained in sedimentary construction is complex and diverse, and its lithofacies composition reflects the comprehensive characteristics of land crust evolution information, geotectonic environment and geological age at the time of formation. Palaeoclimate is a key condition for the formation of uranium mineralization, oxidation-reduction geochemical environment. The relatively humid paleoclimate of the sedimentary period is a favorable condition for the formation of reducing media in sand and surrounding rock, and the arid-semi-arid climate conditions are necessary conditions for the oxidative transport of uranium-forming minerals from the source area to the reduction zone. Under the background of the overall relatively arid paleoclimate, a primary oxidation zone was formed near the erosion source zone and the top of the flow unit of each layer. In relatively low-lying areas, dispersed organic matter is easily preserved and can form primary gray sandstone, with initial pre-enrichment of uranium[70]. The palaeoclimatic change from temperature and humidity to drought is conducive to the formation of oxidation-reduction sequences, the formation of reducing sand bodies such as organic, pyrite and other reducing sand bodies and the pre-enrichment of uranium. Due to the increase of uranium content in water by evaporation, when the aqueous solution with high uranium content enters the reducing sand body formed in a humid climate, a metagenic uranium deposit is formed after long-term continuous action. For example, in the Songliao

Basin, the paleoclimate has gone through the early Cretaceous warm-humid-semi-dry heat alternating period→ the late Cretaceous dry-humid-humid-warm and humid periodThe dry heat alternating period→ the late Cretaceous dry heat, humid heat period→ Paleogene to Quaternary warm humid subthermal-semi-humid period and other complex evolutionary processes. The dry-hot-humid hot, warm-wet alternating paleoclimate from the Early Cretaceous to the middle Cretaceous is generally conducive to pre-enrichment or synbiotic mineralization of uranium in the formation. The dry hot, semi-arid and warm paleoclimatic environment from the late Cretaceous to the early Paleogene was conducive to the activation and migration of uranium in rocks to form oxygen-containing uranium-containing underground water and the occurrence of metagenetic oxidation and uranium mineralization[71].

The replenishment- diameter- drainage fluid mineralization system mainly emphasizes the transport of surface oxygen-containing uranium-containing fluids and deep hydrocarbon-containing fluids triggered by tectonic activities, which are used at the edge of paleooil and gas reservoirs (fractures) (Top), the fluid interacts, couples to mineralize, and becomes a complete fluid mineralization system. The "source-sink" system focuses more on the transport path of uranium-containing materials, focusing on clarifying the transport path of uranium source materials in the sedimentary and mineralization stages, which is a supplement to the sandstone-type uranium ore replenishment-path-discharge system. However, the genesis of sandstone uranium ore is complex, and the above theoretical system cannot cover all sandstone-type uranium ore sedimentation types. If the time of uranium source pre-enrichment has multiple time windows, and the geological time span of the oxidation zone is very large, the "ore-rock (sedimentary) time difference" can be further divided into Jurassic, Cretaceous, Paleogene, Neogene paleo oxide zone type; For example, the theory of "seepage to infiltration basin" by Soviet scholars belongs to the hydrodynamic conditions of the paleoregional area under normal uranium mineralization. The establishment of sedimentary system of uranium mineralization is complex and changeable, and the sedimentary system established by the predecessors focuses on different directions, but in summary, the five main line conditions with uranium source as the basis, redox environment as the core, sedimentation construction as the key influencing conditions, transport medium as the carrier, and structural activities as the guarantee are the fundamental conditions running through the whole process of uranium deposition and mineralizationIn addition, it is still necessary to consider the influencing factors such as geotectonics, substrate maturity, new tectonic movement, and regional reduction capacity. Therefore, we urgently need to summarize a more complete theory of uranium deposition system in order to have a more comprehensive understanding of the characteristics of sandstone-type uranium deposits in China.

4. Conclusion

The sedimentary system hypothesis mainly focuses on the five links of "Raw, Accumulation, Deposition, Transport and Preserve" of the sandstone-type uranium ore sedimentation system, considers the various links related to the existing sandstone-type uranium ore sedimentation, sorts out the internal relationship and external evolution of each link, and summarizes the "simplified model of multi-factor uranium mineralization control under complex conditions". Complex conditions mainly refer to the multiplicity of various influencing factors; diversity of conditions affecting mineralization control; The diversified expressions of the five main line conditions of uranium source, redox environment, sedimentary construction, transport medium and structural ore control constitute a complex sedimentary system of sandstone-type uranium ore. The simplified model of multi-factor uranium mineralization control under complex conditions is based on the "source-sink" theory, adding two links, sedimentary construction and structural ore control, and enriching the diversified sources and multi-stage links of related influencing factors, which can be roughly divided into the following five parts:

1) Raw: Uranium ore sources have multiple origins, commonly formed by the accumulation of uranium-rich rock layers in Zhouyuan through complex physical and chemical processes; However, the deep crust is transported to the surface by volcaniclastic rocks.

2) Accumulation: Uranium-rich oxygenated water chemically reacts with shallow reducing hydrocarbons and accumulates in the sandstone layer; or uranium-rich oxygenated water reacts with reducing sand bodies and deposits in situ; Or uranium-rich oxidized water deposited in deep strata is subjected to a chemical reaction by the rolling boiling of reducing hydrocarbon gas from deeper layers to precipitate uranium ion deposition.

3) Deposition: favorable paleoenvironmental changes cooperate to form a favorable sedimentary structure, and the commonly formed "mud-sand-mud" ensures the passage of uranium-rich transport, avoids lateral escape, and is conducive to uranium enrichment and deposition; The excellent permeability and porosity of the central sand body ensure smooth passage while providing sufficient space for uranium storage.

4) Transport: Whether atmospheric precipitation concentrates uranium from the periphery, or migrates to the sedimentary interface through underground runoff, or is carried by deep groundwater, the continuous migration of oxygenated uranium-rich water not only brings sufficient hydrodynamic forces but also brings rich uranium deposition, of course, hydrocarbon-rich reducing liquid is also an essential link.

5) Preserve: The semi-open channel formed by the shallow stratum structure is conducive to the deposition and preservation of uranium, and the formation of stratum fractures provides channels and space for the discharge of hydrocarbon gas-liquid and oxygen-rich uranium-rich water after reaction.

Compared with the traditional complement-diameter-discharge sedimentation system, the influence of sedimentary construction and structural ore control on the enrichment and sedimentation of uranium ore body is fully considered. At the same time, the complex material sources of the "source-sink" system are described in detail, and the tectonic fracture effects of uranium elements other than the transport path are carefully divided and supplemented, and the cyclical mineralization characteristics of multiple periods and sources are added.

5. Discussion

The "simplified model of multi-factor uranium mineralization control under complex conditions" summarized by the sandstone-type uranium sedimentary system "Raw, Accumulation, Deposition, Transport and Preserve" is currently in the stage of superficial hypothesis establishment, and a lot of research work is still needed. At present, the five links of "Raw, Accumulation, Deposition, Transport and Preserve" of the sedimentary system still need to be improved and improved in combination with the formation analysis of the real ore body, and corresponding adjustments or even overturning re-enactment. The next part of the work will be further discussed with modelling, system remodeling, and deep multi-stage, cyclic sedimentary uranium deposits.

References

[1] IAEA at COP26: How Nuclear Energy Can Help Combat Climate Change [EB/OL]. https:www. cnnpn. cn/article/26405.html?hash=35WgGy,2021.

[2] A letter sent to Rt Hon Alok Sharma MP, President, COP26 from Dr Sama Bilbao León,Director General,World Nuclear Association[EB/OL]. https://www. world-nuclear.org/world-nuclearassociation-climate-staements/letter-sent-to-the- cop26-president.aspx, 2021.

[3] Analysis of the development status of China's uranium mining industry and research report on investment prospects (2022-2029)[R]Shenzhen: China Business Industry Research Institute, 2022

[4] The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2021-2040.[EB/OL].https://www.

world-nuclear.org/our-association/publications/global-trends-reports/nuclear-fuel-report.aspx,2021.
[5] World Nuclear Performance Report 2022 Edition[EB/OL].https://world-nuclear.org/our-association/publications/global-trends-reports/world-nuclear-performance-report.aspx, 2022.
[6] Zhang Xiao, Cai Yuqi, Song Jiye, et al. Uranium resource exploration and development dynamics and nuclear energy development strategy in Asia[J]Uranium Geology, 2023, 39(01): 84-100
[7] Zhang Wanliang. The main uranium ore types, characteristics and spatial distribution in China[J].Journal of Geological Prospecting, 2017,32(04):526-534
[8] Kang, HuanChen, Yue-long Li, Da-peng Zhao, Jun-xiang Cui, Fu-rong Xu, Yun-liang.Deep-penetrating geochemistry for concealed sandstone-type uranium deposits: A case study of Hadatu uranium deposit in the Erenhot Basin, North China [J].Journal of Geochemical Exploration: Journal of the Association of Exploration Geochemists, 2020, 211.
[9] Chao L U, Yun-Biao P, Xin-Yang L, et al. Sedimentary Backgrounds of Sandstone-type Uranium Deposits in Western Manite Depression of Erlian Basin[J].Uranium Geology, 2013.
[10] The People's Republic of China nuclear industry standard EJ/T976-96 "Guidelines for granite-type uranium prospecting" [S]
[11] The People's Republic of China nuclear industry standard EJ/T996-96 "Guidelines for Prospecting for Volcanic Rock-type Uranium Ore" [S]
[12] The People's Republic of China nuclear industry standard EJ/T832-94 "Guidelines for prospecting for carbon-silica mudstone-type uranium ore" [S]
[13] The People's Republic of China nuclear industry standard EJ/T920-95 "Guidelines for uranium prospecting in terrestrial sedimentary basins" [S]
[14] Cai Yuqi, Zhang Jindai, Li Ziying, et alOutline of uranium resource characteristics and mineralization law in China[J].Acta Geological Sinica,2015,89(06):1051-1069
[15] JIAO Yangquan, WU Liqun, RONG Hui, et al.Sedimentation, diagenesis and uranium mineralization: innovative discoveries and cognitive challenges in sandstone-type uranium ore research in China[J].Earth Science, 2022, 47(10): 3580-3602
[16] Han Zhongzhong, Lin Zhongxiang, Wu Zhaojian, et al.Collaborative exploration of coal uranium in the Cenozoic basin and suggestions for countermeasures[J].Geological Review, 2022, 68(03):945-954
[17] Zhao Long, Chen Hao, Cai Chunfang, et al.Geochemical characteristics of hydrocarbons in rich mineral sandstones of Qianjiadian uranium deposit in southwest Songliao Basin[J].Geological Bulletin of China,2022,41(Z1): 498-508
[18] Penney. Australian sandstone-hosted uranium deposits[J]. Applied Earth Science, 2012, 121(2).
[19] Dwivedy, K. K. Possibilities of new uranium discoveries in the environs of Domiasiat, Meghalaya, India. In: Recent developments in uranium resources and supply. TECDOC 823, IAEA, Vienna, 1995:145-162.
[20] Hoik G J, Kyser T K, Chipley D,et al. Mobile Pb-isotopes in Proterozoic sedimentary basins as guides for exploration of uranium deposits[J]. Journal of Geochemical Exploration, 2003: 297-320.
[21] Golubev, V.N., Chernyshev, I.V., Kochkin, B.T. et al. Uranium Isotope Variations (234U/238U and 238U/235U) and Behavior of U−Pb Isotope System in the Vershinnoe Sandstone-Type Uranium Deposit, Vitim Uranium Ore District, Russia.[J]. Earth Sci. 2022,33(317-324).
[22] KUBLER M. The sedimentology and uranium mineralization of the Beaufort Group in the BeaufortWest-Fraserburg-Merweville Area,Cape Province[D]. Johannesburg, South Africa: Faculty of Science University of the Witwatersrand, 2015.
[23] Rao, N.K., Sunil Kumar, T.S., and Narasimhan, D. Uraniferous organic matter in the sandstone-type uranium ore from Domiasiat, Meghalaya, India. Jour. Geol. Soc. India, 1995,v.45(4):407-425.
[24] Kaul, R. and Varma, H.M. Geological evaluation and genesis of the sandstone-type uranium deposit at Domiasiat, West Khasi Hills district, Meghalaya, India. Exploration and Research for Atomic Minerals, 1990,v. 3: 1-16.
[25] Wu Liqun,Jiao Yangquan,Mason R,et al. Sedimentological setting of sandstone-type uranium deposits in coal measures on the southwest margin of the Turpan-Hami Basin[J]. China Journal of Asian Earth Sciences 2009, 36: 223-237.
[26] Purnajit Bhattacharjee,M. Rengarajan,S. K. Srivastava,S. Hamilton,R. Mohanty. Palaeochannel-controlled depositional features of the cretaceous lower Mahadek uranium Mineralisation in Umthongkut area, West Khasi Hills, Meghalaya [J]. Journal of the Geological Society of India, 2017, 90(2).
[27] Dhana Raju, R., Panner Selvam and Sinha, R.M.Petrology and geochemistry of the Neoproterozoic South Khasi Batholith and related Granitoids in the Khasi Hills District, Meghalaya, India and their bearing on Uranium mineralization. Exploration and Research for Atomic Minerals, 1996, v. 3: 1-27.
[28] D'cruz, E, Mathur, S.K., Sachan, A.S., Sen, D.B. and Dwivedy, K.K.Depositional systems and their bearing on the ore grade mineralization in Cretaceous Domiasiat Uranium Deposit, West Khasi Hills District, Meghalaya. Mem. Geol. Soc. India, 1996, 37:387-403.
[29] Chen Zuyi, Chen Daisheng, Gu JiangResearch and evaluation of uranium deposits in China (Volume III sandstone-type uranium deposits)[M]Beijing: China Nuclear Industry Geology, 2013

[30] Samuel S. Adams, 1991. "Evolution of Genetic Concepts for Principal Types of Sandstone Uranium Deposits in the United States", Historical Perspectives of Genetic Concepts and Case Histories of Famous Discoveries, Richard W. Hutchinson, Richard I. Grauch.
[31] Qin Yanwei.Characteristics of ancient river valley oxidation zone and uranium mineralization in the Lower Cretaceous Saihan Formation in the Basaiqi area of the Erlian Basin [D]. Jilin University, 2022
[32] E.N. Hashman.Uranium deposits in Wyoming and South Dakota [J].Foreign Radioactive Geology, 1974, No.12(03): 21-32
[33] Wang Zhengbang.Geological development status and prospect of foreign ground immersion sandstone-type uranium ore [J].Uranium Geology, 2002, (01): 9-21
[34] Xiong Fuqing, Sun Xitian, et al. Перельман.Water-formed uranium deposits [M]. transXi'an: Northwest Bureau of Geology of Nuclear Industry, 1995
[35] Petrov.N.N.,Yazikov.V.G.,Aubakirov.H.B.,Plenanov.V.N.,Vershkov.A.F.. Luhtin.V.F.,Uranov LocationKazakhstana (Экзогенные), AlmatыГЫЛЫМ,1995.
[36] Karimov.H.K.,Bobonorov.N.S., Brovin.K.G.Goljdshtein.R.I., Korsakov.Yu.F.,A.P.Mazurkevich,B.I. Natalchenko, E.A. Tolstov,E.M. Shmariovich, UchkudukskiyTipUranovikhPlace of births Pecpubliku Uzbekistan, Tashkent, Publikuduki Ti pUranoviy Uzbeki Республики Uzpubliki Ресбублиkу, 1996.
[37] Максимова, Шмариович .Interlayer infiltration mineralization [M]Xia Tongqing, Pan Naili, transXi'an: Northwest Bureau of Geology of Nuclear Industry, 1995
[38] Zhao FengminGeology of uranium ore in Russia [M].Beijing: Beijing Institute of Geology, 2006
[39] Zhang JindaiInnovation and development of sandstone-type uranium mineralization theory in China[J].Uranium Geology, 2016, 32(06):321-332
[40] Wen-Bo Z , Xiao H , Yang L I ,et al.Sedimentary System of Sandstone-Type Uranium Deposits and Its Relationship with Uranium Mineralization——A Case Study of Beier-Wuerxun Depression[J].Journal of East China University of Technology(Natural Science), 2019.
[41] Chen Daisheng, Liu Wusheng, Jia Licheng. Paleoclimatic evolution of the Middle Cenozoic era in China and its control effect on sandstone-type uranium ore in basins[J].Uranium Geology,2011,27(06):321-326+344
[42] LI Ziying, FANG Xiheng, QIN Mingkuan, et al.Uranium mineralization in sandstone in northern Ordos Basin[M].Beijing:Geological Publishing House,2019:92-116,175-203
[43] Wang Mou, Li Shengfu.Discussion on the influence of tectonic interaction on sandstone-type uranium deposits in the inter-layer oxide zone of the southern margin of the Ili Basin[J].World Journal of Nuclear Geology, 2006, (04): 199-203
[44] Chen X H , Gong E P , Zhao Z H ,et al.Analyzing the Sedimentary System of Sandstone-Type Uranium Deposits in the Pingzhuang Basin[J].Journal of Northeastern University, 2011, 32(4):583-586.DOI:10.3724/SP. J.1011. 2011. 00415.
[45] Tor T S, Helland H W, Martinsen O J, et al. Relationships between morphological and sedimentological parameters in source-tcrsink system:A basis for predictingsemi-quntitative chearacteristics in subsurface systems[J]. Basin Research, 2009, 21:361-387.
[46] Wang Xingxing, Zhu Xiaomin, Song Shuang, et al.The "source-sink" system of the lower section of Shasanxia of the Shahe Street Formation in the Paleogene Shahe Street Formation in the Chexiwa Depression Steep Slope Zone of the Bohai Bay Basin[J].Journal of Palaeogeography, 2016,18(01):65-79
[47] Xu Changgui.Principle of source-sink spatiotemporal coupling sand control in continental fault basins: basic ideas, conceptual systems and sand control modes[J].China Offshore Oil and Gas, 2013, 25(04): 1-11+21+88
[48] Lin Changsong, Xia Qinglong, Shi Hesheng, et al.Geomorphological evolution, source-sink process and basin analysis[J].Earth Science Frontiers,2015,22(01):9-20
[49] Chen Anqing, Zhang Xiaoxing, Mi Wentian, et alCharacteristics of sand bodies and accumulation mode of concentrated sand accumulation in the Middle Jurassic Zhiluo Formation in the southwest of the Ordos Basin[J].Journal of Earth Sciences and Environment,2019,41(05):517-528
[50] JIAO Yangquan, WU Liqun, PENG Yunbiao, et al.Comprehensive analysis of sedimentary-tectonic background of sedimentary uranium formation and development in the ancient Asian tectonic domain of northern China[J].Earth Science Frontiers,2015,22(01):189-205
[51] HE Feng, LIU Xinyang, LIU Weihong, et al.Study on "source-sink" system of sandstone-type uranium ore in the southwest margin of Ordos Basin[J].Uranium Geology, 2022, 38(04): 671-682
[52] LI Shengxiang, OU Guangxi, CAI Yuqi, et al.Basin fluid and uranium mineralization[J].World Nuclear Geology Science, 2005(01): 24-30
[53] Chen Zhengle, Chen Xuanhua, Wang Xiaofeng, et al.Characteristics and mineralization conditions of geo-leachable sandstone-type uranium deposits[J]. Geology of Mineral Deposits, 2002,21(S1):853-856
[54] Ye Tianzhu, Lv Zhicheng, Pang Zhenshan, et al.Prospecting prediction theory and method in exploration area (general)[M].Beijing: Geological Publishing House, 2014

[55] ZHANG Zilong, FAN Honghai, HE Feng, et al.Analysis of mineralization conditions of Cretaceous uranium in the southwest margin of Ordos Basin[J].Uranium Geology,2018,34(04):193-200
[56] LU Baolong. Uranium mineralization conditions and long-term forecast in the southern Ordos Basin[D]. Northwestern University, 2013
[57] LI Qiang, CHEN Qing, WANG Jibin, et al.Geochemical characteristics of sandstone-type uranium ore elements in the western margin of Qaidam Basin and their geological significance[J].Bulletin of Mineralogy, Petrology and Geochemistry, 2022, 41(06): 1145-1164
[58] LI Ziying, FANG Xiheng, CHEN Anping, et al.Genesis of gray-green sandstone in the target layer of sandstone-type uranium ore in northern Ordos Basin[J].Science in China (Series D: Earth Sciences), 2007(S1): 139-146
[59] Ma Yanping, Liu Chiyang, Si Weiliu, et al.Petrological records of flow-rock interactions in the northeast Ordos Basin indicate hydrocarbon dispersion[J].Journal of Xi'an Shiyou University(Natural Science Edition),2014,29(02):37-42+49+4
[60] Bechtel A,Pervaz M,Püttmann W.1998.Role of Organic Matter and Sulphate-Reducing Bacteria for Metal Sulphide Precipitation in the Bahloul Formation at the Bou Grine Zn/Pb Deposit(Tunisia). Chemical Geology,144(1-2):1-21.
[61] Bonnetti,C.,Cuney,M.,Malartre,F.,et al.,2015.The Nuheting Deposit,Erlian Basin,NE China:Synsedimentary to Diagenetic Uranium Mineralization.Ore Geology Reviews,69:118-139.
[62] Bonnetti,C.,Liu,X.D.,Yan,Z.B.,et al.,2017.Coupled Uranium Mineralisation and Bacterial Sulphate Reduction for the Genesis of the Baxingtu Sandstone-Hosted U Deposit,SW Songliao Basin,NE China.Ore Geology Reviews,82:108-129.
[63] HUANG Shaohua,QIN Mingkuan,XU Qiang,HE Zhongbo,GUO Qiang.Hydrocarbon fluid action characteristics and uranium mineralization significance of Xishan kiln formation in the northwest margin of Junggar Basin[J].Earth Science,2019,44(09):3060-3073
[64] ZHANG Bo,MIAO Peisen,XIAO Keyan,LI Jianguo,ZHAO Hualei,CHEN Yin,TANG Chao,Si Qinghong, Zhu Qiang.Geological characteristics, mineralization law and prospecting mark of Pengyang uranium ore in the southwest margin of Ordos Basin[J/OL].Acta Geologica Sinica, 2023: 1-12
[65] HUANG Shaohua,QIN Mingkuan,ZHOU Wenbo,LIU Zhangyue,LIU Tong,ZHAO Zhiwei,DONGYANUranium mineralization conditions, characteristics and genesis of sandstone in the lower section of the Yimin Formation of the Kerulun Sag in Inner Mongolia[J].Journal of Earth Sciences and Environment,2020,42(02):199-214
[66] HUANG Shaohua,LI Jimu,LIU Zhangyue,LIU Jialin,DONGYAN,GENG Yingying,LIU Mengkui.Uranium storage status and mineralization age in the lower section of the Yaojia Formation in the HLJ uranium belt in Qianjiadian depression[J].Uranium Geology, 2022, 38(04): 631-642
[67] Xiao Wei. Positioning conditions and mineralization mechanism of Fuda granite-type uranium ore in southern Zhuguang [D].Beijing Institute of Geology, 2022
[68] Yu Ren'an, Jin Ruoshi, Li Tong, etc. Analysis of geological conditions and key ore control elements of sandstone-type uranium ore mineralization in Ordos Basin[J/OL].Acta Geologica Sinica, 2023: 1-18
[69] DAI Pengfei,LU Baolong,WANG Gang,NIU Ting,HE Feng.Analysis of sandstone-type uranium ore mineralization conditions and prospecting potential in Zongkouzi Basin in southern Beishan, Gansu Province[J].Journal of East China University of Technology (Natural Science Edition), 20 22, 45(04): 363-371
[70] Weng Haijiao, Zhang Shaohua, Liu Xin, etc. Study on sandstone-type uranium ore reservoir structure and uranium mineralization in southern Songliao Basin[J/OL].Geological Bulletin, 2023: 1-14
[71] Ning Jun, Li Jimu, Lu Tianjun,Tong Shumin,Zhang Liangliang,Wang Haitao,Huang Shaohua.Characteristics of clay minerals in the lower section of the Yaojia Formation of Hailijin uranium deposit in the southern Songliao Basin and its uranium mineralization significance[J].Uranium Geology, 2023, 39(02): 188-201