Multistage Enrichment of the Sawafuqi Uranium Deposit: New Insights into Sandstone-hosted Uranium Deposits in the Intramontane Basins of Tian Shan, China

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Abstract: Meso-Cenozoic intracontinental orogenic processes in the Tian Shan orogenic belt have significant effect on the sandstone-hosted uranium deposits in the intramontane basins and those adjacent to the orogen. The Sawafuqi uranium deposit, which is located in the South Tian Shan orogenic belt, is investigated to reveal the relationships between uranium mineralization and orogenies. Recent exploration results show that the Sawafuqi uranium deposit has tabular, stratiform, quasi-stratiform, and lens-like orebodies and various geological characteristics different from typical interlayer oxidation zone sandstone-hosted uranium deposits. Systematic studies of ore samples from the Sawafuqi uranium deposit using a variety of techniques, including thin section observation, α-track radiograph, electron microprobe and scanning electron microscope, suggest that uranium mineralization is closely related to pyrite and organic matter. Mineralization-related alterations in the host rocks are mainly silicification and argillation including kaolinite, illite (and illite-smectite mixed layer) and chlorite. Three stages of mineralization were identified in the Sawafuqi uranium deposit: (i) uranium-bearing detritus and synsedimentary initial pre-enrichment; (ii) interlayer oxidation zone uranium mineralization; and (iii) vein-type uranium mineralization. The synsedimentary uranium pre-enrichment represents an early uranium enrichment in the Sawafuqi uranium deposit, and interlayer oxidation zone uranium mineralization formed the main orebodies, which are superimposed by the vein-type uranium mineralization. Combining the results of this study with previous studies on the Meso-Cenozoic orogenies of South Tian Shan, it is proposed that the synsedimentary uranium pre-enrichment of the Sawafuqi uranium deposit was caused by Triassic Tian Shan uplift, and the interlayer oxidation zone uranium mineralization occurred during the Eocene-Oligocene period, when tectonism was relatively quiet, whereas the vein-type uranium mineralization took place in relation to the strong orogeny of South Tian Shan since Miocene.

Key words: South Tian Shan, intracontinental orogeny, Sawafuqi uranium deposit, multistage uranium mineralization

1 Introduction

Typical sandstone-hosted uranium orebodies formed by interlayer oxidation are roll- or quasi-roll-shaped and were first described in the Colorado Plateau, U.S.A (Wright, 1955; Shawe, 1956), with the uranium grade in the ores ranging from 0.02% to 0.07% (OECD, 2008). Generally, during diagenesis, hexavalent uranium is reduced by organic matter and pyrite formed in the sandstones, organic acids produced in mudstones, and oil and gas ascended from the deeper parts of basins, and uranium minerals precipitate, forming tabular or roll-shaped uranium orebodies along the redox front (Granger et al., 1961; Saucier, 1980; Turner-Peterson and Fishman, 1986). Organic matter present in the form of hydrocarbons can produce secondary reduction and enrichment of high-
grade uranium ores (Crawley et al., 1985; Granger and Santos, 1986; Rieger et al., 2008; Beata et al., 2009; Fuchs et al., 2015). For example, sandstone-hosted uranium deposits in the northeastern Ordos Basin, China, underwent multistage uranium mineralization, including phreatic oxidation, interlayer oxidation, and modification by hydrocarbon-bearing fluids that enriched the uranium ores (Li et al., 2005; 2006). The mixing of fluids from different sources and, especially, the uranium mineralization owing to hydrothermal fluids, has attracted attention of a number of researchers (Li Ziyang et al., 2006; Wu et al., 2007; Du Letian and Ou Guangxi, 2007; Nie Fengjun et al., 2010; Chi and Xue, 2014; Jin Ruoshi et al., 2014; Zhang Chengyong et al., 2015; Cao et al., 2016; Jiao et al., 2016; Bonnetti et al., 2017; Zhang et al., 2017).

The South Tian Shan orogeny started with the collision between the Tarim and Junggar blocks in Late Devonian–Early Permian, with multistage uplift and erosion since then (Gao et al., 1998; Bullen et al., 2001; He Guoqi et al., 2001; Shu et al., 2002; Biske and Seltsmann, 2010; Han et al., 2010; Charvet et al., 2011). The stress state that fluctuated between compression and relaxation formed the structural–metamorphic–hydrothermal metallogenic system. Large-scale mineralization occurred during the orogeny (Zhai Yusheng, 1996; Deng Jun et al., 2000; Hou Zengqian, 2010). Fluids originating from the junction between the orogen and the foreland basin carried heat, metallic elements and organic matter migrated to the basin and formed huge metal sulfide deposits as well as stratabound sandstone-hosted uranium deposits at the basin edge (Mitchell and Garson, 1981; Oliver, 1992; Hou Zengqian et al., 2004; Leach et al., 2005). Thus, the Tian Shan Mountain uplift in the Mesozoic and Cenozoic have been related to the formation of intramontane basins as well as the generation of mineral deposits such as sandstone-hosted uranium and stratabound Pb–Zn deposits (Hendrix, 2000; Bullen et al., 2001; Smieja-Król et al., 2009). Although the uranium mineralization in the Chu-Sarysu and Syr Darya basins in south-central Kazakhstan has been attributed to the Tian Shan orogeny (Jaireth et al., 2008; Chi and Xue, 2014), few have studied the role of orogeny-related hydrothermal activity in the sandstone-hosted uranium deposits.

The Sawafuqi uranium deposit in South Tian Shan is the only large-scale sandstone-hosted uranium deposit in the Jurassic strata in China. Recent exploration results have shown that the deposit comprises tabular, stratiform, quasi-stratiform, and lens-like orebodies that differ from typical sandstone-hosted uranium deposits (Fang Minqiang, 2010; Wu Kongyun et al., 2010). The ore thicknesses and grades gradually increase downward, with uranium grade higher than 1.0% in some sandy conglomerate-type ores (Liu Zhangyue, 2008a; Shen Pingxi, 2010a). However, no consensus has been reached on the genesis of the deposit. Most researchers believe that the orebodies formed at the interlayer oxidation front and their spatial distribution is controlled via lithology and the oxidation zone (Wu Kongyun et al., 2010; Shen Pingxi, 2010b; Lin Xiaobin et al., 2013). Others, however, argue that the uranium mineralization is mainly controlled by pyrite and organic matter, and the uranium deposit may be associated with oil and gas (Chen Hongbin et al., 2007). In this paper, detailed petrographic analysis of the ores and host rocks was carried out in combination with α-track radiography, electron microprobe analysis (EPMA), and scanning electron microscopy (SEM), in order to study the mechanisms of enrichment of the Sawafuqi uranium deposit. The paper aims to study the role of orogeny in the formation of the Sawafuqi uranium deposit and, specifically, the relation between intracratonic orogeny and sandstone-hosted uranium deposits.

2 Metallogenic Background

The Sawafuqi uranium deposit is located in the Kurgan Intramontane Basin, in the South Tian Shan orogenic belt. The Kurgan Intramontane Basin is the result of the continuous evolution of the Tarim Basin owing to the collision of the Yining–Central Tian Shan landmass and the Tarim Plate in Late Paleozoic (Zhu et al., 2008; Gao et al., 2011). This 58 km long (EW) and 2–4 km wide (NS) basin was initially a part of the Tarim Basin and became an intramontane basin separated from the Tarim Basin during the uplift of the region. The Kurgan Basin is bound by a piedmont fault (F1) to the north, where Carboniferous (C) strata and Hercynian granites (τ_{4C}) are exposed, and by the Mansuetage Uplift and the Sinian Sawafuqi Group (Z_{3sw}) to the south bordering the Tarim Basin. The Lower Permian Xiaotikanlike Formation (P_{1xq}), in the southwest of the Kurgan Basin, is dominated by volcanic rocks. The basement comprises Carboniferous and Lower Permian rocks. The basin cover includes the Middle–Upper Triassic Xiaoquangou Formation (T_{2xq}), the Jurassic (J) and Lower Cretaceous Yageliemu Formation (K_{1y}), the Pliocene Atushi Formation (N_{2x}), and Quaternary diluvial and glacial sediments (Q_{4d}) (Liu Zhangyue et al., 2011) (Fig. 1).

The northern boundary of the Kurgan Intramontane Basin is marked by the F1 fault, which runs through the northern margin of the Tarim Basin and constitutes the boundary between the Tarim Plate and South Tian Shan. The fault not only controls the piedmont slope but also affects the monoclinical structures of the northern Tarim Basin. The piedmont slope, through controlling the
Fig. 1. (a). General tectonic map of the Tianshan orogenic belt and adjacent areas (modified from Gao et al., 2011; Yang et al., 2017); (b). Geological map of the Kurgan Intramontane Basin and location of the Sawafuqi uranium deposit; (c). Cross section of the Sawafuqi uranium deposit (modified from Liu Zhangyue et al., 2008a).
groundwater flowing from South Tian Shan, is critical to the formation of the sandstone-hosted uranium deposits. The southern boundary of the Kurgan Intramontane Basin is controlled by the F2 thrust fault that has an intermittently exposed fault plane along strike. The F1 and F2 faults control the formation and evolution of the Kurgan Intramontane Basin and are critical to the formation of the Sawafuqi uranium deposit.

The Jurassic sequence, which has a maximum thickness of more than 700 m, is composed of the Lower Jurassic Qixingbulake Formation, the Middle-Upper Jurassic Tiemiersu Formation and the Upper Jurassic Qigu Formation (Fig. 2). The 240-m-thick Qixingbulake Formation is composed of conglomerates, sandy conglomerates, and interbedded medium- to coarse-grained sandstones. A sequence of thick-bedded conglomerates marks the base of this formation, with poor roundness and sorting, representing alluvial fan sediment. The Tiemiersu Formation has a thickness of 245 m and is divided into two members (J2-3tm1 and J2-3tm2). The 89-m-thick lower member is mainly interbedded by conglomerates, sandy conglomerates, medium-grained sandstones and mudstones in unequal thickness, with two thin coal seams. Cross-beddings are observed locally. The 156-m-thick upper member is characterized by three thick-bedded sandy conglomerate sequences of braided river and three sandy mudstone sequences of swamp with interbedded carbonaceous shales and two thick coal seams. The Tiemiersu Formation can be divided into five coarse-to-fine sedimentary cycles. The Qigu Formation is composed of 216-m-thick red mudstones of lacustrine facies, with a base of thin-bedded sandy conglomerates and sandstones. Horizontal beddings were observed.

### 3 Uranium Mineralization

The Sawafuqi uranium deposit is hosted in the coal-bearing clastic rocks of the Middle–Lower Jurassic Tiemiersu Formation, where ten uranium orebodies from south to north are located and four industrial grade uranium orebodies are developed (UII-1, UII-2, UII-3 and UII-4) (Fig. 2). The ore-bearing rocks are predominantly conglomerates and coarse, medium, and fine sandstones. The host sandstones contain abundant carbonaceous debris (Fig. 3a), organic matter veins (Fig. 3b) and pyrite (Fig. 3c). Total organic carbon is 0.50%–0.54% and total sulfur is 0.35%–0.39% (Liu Zhangyue et al., 2008b).

Cracks are common in the host rocks owing to the F1 Fault and are filled by both silica-rich and organic material, especially between the sandstones and coal beds. The silica-rich veins in the coal seams are strongly deformed. The veins filled with organic material in the

![Fig. 2. Generalized stratigraphic column of the Jurassic strata in the Sawafuqi uranium deposit (modified from Liu Zhangyue et al., 2008a).](image-url)
sandstones are cut by silica-rich veins (Fig. 3d). The uranium mineralization is closely related to the organic material and pyrite. The ore beds are steeply inclined 55°–85° and are reversed in the northern mining area.

Compared with typical sandstone-hosted uranium deposits with obvious red interlayer oxidation zones, no clear red or yellow oxidation zones are present in the host sandstones. However, there are numerous yellowish red residual oxidation stripes or spots in the grayish-white host rocks (Fig. 3e). The orebodies are stratiform, quasi-stratiform, tabular, with variable thicknesses, and few are lenticular, but no roll-shaped orebodies are present (Fig. 4). EW-striking uranium mineralization is present in EW-striking sandstones adjacent to mudstones or coal seams.

Uranium mainly exists as absorbed uranium and uranium minerals. Uranium is mainly absorbed by organic matter, iron-titanium oxides, and clay minerals. Uraninite is common and is associated with poorly crystalline pyrite and organic-matter-filled veins (Chen Hongbin et al., 2007; Shen Pingxi, 2010a).

4 Sample Collection and Analytical Methods

4.1 Sample collection

Ore-bearing sandstone and conglomerate samples from drill (cutting through UII-1 and UII-2) cores were collected. An HD-2000 hand-held gamma radiometer, manufactured by the Beijing Research Institute of Uranium Geology, CNNC, was used to first scan samples from drill cores. The scanning time was 10 s, and ore-bearing samples with more than 30 nC·kg⁻¹·h⁻¹ (Gamma radiation exposure rate) were collected.
4.2 Analytical methods

First, the caked mud on the surface of the drill core samples was removed. Then, the samples were washed with distilled water, and then cut and polished into thin sections roughly 0.05 mm thick. A Carl Zeiss Axioskop 40 polarizing microscope was used to study the polished thin sections. Thin sections rich in uranium minerals were further examined with EPMA using a JXA-8100 microprobe (JEOL Ltd.). ZAF corrections were used for the correction procedure. The operating conditions were: acceleration voltage 20 kV, current intensity 10 nA, and beam diameter 1 μm.

After EPMA, the carbon-coated thin sections were polished again to remove the carbon coating, cleaned with alcohol, and dried in air. Nuclear emulsions were evenly applied to the clean and dry thin sections in a darkroom before placing into a black case for α-track formation (approximately 15 days). Finally, the α-track distribution, density, and pattern were observed under a microscope.

Sample processing and analysis were conducted at the Beijing Research Institute of Uranium Geology, CNNC. Uranium minerals in sandstone-hosted uranium deposits are relatively microcrystalline and commonly fill the intergranular pores. They are easily damaged and difficult to preserve during grinding. Thus, in this study, in situ SEM was used to study the uranium ores at the Research Institute of Petroleum Exploration & Development’s Experimental Research Center. First, areas with relatively well-developed veins filled with organic matter, pyrite, and clay minerals that are closely related to uranium minerals were selected for SEM EDS analysis using a TESCAN-VEGA II LMU SEM with a LINK-ISISX alpha particle spectrometer. The SEM was operated at 15 kV in high-vacuum mode, with manual aperture and 4.5 beam spot size. To improve the quality of the analyses, all the samples were covered by sputtering a thin Au coat to ensure surface conductivity.

5 Results

5.1 Uranium ore mineralogy

The detrital grains of the sandstone ores are mainly composed of metamorphic and igneous quartz, generally brown and occasionally mottled by iron staining, as single crystals or polycrystalline aggregates with compaction fractures (Fig. 5a). There is also authigenic quartz that occasionally overgrows detrital quartz grains (Figs. 5b and 5c), presumably owing to silica-rich or acidic fluids. Feldspar grains were rarely observed. Metamorphic rock and volcanic tuffaceous detritus (e.g., sandy mudstone, argillaceous sandstone, slates, granites, volcanic tuff) are present.

Pyrite is commonly found in the cement or carbonaceous debris and is roughly divided into two types based on crystal morphology. Crystalline pyrite forms cubes, pentagonal dodecahedra (Fig. 5d), and strawberry-like grains (Fig. 5e) and mainly coexists with organic matter, finely dispersed in the cement and intergranular pores. The cubic pyrite occasionally has uraninite in the center (Fig. 5f). Subhedral pyrite is observed in intergranular pores and cement particles (Fig. 5g), and is closely associated with uranium mineralization.

Carbonized plant debris, with visible plant cellular structure (Fig. 5h), is parallel to bedding. In contrast, externally derived organic matter is present in veins and cracks (Fig. 5i), filling the intergranular pores and microcracks that cut the bedding. Carbonaceous debris is common in the sandstones, whereas organic matter veins are relatively common in the mineralized conglomerates and sandstones.

Uraninite is the dominant uranium mineral, and uranium is also absorbed in clays and carbonaceous debris. Based on α-track radiography, the α-tracks generated by the absorbed uranium are relatively short, sparse, and disorderly (Figs. 5j and 5k). In contrast, the α-tracks generated by uraninite form a dense radial pattern around the uranium minerals (Fig. 5l).

5.2 Alteration and uranium mineralization

5.2.1 Clay alteration

Feldspar and mica minerals in the ore-bearing sandstone are replaced by clay minerals. The alteration types are kaolinization, illitization (mixed illite-smectite), and chloritization.

Kaolinization is common in all ores. It is associated with the cement and occasionally with pyrite and iron-stained spots. Kaolinite in intergranular pores is flaky and vermicular (Fig. 6a). Most kaolinite grains cover the surface of quartz or are distributed in fieldspar dissolution pores (Fig. 6b). Kaolinization generally indicates the acidified front of the interlayer oxidation zone, spatially close to the redox front (Devoto, 1978; Harshman, 1972).

Illite and smectite commonly occur in mixed layer with disseminated pyrite that is locally oxidized and iron-stained. Illitization affects the carbonaceous debris and quartz, and is associated with uranium minerals (Fig. 6c). SEM analysis suggests that illite replaces K-feldspar and is observed on detrital grain surfaces and filling intergranular pores (Fig. 6d). Illitization is associated with the oxidation zone or the redox front. The ore-forming acidic fluids may have changed to alkaline as the oxidizing uranium-bearing fluids migrate to the reduced zone. Illitization is referred to be produced in this transition that signifies the commencement of uranium
Chlorite is fibrous and replaces intergranular matrix (Fig. 6e), carbonate cements (Fig. 6f) and mixed illite-smectite (Fig. 6g). Based on the sequence of metasomatic minerals, chloritization occurs after kaolinization and illitization, and is commonly the product of epithermal alteration (Nutt, 1989; Komninou and Sverjensky, 1995; Li et al., 2007; Zhang et al., 2017).

5.2.2 Silica-rich veins
Silica-rich veins, consisting of microcrystalline or amorphous quartz, are common in the host rocks and are observed in the intergranular pores, cement, and fractured detritus. The silica-rich veins are impure and may contain pyrite, clay minerals, and uraninite (Fig. 6h). SEM images show that such silica-rich veins consist of amorphous quartz and uraninite (Figs. 6i and 6j). The silica-rich veins cut the organic matter veins (Fig. 6k), the clay minerals or string-shaped uraninite veins (Fig. 6l), and clearly formed after the main uranium mineralization.

5.3 Uranium mineralization
Three stages of uranium mineralization were identified in the Sawafuqi uranium deposit: (i) uranium-bearing...
detritus and synsedimentary pre-enrichment; (ii) interlayer oxidation zone uranium mineralization; and (iii) vein-type uranium mineralization.

5.3.1 Synsedimentary uranium pre-enrichment

Synsedimentary uranium pre-enrichment is attributed to the sedimentation of uranium-bearing detritus. The uranium-bearing detritus comprises metamorphic quartz and slate grains, and is attributed to denudation, transport, and sedimentation from preexisting uranium deposits in the source area. Within the uranium-bearing detritus, uraninite exists as microparticles or aggregates (Figs. 7a–7c). Compared with epigenetic infiltration-type uranium mineralization that forms either string-shaped uraninite that fills intergranular pores or fractures or massive uraninite that precipitates around reducing agents, the detrital uraninite is sparse and does not fill fractures. Thus, such uraninite grains do not belong to the infiltration-type uranium mineralization and are likely transported from the provenances. EPMA analysis shows that the UO₂ content in these uraninite grains is between 78.1% and 92.9%, SiO₂ is between 0.6% and 10.0%, FeO is between 0.5% and 0.6%, and there are small amounts of K, Na, Y, Ca, Ti, and P. Totals of the analyzed elements are between 98.3% and 100% (Table 1). In general, this type of uraninite is relatively pure.
5.3.2 Interlayer oxidization zone uranium mineralization

The interlayer oxidization zone mineralization is the most common mineralization type in the Sawafuqi uranium deposit. Uraninite aggregates commonly fill the intergranular pores, forming strings of single particles of several μm (Fig. 7d). Uranium mineralization is closely related to pyrite and carbonized plant debris. Uraninite precipitates around pyrite (Fig. 7e) and carbonaceous debris (Fig. 7f), and fills the plant cells (Fig. 7g). EPMA analysis shows that the UO₂ content in such type of uraninite is between 53.2% and 59.6%, SiO₂ is between 1.9% and 4.3%, FeO is between 5.5% and 11.1%, and there are small amounts of K, Na, Al, Y, Ca, P, and Cr. Due to the small size of the uranium minerals, the totals of the analyzed elements, affected by surrounding gaps or carbonaceous debris, are between 74.8% and 86.4%, much lower than 100% (Table 1). Compared with synsedimentary uraninite, the purity of the uraninite formed in this stage is low, with markedly high Fe and low Si contents.

5.3.3 Vein-type uranium mineralization

The vein-type uranium mineralization is closely associated with the silica-rich veins. Fine uraninite grains are dispersed in the silica-rich veins (Fig. 6j). In addition, the irregular uraninite aggregates associated with intrusion of the organic matter veins occasionally fill the intergranular pores and cement the debris (Fig. 7h). Furthermore, the uraninite and pyrite grains are part of the cement, in which uraninite forms block in cubic pyrite or intermingles with poorly crystallized pyrite (Fig. 7i). EPMA analysis shows that the UO₂ content in these uraninite grains is between 72.5% and 87.7%, SiO₂ is between 2.1% and 5.2%, FeO is between 0.7% and 4.2%, TiO₂ is between 2.7% and 3.6%, and there are small amounts of K, Na, Al, Ca, P, and Cr. Due to the small size of the uraninite minerals, the totals of the analyzed elements, affected by surrounding gaps or carbonaceous debris, are between 74.8% and 86.4%, much lower than 100% (Table 1). Compared with the interlayer oxidization zone uranium mineralization, this type of uraninite has high U purity, low Fe, and high Ti contents.

6 Discussion

6.1 Uranium mineralization sequence

Based on the above, the formation sequence of uranium and alteration minerals is listed in Table 2. It can be concluded an obvious formation sequence among the alteration minerals and three uranium mineralization stages.

A large number of well-rounded and uraninite-bearing detrital grains are present in the host rocks, in which
Uraninite occurs as irregular aggregates that are interpreted to have been transported from elsewhere and deposited. It is therefore referred to as the synsedimentary mineralization stage, which contributes to the early uranium pre-enrichment of the deposit.

Macroscopic observations suggest that there are numerous yellowish red interlayer oxidation residues in the grayish white host sandstones. It is interpreted that the interlayer oxidation zone has been bleached and replaced by intense kaolinization. Uranium mineralization is attributed to infiltration by the interlayer oxidation groundwater and is closely associated with pyrite and carbonized plant debris, and is typically characterized by continuous string-shaped uraninite particles filling intergranular pores and forming the main uranium orebodies in the Sawafuqi uranium deposit.

Both macroscopic and microscopic observations suggest that the host rocks have suffered from silica-rich vein superimposition, with numerous silica-rich veins cutting organic matter veins or string-shaped uraninite.

Table 2 The formation sequence of uranium and alteration minerals in the Sawafuqi uranium deposit

<table>
<thead>
<tr>
<th>Mineralization stages</th>
<th>Uranium minerals</th>
<th>Alteration minerals</th>
<th>Major associated elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synsedimentary uranium pre-enrichment</td>
<td>Uraninite microparticle and aggregate in the detritus.</td>
<td>Carbonate and clay cement.</td>
<td>Si, Ca, Ti</td>
</tr>
<tr>
<td>Interlayer oxidation zone uranium mineralization</td>
<td>String-shaped uraninite filling intergranular pores or plant cells.</td>
<td>Kaolinite replacing feldspar.</td>
<td>Fe, S, Si</td>
</tr>
<tr>
<td></td>
<td>Uraninite absorbed by carbonaceous debris and clay.</td>
<td>Biotite and I/S mixed layer replacing primary carbonaceous debris, matrix and other detritus.</td>
<td></td>
</tr>
<tr>
<td>Vein-type uranium mineralization</td>
<td>Uraninite in cubic pyrite.</td>
<td>Organic matter veins.</td>
<td>Si, Ti, Fe</td>
</tr>
<tr>
<td></td>
<td>Uraninite associated with silica-rich and organic matter veins.</td>
<td>Cubic and subhedral pyrite.</td>
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<td></td>
<td></td>
<td>Kaolinite.</td>
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<td>Chlorite replacing I/S mixed layer, primary carbonate and matrix.</td>
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<td>Silica-rich veins cutting string-shaped uraninite, organic matter veins and clay cement.</td>
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Fig. 7. Uranium mineralization types and spatial distribution of uraninite in the ores.
(a), Uranium-bearing detritus with brightly dotted uraninite. (b), Uranium-bearing metamorphic quartz with brightly dotted uraninite. (c), Micro-fine uraninite particles in the quartz detritus and electron microprobe measurement points. (d), String-shaped uraninite filling the intergranular pores and electron microprobe measurement point. (e), Uraninite precipitating around pyrite and electron microprobe measurement points. (f), Carbonaceous debris with bright uraninite. (g), Uraninite filling plant cells. (h), Uraninite cementing detritus and electron microprobe measurement points. (i), Uraninite in subhedral pyrite and electron microprobe measurement points.
grains, and chloritization. The yellowish red interlayer oxidation zone was bleached by the silica-rich fluids. The uranium mineralization owing to such superimposition is mostly associated with the silica-rich veins and is characterized by high U and Ti, and low Fe content. The first two stages of uranium mineralization were superimposed by silica-rich veins that formed high-grade tabular uranium orebodies.

The three stages of uranium mineralization, especially the silica-rich vein superimposed uranium mineralization, are uncommon in sandstone-hosted uranium deposits. The Sawafuqi uranium deposit, in the Kurgan Intramontante Basin, is attributed to tectonic deformation and presumably is directly associated with the South Tian Shan orogeny.

6.2 Mesozoic–Cenozoic uplift and erosion in South Tian Shan

Gao Zhiyong et al. (2015) reviewed data and identified four uplift stages in the South Tian Shan Mountain since Mesozoic: (i) the first uplift occurred in Late Triassic–Early Jurassic approximately 220–180 Ma ago; (ii) the second uplift occurred in the Late Jurassic–Early Cretaceous approximately 150–100 Ma ago; (iii) the third uplift occurred in the Late Cretaceous–Eocene approximately 95–45 Ma ago; and (iv) the fourth uplift occurred in the Miocene–Quaternary approximately 25 Ma ago. The uranium mineralization ages for the different sandstone-hosted uranium deposits in intramontane basins and those adjacent to the Tian Shan Mountain from China to Central Asia are 76 Ma, 48–21.4 Ma, and 7 Ma (Chen Zuyi et al., 2010). These ages are interpreted to represent the tectonically quiescent stages, namely, the deplanation period after the uplift (Liu Hongxun et al., 2009; Chen Zuyi et al., 2010). Tectonically quiescent setting is favorable for long-term infiltration of uranium-bearing groundwater into host rocks and producing sandstone-hosted uranium deposits. It is thus proposed that the uranium mineralization was driven by the uplift.

6.3 Synsedimentary uranium pre-enrichment

The detritus of the host rocks of the Sawafuqi deposit comprises metamorphic rocks, volcanic rocks, and granites, pointing to complex sources. The Lower Sinian Sawafuqi Group outcrops in the provenance area and is observed in the Mansuertage Uplift to the south of the Sawafuqi uranium deposit. The group consists of thick-bedded siliceous rocks, siliceous–argillaceous slates, sandstones, metavolcanics, and meta-volcaniclastic rocks. These rocks have experienced fragmentation, sericitization, chloritization, epidotization, and silicification to varying degrees. Two uranium occurrences and numerous uranium anomalies developed in the silicified fracture zones. Furthermore, previous investigations have confirmed the high uranium content of the Lower Sinian Sawafuqi Group (21.1–194.9 ppm, with an average uranium content of 61.2 ppm) (Liu Zhangyue, 2008a). It is assumed that the uranium enrichment and mineralization occurred in this stratum during the orogeny related to the accretion of the Qiangtang Block to the southern Tarim Plate and rejuvenation of the Tian Shan orogenic belt (Yin et al., 1988; Graham et al., 1993), which was induced by tectonic-thermal events occurred in South Tian Shan during Triassic period (Hendrix et al., 1994; Lu et al., 1994; Greene et al., 2005; Jolivet et al., 2010). The orogeny subsequently uplifted the Lower Sinian Sawafuqi Group and made it an important source for the Jurassic strata in the Kurgan Intramontante Basin. At the beginning of Jurassic, the Sawafuqi area entered a period of sedimentation after the collision, with a high depositional rate (Jia et al., 1997; Liu Zhangyue et al., 2008b). Such tectonosedimentary features prevented the long-distance transport of the uranium-bearing detritus and consequently the oxidation or dissolution of uraninite. The rapid transport and deposition of uranium-bearing detritus produced the synsedimentary uranium pre-enrichment of the Sawafuqi uranium deposit.

6.4 Interlayer oxidation zone uranium mineralization

Driven by the Kohistan-Dras event in Late Cretaceous, tectonic uplift occurred in the northern margin of the Tarim Basin during the Paleocene (Li et al., 2004; Liu Hongxu et al., 2009; Yu et al., 2014; Yang et al., 2017), when the F1 fault was reactivated and tilted the piedmont Middle–Lower Jurassic host rocks, producing a sloped belt favorable for uranium mineralization. The long-term deplanation during Eocene–Oligocene after the Tian Shan Mountain uplift in the Paleocene caused extensive deposition of shallow lacustrine elastic rocks in the northern margin of the Tarim Basin (Li and Peng, 2010; Yu et al., 2014). Therefore, the Eocene–Oligocene tectonic environment was relatively quiet and conducive to long-term interlayer infiltration and oxidation by uranium-bearing underground water in the host rocks, which provided a stable time interval for interlayer oxidation zone and uranium mineralization. U–Pb ages for the Sawafuqi uranium deposit are 38.9 Ma and 6.6 Ma (Liu Hongxu et al., 2009). The former was from the uranium ore without silica-rich veins, whereas the latter was from the uranium ore with silica-rich veins.

Fluids flowing through the provenance area were rich in HCO$^-$ and slightly alkaline and could dissolve and transport uranyl carbonate ions, such as UO$_2$(CO$_3$)$_2^{2-}$ and UO$_4$(CO$_3$)$_3^{4+}$. The uranium-bearing oxygenated fluids
permeated the interlayer sandstones that were rich in pyrite and carbonaceous debris. Sulfuric and organic acids were produced respectively, which lowered the fluid pH from weakly alkaline to weakly acidic and leached the plagioclase and potassium feldspar grains, producing kaolinization and illitization in the ore. Moreover, as the free oxygen in the fluids was exhausted, the high-valence uranium ($\text{U}^{6+}$) and associated elements in the solution were reduced, concentrated, and precipitated during the relatively enclosed acidification process (Rackley, 1972). It was known from the $\alpha$-track radiography that the carbonaceous debris and clay minerals in the ore absorbed small quantities of uranium that together with uraninite formed the main uranium mineralization stage.

### 6.5 Formation of the vein-type uranium mineralization

Since the Miocene, especially the Pliocene, the collision between the Indian and Eurasian Plates led the northern margin of Tarim Basin to enter a period of strong tectonic deformation (Hendrix et al., 1994; Yang et al., 2017), when the F1 piedmont thrust fault caused the severe deformation of the Middle–Lower Jurassic host rocks and produced stockwork fractures in the Sawafuqi uranium deposit. The fractures in the coal-bearing clastic rocks are mainly filled by organic matter, whereas those adjacent to the F1 fault in Carboniferous and Jurassic strata are filled by silica-rich veins. The above suggest that owing to the intense intracontinental orogeny, deep hydrothermal fluids migrated upward along the F1 fault and altered the coal seams, accelerating the thermal evolution of the coal measures and generating hydrocarbons. The organic matter veins in the coal-bearing clastic rocks may be the product of the thermal metamorphism of the coal seams. According to Grayer (1998), the temperature of the fluids draining from the collisional orogenic belt to the basin can be as high as 300°C, leading coal to progressively change from bituminous coal to anthracite. The vitrinite reflectance (Ro) in the mining area is 0.42%–0.90% (Lu Xiuxiang et al., 2006; Liu Zhangyue et al., 2011), presumably, owing to the non-uniform thermal alteration of the coal seams. Altered by the hydrothermal fluids, the coal seams generated coal-derived liquid hydrocarbons that penetrated into the sandstones adjacent to the coal seams, further dissolving the feldspar grains in the host rocks and forming kaolinite. The latter covered the earlier red or yellowish red interlayer oxidation zone, causing it to fade and bleach (Beitler et al., 2003; Parry et al., 2004). In addition, the hydrothermal fluids altered the interlayer oxidation zone, forming a stockwork of silica-rich veins, quartz overgrowths, organic matter veins, and chlorite alteration in the ore-bearing sandstones. It subsequently led to the uranium redistribution, and thus formed the tabular, stratiform, and lens-like orebodies. The 6.6 Ma is inferred to be the age of the superimposed epithermal uranium mineralization.

### 7 Conclusions

Significantly different from typical interlayer oxidation zone sandstone-hosted uranium deposits, the Sawafuqi uranium deposit is located in the tectonically active area within South Tian Shan, where the uranium orebodies are tabular, stratiform, quasi-stratiform, and lens-like and are characterized by high-grade uranium ore (locally more than 1.0%). Uranium mineralization is closely associated with pyrite and organic matter, especially in scattered anhedral (or subhedral) pyrite and organic matter veins. The mineralization-related alteration in the uranium ores includes kaolinization, illitization, chloritization, and silicification.

The microscopic observations of the uranium ore, combined with EPMA and $\alpha$-track radiography, identified three stages of uranium mineralization in the Sawafuqi uranium deposit: (i) uranium-bearing detritus and synsedimentary pre-enrichment; (ii) interlayer oxidation zone uranium mineralization; and (iii) vein-type uranium mineralization. Uraninite in the uranium-bearing detritus is of high purity, with the UO$_2$ content of 78.1%–92.9%, whereas uraninite formed by the interlayer oxidation zone is of low purity and has high Fe content. Uraninite associated with silica-rich veins is pure and Ti-rich. The primary synsedimentary mineralization stage is responsible for the early uranium pre-enrichment. The interlayer oxidation formed the major uranium orebodies, and the late epithermal fluids redistributed the uranium minerals and formed the superimposed enrichment.

Tectonic activity drove the three stages of uranium mineralization in the Sawafuqi uranium deposit. In the Triassic, the Sinian Sawafuqi Group, with uranium-rich strata, started to uplift and was the main source for the Middle–Lower Jurassic sediments. The rapid transport and deposition of the uranium-bearing detritus resulted in the synsedimentary uranium pre-enrichment of the Sawafuqi uranium deposit. During the Eocene–Oligocene, the stable tectonic setting favored the long-term infiltration of uranium-bearing groundwater that produced the interlayer oxidation zone and the associated uranium mineralization. Since the Miocene, the South Tian Shan entered a period of intense orogeny, and hydrothermal fluids migrated into the host rocks and redistributed the previously formed uranium orebodies, forming numerous silica-rich veins and superimposed uranium mineralization.
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