A Review of the Genetic Mechanism of Megacrystalline Uraninite in the Kangdian Region, China

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Abstract: Naturally occurring granular uranium particles are typically fine and are often found as accessory minerals. However, reports of megacrystalline uraninite are rare. The discovery of megacrystalline uraninite is a significant achievement in uranium prospecting and mineralogy in the Kangdian region and China. Our team’s research and review of previous studies have led to a systematic summary of the formation age, genetic types, relationship with migmatization, and metallogenic dynamic background of megacrystalline uraninite in the Kangdian region. The key findings are as follows: (1) the formation age of megacrystalline uraninite is Neoproterozoic (790–770 Ma); (2) migmatization preceded uranium mineralization; (3) the formation of megacrystalline uraninite is linked to high-temperature, low-pressure metamorphism caused by partial melting; (4) and the formation of megacrystalline uraninite may be associated with the Rodinia rifting event. This review aims to enhance our understanding of uranium mineralization during the Neoproterozoic in China and worldwide.

Keywords: megacrystalline uraninite; uranium mineralization; neoproterozoic; partial melting

1. Introduction

In nature, uranium can combine with various chemical elements, leading to the discovery of uranium and uranium-bearing minerals in different geological environments [1–5]. Uraninite, a significant industrial uranium mineral, serves as the main source of natural uranium ores [6]. It can be categorized into two types based on mineral morphology and characteristics: uraninite formed under high-temperature conditions (granular crystalline uraninite) and pitchblende formed under low-temperature conditions (cryptocrystalline uraninite) [7]. Uraninite is commonly found as an accessory mineral in igneous rocks, especially granite [1,2]. Despite this, research on uraninite has been less extensive than that on pitchblende [4] due to its fine particle size and scattered distribution, with few reports on megacrystalline uraninite [8].

Recently, numerous occurrences of megacrystalline uraninite have been found in migmatites within a 300 km wide area in the Kangdian region of China [9,10]. The most notable features of these occurrences are their large grain sizes, some up to centimeters in scale, and fully formed crystals. Naturally occurring uraninite of such a significant size is exceptionally rare, garnering widespread attention in industry and serving as a compelling research subject for investigating the genesis mechanism of megacrystalline uraninite [11–14]. This article systematically summarizes the formation age, conditions, relationship with migmatization, and metallogenic dynamic background of megacrystalline uraninite based on our team’s research and a comprehensive review of previous studies. It offers valuable insights into the formation and evolution of this unique mineral and
briefly identifies key scientific questions for the future. This review aims to enhance our current understanding of uranium mineralization during the Neoproterozoic period in China and worldwide.

2. Geological Background

The Kangdian region is located on the western margin of the Yangtze Plate and covers parts of the Yunnan and Sichuan provinces [15–19] (Figure 1a,b). The Kangdian region has a complex geological history, characterized by multiple episodes of mineralization. It includes several tectonic units and prominent polymetallic belts containing abundant mineral resources. Therefore, the Kangdian region is an important mineral resource in southwestern China [14,20–22]. The stratigraphy preserved in the outcrops in the Kangdian region is relatively complete, including Proterozoic to Quaternary strata [23–28]. This region contains thick Meso-Neoproterozoic strata, representing some of the most developed Precambrian strata in China. Magma activities in the region are frequent and intense, ranging from deep-seated intrusion to eruption and from basic to ultrabasic to acid to alkaline. Magmatic rocks from the Jinning (a tectonic movement in the middle Neoproterozoic) to Himalayan periods are distributed to varying degrees, forming a complete magma series and a variety of magmatic rock assemblages in the region [29,30].

Since the 1950s, hundreds of uranium occurrences have been discovered in the Kangdian region after more than 70 years of exploration and research. Uraninite was recovered...
from a high-grade metamorphic rock sequence and has been reported in IOCG (Iron Oxide-Copper-Gold) deposits observed in Na-rich metavolcanic and metasedimentary rocks, as well as in low-grade metasedimentary rocks in the Kangdian region [9–14,17,32–34]. Migmatite-type uranium deposits in the western belt of the Kangdian region occur in a high-grade metamorphic rock sequence. This type of uranium mineralization is characterized by host rocks composed of migmatite containing both matrix and vein bodies. The matrix consists of granitic gneiss, mica schist, and plagioclase amphibolite schist, while the vein bodies are primarily felsic or albite. Felsic or albite veins that host mineralization intrude into the migmatite through faults or schistosities, appearing as veins, masses, and lenses. The boundaries between the ore-bearing veins and surrounding rocks are distinct, with little evident alteration of the surrounding rocks [9,14].

3. Uranium Occurrence Overview

3.1. Haita Area

The Haita area is located 10 km west of Miyi County and is primarily exposed to the Wumaqing Formation of the Kangding Group (Figure 1c). The lithology of this formation consists mainly of two-mica schist, biotite schist, biotite plagioclase gneiss, and plagioclase gneiss. Influenced by regional geological activities, these strata are generally metamorphosed, with intense local migmatization resulting in the formation of migmatized biotite quartz schist, biotite-banded migmatite, felsic biotite two-feldspathic banded migmatite, and other rocks. Magmatic activity in the area is mainly represented by Jinning period granite (Dingzhen rock mass). This granite intrudes into the Wumaqing Formation along the axis of the Salian anticline. The fault structures in the area are oriented in a north–south direction, and a nearly north–south ductile shear zone is developed. Three uranium occurrences were discovered in the Haita region: A10, A19, and 2811.

(1) Occurrence 2811 is characterized by the discovery of a lens-shaped quartz vein containing megacrystalline uraninite within the structural fracture zone of a migmatized plagioclase gneiss (Figure 2a). The attitude of the quartz vein is largely consistent with the attitude of the fracture planes. The morphology of perfect uraninite crystals was visible to the naked eye. The uraninite crystals were mainly isometric and granular in shape and distributed in the quartz vein. Most particles were approximately 0.5 cm, and the maximum size can reach approximately 1 cm (Figure 2b,c,e). The content (volume) of uranium generally ranges from 1 to 5%, and locally, it can reach more than 20%. According to the limited trough exploration (depth of nearly 1 m), the content of megacrystalline uraninite tends to increase toward the deep area. Detailed microscopic examination reveals that the main minerals associated with the uraninite are quartz, feldspar, titanite, apatite, brannerite (formed by the alteration of titanite), ilmenite, and minor amounts of biotite and zircon (Figure 2b,c,e).

(2) Occurrence A19 is mainly uranium-molybdenum paragenesis-type uranium mineralization, and the host rocks is felsic (Figure 3a,b). A felsic vein containing uraninite intruded along the schistosity into the plagioclase gneiss. A large number of euhedral dark minerals (pyroxene and amphibole) were found in the felsic veins (Figure 3c), which may have been formed by the metasomatism of the gneiss. Molybdenite minerals were widely distributed in quartz veins, and the mineral assemblage was mainly composed of quartz, feldspar, uraninite, titanite, apatite, and molybdenite (Figure 3d–f).

(3) Occurrence A10 exhibited severe weathering, and only secondary uranium minerals were visible. It was difficult to identify the host rocks and primary uranium minerals. The exposed area on the surface was relatively large, approximately 1 m wide and 10 m long. Uranium mineralization mainly occurs in the felsic vein and is sparsely distributed in the schist at the contact between the dike and the surrounding rocks. Locally, large amounts of secondary uranium minerals, such as autunite and uranophane, were observed.
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3.2. Datian Area

The Datian 505 uranium deposit is located in the southwestern area of Datian Town in the Renhe District, Panzhihua City, China (Figure 1d). After extensive exploration, the deposit was classified as a small-scale uranium deposit. The strata belong to the Zanli and Lengzhuguan Formations of the Kangding Group, which consist primarily of moderately to deeply metamorphosed rocks with widespread migmatization dominated by plagioclase amphibole schist, plagioclase amphibole gneiss, and muscovite quartz schist. The main F3 fault is a secondary fault of the Yuanmou-Lyzhijing fault. This fault has given rise to two sub-faults within the Datian area: the F1 and F2 faults, which correspond to mineralization...
zones I and II, respectively, within the Datian uranium deposit. Both faults F1 and F2 trend east–west and are roughly parallel to each other. The F1 fault is approximately 2.5 km long and 250 m wide, while the F2 fault is approximately 1.5 km long and 200 m wide. The exposed rock bodies in the area are primarily Datian diorite and Heime granite. The basic dikes in the Datian area are relatively well developed and mainly consist of various diabases (porphyries).

(1) Metallogenic belt I of 505 is primarily controlled by the F1 fault, with the mineralization section showing obvious fault control. Borehole cores revealed that uraninite is distributed in an automorphic granular form, similar to the coarse-grained uraninite found in quartz veins at the Haita 2811 uranium occurrences (Figure 4a). The crystals were mainly cubic and octahedral polytypes with a rhombic-dodecahedral shape, and a small amount was cubic. The particle size is generally 1–5 mm, and uraninite has no epigenetic oxidation. Detailed petrographic identification showed that uraninite was mainly hosted in felsic veins, which were primarily composed of feldspar and small amounts of quartz minerals. Therefore, the mineral assemblage of uraninite in the boreholes of mineralization zone I included quartz, titanite, molybdenite, monazite, and pyrite.

(2) Metallogenic Belt II of 505 is controlled by the F2 fault. Enriched uranium ore boulders have been continuously discovered in ditches within the Metallogenic belt II, with the highest grade reaching 58%. The Nuclear Industry 280 Research Institute conducted trenching work at the anomalous location of metallogenic belt II, revealing a uranium-rich steep wall and multiple uranium-rich albite lenses intruding along the bedding within the surrounding rocks. Recent research has indicated that enriched uranium boulders originate from the steep uranium-rich wall. In enriched uranium boulders, uraninite is distributed in the form of clumps, and the post-genesis oxidation of uraninite is evident. Due to the influence of oxidation, the mineral association of uraninite is unclear; however, relatively large amounts of titanite and quartz minerals can be observed. There is a significant titanite–uranium mineralization phenomenon at the edges of titanite, and the mineral assemblage includes quartz, uraninite, and titanite (Figure 4b,c).
3.3. Mouding Area

The 1101 uranium occurrence is situated in Xujie Town, Mouding County, Yunnan Province (Figure 1e). The strata in the area range from the Paleoproterozoic to the Quaternary period. The main exposed strata are from the Pudeng Formation of the Juning Group during the early Neoproterozoic era, primarily consisting of two-mica schist with garnet, two-mica gneiss, monzogranite (Shuiqiaosi rock mass), basic gneiss, and migmatite. Previous studies indicate that the Pudeng Formation strata underwent amphibolite facies metamorphism around 860–830 Ma. There is also evidence of late intrusive activity of the Yaomingcun rock mass (780 Ma) in the region. The faults in the area mainly extend in a north–south direction. The 1101 uranium occurrence comprises seven mineralized zones within the north–south fault zone. Sections 6575, 7022, and 120 were relatively small, while sections 116, 165, 110, and 111 were larger in scale. Previous researchers have found megacrystalline uraninite in albite dikes at the surface outcrop of section 111.

At the 111 section of the 1101 uranium occurrence, the megacrystalline uraninite discovered on the outcrop exists in the form of aggregates (Figure 5a,b), with the largest grains reaching the centimeter scale. The uraninite masses show significant brecciation and are sometimes found as vein-like occurrences. The morphology of the uraninite differs significantly from that found in the Haita 2811 uranium occurrence and Datian 505 uranium deposits. The uraninite grains are relatively small, with cubes being the dominant form and occasionally a combination of cubes and octahedra. Electron probe imaging revealed a relatively prominent zonal structure. Mineral assemblages associated with uraninite include albite, quartz, titanite, rutile, tourmaline, galena, muscovite, and a significant amount of secondary uranium minerals (Figure 5c–f).

Figure 5. (a,b) Megacrystalline uraninite in the form of aggregates (section 111), (c) tourmaline in albite vein, (d,e) uraninite associated with titanite, (f) two-stage titanite. Abbreviations: Tur, tourmaline (Yin [35]).

4. Analytical Methods

Systematic sample collection was performed for uranium-rich veins and surrounding rocks in the study area. Pre-processing of the samples was conducted at the Geological Testing Center of the Hebei Geological Surveying and Mapping Institute (Langfang, China). Rock and mineral identification, along with scanning electron microscopy, were performed at the Chengdu University of Technology (Chengdu, China) and East China University of Technology Nanchang, China. The major and trace geochemical tests of rock samples were completed at the Test Center of the Beijing Research Institute of Uranium Geology (Beijing, China) and the No. 230 Research Institute of China National Nuclear Corporation.
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(Changsha, China). U-Pb isotope dating and trace element content measurement for zircon, titanite, and monazite associated with megacrystalline uraninite in uranium-rich veins were analyzed by LA-ICP-MS at Wuhan Spectrum Analytical Technology Co., Ltd. (Wuhan, China) and Nanjing FocuMS Technology Co., Ltd. (Nanjing, China). The analytical instrument used was a coherent 193 nm excimer laser ablation system coupled with an Agilent 7900 inductively coupled plasma mass spectrometer. U-Pb isotope dating of megacrystalline uraninite was carried out by LA-ICP-MS and TIMS analysis at the Test Center of the Beijing Research Institute of Uranium Geology (Beijing, China). The plotting of U-Pb age Concordia diagrams and the calculation of age-weighted averages for the megacrystalline uraninite, zircon, titanite, and monazite samples were performed using Isoplot/Ex version 3 [36]. The major element analysis of megacrystalline uraninite was conducted using EPMA at the East China University of Technology (Nanchang, China) and the Tianjin Geological Survey Center of the China Geological Survey (Tianjin, China). The analysis of major elements of megacrystalline uraninite is presented in Table S1.

5. Genetic Mechanism of Megacrystalline Uraninite

5.1. Formation Age of Megacrystalline Uraninite

In recent years, with the rapid development and application of micro-area in-situ techniques, methods such as LA-ICP-MS, SIMS U-Pb dating, and electron probe dating have been successively applied to determine the age of uranium minerals. A series of chronological tests focusing on megacrystalline uraninite and its associated minerals was conducted in the Kangdian region.

(1) Haita uranium occurrence (Table 1): Yin [35] calculated the formation age of the megacrystalline uraninite at the 2811 uranium occurrence to be 257.2 ± 4.9 Ma based on EPMA data. Additionally, the Nuclear Industry Beijing Geological Research Institute obtained ages of 799.2 ± 5.6 Ma (U-Pb isochron) and 782.8 ± 1.7 Ma (U-Pb isotope) for the megacrystalline uraninite and its associated titanite at the 2811 uranium occurrence [14]. Liu [37] reported three groups of Re-Os isotopic ages obtained from molybdenite coexisting with uraninite in felsic veins at the A19 uranium occurrence, with a weighted average age of 761 ± 19 Ma. Yin [35] calculated the formation age of the megacrystalline uraninite at the A19 uranium occurrence to be 241.7 ± 7.5 Ma based on EPMA data. Xiang et al. [31] conducted in situ LA-ICP-MS U-Pb dating on titanite, a mineral coexisting with uraninite in felsic veins at the A19 uranium occurrence and obtained a weighted average age of 778 ± 12 Ma (MSWD = 0.096) (Figure 6a).

(2) Datian 505 uranium deposit (Table 1): Cheng et al. [38] used the LA-ICP-MS method to test the U-Pb age of uraninite in the borehole of Metallogenic belt I, obtaining an age of 839 Ma. Yin [35] calculated the formation age of uraninite (Metallogenic belt I) based on the EPMA data from Cheng et al. [38] to be 769 ± 15 Ma. Xu et al. [39] used the LA-ICP-MS method to test the U-Pb age of monazite, a mineral coexisting with uraninite, in the borehole of Metallogenic belt I, obtaining an age of 769.8 ± 9.7 Ma (Figure 6b). Xu et al. [40] used the traditional TIMS method to test the formation age of uraninite in a uranium-rich steep-walled lenticular uranium orebody in Metallogenic belt II, which was determined to be 775−777.6 Ma. Ouyang [41] calculated the formation age of uraninite based on electron probe data to be 774.9−785.5 Ma. Wang et al. [13] conducted SIMS zircon U-Pb isotope testing on the uranium-rich steep-wall lenticular uranium orebody of Metallogenic belt II, and the results showed that the upper intercept age of zircon U-Pb was 821 ± 22 Ma. Xiang et al. [31] conducted LA-ICP-MS U-Pb isotope dating on titanite, a mineral coexisting with uraninite in the uranium-rich steep-wall lenticular uranium orebody of Metallogenic belt II, obtaining a concordant age of 777 ± 14 Ma, which he believes can represent the formation age of the uraninite (Figure 6c).
Table 1. Different ages come from different minerals.

<table>
<thead>
<tr>
<th>Location</th>
<th>Age (Ma)</th>
<th>Mineral</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haita 2811</td>
<td>257.2 ± 4.9</td>
<td>Uraninite</td>
<td>EPMA</td>
</tr>
<tr>
<td>Haita 2811</td>
<td>799.2 ± 5.6</td>
<td>Uraninite</td>
<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Haita 2811</td>
<td>782.8 ± 1.7</td>
<td>Titanite</td>
<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Haita A19</td>
<td>761 ± 19</td>
<td>Molybdenite</td>
<td>Re-Os</td>
</tr>
<tr>
<td>Haita A19</td>
<td>241.7 ± 7.5</td>
<td>Uraninite</td>
<td>EPMA</td>
</tr>
<tr>
<td>Haita A19</td>
<td>778 ± 12</td>
<td>Titanite</td>
<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Datian 505 I</td>
<td>839</td>
<td>Uraninite</td>
<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Datian 505 I</td>
<td>769 ± 15</td>
<td>Uraninite</td>
<td>EPMA</td>
</tr>
<tr>
<td>Datian 505 I</td>
<td>769.8 ± 9.7</td>
<td>Monazite</td>
<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Datian 505 II</td>
<td>775–777.6</td>
<td>Uraninite</td>
<td>TIMS</td>
</tr>
<tr>
<td>Datian 505 II</td>
<td>774.9–785.5</td>
<td>Uraninite</td>
<td>EPMA</td>
</tr>
<tr>
<td>Datian 505 II</td>
<td>821 ± 22</td>
<td>Zircon</td>
<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Datian 505 II</td>
<td>777 ± 14</td>
<td>Titanite</td>
<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Mouding 1101</td>
<td>1006.9</td>
<td>Uraninite</td>
<td>TIMS</td>
</tr>
<tr>
<td>Mouding 1101</td>
<td>1096.4</td>
<td>Uraninite</td>
<td>TIMS</td>
</tr>
<tr>
<td>Mouding 1101</td>
<td>950</td>
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<td>LA-ICP-MS</td>
</tr>
<tr>
<td>Mouding 1101</td>
<td>1057</td>
<td>Zircon</td>
<td>LA-ICP-MS</td>
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<tr>
<td>Mouding 1101</td>
<td>951 ± 36</td>
<td>Uraninite</td>
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<tr>
<td>Mouding 1101</td>
<td>861 ± 21</td>
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<td>LA-ICP-MS</td>
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<tr>
<td>Mouding 1101</td>
<td>788 ± 6</td>
<td>Titanite-II</td>
<td>LA-ICP-MS</td>
</tr>
</tbody>
</table>

**Figure 6.** (a) Titanite age of Haita 2811, (b) monazite age of Datian 505 I, (c) titanite age of Datian 505 II, (d) titanite I age of Mouding 1101, (e) titanite II age of Mouding 1101, (f) titanite gneiss age of Mouding 1101 (data from Xiang et al. [31], Yin [35]).
Mouding 1101 uranium occurrence (Table 1): Ni et al. [42] measured the age of uraninite in the albite dike of 1101 uranium occurrence using the traditional TIMS method, obtaining a value of 1006.9 Ma. Wang [43] used the traditional TIMS method to determine the age of uraninite in the albite dike of the Mouding 1101 uranium occurrence, which was found to be 1096.4 Ma. Wu et al. [44] conducted LA-ICP-MS U-Pb isotope dating of uraninite in an albite dike of 1101 uranium occurrence, suggesting that the uraninite formed at 950 Ma and exhibited magmatic genesis characteristics. Wang et al. [13] tested the SIMS age of zircons in uranium-rich albite dikes and obtained a result of 1057 Ma, explicitly stating that uranium mineralization is the farthest end product during the evolution and differentiation of the Shuiqiaosi highly differentiated rock mass. Liu et al. [45] conducted in situ LA-ICP-MS U-Pb dating of uraninite in uranium-rich albite dikes, concluding that the uraninite formed at 951 ± 36 Ma. Xiang et al. [31] found that titanite minerals in uranium-rich albite dikes were closely associated with uraninite. Titanite exhibits distinct two-stage characteristics: electron probe scanning revealed that the rim titanite (Ttn-II) is richer in Fe and Nd elements than the core titanite (Ttn-I). A comparison of U content between the rim titanite (Ttn-II) and the core titanite (Ttn-I) also showed that the U content in Ttn-II is much higher than that in Ttn-I (Figure 5f). Testing revealed a concordant age of 861 ± 21 Ma for the core titanite (Ttn-I) and 788 ± 6 Ma for the rim titanite (Ttn-II) (Figure 6d,e). The age of the rim titanite indicates the formation of megacrystalline uraninite.

Limited by the fragility of closed systems of uranium minerals and the need for standard uranium mineral samples for matrix-effect calibration, dating results for uranium minerals have been controversial [46,47]. Compared to traditional dating methods, the EPMA dating technique offers several advantages, including high spatial resolution, high sample utilization, increased test efficiency, and no need for diluents [48–50]. However, its significant drawback is the inability to determine whether the measured samples have undergone late alteration. For example, the age of uranium minerals in the Haita area might reflect U-Pb isotope resetting caused by the Emei Mountain mantle plume explosion. Some researchers have used the GBW04420 standard sample to determine the formation age of certain uranium deposits using in situ U-Pb analysis technology [44,45,51]. However, the accuracy of the GBW04420 standard sample test has been questioned by some domestic scholars. They argue that the formation age of the standard sample is relatively recent and that the distribution of uranium elements is not uniform. These scholars have explicitly stated that the test results of the standard sample should be treated with caution [52]. Therefore, the most reliable method for determining the mineralization age is U–Pb isotope dating of uranium-bearing accessory minerals (such as zircon, titanite, and apatite) that coexist with uranium minerals. However, because of the decay caused by the excessively high content of radioactive elements such as U and Th in zircons that coexist with uranium minerals, known as zircon metamorphism, the accuracy of dating results is significantly reduced [53]. Similar to zircons, titanite, and monazite minerals are commonly found as accessory minerals in various rocks [54,55]. The titanite and monazite mineral contents of radioactive elements, such as U and Th, are much lower than those of zircons and are controlled by their crystal properties, resulting in a lower probability of metamorphism [55–57]. Titanite and monazite often form prior to uraninite during crystallization, and their low probability of metamorphism makes their dating accuracy higher than that of zircons, making them valuable dating minerals in high-uranium environments. Therefore, by combining previous research data and referencing the dating results of titanite and monazite minerals, it is believed that the formation age of megacrystalline uraninite in the Kangdian region was approximately 770–790 Ma, belonging to the Neoproterozoic.

Uranium, as a trace element, is widely distributed in the Earth’s crust [58–61], and uranium mineralization triggered by uranium enrichment is a product of geological processes at a certain stage of crustal evolution. Therefore, different uranium mineralization epochs and types are closely related to the crustal development and evolutionary history of different regions [2,6,8,62]. Hazen et al. [8] clarified the evolution principles of uranium and thorium minerals based on their known genesis and near-surface distribution pat-
terns, dividing them into four stages: the first period where no uranium deposits formed (before 3.1 Ga); the second period, approximately 3.1–2.2 Ga, represented by uranium deposits such as Witwatersrand (South Africa) and Blind River (Canada); the third period, approximately 2.2–0.45 Ga, saw the emergence of many new types of U deposits, including unconformity-related, magmatic, volcanic, sodic metasomatism, vein-type, skarn, and IOCG deposits; and the fourth period, from approximately 0.45 Ga to the present, represented by sandstone-type uranium deposits (Figure 7a). Notably, this aligns with the findings summarized by Cai et al. [6] on uranium mineralization epochs in China, where uranium mineralization was primarily associated with the third and fourth periods mentioned above. Uranium mineralization since the Cretaceous (135 Ma to the present) is representative and closely related to the activation of the circum-Pacific tectonic belt and the activities of the Neo-Tethys tectonic belt. Relatively fewer uranium deposits were formed during the 1.8–0.6 Ga period, and uranium mineralization events during the Neoproterozoic, particularly between 1.0–0.7 Ga, are even less reported (Figure 7b). These studies indicate a global gap in Neoproterozoic uranium mineralization events. This study preliminarily verified that the uranium mineralization epoch in the Kangdian region, represented by megacrystalline uraninite, belongs to the Neoproterozoic, confirming the existence of Neoproterozoic uranium mineralization in the Kangdian area. Against the backdrop of scarcity or absence of global Neoproterozoic uranium mineralization events, the Kangdian region has become an ideal area for studying Neoproterozoic uranium mineralization, making it an important window for studying Neoproterozoic uranium mineralization in China and globally.

![Figure 7](image-url)

**Figure 7.** (a) Plot displaying the uneven distribution of global uranium resources during geologic time (modified after Hazen et al. [8]), (b) plot displaying the proportion of uranium resources in China associated with different ages (modified after Cai et al. [6]).

5.2. Formation Condition of Megacrystalline Uraninite

Previous studies have investigated the distribution patterns of rare earth elements (REE) in uranium minerals formed at varying temperatures and genesis [63,64] stages of formation. Frimmel et al. [7] revised the criteria for identifying mineralization temperatures and genetic types by analyzing U/Th ratios, total REE contents, and REE patterns. They also discovered that trace element contents, such as Zr and Y, can be utilized to trace the origins of uraninite. Xu [10] conducted tests on trace elements in megacrystalline uraninite from the Haita 2811/A19 occurrences using the LA-MC-ICP-MS method at Wuhan Shangpu Testing Technology Co., Ltd. The tested uraninite samples exhibited high total REE content and relatively flat seagull-shaped REE patterns, indicating insignificant fractionation of REEs during uraninite formation and suggesting high-temperature environments. A comparison of the REE patterns of coarse-grained uraninite with those of typical uranium minerals from uranium deposits worldwide revealed similarities to those from magmatic
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(pegmatite-alaskite) uranium deposits. The felsic minerals coexisting with uraninite in the uranium-rich veins can explain the negative Eu anomalies observed in the REE patterns. In addition, the U/Th ratio of all megacrystalline uraninite samples is less than 100, with relatively uniform REE and Y contents, and the Zr content is high and stable. Therefore, we suggest classifying this type of uranium mineralization as a subclass of the magmatic category, specifically the pegmatite-alaskite type, which is related to partial melting under high-temperature and low-pressure metamorphic conditions.

Furthermore, by compiling previously tested zircon data from felsic and quartz veins hosting uranium mineralization in the Haita area, it was found that zircon samples from both types of veins exhibited low Hf contents, indicating a low degree of evolution for these veins. This observation suggests that they may have formed through low-degree partial melting of basement materials, which is consistent with the genetic type reflected by the REE patterns of uraninite in the Haita area. Yin [35] conducted Nd isotope testing on uraninite and its associated titanite. The results indicated that titanite and uraninite had consistent Nd isotopes, suggesting that uranium likely originated from ancient lower crustal materials. Xiang et al. [31] calculated the mineralization temperature and pressure based on the geochemical parameters of titanite minerals coexisting with uraninite \( (P = 0.17\text{~}–0.35 \text{ Gpa}, T = \sim 670–891 ^\circ \text{C}) \) (Table 2). These values are also consistent with the geochemical characteristics of uraninite, indicating a close relationship between its genesis and partial melting under high-temperature and low-pressure metamorphic conditions.

<table>
<thead>
<tr>
<th>Location</th>
<th>Object</th>
<th>Mineral</th>
<th>Temperature (°C)</th>
<th>Pressure (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haita</td>
<td>Uranium-rich vein</td>
<td>titanite</td>
<td>693–796</td>
<td>0.17–0.33</td>
</tr>
<tr>
<td>Datian 505</td>
<td>Uranium-rich vein</td>
<td>titanite</td>
<td>738–800</td>
<td>0.19–0.28</td>
</tr>
<tr>
<td>Mouding 1101</td>
<td>Uranium-rich vein</td>
<td>titanite</td>
<td>671–778</td>
<td>0.29–0.35</td>
</tr>
</tbody>
</table>

Data from Xiang et al. [31], Yin [35].

5.3. Migmatization and Uranium Mineralization

Ou [65] conducted LA-ICP-MS U-Pb testing on zircons from migmatite gneiss samples surrounding the uranium occurrences at Haita 2811. The results showed that the zircon cores had an age of 1733 ± 15 Ma, while the zircon rims had an age of 832 ± 20 Ma. The age of the zircon rims represents the timing of migmatization in the Haita area. Yin et al. [66] performed LA-ICP-MS U-Pb testing on zircons from graphite-rich quartz schist samples near Metallogenic belt II of the Datian 505 uranium deposit. The zircons, modified by later hydrothermal fluids, exhibited age values ranging from 482.1 to 861.8 Ma. Two groups of concordant ages were obtained as 838 ± 6.3 and 774 Ma. It was believed that 838 ± 6.3 Ma might correspond to migmatization, while 774 Ma was consistent with the formation age of uraninite. Xiang et al. [31] conducted LA-ICP-MS U-Pb testing on titanite from plagioclase amphibole gneiss samples surrounding uranium occurrences in the 111 section of the Mouding 1101 uranium deposit. The long-axis direction of titanite was consistent with the schistosity direction, indicating that titanite formed concurrently with schistosity. Therefore, titanite in gneiss is a product of migmatization or metamorphism in the original rock. A concordant lower intercept age of 859 ± 34 Ma was obtained, which represented the timing of migmatization and was consistent with the age of the previously mentioned titanite cores (Ttn-I) of 861 ± 11 Ma (Figure 6f).

Numerous studies have been conducted on the geochemical characteristics of the U-rich veins and their surrounding rocks in the Kangdian region [31,35,41]. In this study, the REE geochemical characteristics in whole rock and single minerals of surrounding rocks and uranium-rich veins at the Haita 2811 and Mouding 1101 uranium sites were investigated. Taking the Haita 2811 uranium occurrence as an example [31,35], these characteristics were then compared with those of uraninite and titanite found within uranium-rich vein to distinguish between migmatization and uranium mineralization. The following observations were made: titanite and uraninite exhibited similar and flat REE
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distribution patterns, high REE contents, and negative Eu anomalies. These similarities indicate high formation temperatures and similar formation environments, suggesting that they formed contemporaneously in a high-temperature setting. The REE distribution patterns of titanite and uraninite are similar to those of the uranium-rich veins, all exhibiting distinct negative Eu anomalies. The REE distribution patterns of the uraninite, titanite, and uranium-rich veins were consistent, whereas those of the uranium-rich veins and their surrounding rocks differed significantly. This observation implies that uranium mineralization is unrelated to migmatization (Figure 8a). Taking the Mouding 1101 uranium occurrence as an example, Yin [35] conducted a detailed comparison of the U content and REE geochemical characteristics of titanite from different parts of uranium-rich albite veins: rim titanite (Ttn-II), core titanite (Ttn-I), and titanite from the surrounding amphibolite gneiss (Ttn-Gneiss). The U content of Ttn-Gneiss and Ttn-I is relatively close, with average values of $20.18 \times 10^{-6}$ and $30.60 \times 10^{-6}$, respectively, while the average U content of Ttn-II is $314.11 \times 10^{-6}$. This suggests that Ttn-II formed contemporaneously with uraninite because its crystal lattice could accommodate more U, resulting in a higher uranium content. Comparing the REE geochemical characteristics of the three types of titanite in the Mouding area, it was observed that Ttn-II exhibits a flat REE distribution pattern, high REE content, and a negative Eu anomaly. In contrast, Ttn-I and Ttn-Gneiss have similar REE distribution patterns but differ significantly from Ttn-II. Titanite minerals in the Ttn-Gneiss were distributed along the schistosity, indicating that they formed in a compressed metamorphic environment representative of migmatization. In contrast, the flat REE distribution pattern of Ttn-II indicates a high-temperature environment. Therefore, classifying titanite based on variations in the U content and REE geochemical characteristics suggests that Ttn-I and Ttn-Gneiss may have formed during migmatization, whereas Ttn-II formed contemporaneously with megacrystalline uraninite (Figure 8b).

Migmatization, a high-grade metamorphism, is widely developed regionally, whereas uranium mineralization only occurs at specific locations, resulting in a significant scale mismatch. Emphasizing the scale of partial melting at the surface, the local migration and formation of smaller felsic veins/albite veins cannot provide a sufficient uranium source for uranium mineralization, nor can they lead to the formation of megacrystalline uraninite. Therefore, studies on petrogenesis and migmatite ages, as well as the geochemical characteristics of migmatites and uraninite, indicate that there is no direct link between migmatization and uranium mineralization. However, Ouyang [41] found that the U content of the migmatite matrix and veins in the Datian area are $6.01 \times 10^{-6}$ and $26.10 \times 10^{-6}$, respectively, indicating significant uranium enrichment in the veins during migmatization. Chang [67] studied quartz schists and gneiss that underwent migmatization in the Haita area and found that they were a set of paragenetic rocks formed by a metamorphic environment representative of migmatization. In contrast, the REE distribution pattern of Ttn-II indicates a high-temperature environment. Therefore, classifying titanite based on variations in the U content and REE geochemical characteristics suggests that Ttn-I and Ttn-Gneiss may have formed during migmatization, whereas Ttn-II formed contemporaneously with megacrystalline uraninite (Figure 8b).
from 5.64 to $12.90 \times 10^{-6}$, and after migmatization, the U content in the formed migmatite veins increases to $12.90 \times 10^{-6}$ to $30.00 \times 10^{-6}$. This reflects the uranium enrichment process during migmatization, which can provide a uranium source for subsequent uranium mineralization events. Previous studies have also shown that under low-level partial melting conditions, uranium can be concentrated to tens of times higher than the parent rock content [68–70]. Therefore, the low-degree partial melting of felsic material during migmatization may be an important mechanism for uranium mineralization in the study area and Kangdian region. Further differentiation and evolution, as well as specific tectonic environments, may be another mechanism for megacrysaline uraninite formation. Therefore, a series of studies based on the U content of the migmatite matrix and veins indicated that uranium enrichment occurred during migmatization. The host rocks for these uranium occurrences are migmatites or metamorphic rocks that have undergone migmatization, and migmatites may provide a partial uranium source for the formation of megacrysaline uraninite.

5.4. Metallogenic Dynamic Background

Ni et al. [42] believed that the first uranium mineralization event occurred in the Kangdian region during the Neoproterozoic due to the amalgamation and rifting of the Rodinia supercontinent. The most significant geological event in the Kangdian region during the Neoproterozoic was the Jinning-Chengjiang Movement (1000–700 Ma), which roughly corresponds to the amalgamation and rifting of the Rodinia Supercontinent. This period marked the mineralization of large-scale copper, iron, tin-tungsten, and lead-zinc deposits in the study area, as well as the main uranium mineralization period [14]. Xu [71] proposed that uranium mineralization in the Kangdian region should have occurred in a crustal extension environment, noting that this was generally consistent with crustal evolution characteristics and crustal movement patterns during the formation of large and super-large uranium deposits worldwide. Therefore, analyzing and studying Neoproterozoic uranium mineralization in the Kangdian region under the global background of Rodinia supercontinent amalgamation and rifting and re-examining it from the perspective of Rodinia supercontinent evolution holds guiding significance.

After the formation of the Rodinia supercontinent, orogenic movements, and regional metamorphism subsided, and evolution toward an extensional environment triggered by the transition from intracontinental subduction to supercontinent rifting began [72–74] (Figure 9a,b). This is represented by the discovery of calc-alkaline and A-type granites near uranium occurrences in the Kangdian region. Early formed faults further expanded and developed under tensile stress, forming multiple fault blocks of various shapes and sizes, which played a crucial role in the later crustal evolution of the Kangdian region. The intense faulting activities caused by crustal extension led to the formation of numerous geological tectonic environments and ore-hosting spaces favorable for uranium mineralization because of the varying locations and modes of activity of the different faults. Fault structures are important factors controlling uranium mineralization and are often associated with a certain scale of fault fragmentation or interlayer fragmentation. Uranium mineralization often occurs near major regional or secondary faults, which are often caused by extension or tensile forces (Figure 9c). Yao and Zhang [75] experimentally demonstrated that a slow decline in temperature is a crucial factor in uraninite formation. As reflected in the mineralogical characteristics of uraninite, megacrysaline uraninite requires a high-temperature environment with slow cooling and temperature decline. The main formation age of megacrysaline uraninite in the migmatites of the Kangdian region is 770–790 Ma, which is consistent with the rifting era of the Rodinia supercontinent. As reflected by the high-temperature and low-pressure environment indicated by the geochemical parameters of uraninite, the extension and decompression caused by supercontinent rifting greatly favored the formation of megacrysaline uraninite. Therefore, it is believed that Neoproterozoic uranium mineralization in the Kangdian region may have been a response to the rifting event of the Rodinia supercontinent.
5.5. Existing Challenge

This article systematically summarizes the formation age, conditions, relationship with migmatization, and metallogenic dynamic background of megacrystalline uraninite, providing valuable insights into its formation and evolution. However, there are still many key scientific issues surrounding megacrystalline uraninite and prospecting in the study region:

(1) The mechanism for locating megacrystalline uraninite is a crucial scientific challenge limiting progress in uranium prospecting. Uranium-rich veins in the study area are scattered, with no large-scale deposits identified. This makes it challenging to assess prospecting potential, creating a bottleneck in uranium exploration in the region.
(2) The precise determination of the formation age of megacrystalline uraninite requires further refinement. Despite obtaining more dating data, the results are inconsistent and scattered. Based on complex metallogenic characteristics and mineral associations, multiple stages of mineralization likely occurred in the study area.

(3) Identifying ore-controlling structures is essential for advancing the search for megacrystalline uraninite. Uranium-rich veins are primarily influenced by ductile shear zones and laminar zones, but their relationship with regional structures remains unclear. This ambiguity may be hindering significant progress in prospecting efforts in the study area.

6. Conclusions

(1) The formation age of megacrystalline uraninite in the Kangdian region is 790–770 Ma, making it an important window for studying Neoproterozoic uranium mineralization in China and globally.

(2) Migmatization preceded uranium mineralization and may have provided a partial source of uranium for the formation of megacrystalline uraninite.

(3) Megacrystalline uraninite is formed in a high-temperature and low-pressure metamorphic environment, which is closely related to the low-degree partial melting of a uranium-rich basement under an extensional setting.

(4) The formation of megacrystalline uraninite may be a response to the rifting event of the Rodinia supercontinent.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min14070642/s1, Table S1: Major element content of megacrystalline uraninite.

Author Contributions: Conceptualization, Z.X. and M.Y.; methodology, M.Y.; software, M.Y.; validation, Y.C., H.S. and C.Z.; formal analysis, M.Y.; investigation, J.Y.; resources, Z.X.; data curation, M.Y. and J.Y.; writing—original draft preparation, Z.X. and M.Y.; writing—review and editing, Z.X. and M.Y.; visualization, M.Y.; supervision, Y.C.; project administration, Z.X.; funding acquisition, Z.X. and M.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by Sichuan Science and Technology Program (No. 2024NSFSC0801), the Doctoral Scientific Startup Foundation of Mianyang Normal University (No. QD2023A07), the Opening Fund of Provincial Key Lab of Applied Nuclear Techniques in Geosciences (No. 202301), the Opening Fund of State Key Laboratory of Nuclear Resources and Environment (No. 2022NRE01), the Program of Uranium Resource Exploration and Development Innovation Center, the Program of China Nuclear Geology (No. AH2023-0410).

Data Availability Statement: Data are mainly derived from published data.

Acknowledgments: We greatly appreciate the help of Guangwen Huang, Zhibo Zhang and Pengfei Fan during daily discussion work.

Conflicts of Interest: The authors declare no conflict of interest.

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