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# Petrography and genetic history of coffinite and uraninite from the Liueryiqi granite-hosted uranium deposit, SE China

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**Abstract**

Coffinite and uraninite banded aggregates from the Liueryiqi granite-hosted uranium deposit, SE China, form a unique "bull's-eye" texture. These aggregates consist of concentric bands of uraninite and coffinite that range in thickness from 1 to 10 μm. Electron microprobe analyses indicate that coffinite and uraninite contain Ca and Al impurities. Altered uraninite, feldspar, quartz or pyrite grains form the center of these aggregates. Other minerals associated with the "bull's-eye" aggregates are marcasite, sphalerite, galena, chalcopyrite, bornite, clausthalite, microcrystalline quartz, fluorite and calcite. The aggregates occur within highly altered and brecciated zones of a two-mica leucogranite. The mineral assemblage associated with these aggregates is consistent with low-temperature fluids (~125 to 200 °C), pH=6.0 to 8.5, Eh=−0.640 to −0.704 V, and dissolved silica contents of $10^{-3.5}$ to $10^{-2.7}$ mol/l (19 to 120 ppm as $SiO_2$). At depth, $CO_2$ concentrations of mineralizing fluids percolating through the breccia and fractured zones of the altered host granites likely ranged from 3.5 to 2.6 mol% at temperatures between 126 and 178 °C and a lithostatic pressure of 500 to 800 bars. Uranium was likely transported as a uranyl dicarbonate ion, which is the dominant dissolved uranium carbonate species in the pH range 6.0 to 8.5. Periodic changes in dissolved silica content in the mineralizing fluids resulted in the formation of the coffinite–uraninite intergrowth-banded aggregates. The precipitating mechanism resulting in the precipitation of the reduced uranium phases was likely the oxidation of reduced $S^{2-}$ and $Se^{2-}$, which were supplied by the mineralizing fluids and were in equilibrium with uranyl ions.


*Keywords:* Granite; Uranium; Coffinite; Banded texture; Genesis; Liueryiqi; China

## 1. Introduction

Although usually of low modal abundance, coffinite is a common ore mineral in sandstone-, carbonaceous-siliceous-pelite-, and granite-hosted uranium

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deposits in China. Coffinite was first characterized by Stieff et al. (1955) and was first found associated with Phanerozoic sandstone-hosted U-deposits from the Colorado plateau, where it replaces organic matter, fills cell cavities in fossilized wood, and is associated with vanadium minerals, uraninite, clay and quartz (Stieff et al., 1956). Coffinite can, however, be found in many other types of U-deposits throughout the world (e.g., Taylor and Harrison, 1958; Moench, 1962; Ludwig and Grauch, 1980; Northrop and Goldhaber, 1990; Min et al., 1995; Fayek et al., 1997, 2002; McMillan, 1998; Jerden and Sinha, 1999; Chernikov, 2000; Lorilleux et al., 2003).

The fine-grained nature of coffinite (~1 to 3 μm) generally makes it difficult to characterize. Therefore, few studies have documented its occurrence and association with ore-stage minerals, exceptions being the studies of Ludwig and Grauch (1980) and Rojkovič (1997). These authors documented the occurrence of coffinite and uraninite aggregates in sandstone-hosted roll-front U-deposits from Wyoming, U.S.A., and Slovakia, respectively. In these studies, the aggregates, which consisted of concentric bands of coffinite and uraninite, were small with less than 5 bands. The objectives of the present paper are to document the occurrence and genesis of relatively large (up to 10 μm thick), well-developed concentric bands of coffinite and uraninite that form large aggregates with "bull's eye" textures. These aggregates are associated with the Liueryiqi granite-hosted U-deposit, SE China.

## 2. Geologic setting

The Liueryilin ore district consists of nine granite-hosted deposits. The district is located in the Jiangxi Province, SE China, and is one of the most economically important uranium ore districts in China. The Liueryiqi deposit is the largest in the district in terms of tonnage. It was discovered in the early 1960s during an airborne radiometric survey and ground follow-up of anomalies, and was mined from 1963 to 1985. The Liueryiqi deposit occurs in the Taoshan granitic complex (Fig. 1). The latter is a composite granitic batholith, with an outcrop area of more than 1000 km$^2$, and is composed of more than 10 granitic plutons of Indosinian (zircon U–Pb age, 193 Ma) and Yanshanian ages (range of zircon U–Pb ages, 144 to 75 Ma). The complex intrudes Sinian–Cambrian schists and gneiss that are more than 7 km thick. Indosinian migmatites occur beyond the Taoshan complex and have Late Triassic K–Ar ages of 227 Ma (Erliuer Geological Party, 1990). Late Cretaceous–Tertiary reddish conglomerates, sandstones and shales are approximately 2500 m thick and fill fault-bounded basins in the region. They rest unconformably on the Sinian–Cambrian metamorphosed rocks and Indosinian migmatites. Several regional NE-trending high-angle faults and fracture zones, extending more than 20 km, traverse the district around the Liueryiqi deposit. The fault zones comprise a multitude of individual reverse faults, and with variable widths from 1 to 10 m. Each of nine deposits in the Liueryilin ore district occur between two regional NE-trending high-angle faults and most deposits lie adjacent to one of these faults (Fig. 1).

### 2.1. Igneous rocks

Granitoid rocks of the Taoshan complex can be petrographically classified into three units with different ages (Erliuer Geological Party, 1990). These are: (1) Indosinian medium- to coarse-grained porphyritic biotite granite (K–Ar age of 231 Ma). This granite forms a stock with an outcrop area of 80 km$^2$, and intrudes the Sinian–Cambrian metamorphosed rocks in the southwestern part of the district; (2) Early Yanshanian medium- to coarse-grained two-mica porphyritic granitic batholith and stock, including the Daguzhai medium-grained porphyritic two-mica granite and the Luobuli medium-grained porphyritic biotite granite; and (3) Late Yanshanian fine- to medium-grained monzonitic granite (whole-rock Rb–Sr age of 96 Ma). This granite occurs as small stocks. Additionally, a large number of intrusive dikes of various compositions (i.e., diabase, lamprophyre, quartz porphyry, granophyre pegmatite and porphyritic microgranite) occur in the district.

### 2.2. Host rocks

The Liueryiqi deposit is located within the Daguzhai granitic body, with an outcrop area of 30 km$^2$, and hosted by Early Yanshanian medium-grained

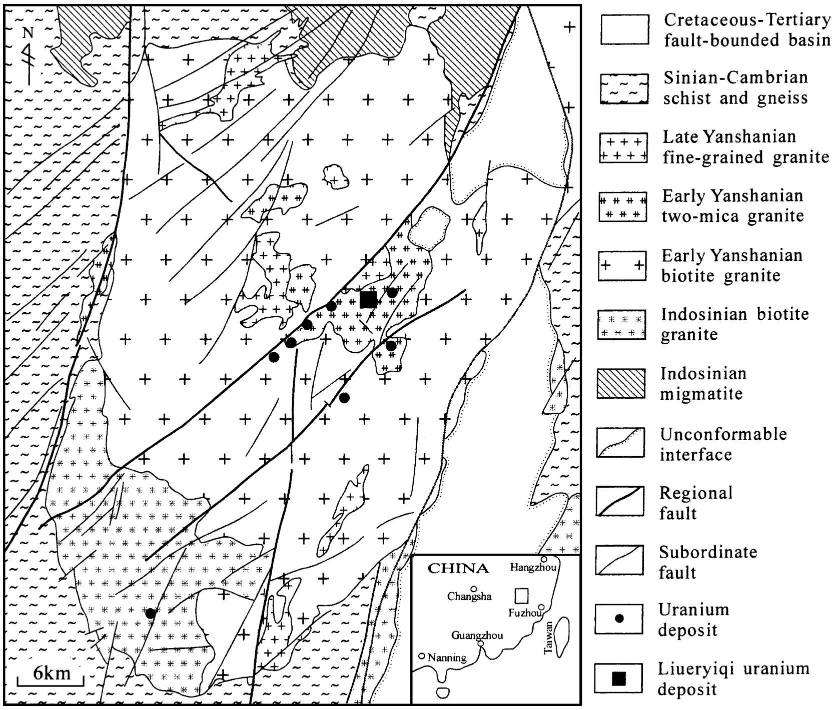


Fig. 1. Geological setting of the Liueryilin uranium district and geographical location of the Liueryiqi uranium deposit (modified after Erliuer Geological Party, 1990).

porphyritic two-mica granite. The host granite is gray-white to pinkish-gray in color and has an Early Cretaceous Rb–Sr age of 136.9±29 Ma (Erliuer Geological Party, 1990). It occurs as a stock and occupies the central portion of the Taoshan granitic complex. The host granite is composed of quartz (30% to 35%), K-feldspar (35%), plagioclase ($An_{15–25}$; 20%), biotite (3%), muscovite (4 to 5%) and trace amounts of zircon, apatite, monazite, sphene, uraninite, allanite, fluorite, magnetite and ilmenite. Feldspar phenocrysts are euhedral to subeuhedral, approximately 1 to 2 cm long, and make up 10% to 15% of the rock. Biotite commonly contains abundant inclusions of zircon, allanite, apatite and uraninite. Muscovites from the host granites have a range of K–Ar ages from 124 to 85 Ma. These ages are younger than the emplacement age of the granite and likely represent subsequent fluids events that have interacted with the early Yanshanian medium- to coarse-grained porphyritic biotite granite. This subsequent alteration of the host granites is not structurally controlled.

### 2.3. The Liueryiqi uranium deposit

Uranium mineralization is restricted to the fractured, strongly altered granite adjacent to the contact zones between the Daguzhai medium-grained porphyritic two-mica granite and Luobuli medium-grained porphyritic biotite granite of early Yanshanian age (Fig. 2). Both granites generally show little foliation. Most of the orebodies occur in the Daguzhai two-mica granite, which was intruded by the Luobuli biotite granite. Two types of structures can be distinguished in the deposit: older, N to NE-trending structures, and a second set of NE-trending structures; both structures result from same regional stress system. Fractured granite near the second set of structures was cemented by fluorite, uraninite, coffinite, microcrystalline quartz, and Fe sulfides. The mineralization is discontinuous and the ore bodies are veined (Fig. 2). A single ore body is 5 to 15 m thick and as much as 50 to 150 m in length. Attitudes of the veined ore bodies are nearly parallel to the foliation and faults and have a dip of 75 to 80° to

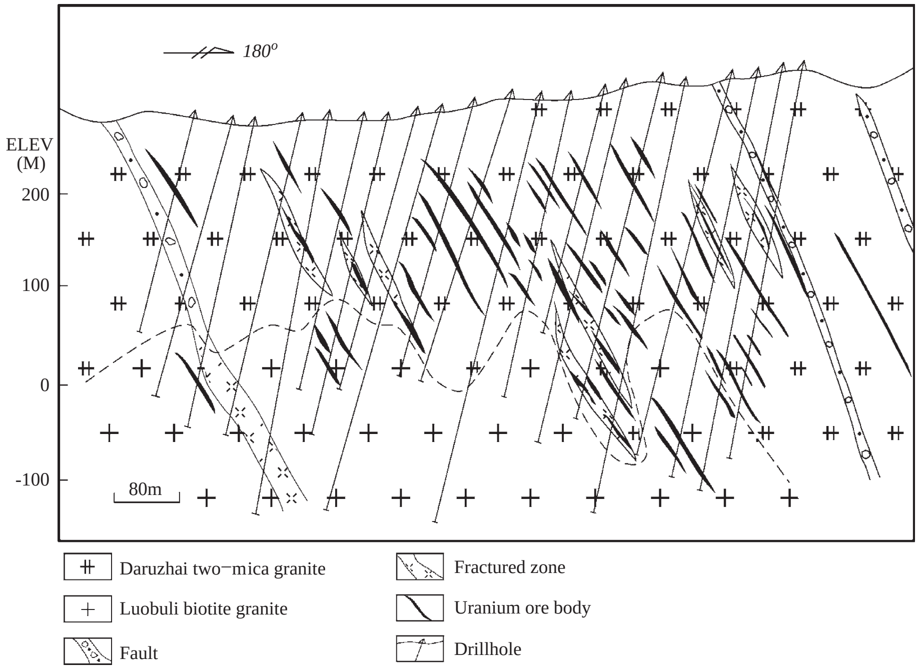


Fig. 2. Geological cross-section of the Liueryiqi uranium deposit in the Daguzhai granitic body (modified after Erliuer Geological Party, 1990).

south. The deposit is generally low-grade, but locally of medium- to high-grade (ranging from 0.1 to 0.3 wt.% U).

Hydrothermal alteration related to U-mineralization in the host granite and mineral assemblages in the ores were studied by Min and Wu (1998). The hydrothermal alteration package associated with U-minerals consists of chloritization, hematitization, silicification, pyritization, damouritization, argillization, fluoritization, and carbonatization. The dominant U-bearing minerals are uraninite and coffinite and several stages are recognized. Trace amounts of secondary hexavalent U-minerals, formed during supergene leaching, are also present. Based on

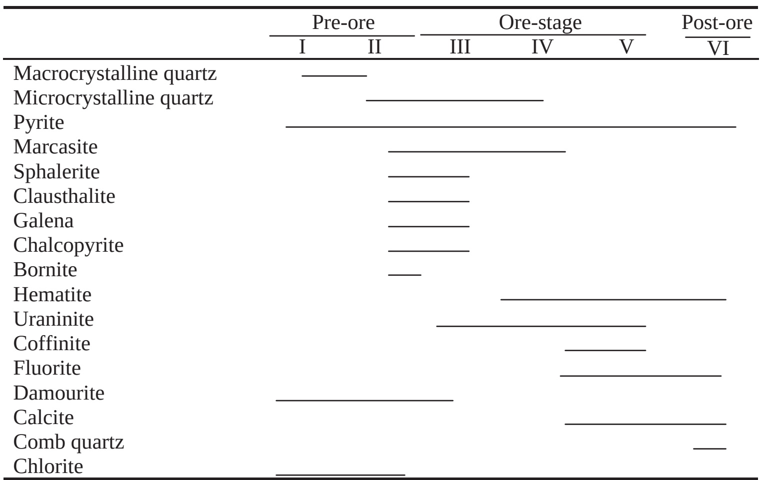


Fig. 3. Mineral paragenesis showing 6 stages of mineralization (see text for explanation).

cross-cutting relationships and textures observed in thin section, the paragenesis of this deposit can be divided into six stages, each separated by periods of brecciation (Fig. 3). Stage I and II minerals are the earliest hydrothermal phases and consist of macro-crystalline quartz, chlorite, and damourite. Stage III minerals include uraninite, pyrite, marcasite, sphalerite, clausthalite, galena, chalcopyrite, bornite, chlorite, and black microcrystalline quartz. Stage IV minerals include uraninite as well as hematite, and reddish

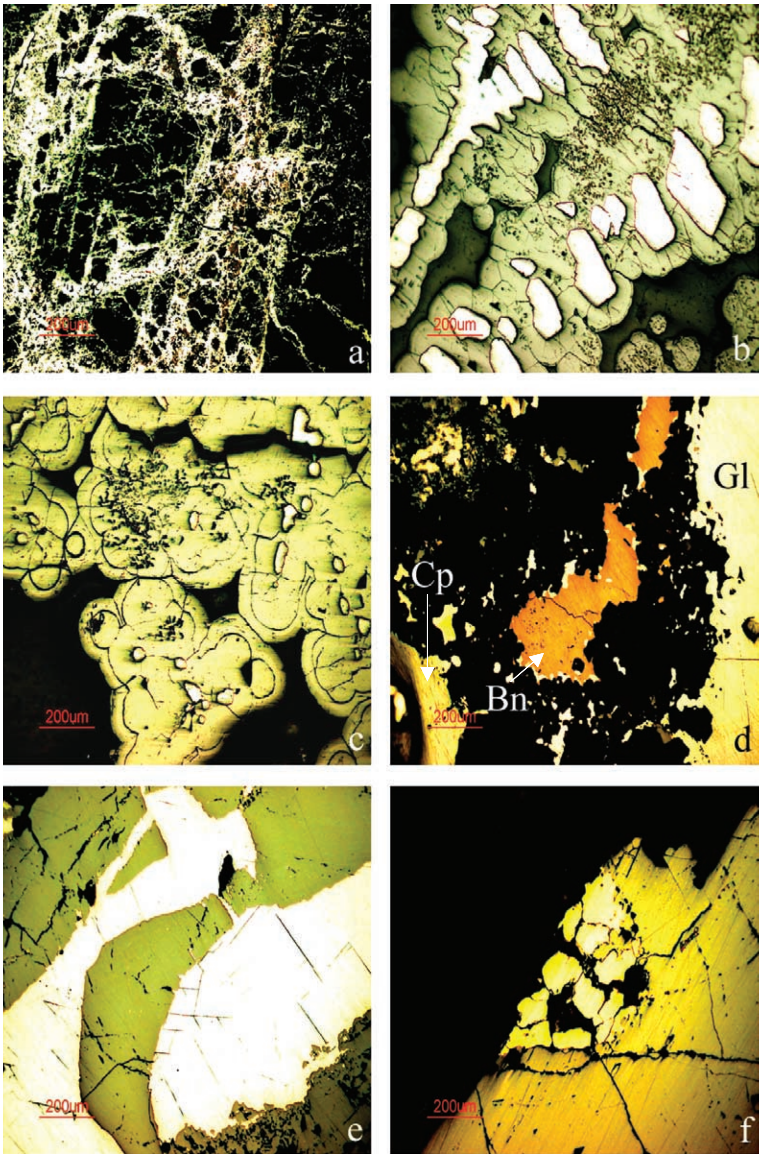


Fig. 4. Reflected light photomicrographs (a) Primary U-minerals (white), composed of coffinite and uraninite, filling network microfractures in the host granites and cementing fragments (dark) of granite and minerals. (b) Fishbone-shaped clausthalite (white) and surrounding uraninite (gray-white) with concentric colloformic textures and abundant shrinkage cracks. (c) Fine-grained galena (white) and surrounding uraninite (gray-white) with concentric colloform textures and abundant shrinkage cracks. (d) Intergrowth of galena (Gl), bornite (Bn) and chalcopyrite (Cp). (e) Intergrowth of galena (white) and sphalerite (dark gray). (f) Intergrowth of chalcopyrite (center, gray-white) with surrounding sphalerite (margin, gray). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

microcrystalline quartz. Stage V minerals include coffinite, uraninite fluorite and calcite. The latest hydrothermal minerals (stage VI) postdate all the U (IV) minerals and consist of calcite, blue-fluorite, comb-textured quartz, and fine-grained U (VI) minerals. The latter include autunite, uranophane, barium–uranophane, torbernite and uranocircite.

The coffinite is intimately intergrown with uraninite. These primary minerals occur as microveinlets, less than 2 mm in width, along fractures within the host granite (Fig. 4), and as disseminated micro-grains (ranging from 1 to 0.1 mm in size) in the gangue minerals. Occasionally, larger veins, ranging from 1 to 2 cm in width, of uraninite and coffinite can be observed in the high-grade ores. Uraninite and coffinite mineral separates give concordant U–Pb ages of 41 Ma (Erliuer Geological Party, 1990).

Quartz formed early in the hydrothermal process is macrocrystalline (stages I and II), and then becomes microcrystalline during stage III. The microcrystalline quartz associated with U-mineralization is often colored red by fine-grained hematite and black by fine-grained pyrite and uraninite. Finally, stage VI quartz has a comb-texture.

## 3. Methodology

The ore samples used in this study came from drifts and drillcore from the Liueryiqi deposit. Polished thin sections were examined for mineralogy, paragenesis and textural relations of the ores using an optical microscope and electron microprobe. Electron microprobe analyses were made with a JEOL JXA-8000 instrument at the State Key Laboratory of Mineral Deposit Research, Nanjing University. Analytical conditions were 20 kV accelerating voltage and $2\times10^{-8}$ A beam current. Standards used were natural uraninite for elements U, Th, and Pb, hornblende for K and Ca and synthetic materials for Mg, Fe and Si.

## 4. Results

Microscopic examination of all high-grade samples (>0.3 wt.% U) shows that coffinite and uraninite typically form fine-grained concentric coffinite–uraninite banded aggregates with a “bull’s-eye” texture (Fig. 5). The center of these aggregates typically consists of granitic fragments or minerals such as quartz, feldspar or pyrite. Bands of uraninite and coffinite range in thickness from 1 to 10 μm and aggregates can consist of up to 20 individual bands. Each band commonly possesses homogeneous reflectance. Microprobe data indicate that, in addition to U and Si, the coffinite and uraninite contain low PbO (≤0.10 wt.%), FeO (≤0.14 wt.%) and $K_2O$ (≤0.22 wt.%), moderate but variable $Al_2O_3$ contents (0.48 to 2.21 wt.%), and high CaO contents (1.96 to 7.23 wt.%) as impurities (Table 1). Some bands of coffinite and uraninite have transitional reflectance (e.g., gray and pale gray bands), indicating a transition between coffinite and uraninite.

## 5. Discussion and conclusions

The genesis of the Liueryiqi deposit has been discussed by Sun (1976); Zheng (1985); Erliuer Geological Party (1990), and Min and Wu (1998). Based on the geological setting, mineralogy, trace element geochemistry, timing, and fluid inclusion data, this deposit is interpreted to have formed from hydrothermal fluids. Liueryiqi and related deposits in the Liueryilin ore district bear remarkable similarities, in terms of geological setting, deposit characteristics, size range and mineralogy, with the Bois Noirs–Limouzat granite-hosted U-deposit, Forez, France (Cuney, 1978).

The Liueryiqi U-deposit was formed by a multi-stage process. Rounded inherited zircons and high $^{87}Sr/^{86}Sr$ initial ratios (0.7142 to 0.7533) (Zheng, 1985) suggest that the Taoshan granitic complex, which hosts the Liueryiqi deposit, obtained its high U content from the Sinian–Cambrian schists and gneiss during magmatic emplacement. Nearly all the U-bearing granites, which host economically significant U-deposits in South China, intrude the Sinian–Cambrian schist and gneiss. During magma emplacement, $CO_2$-rich fluids, generated during amphibolite facies metamorphism of the country rock, are likely to have mobilized U from the sediments (e.g., Cuney, 1978). During magmatic differentiation the U content of the residual melts likely increased. Granites in the complex have U contents ranging from 6.5 ppm (Indonesian granite) to 14.1 ppm (the Yanshanian granite; Zheng, 1985) During post-magmatic alter-

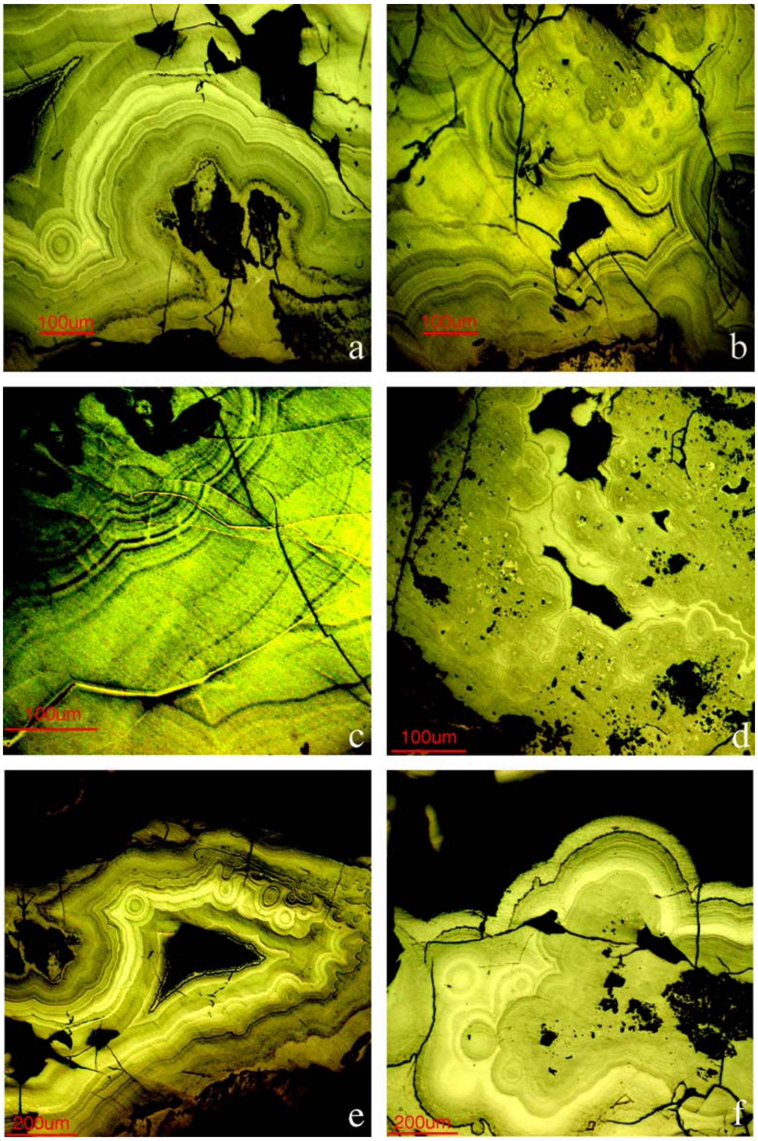


Fig. 5. Photomicrographs in reflected light of polished sections. (a)–(f) Concentric banded aggregates of coffinite (dark gray) and uraninite (gray white), and their "bull's-eye" texture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ation of the host granites, including chloritization of biotite, transformation of orthoclase into microcline, sericitization of oligoclase, albitization and muscovite precipitation, a transfer of U from the more refractory accessory minerals makes that U more readily leachable by hydrothermal solutions (Cuney, 1978).

There were likely two sources of heat causing hydrothermal remobilization of uranium. One source of heat was the decay of radioactive elements in the granite. A second source was likely to have been the Yanshanian tectonism, which may have been sufficient to produce a convective circulation of fluids in host granites. Uranium was likely transported as carbonate complexes because the presence of minor amounts of calcite associated with stage V minerals suggest that the hydrothermal fluids were carbonate-

Table 1
Microprobe analyses (wt.%) of coffinite and uraninite within the concentric coffinite–uraninite intergrowth-banded aggregates of Fig. 5a

| Band | Mineral | $U_3O_8$ | $SiO_2$ | PbO | CaO | FeO[a] | $K_2O$ | $Al_2O_3$ | $ThO_2$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 (White) | Uraninite | 82.20 | 9.48 | 0.05 | 5.14 | 0.09 | – | 1.08 | – | 98.04 |
| 2 (Dark) | Coffinite | 72.54 | 21.30 | – | 2.02 | – | – | 2.15 | – | 98.01 |
| 3 (White) | Uraninite | 82.78 | 8.48 | 0.02 | 5.42 | – | 0.23 | 1.07 | 0.02 | 98.02 |
| 4 (Dark) | Coffinite | 69.30 | 24.04 | 0.04 | 2.19 | – | 0.12 | 2.25 | 0.11 | 98.05 |
| 5 (White) | Uraninite | 84.24 | 7.12 | 0.09 | 4.91 | – | 0.10 | 1.04 | – | 97.50 |
| 6 (Dark) | Coffinite | 71.16 | 22.66 | – | 2.08 | 0.03 | 0.15 | 1.93 | – | 98.01 |
| 7 (White) | Uraninite | 82.02 | 8.75 | – | 5.87 | – | 0.12 | 1.11 | – | 97.86 |
| 8 (Dark) | Coffinite | 73.89 | 20.00 | – | 1.96 | 0.14 | – | 2.01 | – | 98.00 |
| 9 (White) | Uraninite | 84.83 | 5.30 | 0.05 | 7.23 | 0.04 | 0.07 | 0.50 | – | 98.02 |
| 10 (Dark) | Coffinite | 71.60 | 22.38 | – | 2.19 | – | 0.09 | 1.75 | – | 97.97 |
| 11 (White) | Uraninite | 84.63 | 7.38 | 0.10 | 3.95 | – | 0.09 | 0.85 | – | 97.00 |

[a] Total Fe as FeO. Microprobe analyses were made within an area of less than 10 μm diameter for each band in Fig. 5a.

rich. Stable (C, O, H) isotope data from silicate minerals associated with uraninite suggest that the hydrothermal solutions were of meteoric origin. Precipitation of the primary U-minerals (uraninite and coffinite) likely resulted from $CO_2$ immiscibility during release of fluid overpressure in the brecciated zones and fractures. Subsequently, sulfides close to the surface environments were oxidized by meteoric waters to form sulfuric acid solutions, which could dissolve the uraninite and coffinite, resulting in formation of the secondary hexavalent U-minerals.

Measured homogenization temperatures for primary inclusions in ore-stage fluorite and calcite range from 182 to 210 °C and from 126 to 178 °C, respectively. The deposit thus has many features in common with intermediate- to low temperature hydrothermal ore deposits. U–Pb ages of stage IV uraninite (Erliuer Geological Party, 1990) are 65 Ma (Late Cretaceous to Early Tertiary), and 41 Ma (early Tertiary) for stage V uraninite. These ages are consistent with late Yanshanian (early Tertiary) tectonism that affected a vast region of Southern China. The U–Pb isotopic evidence would suggest a connection between migration of the mineralizing fluids and the regional tectonism, leading to formation of the Liueryiqi deposit.

Intergrowths of coffinite with uraninite occur in numerous types of U-deposit, including sandstone-hosted roll-type (Stieff et al., 1956; Moench, 1962; Brookins, 1975; Ludwig and Grauch, 1980; Northrop and Goldhaber, 1990; Fayek et al., 1997; Chernikov, 2000), unconformity-type (McMillan, 1998; Jerden and Sinha, 1999; Fayek et al., 2002; Lorilleux et al., 2003), carbonaceous–siliceous–pelite-hosted (Min et al., 1995), volcanic rock-hosted hydrothermal U-deposits (Castor and Henry, 2000), natural fission reactors (Finch and Murakami, 1999; Bros et al., 2003), granite-hosted U-deposits (Cuney, 1978; Min and Zhang, 1992), as well as in other type of hydrothermal deposits (Villar et al., 2002). Many studies have shown that coffinite and uraninite can form at low temperatures and pressures. Hemingway (1982) and Brookins (1975) showed that, under reducing conditions ($fO_2<10^{-40}$), both coffinite and uraninite can coexist at low temperatures and pressures (25 °C, 1 atm). Uraninite preferentially precipitates from hydrothermal fluids when the Si content is below $10^{-3.5}$ to $10^{-2.7}$ mol/l (19 to 120 ppm as $SiO_2$), whereas coffinite becomes more stable when the Si content exceeds $10^{-2.7}$ mol/l (120 ppm as $SiO_2$) (Brookins, 1975; Langmuir, 1978; Hemingway, 1982). Fuchs and Hoekstra (1959), and Rafalskiv (1963) succeeded in synthesizing coffinite over a range of pH (7.2 to 10.5), temperatures between 200 and 300 °C and an Eh <0 mV from a solution containing 0.5 M $Na_2CO_3$+$10^{-3}$ M $UCl_4$+$10^{-3}$ M $Na_2SiO_3$. However, laboratory synthesis of coffinite is more complicated than synthesizing uraninite. Therefore, constraining the thermodynamic properties of coffinite has yet to be achieved (Northrop and Goldhaber, 1990). Nevertheless, Hemingway (1982) showed that an estimate of the free energy of formation of coffinite can be deduced from thermodynamic data of zircon ($ZrSiO_4$) and huttonite ($ThSiO_4$).

The study of coffinite in natural systems shows that coffinite precipitates under low temperature and pressure conditions. For example, coffinite and uraninite, from the Lakeview rhyolite-hosted hydrothermal U-deposits, northwestern Nevada, U.S.A., occur as rectangular grains, which appear to be coeval with pyrite (Castor and Henry, 2000). Co-precipitation of coffinite, uraninite and pyrite indicates that these minerals formed under reducing conditions. However, uraninite generally post-dates the sulfides (pyrite, marcasite, galena, etc.) and selenide (clausthalite) (Figs. 4b,c) (Naumov, 1978; Min and Zhang, 1992). Fluid inclusion temperatures range from 120 to 200 °C.

Although banded coffinite–uraninite aggregates have been previously reported in sandstone hosted U-deposits (Ludwig and Grauch, 1980; Rojkovič, 1997), this study is the first to report their presence in granite-hosted deposits. Based on geological and petrographic observations, fluid inclusion and geochemical data (Sun, 1976; Zheng, 1985; Erliuer Geological Party, 1990; Min and Wu, 1998), U-mineralization at the Liueryiqi deposit was precipitated within brecciated and fractured zones in altered granite where the pressure at the time of U-mineralization was hydrostatic. The total thickness of the overlying sedimentary and granitic cover is estimated to have been 3 km. Therefore, pressure at the time of U-mineral precipitation was between 500 to 800 bars. Homogenization temperatures for fluid inclusions considered contemporaneous with coffinite–uraninite precipitation range from 126 to 178 °C.

The coffinite–uraninite banded aggregates are associated with stage V minerals such as calcite (Figs. 3 and 5). The association between U mineralization and calcite suggests that fluids flowing through the brecciated and fractured zones of the altered granite were rich in $CO_2$, and could have had $CO_2$ contents between 3.5 and 2.6 mol% at temperatures between 126 and 178 °C. This suggests that U (VI) in the mineralizing fluids was most likely transported as uranyl tri- or dicarbonate ion. Prior to coffinite–uraninite precipitation, the pH of the mineralizing fluid was likely to have been 3.5 to 5.5, because marcasite, a mineral that predates the U-minerals, is only stable under a pH ranging between 3.5 and 5.5 at 150 °C (Kullerud, 1966). However, based on thermodynamic calculation (Zheng, 1985), uranyl dicarbonate ion was most likely the dominant dissolved carbonate species since the mineralizing fluids likely had a pH range between 6.0 to 8.5 and the Eh was −0.640 to −0.704 V. Therefore, coffinite and uraninite likely precipitated in a weakly alkaline, reducing environment.

The reducing agent of the uranyl ion may be oxidation of reduced $S^{2-}$ and $Se^{2-}$ in the mineralizing fluids and in equilibrium with uranyl ions (Naumov, 1978). However, U-minerals may have also precipitated due to a drop in pressure. As fluids permeated the breccia and fractures zones, changes from lithostatic to hydrostatic pressure likely lead to dissociation of the uranyl dicarbonate complex. Periodic changes of dissolved silica content in the mineralizing fluids resulted in formation of the banded aggregates of coffinite and uraninite at ~150 °C. Although dissolved silica contents in the mineralizing fluids associated with stage V minerals were not analyzed, a similar silica content limit to that in low-temperature sandstone-hosted U-deposits, ranging from $10^{-3.5}$ to $10^{-2.7}$ mol/l (19 to 120 ppm as $SiO_2$), as reported by Langmuir (1978), is possible. Periodic changes in dissolved silica content are attributed to interaction between mineralizing fluids and host granites.

Based on the data of Hemingway (1982), coffinite from the Liueryiqi deposit likely formed from the reduction of $UO_2^{2+}$ to $UO_2^{+}$ ($U^{5+}$), which decreased the solubility of the dissolved U and lead to adsorption $UO_2^{+}$ onto a silicate or sulfide grain boundary surfaces. When the surface was Si-rich, bonding between the linear $(O–U–O)^{+}$ molecule and silica may have resulted, thus precipitating coffinite. Eh–pH changes were likely unimportant in the formation of the coffinite–uraninite banded aggregates because a rapid, periodic change in Eh–pH is unlikely. In addition, Hemingway (1982) showed that coffinite could form over a range of temperatures (25 to 1000 °C). Therefore, slight fluctuations in temperature cannot account for the alternate banding between uraninite and coffinite.

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