



Mineralogy, geochemistry and ore genesis of the Dawan uranium deposit in southern Hunan Province, South China

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ABSTRACT

The Dawan deposit in southern Hunan Province is one of the large-scale metasedimentary rock-hosted uranium deposits in China. Uranium orebodies occur mainly as big vein type and disseminated veinlet type, and are chiefly hosted within the Cambrian metasedimentary rocks, but some small ore veins can extend into the Jurassic Jinjiling granites. The dominant uranium ore minerals include pitchblende and coffinite. Coffinite often replaces and rims the pre-existing pyrite, and pitchblende occurs as veinlets and disseminated grains filled the fracture zones of metasedimentary rocks. It is suggested that the coffinite was most likely formed by initial reduction of U^{6+} to U^{4+} by pyrite from an oxidized Si-rich fluid at an early mineralization stage, whereas the pitchblende may have formed at a later stage in a relatively reduced and Si-poor fluid. Chlorite alteration is widespread and is inter-grown with pitchblende in ores. Electron microprobe analysis reveals that the chlorite belongs to Mg-rich clinocllore, which is different to the Fe-rich chlorite in most granite-hosted and volcanic rock-hosted uranium deposits in South China. The hydrothermal alteration temperatures were estimated to be 189–227 °C according to chlorite geothermometer. The ores show similar trace element characteristics to those of metasedimentary wall-rocks, but different from those of the Jinjiling granites. Negative Ce anomalies of the ores indicate an oxidized hydrothermal fluid, which was most likely derived from circulated meteoric water. The $\epsilon_{Nd}(t)$ values of the ores are lower than those of the Jinjiling granites, but fall into the range of the basement strata. Sulfur isotopic compositions of hydrothermal pyrites vary from -9.5% to -7.7% , similar to those from the wall-rocks, which implies that the sulfur in ore-forming fluids was mainly derived from diagenetic sulfur in the sedimentary strata. Pyrite in ores shows highly radiogenic lead isotopic compositions ($^{206}Pb/^{204}Pb = 19.684\text{--}89.234$ and $^{207}Pb/^{204}Pb = 15.722\text{--}19.683$). In a plot of $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$, the data show a good linear array and yield an isochron age of 479 ± 69 Ma (MSWD = 1.6), which is much older than the granites but relatively close to the age of the host metasedimentary strata, indicating that the uranium source was probably derived from the wall-rock strata. It is suggested that the Dawan deposit is a hydrothermally reworked uranium deposit (referred to as the carbonaceous-siliceous-pelitic rock type by many Chinese geologists) with a close relationship with the host metasedimentary rocks. The Dawan deposit has no genetic relationship to the Jinjiling granite, contrary to what was previously suggested, and therefore the exploration in this area should focus on the conjunct occurrence of the Cambrian metasedimentary rocks rich in organic carbon and pyrite and the tectonic faulting which fractured and brecciated the strata.

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1. Introduction

South China is rich in vein-type hydrothermal uranium deposits, which have provided the major sources of uranium for the country in the past several decades. These deposits are hosted by three types of rocks: granitic, volcanic, and carbonaceous-siliceous-pelitic sedimentary rocks. The ages of the host rocks are highly variable, mostly ranging from Precambrian to Jurassic, but the main uranium mineralization ages are

Cretaceous to Tertiary (see reviews by [Min, 1995](#); [Hu et al., 2008](#)). [Hu et al. \(2008\)](#) proposed a genetic model for these vein-type uranium deposits in South China, in which formation of the veins was suggested to be related to Cretaceous–Tertiary crustal extension and associated magmatism. However, many aspects of the genesis of these uranium deposits in South China remain unresolved, especially for the origin of the ore-forming fluids, the uranium sources and the mineralization processes. The ore-forming fluids can be of various types including connate, diagenetic brines, meteoric waters, and mantle-derived fluids ([Beijing Institute of Uranium Geology, 1982](#); [Deng et al., 2003](#); [Derome et al., 2005](#); [Du, 1982](#); [Du and Wang, 1984](#); [Hu et al., 2008, 2009](#); [Jiang et al., 2006](#); [Ling, 2011](#); [Mercadier et al., 2012](#); [Min, 1995](#); [Pal et al., 2010](#);

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Richard et al., 2011; Skirrow et al., 2009; Wang and Liu, 1987). The uranium in the ore-forming fluids of the uranium deposits in South China can be extracted from granites, volcanic rocks and sedimentary rocks (Hu et al., 1993, 2008; Min, 1995; Min et al., 1999; Wang and Liu, 1987; Zhang and Zhang, 1991; Zhang et al., 2003; Zhao et al., 2011), and deposition of the uranium minerals may be caused by changes in Eh, pH, pressure and temperature (Beijing Institute of Uranium Geology, 1982; Zhang and Zhang, 1991; Zheng et al., 1986, 1996). Thus, detailed geology and geochemistry studies on individual deposits are needed in order to evaluate ore genesis and to guide further exploration of uranium deposits in South China.

The Dawan uranium deposit is one of the large-scale deposits in South China, with >3000 t uranium resources. This deposit is located in Lanshan County, southern Hunan Province, South China. Orebodies are hosted by Cambrian metasedimentary rocks and can be classified into the carbonaceous-siliceous-pelitic rock type uranium deposits (Min, 1995). The deposit is also located close to the Jurassic Jinjiling A-type granites, which have obviously higher U contents (8–16 ppm, Fu et al., 2005) than the average upper continental crust (2.7 ppm, Rudnick and Gao, 2003). Therefore, some researchers suggested that the uranium mineralization might have a genetic relationship to the Jinjiling granites (China Nuclear Geological Bureau, 2005; Yang, 2011). Previous and on-going explorations have mainly been carried out along the boundary of the granitic body with country sedimentary rocks. A lot of studies have focused on geochemistry and petrogenesis of the Jinjiling granites (Fu et al., 2004, 2005; Huang et al., 2011; Jiang et al., 2009; Zhang et al., 2001). The ore genesis and mineralization processes of the Dawan deposit, however, are poorly understood. The mineralization age (~80 Ma, China Nuclear Geological Bureau, 2005) is obviously younger than the emplacement age of the Jinjiling granites (~156 Ma, Fu et al., 2004). What effects did the metasedimentary strata and the Jinjiling granites have in the ore formation? In this paper, we present mineral compositions, trace element concentrations and

Nd–Sr–S–Pb isotopic data for the ores and host rocks in the Dawan deposit. The aim of this study is to constrain the sources of uranium and mineralization processes and to establish the genetic model of this deposit. This approach will be used to guide on-going exploration in this area.

2. Geological settings

The Dawan uranium deposit is located south-west of and adjacent to the Jinjiling granites (a part of the Jiuyishan batholith). The Jiuyishan is a composite granitic batholith, with a total outcrop area of more than 1300 km², and is composed of Devonian Xuehuading granites, Jurassic Jinjiling and Shaziling granites and Jurassic Xishan granitic intrusive and volcanic complex (Fig. 1). The Jiuyishan batholith is located in the western part of the Nanling Mountain Region, which contains abundant Mesozoic granites and the most important W–Sn, Nb–Ta and U deposits in South China.

The Jinjiling granitic body has an outcrop area of 390 km². It was emplaced into Neoproterozoic Sinian and Cambrian metamorphic rocks at 153–156 Ma (zircon U–Pb dating, Fu et al., 2004; Huang et al., 2011). The Jinjiling granites consist mainly of syeno-granite and alkali-feldspar granite with alkali feldspar (46–57%), plagioclase (2–16%), quartz (31–42%) and biotite (3–7%). Recently, the Jinjiling granites have been considered as A-type granite (Fu et al., 2005; Huang et al., 2011; Jiang et al., 2009) and were probably generated by partial melting of granulitized Paleo-proterozoic metamorphic basement in the lower crust (Huang et al., 2011; Jiang et al., 2009). U contents of the Jinjiling granites vary from 8–16 ppm (Fu et al., 2005; Jiang et al., 2009), about 3–5 times higher than the average upper continental crust (2.7 ppm, Rudnick and Gao, 2003).

The studied area is located in the Cathaysian Block. The basement of the southern Hunan consists of the Paleo- to Meso-proterozoic metamorphic rocks. The basement was overlain by the Neoproterozoic to

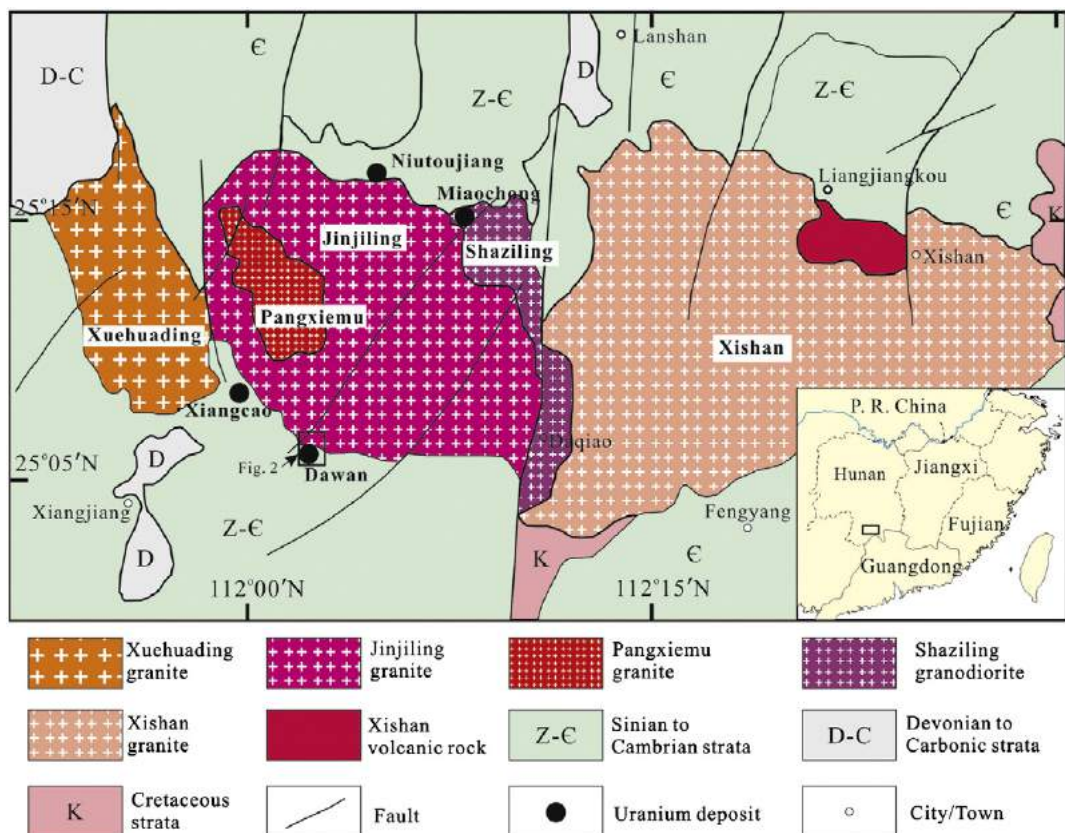


Fig. 1. Simplified geological map of the Jinjiling granites and the Dawan uranium deposit.

Paleozoic continental to neritic marine sedimentary rocks. These pre-Mesozoic sequences were unconformably overlain by the lower Mesozoic terrestrial clastic rocks during the Indosinian Orogeny. The outcropping Sinian–Cambrian meta-sedimentary rocks in the district consist mainly of organic carbon-rich slates, quartzites and phyllites. A number of uranium deposits occur in the metasedimentary rocks in this area, such as the Dawan, Xiangcao, Niutoujiang and Miaochong deposits (Fig. 1). The major host rocks are the Cambrian Xiangnan and Chayuantou Formation. The Xiangnan Formation includes about 700 m thick gray-green-black carbonaceous slates, siliceous slates and quartzites. The metamorphic grade is lower than greenschist facies. The slate rocks are rich in organic carbon and pyrite. The Chayuantou Formation includes about 1200 m thick gray siliceous slates and quartzites.

The most important deep fault in southern Hunan Province is the NE trending Chenzhou–Lingwu fault. Wang et al. (2008) suggested this fault as a boundary between the Yangtze Block and the Cathaysia Block during the Neoproterozoic collision. Several regional NE-trending high-angle faults and fracture zones with lengths of more than 10 km traverse the entire district. These faults might be the second-order and/or third-order faults of the Chenzhou–Lingwu fault. The uranium orebodies are mainly controlled by these NE-trending faults and fracture zones.

3. Geology of the Dawan deposit

The Dawan uranium deposit was discovered in 1956, and was intensely explored in the 1960s and 1970s. It was mined as a middle-scale deposit in the 1990s. Now, a new round of geological surveys and mineral exploration is being carried out in this area, and this deposit has become a large-scale one.

The uranium orebodies in the Dawan deposit are chiefly hosted within the lowest part of Cambrian Xiangnan Formation (Fig. 2), but some small orebodies may extend into the granitic body along the faults. A total of 81 orebodies have been discovered in this deposit. The orebody occurs as lenticular and irregular shapes, which is 40–160 m long, 40–185 m deep, and 0.5–9 m wide (Fig. 3). Most of the orebodies occur within the NE-trending, 65°-dipping F4 fault, extending ~4 km in length with widths varying between 5 cm and 6 m.

There are two major types of ores: the big vein type and the disseminated veinlet type. The 0.5–5 mm wide pitchblende veinlets and the disseminated pitchblende grains, up to 1 mm in size, are the most important mineralization. The pitchblende veinlets occur in the fractures of the rocks which may crosscut the mineral grain boundaries. The ore grades vary from 0.1% to 1%, with an average grade of 0.152%. Except for pitchblende, the coffinite is also an important ore mineral in the deposit. The gangue minerals include pyrite, chlorite, illite, quartz, sericite and calcite. Hydrothermal alteration of the host rocks include silicification, chloritization, illitization, pyritization and carbonate alteration. The granitic rocks close to the orebodies also display slight alteration of chloritization, silicification and potash feldspathization. Sedimentary rocks within 500 m of the Jinjiling granite show contact metamorphism and they became biotite hornfels, axinite hornfels and pyroxene hornfels. Some of the orebodies occur in the contact metamorphism aureole, but most of them do not occur in the aureole. Thus, we do not suggest that the contact metamorphism aureole played an important role in the ore formation.

Based on cross-cutting relationships and texture observations in thin sections of ore samples (Fig. 4), the paragenesis of hydrothermal minerals in the Dawan deposit can be divided into four stages (Fig. 5). Stage I (pre-mineralization stage) consists of macrocrystalline quartz, pyrite and minor chlorite and illite. Stage II (early mineralization stage) is the main uranium deposition stage and includes coffinite, pyrite, galena, chlorite, illite, macrocrystalline quartz and microcrystalline quartz (Fig. 4a). Stage III (late mineralization stage) includes pitchblende, pyrite, galena, chlorite, illite and microcrystalline quartz (Fig. 4b–4e). The latest hydrothermal minerals (Stage IV, post-mineralization stage) postdate all the U minerals and include calcite, kaolinite and minor fluorite (Fig. 4f).

The primary U-minerals occur as microveinlets, 0.5–5 mm in width, along fractures, and as disseminated micro-grains. The precipitation of coffinite is spatially and genetically related to pre-existing pyrites. As shown in Fig. 4a, coffinite often replaces and rims the pyrite. The pitchblende may fill the fractures of the rocks or crosscut the mineral grain boundaries (Fig. 4b).

Pyrite is abundant in ores, and two types of pyrite are identified. Type 1 pyrite formed prior to the ore mineralization stage and includes the pre-existing pyrites in host sedimentary strata and recrystallized at

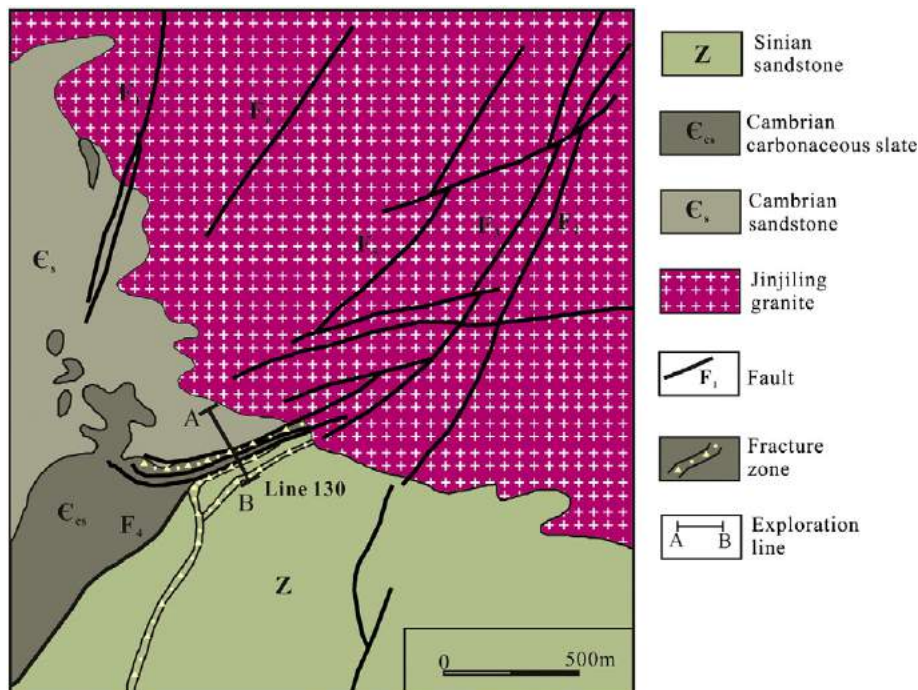


Fig. 2. Geological map of the Dawan uranium deposit.

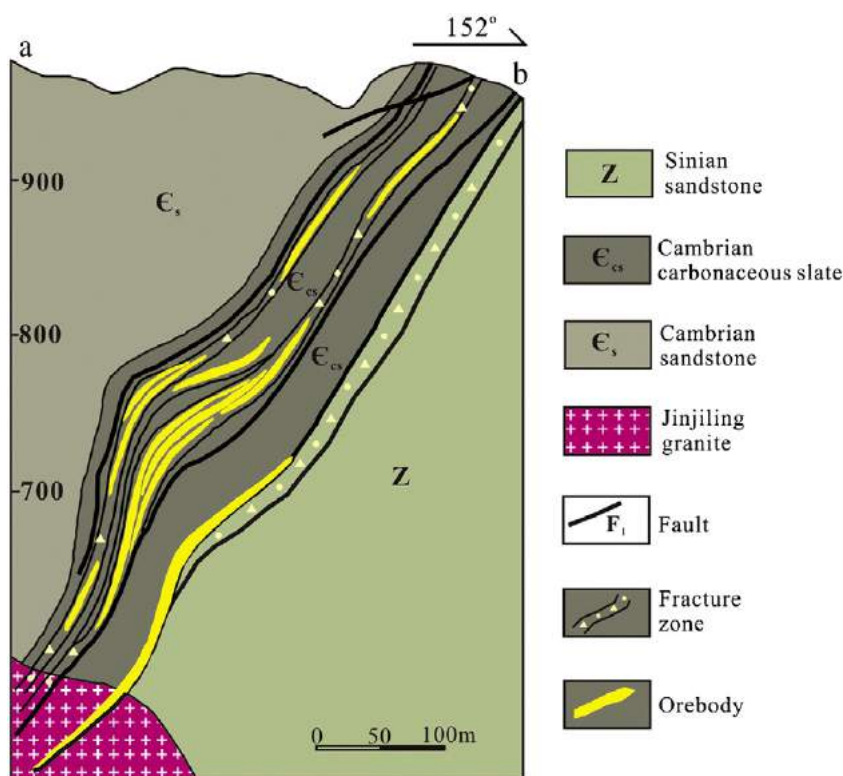


Fig. 3. Cross-section of Exploration Line 130 (in Fig. 2) in the Dawan uranium deposit.

Stage I, which are replaced by microcrystalline quartz and U-minerals at Stage II and Stage III (Fig. 4a, 4c). Type 2 pyrite formed from the hydrothermal fluids during the early and late mineralization stages (Stage II and Stage III), and is inter-grown with quartz, chlorite and pitchblende (Fig. 4d, e).

4. Samples and analytical methods

We collected representative uranium ore samples, metasedimentary host rock samples (slates), and fresh granitic rock samples both from the outcrops and underground mining tunnels. Textures of the ores have been observed using thin sections and polished slabs. Hydrothermal minerals (chlorite, illite, pitchblende and coffinite) in ores were analyzed for their chemical composition. Two host rock slates and four ore samples were analyzed for their major and trace element concentrations and Sr–Nd isotopic compositions. Pyrites in ores were separated and analyzed for sulfur and lead isotopes. Samples of fresh granitic rocks from the Jinjiling pluton were also collected and data on these samples have already been reported in Jiang et al. (2009).

Mineral chemistry analyses were obtained from polished thin sections using a JEOL JXA-8100 electron microprobe at State Key Laboratory for Mineral Deposits Research at Nanjing University, China. The measurements were carried out using a beam size of 1 μm , an accelerating potential voltage of 15KV, and a probe current of 15 nA. Matrix effects were corrected using the ZAF software provided by JEOL. The accuracy of the reported values is 1%–5% depending on the abundance of the elements.

Major element compositions of whole rocks and ores were analyzed using an ICP-AES at the same laboratory after alkaline fuse digestion, with analytical uncertainties better than 0.5% for all major elements. Trace element contents were determined by a Finnigan MAT Element II HR-ICP-MS at the same laboratory, and the analytical procedures were similar to those described by Gao et al. (2003). About 50 mg of powdered sample was dissolved in high-pressure Teflon bombs using a HF + HNO₃ mixture. Rh was used as an internal standard to monitor signal drift during ICP-MS measurement. The USGS rock standards GSP-1

and AGV-2 were chosen for calibrating element concentrations of the measured samples. Analytical uncertainties were <10%.

Sr and Nd isotope analyses of the whole rock samples were obtained using the same chemical separation and mass spectrometry methods described by Pu et al. (2004, 2005). About 100 mg samples were dissolved in the same way as for trace element analyses. Complete separation of Sr was achieved by a combination of cation-exchange chromatography in H⁺ form and pyridinium form with the DCTA complex. Nd was then separated from the REE fractions by cation-exchange resin using HIBA as eluent. Determination of Sr and Nd isotopic composition was carried out by a Finnigan MAT Triton TI TIMS at the same laboratory. The Sr isotopic data are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. The Nd isotopic data are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The NIST-987 Sr standard gave an average value of 0.710258 ± 0.000006 ($n = 5, 2\sigma$) in this study. The JNDi-1 Nd standard gave an average value of 0.512118 ± 0.000005 ($n = 5, 2\sigma$), which is similar to the suggested value of 0.512115 ± 0.000007 (Tanaka et al., 2000). For the calculation of $\epsilon_{\text{Nd}}(t)$ values, we have adopted a decay constant for ^{147}Sm of $6.54 \times 10^{-12} \text{ year}^{-1}$ (Lugmair and Marti, 1978) and chondritic values of $^{143}\text{Nd}/^{144}\text{Nd}$ (0.512638) and $^{147}\text{Sm}/^{144}\text{Nd}$ (0.1967) (Jacobsen and Wasserburg, 1980). Depleted mantle values of $^{143}\text{Nd}/^{144}\text{Nd}$ (0.513151), $^{147}\text{Sm}/^{144}\text{Nd}$ (0.2136) and a mean crustal value of $^{147}\text{Sm}/^{144}\text{Nd}$ (0.118) (Jahn and Condie, 1995) have been used to calculate the two-stage depleted mantle model ages.

High purity (>99%) pyrites were separated from ten ore samples by careful hand picking under a binocular microscope. Sulfur isotopic compositions of pyrite were analyzed by the conventional SO₂ method with a gas source mass spectrometer (Finnigan MAT 251EM) at the Institute of Mineral Deposits, Chinese Academy of Geological Sciences. The sulfur isotope results are presented in the standard δ notation, expressed in per mil (‰) with respect to Canyon Diablo Troilite (V-CDT). The analytical precision is 0.2‰.

Lead isotopic analyses of pyrite were carried out by the following procedures (Zhao et al., 2007). About 50 mg of pyrites were completely dissolved in ultrapure HNO₃ + HCl. After drying, the residue was redissolved in HNO₃ and dried again. Finally, the sample residue was

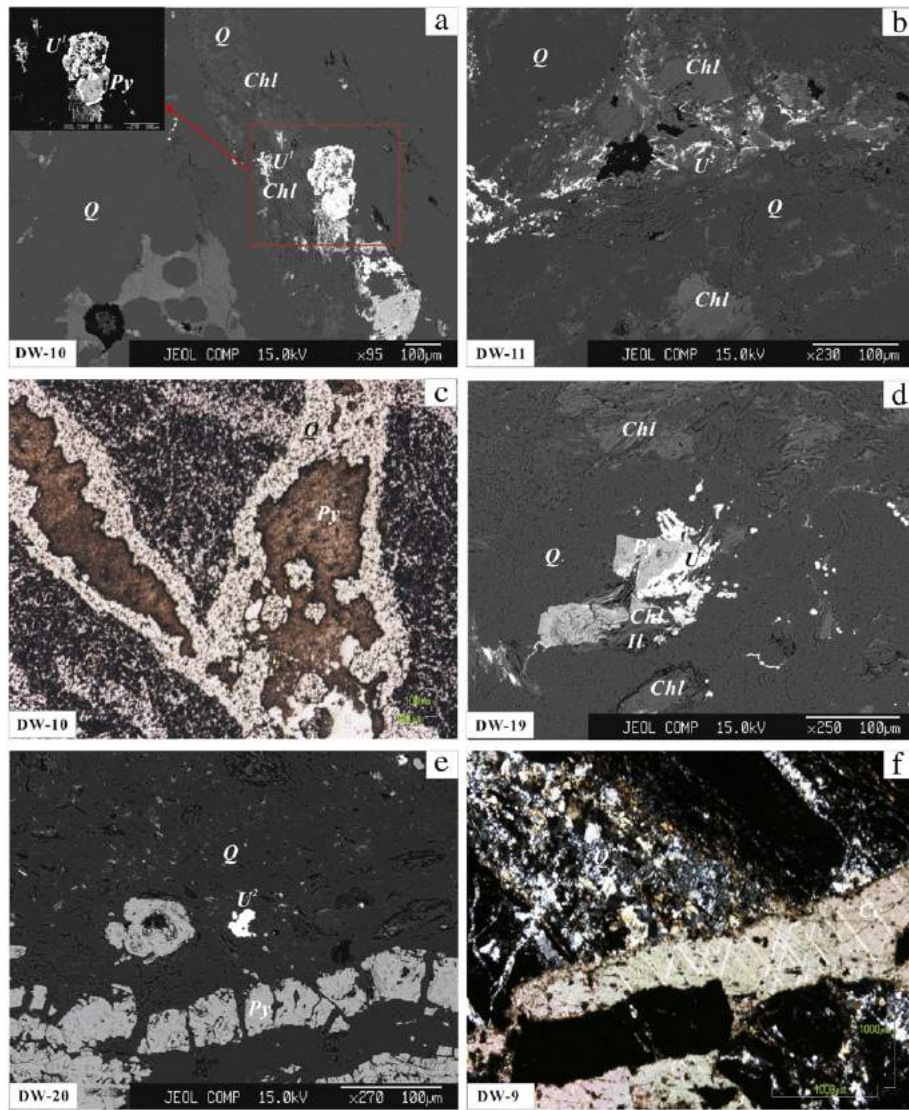


Fig. 4. Backscatter electron (BSE) images (a, b, d, e) and photomicrography (c, f) of thin sections representing the mineral assemblage in the Dawan uranium deposit. a. Fracture with coffinite that replaced pre-existing pyrite, chlorite and quartz. b. Fracture filled by pitchblende, chlorite and quartz; c. residue pre-existing pyrite, which was replaced by microcrystalline quartz; d–e. Pitchblende co-precipitated with hydrothermal pyrite, chlorite and illite. f. Microcrystalline quartz vein was cut by a later calcite vein. U¹—coffinite, U²—pitchblende, Q—quartz, Py—pyrite, Chl—chlorite, Il—illite, Cc—calcite.

dissolved in HBr and then loaded into a column with 50 ml of AG 1-X8 anion resin to separate the Pb fraction. The extracted Pb was further purified in a second column in a similar way. Approximately 100 ng Pb was loaded onto a single rhenium filament using the silica-gel

technique (Gerstenberger and Haase, 1997). Pb isotopic ratios were measured with a Finnigan MAT Triton TI thermal ionization mass spectrometer (TIMS) at State Key Laboratory for Mineral Deposits Research at Nanjing University. Analytical reproducibilities of 0.01% (2σ) for

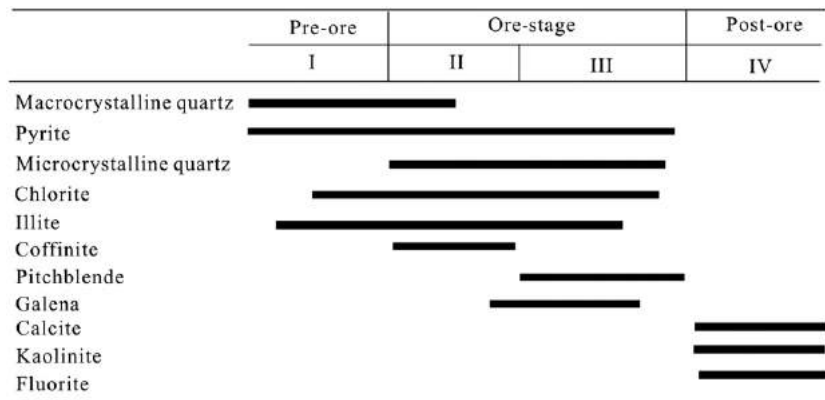


Fig. 5. Paragenetic chart summarizing the relative timing of mineral assemblages in the Dawan uranium deposit.

$^{206}\text{Pb}/^{204}\text{Pb}$, 0.01% for $^{207}\text{Pb}/^{204}\text{Pb}$ and 0.02% for $^{208}\text{Pb}/^{204}\text{Pb}$ were attained in this study. Mass fractionation corrections (1.0030 for $^{206}\text{Pb}/^{204}\text{Pb}$, 1.0045 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 1.0066 for $^{208}\text{Pb}/^{204}\text{Pb}$) have been applied on the basis of multiple analyses of NBS-981 Pb isotope reference material (Todd et al., 1996).

5. Results

5.1. Chemical compositions of U-minerals

Representative electron microprobe analyses for coffinite and pitchblende in ores are listed in Table 1. Coffinites have variable UO_2 contents (72.94–81.19%) and SiO_2 contents (7.77–18.32%). They also have minor CaO contents (1.37–5.03%) and Al_2O_3 contents (0.80–4.72%). Relatively low SiO_2 contents correspond to a fine admixture of coffinite and pitchblende and relatively high Al_2O_3 contents correspond to a fine admixture of coffinite and minor clay minerals. Pitchblendes have higher UO_2 contents (82.27–94.30%) and lower SiO_2 contents (1.45–4.66%). Both coffinites and pitchblendes have very low ThO_2 contents (<0.05%). In the plot of UO_2 vs. SiO_2 (Fig. 6), the data from pitchblendes and coffinites show a linear variation trend, which indicates a fine admixture of coffinite and pitchblende with variable amounts of each mineral.

5.2. Chemical compositions of chlorite and illite

Chlorites inter-grown with pitchblendes in ores were analyzed by electron microprobe. The compositions and calculated chemical formulae are listed in Table 2. Chlorites in the ores show relatively high MgO contents (12.16–18.44%) and low FeO contents (19.45–23.92%). They have very low K_2O contents (<0.24%), TiO_2 contents (<0.05%) and Na_2O contents (<0.06%). In the classification of Bayliss (1975), chlorites in ores belong mainly to Mg-rich clinocllore (Fig. 7).

Chlorite is a common hydrothermal alteration mineral occurring in most uranium deposits in South China. Chlorite in granite- and volcanic rock-hosted uranium deposits is mainly Fe-rich chlorite. For example, chlorites from the large-scale Xiangshan volcanic rock-type uranium deposit have higher FeO contents (41.49–43.84%) and lower MgO contents (3.69–4.00%) (see Table 2, Zhang et al., 2007a). Chlorites from the large-scale 201 and 361 granite-rock type uranium deposit in South China also show high FeO contents (39.11–39.79%) and low MgO contents (2.51–2.67%) (see Table 2, Zhang et al., 2007b). Chemical compositions of chlorite from the Dawan deposit are obviously different to those from granite-type and volcanic rock-type uranium deposits. Biotites from the Jinjiling granites belong to Fe-rich annites (Zhang et al., 2001). These Mg-rich chlorites in the Dawan ore deposit might have been altered from pre-existing biotites at the metasedimentary strata.

Illite is also a common hydrothermal alteration mineral in many uranium deposits (e.g., Polito et al., 2004, 2009). The compositions of illites

in the Dawan deposit and calculated chemical formulae are listed in Table 3. SiO_2 contents of illite vary from 49.01% to 54.85%, and Al_2O_3 contents vary from 28.53% to 37.04%. Illites have variable K_2O contents of 2.97% to 9.31%. Large variation in compositions indicates that these illites might belong to different generations: some inherited from enclosing rocks and some re-equilibrated and newly formed during hydrothermal alteration.

5.3. Major, trace and rare earth element concentrations of ores and host rocks

Two host rock slate samples and four ore samples were analyzed for major, trace and rare earth element concentrations (Table 4). The slates have SiO_2 contents of 72.26% to 74.29%, Al_2O_3 contents of 12.45% to 12.82%, and K_2O contents of 2.74% to 3.32%. The ores show higher SiO_2 contents (74.89–85.66%) resulting from silicification during hydrothermal alteration, lower Al_2O_3 (5.13–6.08%), TiO_2 (0.21–0.61%) and K_2O (1.09–1.56%) contents. The ores have higher Fe_2O_3 contents and lower FeO contents than those of host rocks, which indicates that the ore-forming fluid is more oxidizing than the host sedimentary rocks.

The two slate samples show U contents of 8.9 and 9.0 ppm, whereas the U contents of the ores vary from 143.9 to 2063 ppm. The slates have higher Th contents (14.25 to 17.35 ppm) and higher Th/U ratios (1.58–1.95) than those of the ores (3.44–12.84 ppm Th and 0.002 to 0.09 Th/U). The ores have much higher V contents (1413–2158 ppm) and slightly higher Mo, Y, HREE, Sr, and Cu contents than the host rocks. The trace element spider distribution patterns of the ores are strongly disturbed compared to the host rocks and show more elevated V, Mo and U peaks (Fig. 8a). The trace element patterns of the ores are quite similar to those of regional Cambrian black shale strata in South China, for example, the Hetang Formation (Fig. 8b) (Zhou and Jiang, 2009). However, these trace element patterns are totally different from those of the Jinjiling granites (Fig. 8c) (Jiang et al., 2009).

Slate host rocks display light-REE enrichments ($\text{LREE}/\text{HREE} = 24.23\text{--}26.29$), negligible Ce anomalies ($\text{Ce}/\text{Ce}^* = 0.88\text{--}0.99$) and slightly negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.60\text{--}0.94$) in a similar way to classical shales (Fig. 9a). Ore samples show similar patterns, but with weaker light-REE enrichments ($\text{LREE}/\text{HREE} = 7.49\text{--}12.82$) and obviously negative Ce anomalies ($\text{Ce}/\text{Ce}^* = 0.58\text{--}0.72$) and slightly positive Eu anomalies (Fig. 9b). REE patterns of both the host rocks and ores are obviously different from those of granites, which display strongly negative Eu anomalies (Fig. 9c) (Jiang et al., 2009).

5.4. Sr–Nd isotopic compositions of ores and host rocks

Sr–Nd isotopic compositions of the ores and host rock samples are listed in Table 5, and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\epsilon_{\text{Nd}}(t)$ values were calculated at the mineralization age ($t = 80$ Ma, CNGB, 2005). Slate samples have high $(^{87}\text{Sr}/^{86}\text{Sr})_{t=80\text{Ma}}$ values (0.7529–0.7554) and low $\epsilon_{\text{Nd}}(t = 80\text{ Ma})$

Table 1
Representative chemical compositions of coffinite and pitchblende in ores from the Dawan uranium deposit.

Analytical spot	Pitchblende						Coffinite					
	1	2	3	4	5	6	7	8	9	10	11	12
UO_2	88.38	87.60	82.27	89.59	94.30	85.45	81.19	72.94	73.95	73.38	77.80	74.06
ThO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.01	0.00
SiO_2	1.45	1.70	2.78	2.18	2.16	4.66	7.77	14.85	18.32	14.28	12.93	14.06
Al_2O_3	0.20	0.17	0.21	0.24	0.15	0.6	0.91	1.69	0.80	4.72	1.05	1.10
MgO	0.12	0.02	0.03	0.04	0.03	0.12	0.00	0.41	0.09	0.54	0.15	0.00
CaO	3.80	3.85	6.22	4.38	0.63	4.53	5.03	1.37	3.56	2.64	2.49	1.60
FeO	1.98	1.73	0.56	0.92	0.69	0.99	0.25	1.57	1.18	1.63	1.32	0.33
MnO	0.59	0.37	1.11	0.72	0.07	0.57	0.90	0.34	0.56	0.48	0.30	0.36
TiO_2	0.04	0.09	0.00	1.07	0.00	0.30	0.18	0.09	0.06	0.69	0.00	0.04
PbO	0.86	2.60	0.96	0.40	0.62	0.49	0.03	0.00	0.30	0.41	0.19	0.01
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
Total	97.41	98.14	94.14	99.52	98.65	97.69	96.32	93.45	98.83	98.77	96.24	91.55

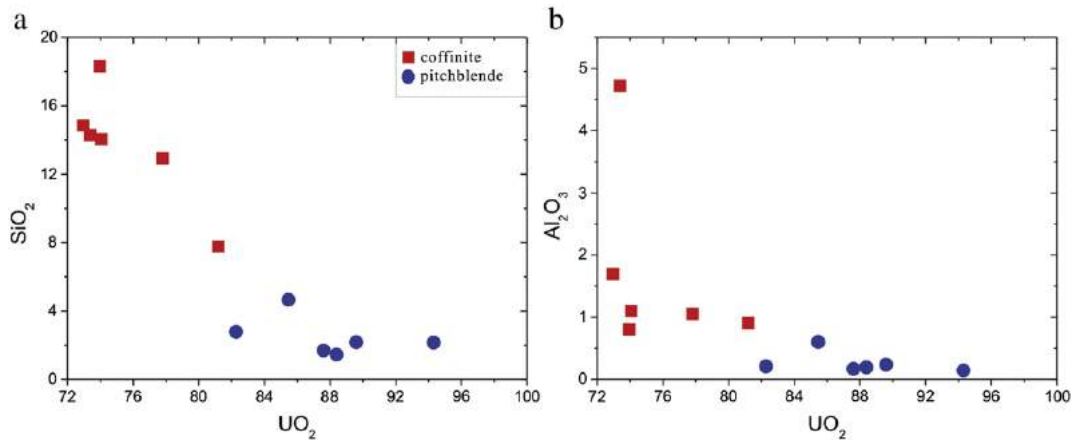


Fig. 6. Plots of SiO_2 vs. UO_2 and Al_2O_3 vs. UO_2 of coffinite and pitchblende in the Dawan uranium deposit.

values of -17.2 . Ore samples show relatively lower $(^{87}\text{Sr}/^{86}\text{Sr})_{t=80\text{ Ma}}$ values of 0.7232 – 0.7505 and higher $\varepsilon_{\text{Nd}}(t=80\text{ Ma})$ values of -14.2 to -12.2 than the host rocks. The Jinjiling granite samples show large variation of $(^{87}\text{Sr}/^{86}\text{Sr})_{t=80\text{ Ma}}$ values from 0.7136 to 0.7561 and obviously higher $\varepsilon_{\text{Nd}}(t=80\text{ Ma})$ values of -7.7 to -7.1 than those of the ores and host rocks (Table 5, Jiang et al., 2009).

5.5. Sulfur isotopic compositions of pyrite

Sulfur isotopic compositions of ten pyrite samples separated from ores are listed in Table 6. Two samples (DW-10 and DW-14) show very low $\delta^{34}\text{S}$ values (-26.3% and -25.9%). Texture observation in thin sections suggested that most pyrites in the two samples were pre-existing pyrites derived from the host rocks and were replaced by coffinite and microcrystalline quartz (e.g. Fig. 4a, c). Other samples have homogeneous $\delta^{34}\text{S}$ values of -9.5% to -7.7% (Fig. 10). These pyrites are mainly hydrothermal pyrites, which probably co-deposited with U-minerals. Pyrites from the Sinian–Cambrian strata in the Xiangcao deposit display variable $\delta^{34}\text{S}$ values from -19.9% to -4.4% with an average value of -8.7% (Min, 1995). Pyrites from the Jinjiling

granite have homogeneous $\delta^{34}\text{S}$ values, varying from -0.63% to $+1.57\%$ (CNGB, 2005).

5.6. Pb isotopic compositions of pyrite

Pyrite samples display variable lead isotopic composition. $^{206}\text{Pb}/^{204}\text{Pb}$ values vary from 19.6843 to 89.2343 , $^{207}\text{Pb}/^{204}\text{Pb}$ values vary from 15.7225 to 19.6830 , and $^{208}\text{Pb}/^{204}\text{Pb}$ values vary from 38.5888 to 39.3020 . The pre-existing pyrites show higher lead isotopic compositions than those of the hydrothermal pyrites. In a plot of $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ (Fig. 11), the data show a good linear trend and give an isochron age of $479 \pm 69\text{ Ma}$ (MSWD = 1.6).

6. Discussion

6.1. Characteristics and origin of ore-forming fluid

Chlorite alteration is a widespread phenomenon in the U deposits, and we can use chlorite composition to estimate the temperatures of hydrothermal alteration and associated mineralization. Walshe and

Table 2
Representative chemical compositions of chlorite in ores from the Dawan uranium deposit.

Deposit	Dawan				Xiangshan ^a				201 and 361 ^b		
Analytical spot	1	2	3	4	4	5	6	7	ZG-05-1	ZG-05-2	ZG-05-3
SiO_2	26.12	26.85	27.75	25.23	25.19	25.43	21.08	23.08	24.67	24.29	24.48
TiO_2	0.05	0.04	0.02	0.05	0.22	0.31	0.02	0.06	0.02	0.09	0.04
Al_2O_3	22.83	22.25	19.70	21.97	19.00	19.04	19.86	19.44	17.30	16.97	17.74
FeO	20.72	19.45	23.92	18.80	41.59	42.76	41.69	43.84	39.79	39.11	39.19
MnO	0.44	0.57	0.43	0.49	0.20	0.21	0.18	0.14	1.08	0.86	1.08
MgO	15.21	15.27	12.16	18.44	4.00	3.69	3.74	2.95	2.51	2.59	2.67
CaO	0.20	0.16	0.08	0.03	0.14	0.04	0.13	0.20	0.02	0.01	0.07
Na_2O	0.02	0.06	0.04	0.01	0.01	0.03	0.04	0.04	0.06	0.00	0.01
K_2O	0.02	0.24	0.06	0.00	0.00	0.16	0.14	0.15	0.04	0.16	0.10
Total	85.61	84.89	84.16	85.02	90.35	91.67	86.88	89.9	85.49	84.08	85.38
Si	2.79	2.88	3.09	2.66	2.84	2.83	2.47	2.63	2.97	2.97	2.94
Al[4]	1.21	1.12	0.91	1.34	1.16	1.17	1.53	1.37	1.03	1.03	1.06
Al[6]	1.66	1.69	1.68	1.39	1.36	1.33	1.20	1.24	1.42	1.41	1.45
Ti	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.01	0.00	0.01	0.00
Fe(3+)	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.14	0.00	0.00	0.00
Fe(2+)	1.85	1.74	2.23	1.65	3.91	3.98	3.72	4.04	4.00	3.99	3.93
Mn	0.04	0.05	0.04	0.04	0.02	0.02	0.02	0.01	0.11	0.09	0.11
Mg	2.42	2.44	2.02	2.90	0.67	0.61	0.65	0.50	0.45	0.47	0.48
Ca	0.02	0.02	0.01	0.00	0.02	0.00	0.02	0.02	0.00	0.00	0.01
Na	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00
K	0.00	0.03	0.01	0.00	0.00	0.02	0.02	0.02	0.01	0.02	0.02
Fe/(Fe + Mg)	0.43	0.42	0.53	0.36	0.85	0.87	0.86	0.89	0.90	0.89	0.89
T(°C)	217	204	189	227	253	255	291	278	239	239	241

^a Data came from Zhang et al. (2007a).

^b Data came from Zhang et al. (2007b).

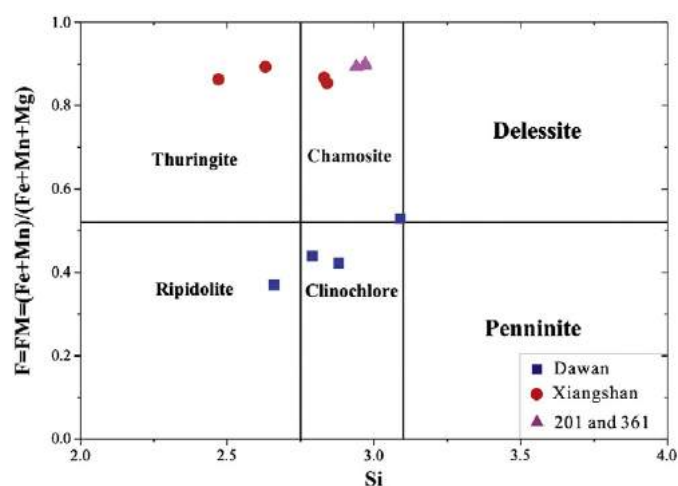


Fig. 7. Classification diagram of chlorite from the Dawan, Xiangshan, 201 and 361 uranium deposits in South China.

Solomon (1981) and Cathelineau and Nieva (1985) proposed chlorite geothermometry using its chemical compositions. The temperature–composition correlations were then modified (e.g. Battaglia, 1999; Cathelineau, 1988; Jowett, 1991; Zang and Fyfe, 1995). In the past, chlorite geothermometry has been successfully applied to estimate temperatures for hydrothermal alteration in many ore deposits and geothermal fields (e.g. Li et al., 1998; Lira et al., 2009; Mücke and Losos, 1999; Zhao et al., 2005). In this study, the modified chlorite geothermometry of Battaglia (1999) is adopted to estimate the temperature for hydrothermal alteration in the Dawan deposit. The calculated temperatures vary from 189 to 227 °C, which are similar to the temperatures of ore-forming fluids in the main mineralization stage of most hydrothermal reworking carbonaceous-siliceous-pelitic rock-type to form uranium deposits in South China (Min, 1995). Hence, the Dawan deposit belongs to a mesothermal hydrothermal deposit.

Pitchblende preferentially precipitates from hydrothermal fluids when the Si content is below $10^{-3.5}$ to $10^{-2.7}$ mol/l (19 to 120 ppm of SiO_2), whereas coffinite becomes more stable when the Si contents exceeds $10^{-2.7}$ mol/l (120 ppm of SiO_2) (Brookins, 1976; Langmuir, 1978; Min et al., 2005). Thus, fluids at the early mineralization stage responsible for coffinite formation have relatively higher Si contents, whereas fluids at the late mineralization stage responsible for pitchblende precipitation have relatively lower Si contents. The decrease of Si in ore-forming fluids was caused by the deposition of quartz.

Uranium exists in two oxidation states. Uranium in the 6^+ state is highly soluble, while uranium in the 4^+ state is highly insoluble. Thus, hydrothermal mobility of uranium generally requires oxidizing fluids (Shock et al., 1997). Ore samples display obviously more negative Ce anomalies than the host slates in the Dawan deposit (Fig. 9). Only when oxidized fluid leached the wallrocks, did it result in depletion of Ce, because Ce as oxidation of Ce^{3+} to Ce^{4+} forms cerianite CeO_2 ,

Table 4

Major (in %), trace and rare earth element (in ppm) concentrations of host rock slates and ores from the Dawan uranium deposit.

Sample	DW-8	DW-9	DW-10	DW-11	DW-12	DW-16
	Slate	Ore	Ore	Ore	Ore	Slate
SiO_2	72.26	74.89	83.79	85.66	71.21	74.29
TiO_2	0.59	0.28	0.27	0.21	0.61	0.65
Al_2O_3	12.82	6.08	5.84	5.13	13.10	12.45
Fe_2O_3	1.36	2.88	1.53	2.16	2.32	1.47
FeO	1.57	0.74	0.36	1.51	1.29	1.12
MnO	0.08	0.04	0.02	0.06	0.08	0.04
MgO	1.86	0.52	0.27	1.26	1.71	0.84
CaO	0.41	4.15	0.24	0.23	0.30	0.39
Na_2O	0.09	0.07	0.06	0.05	0.15	0.27
K_2O	3.32	1.40	1.19	1.09	4.64	2.74
P_2O_5	0.16	0.13	0.15	0.12	0.15	0.15
LOI	5.30	8.76	6.05	2.37	4.23	5.37
Total	99.82	99.94	99.77	99.85	99.79	99.78
Li	50.77	42.7	33.9	49.38	50.77	181.0
Be	4.28	5.78	3.62	4.96	5.96	4.08
Sc	11.81	7.18	5.76	4.55	13.58	11.24
Ti	3834	1790	1672	1271	3810	4263
V	142.2	2159	1747	1516	1413	134.7
Cr	82.03	169.5	136.5	104.1	129.5	121.8
Mn	574.2	256.6	90.01	436.6	488.6	167.8
Co	4.59	7.46	7.49	27.1	13.1	19.7
Cu	23.46	140.2	62.33	43.27	49.91	23.97
Zn	139.2	78.73	53.74	195.9	110.6	184.9
Ga	19.90	18.18	14.57	13.80	23.62	15.03
Rb	152.0	126.8	84.11	82.40	224.1	127.9
Sr	16.31	81.77	47.42	31.41	46.89	32.58
Y	21.88	54.76	50.34	37.32	40.47	32.31
Zr	221.0	95.53	86.75	64.71	146.2	289.7
Nb	11.84	4.37	3.39	2.94	12.43	11.66
Mo	3.58	15.45	26.68	15.43	36.85	8.50
Cd	1.33	0.62	1.20	5.67	2.14	1.19
Sn	2.90	1.29	1.85	0.80	2.61	1.95
Cs	11.19	10.8	5.04	14.82	18.61	12.76
Ba	984.4	179.6	236.0	194.8	1176	607.2
La	37.14	44.39	23.72	15.00	37.40	46.16
Ce	63.41	53.36	29.71	22.68	54.86	92.55
Pr	7.24	10.25	5.82	3.79	8.29	9.95
Nd	26.02	38.97	24.48	15.04	30.98	37.95
Sm	4.33	6.95	5.84	3.73	6.12	7.22
Eu	1.26	1.45	1.56	1.13	1.57	1.36
Gd	3.71	6.56	6.52	4.28	6.19	6.32
Tb	0.45	1.00	0.94	0.60	0.82	0.73
Dy	3.15	7.93	7.04	4.70	6.15	5.14
Ho	0.68	1.87	1.61	1.01	1.41	1.08
Er	2.11	5.71	4.80	3.08	4.37	3.29
Tm	0.31	0.81	0.69	0.42	0.64	0.48
Yb	1.99	4.99	4.08	2.52	3.85	2.85
Lu	0.33	0.80	0.67	0.41	0.63	0.47
Hf	5.36	1.93	1.64	1.31	3.66	7.6
Ta	0.93	0.36	0.33	0.24	0.94	0.98
W	4.04	7.46	9.63	7.41	6.74	1.58
Pb	10.11	14.37	26.71	20.96	23.08	13.74
Bi	0.12	0.26	0.33	0.20	0.23	0.13
Th	14.25	5.67	4.73	3.44	12.84	17.35
U	8.99	2063	1301	1920	143.9	8.89
$\text{Fe}_2\text{O}_3/\text{FeO}$	0.87	3.89	4.25	1.43	1.8	1.31
LREE/HREE	26.29	10.98	7.49	8.02	12.82	24.23
Ce/Ce*	0.88	0.58	0.59	0.71	0.72	0.99
Eu/Eu*	0.94	0.65	0.77	0.86	0.77	0.60
Th/U	1.585	0.003	0.004	0.002	0.089	1.952

Table 3

Representative chemical compositions of illite in ores from the Dawan uranium deposit.

Analytical spot	1	2	3	4	5	6
SiO_2	49.17	49.01	57.36	54.85	51.09	50.21
TiO_2	0.03	0.76	0.00	0.00	1.02	0.47
Al_2O_3	35.77	36.54	28.53	30.62	35.00	37.04
FeO	1.93	0.66	4.64	3.45	0.85	0.90
MnO	0.05	0.01	0.04	0.12	0.02	0.01
MgO	1.12	0.64	3.01	2.30	0.88	1.06
CaO	0.13	0.01	0.35	0.36	0.02	0.07
Na_2O	0.16	0.38	0.09	0.22	0.27	0.32
K_2O	9.31	9.02	2.97	5.30	9.30	7.64
P_2O_5	0.01	0.00	0.01	0.01	0.01	0.00
Total	97.68	97.03	97.01	97.22	98.46	97.71

which is highly insoluble. Thus, ore-forming fluids should be relatively oxidizing fluids. The fact that coffinite replaced pre-existing pyrite suggests the initial ore-forming fluids can oxidize pyrite. Therefore, initial ore-forming fluids display characteristics of intermediate temperature, high oxygen fugacity and high Si contents. The co-precipitation of pitchblende and pyrite indicate that the fluids for pitchblende precipitation are relatively more reduced than those for coffinite precipitation. Thus, the ore-forming fluids evolved from oxidizing to reduced, and

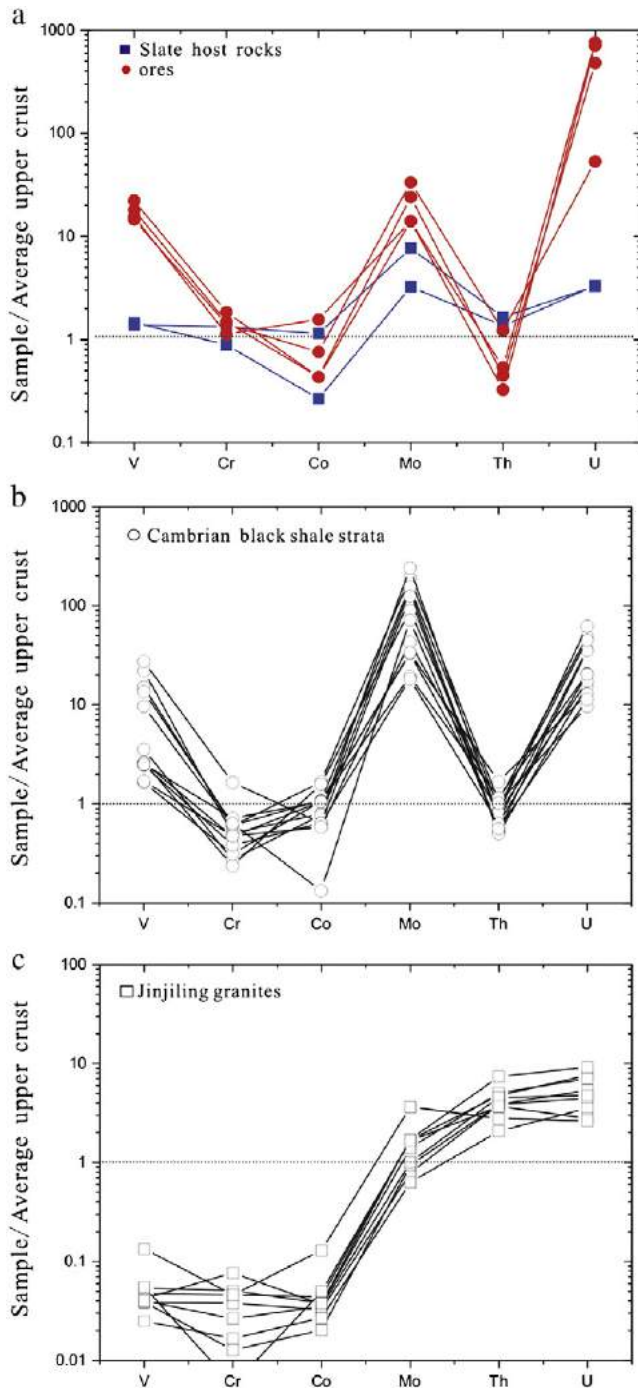


Fig. 8. Spider distribution patterns of redox-sensitive trace element and Th in ores from the Dawan uranium deposit, Cambrian black shale strata, and the Jinjiling granites. Data of Cambrian black shale strata are from [Zhou and Jiang \(2009\)](#); data of the Jinjiling granites are from [Jiang et al. \(2009\)](#).

from Si-rich to Si-poor, from the early mineralization stage to the late mineralization stage.

The U–Pb isotopic ages of coffinites gave the main mineralization ages of about 80 Ma ([China Nuclear Geological Bureau, 2005](#)), which was 70 m.y. later than the emplacement of the Jinjiling granites (~156 Ma, [Fu et al., 2004](#)). Thus, the ore-forming fluids were unlikely to have derived from granitic magmas. Such high oxidizing fluids are generally suggested to be circulated meteoric water (e.g. [Ling, 2011](#); [Mercadier et al., 2011](#)). Although the ages of the host rocks varied widely, most uranium mineralization in South China occurred at the late Cretaceous to Tertiary ([Hu et al., 2008](#)). Hydrogen and oxygen isotopes also

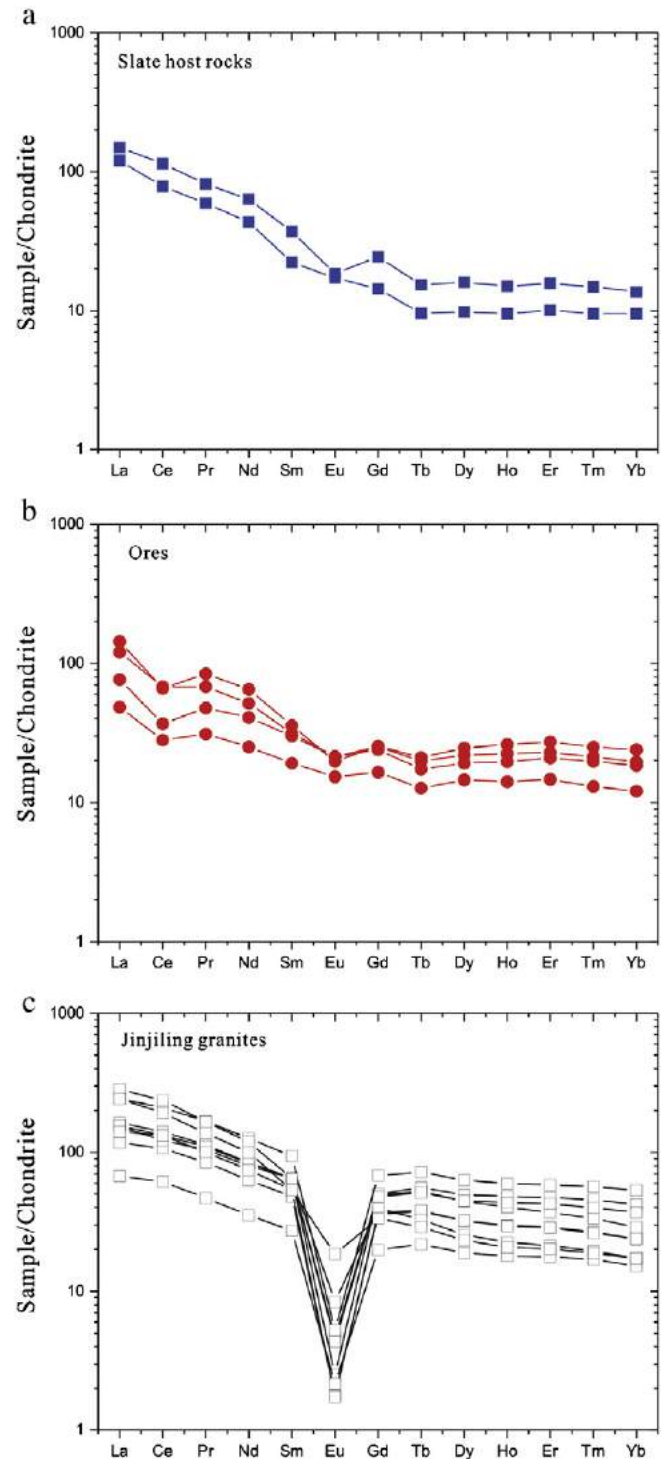


Fig. 9. Rare earth element distribution patterns of the ores and host rocks of the Dawan uranium deposit and the Jinjiling granites. Data of the Jinjiling granites are from [Jiang et al. \(2009\)](#).

support the idea that the water in ore-forming fluids for most uranium deposits in South China was dominantly meteoric water ([Hu et al., 2008](#); [Min, 1995](#)). The tectonic regime of South China changed from compression in the late Jurassic to extension in the Cretaceous (e.g. [Hu et al., 2008](#); [Li, 2000](#)). The extension resulted in the formation of numerous northeast-southwest-trending grabens and extensional basins in South China. These basins are filled with Cretaceous–Tertiary red beds. Such an extensional environment is suitable for driving circulation of meteoric water within fault systems to form hydrothermal fluids.

Table 5

Sr–Nd isotopic compositions of ores and host rocks from the Dawan uranium deposit and the Jinjiling granites. Data of granites came from Jiang et al. (2009).

Sample	Rocks	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	Error (2SE)	$(^{87}\text{Sr}/^{86}\text{Sr})_{t=80\text{ Ma}}$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Error(2SE)	$\varepsilon_{\text{Nd}}(t=80\text{ Ma})$	T_{DM}^2 (Ga)
DW-8	Slate	152.0	16.31	27.16	0.786280	0.000006	0.755404	4.33	26.02	0.101	0.511708	0.000003	−17.2	2.28
DW-9	Ore	126.8	81.77	4.49	0.728271	0.000004	0.723164	6.95	38.97	0.108	0.511957	0.000002	−12.4	1.89
DW-10	Ore	84.1	47.42	5.14	0.731914	0.000006	0.726068	5.84	24.48	0.144	0.511983	0.000002	−12.2	1.88
DW-11	Ore	82.4	31.41	7.61	0.737827	0.000004	0.729175	3.73	15.04	0.150	0.511946	0.000003	−13.0	1.94
DW-12	Ore	224.1	46.89	13.90	0.766319	0.000005	0.750516	6.12	30.98	0.119	0.511872	0.000004	−14.2	2.03
DW-16	Slate	127.9	32.58	11.42	0.765847	0.000003	0.752867	7.22	37.95	0.115	0.511714	0.000004	−17.2	2.28
JJL-1	Granite	571.1	12.92	130.04	0.878146	0.000006	0.730334	9.34	37.87	0.149	0.512253	0.000004	−7.0	1.46
JJL-5	Granite	584.6	10.68	161.37	0.898495	0.000005	0.715078	10.48	44.67	0.142	0.512217	0.000005	−7.7	1.51
JJL-6	Granite	748.6	20.92	105.22	0.875747	0.000004	0.756145	18.32	75.44	0.147	0.512235	0.000004	−7.4	1.48
JJL-7	Granite	776.2	11.74	195.60	0.935972	0.000006	0.713647	5.32	21.15	0.152	0.512253	0.000002	−7.1	1.46
JJL-8	Granite	347.0	33.04	30.56	0.768133	0.000006	0.733394	12.60	71.13	0.107	0.512210	0.000007	−7.4	1.49
JJL-9	Granite	248.6	136.86	5.26	0.726589	0.000007	0.720605	10.38	59.76	0.105	0.512223	0.000008	−7.2	1.47

6.2. Sources of sulfur and uranium

There are two types of pyrites in ores, one formed prior to the ore mineralization stage, including the pre-existing pyrites in host sedimentary strata and crystallized at Stage I and the other formed from the hydrothermal fluids during the mineralization stages (Stage II and Stage III). Two pyrite samples have very low $\delta^{34}\text{S}$ values (−26.3‰ and −25.9‰), which implies that the pyrite is pre-existing, biogenic pyrite in sedimentary strata. The hydrothermal pyrites display homogeneous $\delta^{34}\text{S}$ values from −9.5‰ to −7.7‰. The $\delta^{34}\text{S}$ values of the pyrite from the Precambrian to Cambrian strata in this area mostly vary from −19.9‰ to −4.4‰, with an average value of −8.7‰ (Min, 1995). The pyrite from the Jinjiliang granites has $\delta^{34}\text{S}$ values of −1.4–+1.6‰ (China Nuclear Geological Bureau, 2005). The similarity of the $\delta^{34}\text{S}$ values of pyrite from the ores and the wall-rocks implies that the sulfur in ore-forming fluids was mainly derived from sulfur in the wall-rocks. The $\delta^{34}\text{S}$ values of the ore-forming fluids had become homogeneous.

The mineralization age of the Dawan deposit is obviously younger than the host strata and the granites. Thus, the uranium deposit is thought to have formed by remobilization of uranium from pre-existing uranium-rich rocks. There are two possible uranium sources for mineralization, namely, the Jinjiling granites and the meta-sedimentary strata.

The U contents of the Jinjiling granites vary from 8 to 16 ppm, which are obviously higher than the average upper continental crust (~2.7 ppm, Rudnick and Gao, 2003). Therefore, some researchers have suggested that the uranium in the Dawan deposit might come from the Jinjiling granites. The Jinjiling granites are biotite granites, and show A-type granite characteristics (Huang et al., 2011; Jiang et al., 2009). In such type of granite, uranium is mainly hosted in mineral phases like uranophane which are refractory when they are not metamict (e.g. Cuney and Friedrich, 1987). Most U-bearing granites in South China contain muscovite, they show high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values (>0.7100) and low $\varepsilon_{\text{Nd}}(t)$ values (<−10), and belong to strongly

peraluminous S-type granites (Dong et al., 2010; Zhang and Zhang, 1991; Zhao et al., 2011). Uranium in these granites was mainly hosted in uraninite, which was easily transferred by oxidized meteoric fluids. However, the leaching experiment indicates that the leaching efficiency of U from the Jinjiling granites is low (31.2 ~ 48.1%) (China Nuclear Geological Bureau, 2005). The leaching ratio was lower at the time of the U deposit formation. The time gap between the granite crystallization and mineralization (~70 Ma) was not sufficient for the metamictisation of the U-bearing minerals from the high-K A₂ type granite. The hydrothermal alteration of the Jinjiling granites is limited only close to the orebodies and fracture zones, whereas away from the orebody the granite remains quite fresh. The $\varepsilon_{\text{Nd}}(t)$ values of ores are lower than that of the Jinjiling granites. Thus, we do not suggest that the Jinjiling granites were a major supplier for the U in the Dawan deposit.

The U contents of the Cambrian sedimentary strata are very high, especially for the organic carbon-rich black shale strata. For example, U contents in the black shales from the Cambrian Hetang Formation in Anhui Province, South China vary from 25.8 to 167 ppm (Zhou and Jiang, 2009). Uranium in these strata is easily leached by continuous oxidized hydrothermal fluids that originated from meteoric water. In a plot of $\varepsilon_{\text{Nd}}(t)$ vs. time (Fig. 12), ore samples fall in the evolution ranges of the basement strata in the Nanling area, but different from the Jinjiling granites. Although $\varepsilon_{\text{Nd}}(t)$ values of the ores are slightly higher than the host slates, they might represent the average values of the source strata. Thus, we suggest that the U in the Dawan deposit was mainly derived from the U-rich metasedimentary strata.

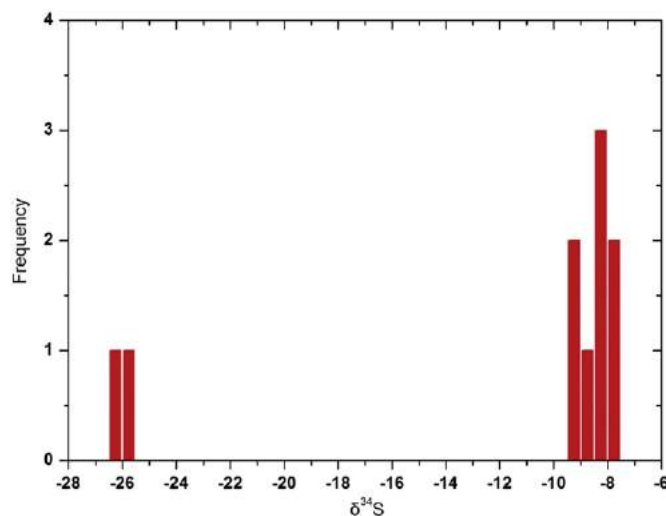


Fig. 10. Histogram of sulfur isotopic compositions of pyrite from the Dawan uranium deposit.

Table 6

Sulfur and lead isotopic compositions of pyrite from the Dawan uranium deposit.

Sample	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\delta^{34}\text{S}(\text{‰})$
DW-01	20.8364	15.7583	38.5888	−7.8
DW-10	56.6291	17.8771	39.3020	−26.3
DW-11	44.1259	17.1015	39.2169	−9.4
DW-14	89.2343	19.6830	39.0602	−25.9
DW-19	23.4813	16.0008	38.9750	−8.5
DW-20	24.1392	15.9440	39.0756	−8.1
DW-22	19.6843	15.7225	38.6240	−8.4
DW-23	20.5807	15.8599	39.0002	−9.5
DW-24	20.8100	15.8737	39.0444	−8.8
DW-25	21.0371	15.8070	38.7240	−7.7

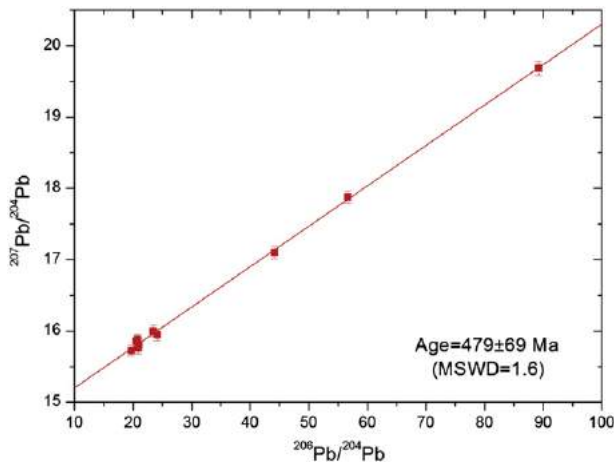


Fig. 11. Plot of $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ of pyrite from the Dawan uranium deposit.

6.3. Genetic model for the Dawan deposit

Uranium ores in the Dawan deposit are of hydrothermal vein-type, according to the classification of Cuney (2009). Although the deposit lies close to the granitic body, the geochemical and isotopic data do not favor a genetic relationship with the granitic magmatism. The characteristics of the Dawan deposit are similar to those of so-called carbonaceous-siliceous-pelitic rock type uranium deposits as defined by many Chinese geologists (e.g., Min, 1995). They are also similar to some Fe Mine type uranium deposits in Spain (e.g. Arribas, 1985; Both et al., 1994; Martín-Izard et al., 2002).

Uranium deposits of carbonaceous-siliceous-pelitic rock type in South China have been subdivided into three genetic groups (Min, 1995): (1) sedimentary-diagenetic deposits in which the ores were formed with the help of original syn-sedimentary U enrichment and subsequent concentration by diagenetic processes, (2) leaching-accumulative deposits in which the ores were formed by secondary leaching of sedimentary strata and subsequent adsorption in carbonaceous-siliceous-pelitic rocks, and (3) hydrothermal-reworked deposits in which the ores were formed by deep circulated leaching and subsequent hydrothermal reworking of older U-rich rocks or low-grade sedimentary-diagenetic ores.

As discussed in the previous sections, U-mineral deposition at the Dawan deposit took place from the ore-forming fluids at a temperature of ~200 °C. The Precambrian-Cambrian metasedimentary strata have high U contents and appear to be the most likely uranium source

rocks. These characteristics are similar to those of hydrothermal reworking deposits (Min, 1995). Thus, we suggest that the Dawan deposit belongs to the hydrothermal reworking carbonaceous-siliceous-pelitic rock type uranium deposit.

During the Cambrian period, sediments enriched in organic matter, silica and clay minerals were deposited in shallow seas surrounding the Jiangnan geanticline in South China. These rocks have a high U content, and may represent a major uranium source rock for carbonaceous-siliceous-pelitic rock type deposit. Owing to the Mesozoic Yanshanian regional extension events (Li, 2000), a number of fault-bounded basins and red-bed basins formed during the Cretaceous-Tertiary in South China (Hu et al., 2008). Associated mafic magmatism also occurred under these basins during this period (Hu et al., 2008). The Cretaceous-Tertiary climate was hot and dry in South China. Subtropical paleoclimatic conditions were favorable for leaching and transportation of uranium from the source rocks by oxidized fluids that originated from meteoric water located at margins of the basins. The hydrothermal fluids driven by heat of magma and tectonism continuously moved upward through the fracture zones of the wall-rocks. Crustal extension and associated magmatism are considered to have heated the circulating fluids. While moving, the hydrothermal solution may further leach U and other metals from the uraniumiferous wall-rocks. In breccia zones and interformational fracture zones of the wall-rocks which contained abundant organic matter, clay minerals and pyrite, U^{6+} in the fluids can be immediately reduced by pyrite and organic matter to form coffinite and pitchblende.

Unconformity-related uranium deposits are the most important U deposit type in the world, currently supplying 33% of the global U market. But most of the U deposits in South China, including the Dawan deposit, belong to the hydrothermal vein-type U deposits. Most unconformity-related U deposits occurred at the Paleoproterozoic basins, and are structurally-hosted either in the basement or in overlying sandstone strata. Most carbonaceous-siliceous-pelitic rock type uranium deposits in South China are hosted by the Sinian-Cambrian metasedimentary strata. They are distributed near some Cretaceous red-basins. For most unconformity-related U deposits, the U came from the basement of the basins or the overlying sedimentary rocks (Cuney and Kyser, 2009). The ore-forming fluids originated from basinal fluids in deep basin paleoaquifers. But uranium in most of the U deposits in South China came from the host rocks (granites, volcanic rocks and sedimentary rocks) and the ore-forming fluids originated from meteoric water (Hu et al., 2008). Generally, the mineralization scale of hydrothermal vein type U deposits in South China is far smaller than those unconformity-related U deposits.

Previous and on-going exploration for uranium deposits in the Dawan area take place along the boundary of the Jinjiling granites. In this study, we suggest that the formation of the deposit has no genetic relationship to the granites. The occurrence of this type deposit in this area was mainly controlled by the following factors: (1) U-rich Cambrian wall-rock strata, (2) host rocks rich in organic carbon, clay and pyrite, (3) tectonics and later faulting which fractured and brecciated the wall-rock, thereby providing permeable zones for circulation of hydrothermal fluids, (4) boundary of the Cretaceous-Tertiary extensional basins, which were favorable for the circulation of hydrothermal fluids that originated from meteoric water. Therefore, further exploration for uranium deposits in this area should pay more attention to the conjunct occurrence of sedimentary strata rocks rich in organic carbon and pyrite and the tectonics faulting which fractured and brecciated the wall-rocks, and should not only focus along the boundary of the granites and the sedimentary strata.

7. Conclusions

The main uranium minerals in the Dawan deposit are pitchblende and coffinite, which were most likely formed from oxidized fluids. Chlorites in ores are Mg-rich clinocllore, and the alteration temperatures

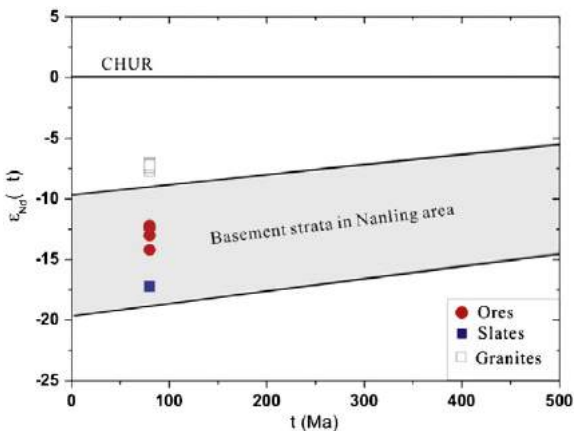


Fig. 12. Plot of $\epsilon_{\text{Nd}}(t)$ vs. time of the ores and host rocks of the Dawan uranium deposit and the Jinjiling granites.

Data of the Jinjiling granites are from Jiang et al. (2009). Ranges of $\epsilon_{\text{Nd}}(t)$ values of the basement strata in Nanling area are from Sun et al. (2005).

were estimated to be 189–227 °C. Ore-forming fluids were most likely derived from deep-circulated meteoric water. Sulfur in ore-forming fluids was mainly derived from diagenetic sulfur in the wall-rock strata, and the uranium source was mainly derived from the U-rich meta-sedimentary strata. Although the deposit occurs adjacent to the Jinjiling granites, the formation of the deposit has no genetic relationship to the granitic magmatism. We suggest that the Dawan deposit belongs to a hydrothermal-reworked carbonaceous-siliceous-pelitic rock type uranium deposit. Exploration in this area should focus on the conjunct occurrence of strata rocks rich in organic carbon and pyrite and tectonics faulting which fractured and brecciated the wall-rocks.

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