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Article

Burial and Exhumation History of the Lujing Uranium Ore Field, Zhuguangshan Complex, South China: Evidence from Low-Temperature Thermochronology

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Abstract: The Zhuguangshan complex hosts the main uranium production area in South China. We report (U-Th)/He and fission track thermochronological data from Triassic–Jurassic mineralized and non-mineralized granites and overlying Cambrian and Cretaceous sandstone units from the Lujing uranium ore field (LUOF) to constrain the upper crustal tectono-thermal evolution of the central Zhuguangshan complex. Two Cambrian sandstones yield reproducible zircon (U-Th)/He (ZHe) ages of 133–106 Ma and low effective uranium (eU) content (270–776 ppm). One Upper Cretaceous sandstone and seven Mesozoic granites are characterized by significant variability in ZHe ages (154–83 Ma and 167–36 Ma, respectively), which show a negative relationship with eU content (244–1098 ppm and 402–4615 ppm), suggesting that the observed age dispersion can be attributed to the effect of radiation damage accumulation on ⁴He diffusion. Correspondence between ZHe ages from sandstones and granites indicates that surrounding sedimentary rocks and igneous intrusions supplied sediment to the Cretaceous–Paleogene Fengzhou Basin lying adjacent to the LUOF. The concordance of apatite fission track (AFT) central ages (61–54 Ma) and unimodal distributions of confined track lengths of five samples from different rock units suggest that both sandstone and granite samples experienced a similar cooling history throughout the entire apatite partial annealing zone (~110–60 °C). Apatite (U-Th-Sm)/He (AHe) ages from six non-mineralized samples range from 67 to 19 Ma, with no apparent correlation to eU content (2–78 ppm). Thermal history modeling of data suggests that the LUOF experienced relatively rapid Early Cretaceous cooling. In most samples, this was followed by the latest Early Cretaceous–Late Cretaceous reheating and subsequent latest Late Cretaceous–Recent cooling to surface temperatures. This history is considered as a response to the transmission of far-field stresses, involving alternating periods of regional compression and extension, related to paleo-Pacific plate subduction and subsequent rollback followed by Late Paleogene–Recent India–Asia collision and associated uplift and eastward extrusion of the Tibetan Plateau. Thermal history models are consistent with the Fengzhou Basin having been significantly more extensive in the Late Cretaceous–Early Paleogene, covering much of the LUOF. Uranium ore bodies which may have formed prior to the Late Cretaceous may have been eroded by as much as ~1.2 to 4.8 km during the latest Late Cretaceous–Recent denudation.

Keywords: zircon and apatite (U-Th)/He; apatite fission track; Fengzhou Basin; Lujing uranium ore field; South China



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1. Introduction

South China has experienced a long history of intra-plate tectonic deformation accompanied by multiple periods of granitic magmatism, resulting in a favorable ore mineralization environment [1,2]. Vein-type hydrothermal uranium deposits in South China

(Figure 1) are hosted in granitic, volcanic, and carbonaceous–siliceous pelitic sedimentary rocks, which formed mainly during Cretaceous–Tertiary post-orogenic extension [3,4]. The Lujing uranium ore field (LUOF), located in the central Zhuguangshan complex, is one of the main areas of granite-related endo- and exo-contact uranium deposits in South China. Uranium deposits were discovered in Lujing in the 1950s. After decades of subsequent mining and research, the isotope geochronology of host rocks and mineralization ages [5–8], features and genesis of the deposit [9–11], and ore-forming structures and fluids [12–14] of the LUOF are now well characterized. However, the post-mineralization exhumation history, crucial for assessing modern ore preservation, remains poorly understood.

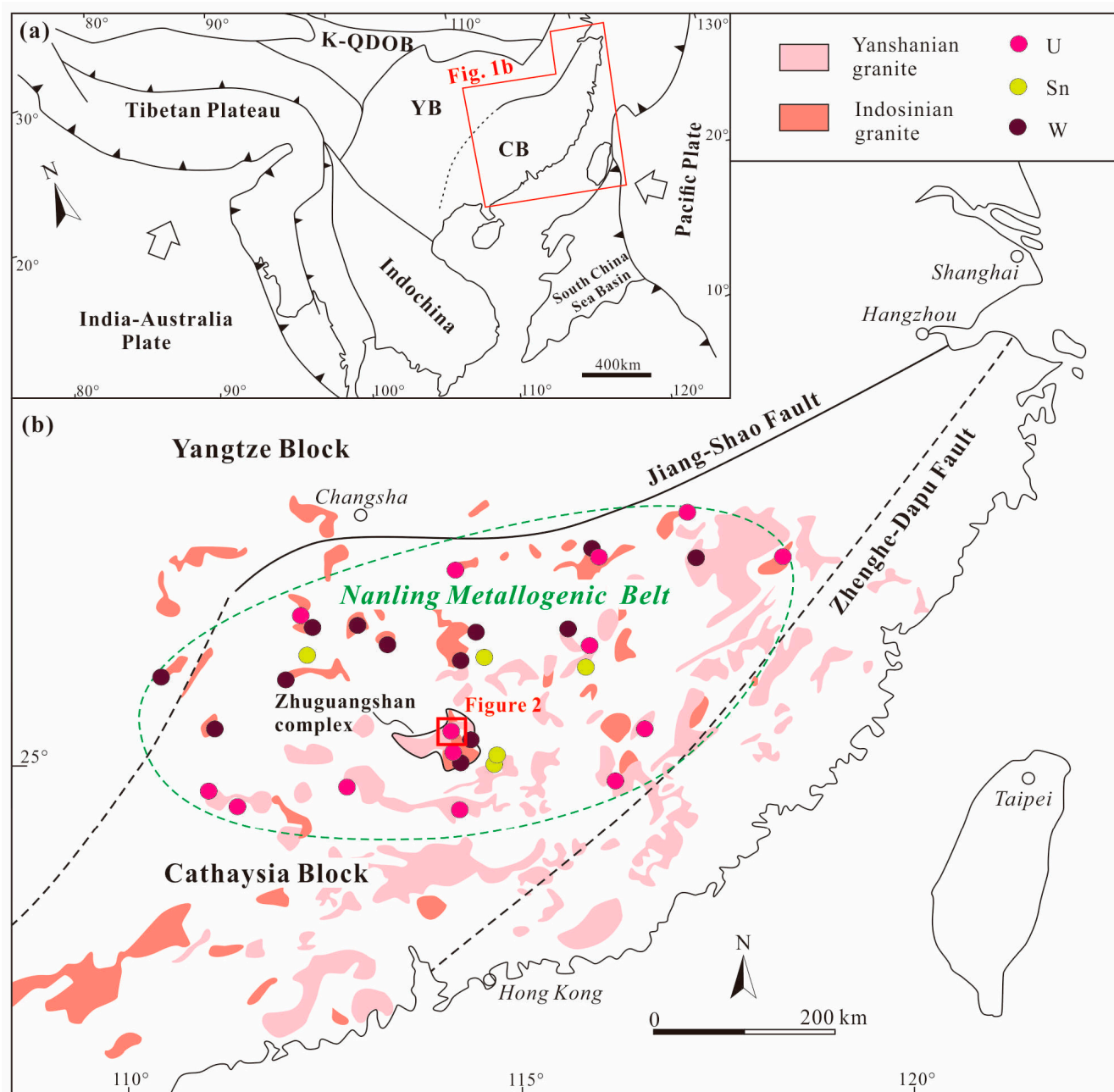


Figure 1. (a) Simplified geological map of South China showing the main tectonic units and (b) the location of W, Sn, and U deposits within the study region (modified after [42]). CB = Cathaysia Block, YB = Yangtze Block, K-QDOB = Kunlun-Qingling-Dabie Orogen Belt.

Constraining the low-temperature thermal history of an ore field is not only critical for understanding the role of exhumation in the temporal–spatial distribution of ore deposits, but it may also enable an assessment to be made regarding the preservation of ore bodies (e.g., [15–18]). Low-temperature thermochronometers, such as the zircon and apatite (U–Th)/He (ZHe, AHe) and apatite fission track (AFT) systems, allow for the upper-crustal cooling history of rocks between temperatures of ~210 and 30 °C to be reconstructed (e.g., [19–21]). These methods are therefore particularly useful for constraining the timing and magnitude of tectono-thermal processes operating from near-surface to a crustal depth of ~7–10 km (e.g., [22]), such as post-mineralization exhumation and erosion histories of ore deposits [16,23] and, in some instances, the timing of metallogenesis of low-temperature hydrothermal deposits [15].

In this study, we present ZHe, AFT, and AHe data and thermal history models for mineralized and non-mineralized granitoid intrusions and overlying sandstones from the LUOF in order to: (i) reconstruct the Cretaceous–Recent time–temperature (t–T) history, and (ii) assess the state of preservation of the LUOF uranium ore bodies.

2. Geological Setting

The South China Block (SCB) is composed of two separate terranes, the Yangtze Block to the northwest and the Cathaysia Block to the southeast, which were amalgamated during the early Neoproterozoic (850–820 Ma) (Figure 1a) [24–26]. During the Mesozoic and Tertiary, the SCB experienced episodic intra-continental extension and magmatic activity caused by northwestward subduction of the paleo-Pacific plate [4,27], resulting in the development of NE–NNE trending normal faults and rift basins throughout the region. The present tectonic landscape of the SCB continues to be influenced by interactions with the surrounding India–Australia, Eurasian, and Pacific Plates (e.g., [28–30]). The E–W trending Nanling Metallogenic Belt, located within the central SCB (Figure 1b), contains abundant hydrothermal mineral deposits, including U, W, Sn, Mo, Pb, and Zn, which formed during major episodes of Mesozoic tectonic–magmatic activity [31–33]. Previously published zircon U–Pb, molybdenite Re–Os, and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Nanling Metallogenic Belt indicate that the Cu–Mo porphyry and their related hydrothermal Pb–Zn–Ag deposits were formed between 175 and 160 Ma, while W–Sn deposits formed between 160 and 150 Ma [2,34–36]. Uranium deposits, hosted by Jurassic to Precambrian rocks, were formed during different mineralization episodes between ~135 and 45 Ma, based on U–Pb age determinations of primary pitchblende from different deposits in the Nanling Metallogenic Belt [3].

The Lujing uranium ore field (LUOF) is located within the central Zhuguangshan complex of the Nanling Metallogenic Belt (Figures 1b and 2). The basement of the field comprises Precambrian and Cambrian epi-metamorphic sandstones originating from shallow marine clastic rocks, overlain by Ordovician argillite, silty slate, and carbonate rocks [9,37]. There are no published U–Pb zircon ages for these units. These are intruded by widespread Indosinian and Yanshanian intermediate to acid igneous rocks and minor Caledonian granites. In the study area, zircon U–Pb SHRIMP ages of 235 ± 1 Ma and 239 ± 5 Ma have been reported for the Indosinian intrusives [5,38]. Wu et al. [39] obtained Rb–Sr isotope data yielding a 155 ± 5 Ma age for a Yanshanian granite. Upper Cretaceous red-colored conglomerates and sandstones rest unconformably on the Cambrian successions. A series of Cretaceous–Paleogene mafic dikes crosscut the LUOF [40].

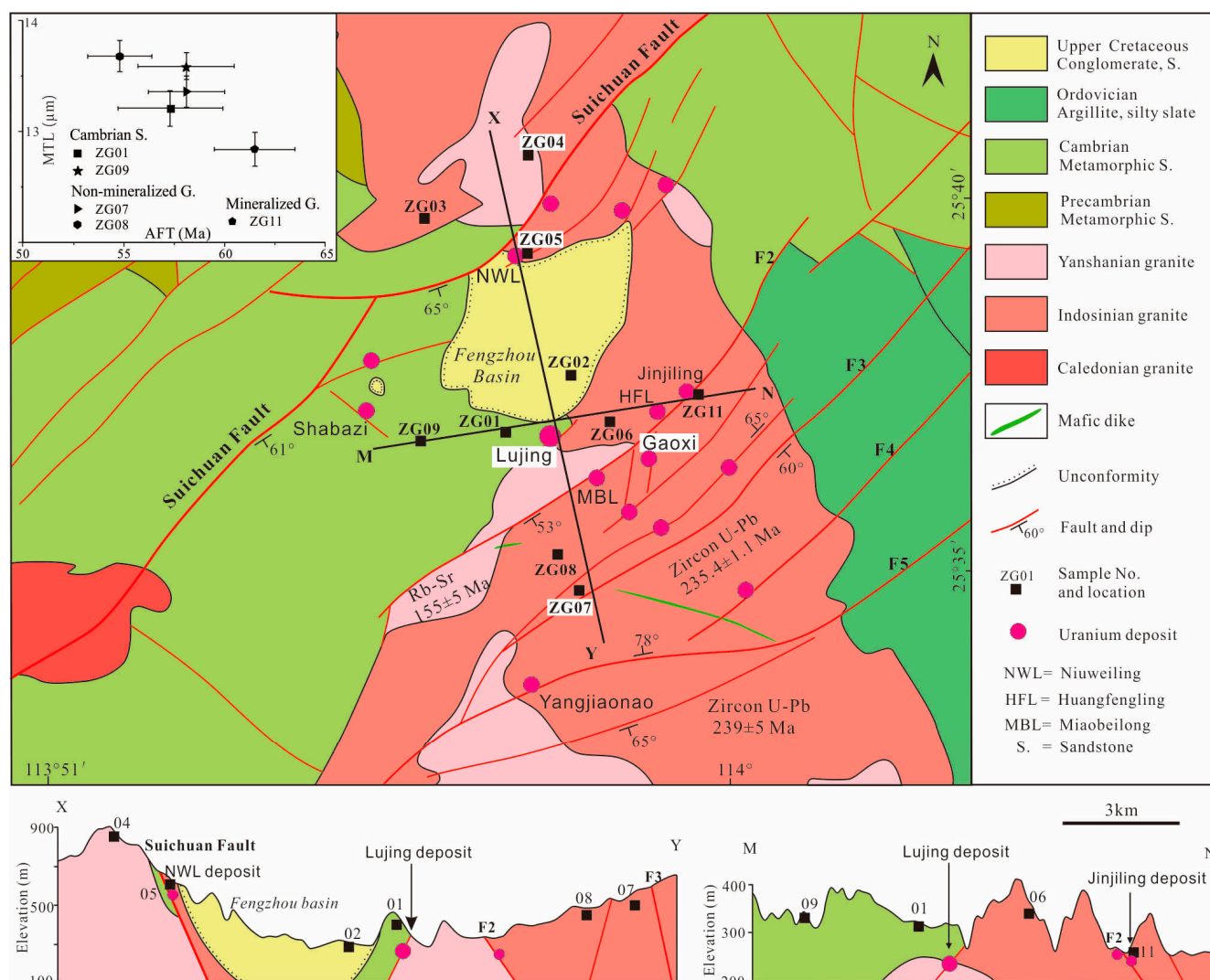


Figure 2. Geological map and cross-sections of the Lujing uranium ore field region showing sample locations, with distribution of uranium deposits and intrusive ages of the Indosinian and Yanshanian granites, for which the references cited do not provide exact sample locations (modified after [6]).

The region is dissected by a series of major NE-trending faults such as the Suichuan Fault, F2, F3, F4, and F5 (Figure 2). The Suichuan Fault developed as a thrust fault during a Late Jurassic–earliest Cretaceous compressive tectonic regime resulting from paleo-Pacific plate subduction beneath the Cathaysia Block [10,41,42]. During the Cretaceous and Paleogene, the tectonic setting generally switched from compression to extension due to rollback and eastward retreat of the subduction zone [3,30,42], giving rise to normal reactivation of the Suichuan Fault and the formation of other NE-trending normal faults in the region. This resulted in formation of the Late Cretaceous–Paleogene Fengzhou Basin within the extended Cathaysia Block (Figure 2), which covers an area of ~16 km² and hosts a sequence of coarse fluvio-lacustrine sandstones and conglomerates attaining present-day thicknesses of >360 m [9]. No independent temperature constraints, such as organic matter maturity or fluid inclusion data, have been reported from the Fengzhou Basin. However, regional outliers of red detrital rocks located in peripheral areas [43], including a relatively extensive outcrop to the west of the Fengzhou Basin (see Figure 2), indicate that the basin may have once been significantly larger.

Hydrothermal alteration and uranium mineralization in the LUOF mainly developed within or at the outer contact of the Indosinian–Yanshanian granite belt during several metallogenic pulses, based on U–Pb age determinations of pitchblende dated between 105 and 47 Ma [11]. This range covers a slightly different time span than reported in an earlier study for the entire belt [3]. This period broadly corresponds to a period of Cretaceous–Tertiary crustal dilation and mafic dike intrusion that affected much of South China [3,44,45]. Ore-forming conditions of uranium deposits in the LUOF region fall in between temperatures of ~150 and 270 °C [11], with pressures of 152–507 bars [10]. These approximately correspond to depths of 0.6 to 2.0 km under lithostatic conditions (assuming 250 bar/km) or 1.5 to 5.0 km under hydrostatic conditions (assuming 100 bar/km) [3]. However, mineralization conditions probably ranged somewhere between hydrostatic and lithostatic pressures because the ore bodies were formed mainly along the NE-trending faults [9,41].

3. Sampling and Methodology

Seven granites and three sandstones were collected from the LUOF along two principal transects (X–Y, M–N, Figure 2), with coordinates and lithologies listed in Table 1. Sample ZG04 was collected from a Yanshanian granite, while six samples ZG03, 05–08, and 11 were obtained from the same Indosinian granite. Mineralized samples ZG05 and 11 were collected from near the Niuweiling and Jinjiling uranium deposits, respectively. Sample ZG02 is from an Upper Cretaceous sandstone in the Fengzhou Basin, and samples ZG01 and 09 are from Cambrian sandstones located southwest of the basin (Figure 2). All samples, excluding mineralized samples ZG05 and 11, were collected from a distance of at least 50 m from the main faults.

Table 1. Sample locations and lithological information from the Lujing uranium ore field.

Lithology-Age	Sample	Longitude °E	Latitude °N	Elevation (m)	ZHe	AFT	AHe
Sandstone-Cambrian	ZG01	113°57'27.33"	25°37'10.47"	322	x	x	x
Sandstone-Cambrian	ZG09	113°56'28.37"	25°37'09.53"	340	x	x	x
Sandstone-Cretaceous	ZG02	113°58'24.51"	25°37'33.61"	281	x	-	x
Granite-Triassic	ZG03	113°56'32.81"	25°39'43.41"	530	x	-	x
Granite-Jurassic	ZG04	113°58'05.71"	25°40'41.11"	849	x	-	-
Granite-Triassic	ZG06	113°58'43.43"	25°37'10.94"	332	x	-	-
Granite-Triassic	ZG07	113°57'44.14"	25°35'02.87"	360	x	x	x
Granite-Triassic	ZG08	113°57'35.57"	25°35'36.64"	312	x	x	x
Mineralized granite-Triassic	ZG05	113°57'52.81"	25°39'17.86"	384	x	-	x
Mineralized granite-Triassic	ZG11	113°59'45.85"	25°37'22.06"	304	x	x	x

Note: ZHe = zircon (U–Th)/He, AFT = apatite fission track, AHe = apatite (U–Th)/He.

Zircon and apatite grains were separated by standard crushing and sieving techniques, followed by ultrasonic cleaning in distilled water, and then separated using magnetic and density liquid techniques. ZHe, AFT, and AHe analyses were carried out in the School of Earth Sciences, University of Melbourne. Grain geometry measurements for (U–Th)/He analyses were recorded for calculation of an α -correction factor and most grains selected had widths > 70 μ m in order to maximize helium gas values and minimize the α ejection correction (F_T) [46]. Reference materials dated as unknowns to assess the quality of apatite and zircon (U–Th)/He analyses were Durango [47] and Fish Canyon Tuff [48], respectively. All analytical procedures followed those described in Gleadow et al. [48], with the exception that ^{233}U and ^{229}Th spikes were applied for ZHe analyses. AFT analysis was performed using FastTracks on image sets captured using TrackWorks (Autoscan Systems Pty. Ltd., Melbourne, Victoria, Australia) after etching in 5M HNO_3 for 20 sec at 20 °C. The uranium concentration of each grain was determined by LA-ICP-MS, using Durango apatite as a secondary reference material.

Thermal history models of 10 samples were generated using QTQt (version 5.6.0) [49]. For AFT data, the annealing model of Ketcham et al. [50] and c-axis projected confined tracks were applied. Dpar measurements were used as the kinetic parameter for AFT annealing. The radiation damage He diffusion models of Gautheron et al. [51] and Guenther et al. [52] were used for AHe and ZHe data, respectively. Only He grains with 1 and 2 terminations were modeled. The present-day surface temperature was set at 20 ± 5 °C. Additional time–temperature (t–T) constraints for Cambrian (509–497 Ma, 20 ± 5 °C) and Upper Cretaceous (101–66 Ma, 20 ± 5 °C) sandstones were also applied, corresponding to their depositional ages, and an assumed paleo-temperature similar to present-day surface conditions.

To test if the observed thermochronology data are consistent with the paleo-Fengzhou Basin having been larger than its modern-day extent, as suggested by the presence of residual red detritus from surrounding areas [43], thermal history models were also run with an additional Late Cretaceous t–T constraint, requiring samples to be relatively close to near-surface during basin formation. The applied temperature range for this additional constraint varied depending on the proximity of samples to the modern-day Fengzhou Basin, allowing for a modest thickness of basement to have been removed along with the periphery of the Fengzhou Basin during the Cenozoic. For the nearest samples (ZG01, 09, 05, 06, and 11), a temperature range of 15–35 °C was used; for distal samples ZG03, 04, 07, and 08, a broader range of 20–60 °C was applied. In all cases, the observed data are more consistent with samples having resided at near-surface temperatures in the Late Cretaceous, supporting the inference of a once more extensive Fengzhou Basin.

4. Results

4.1. Zircon (U–Th)/He Data

Thirty-eight single-grain ZHe ages, obtained from all samples listed in Table 1, are presented in Table 2. All grains selected for analysis under a binocular microscope possessed two crystal terminations (excluding one grain from sample ZG05; see Table 2) and were free of any discernible inclusions, cracks, or obvious metamict textures/colors. ZHe data are characterized by significant variability, with ages ranging from 167 to 36 Ma. They show a negative trend with respect to effective uranium concentration (eU; $eU = U \text{ ppm} + 0.235 \times Th \text{ ppm}$), a proxy for accumulated radiation damage (Figure 3a). However, there is no clear relationship between ZHe age and equivalent spherical radius (Figure 3b). In samples where eU values range between ~2000 and 5000 ppm, 12 out of 15 ZHe ages do not follow a pronounced negative trend but rather form a “pediment-like” slope covering the age range $\sim 48 \pm 12$ Ma. Cambrian sandstone samples ZG01 and 09 yielded ZHe ages between 167 and 89 Ma, with eU contents < 800 ppm. Most granite samples yielded relatively young ZHe ages (88 to 36 Ma) with high eU values (~1200–4615 ppm). However, granite samples ZG06 and ZG08 yielded two low eU (<500 ppm) grains with older ZHe ages of 118 and 167 Ma, respectively. Mineralized Indosinian granite samples ZG05 and 11 from the Niuweiling and Jinjiling deposits produced grains with eU values ranging from ~1200 to 3700 ppm and ZHe ages between 88 and 46 Ma. Detrital zircons from the Cretaceous section in the Fengzhou Basin sample ZG02 yielded relatively low eU concentrations (<700 ppm) and relatively old ZHe ages (154–110 Ma) that are generally similar to results from nearby granite samples ZG06 and 08 with low eU values (see Table 2). The sole exception is a single grain (81.3 ± 5.0 Ma; eU content of 1098 ppm) that is more akin to the ZHe results from the Cambrian sandstone samples.

Table 2. Zircon (U-Th)/He data from the Lujing uranium ore field region, South China.

Grain No.	⁴ He (ncc)	Mass (μg)	F _T	U (ppm)	Th (ppm)	Th/U	eU (ppm)	Grain Length (μm)	Grain Half-Width (μm)	Rs (μm)	Corrected Age (Ma)	Error ± 1σ (Ma)	Crystal Morphology
Sandstone													
ZG01-01	57.28	7.9	0.81	432.4	46.0	0.11	443.2	220.8	55.1	66.1	132.2	8.2	2T
02	65.97	11.1	0.81	357.2	87.2	0.24	377.7	291.9	52.6	66.9	128.2	7.9	2T
03	72.86	7.6	0.80	571.0	67.4	0.12	586.8	220.3	53.4	64.5	133.3	8.3	2T
04	64.54	9.8	0.81	430.3	242.4	0.56	487.2	265.2	53.0	66.3	109.7	6.8	2T
05	78.73	6.5	0.79	766.5	42.2	0.06	776.4	212.7	50.0	60.7	126.5	7.8	2T
ZG09-01	26.53	8.8	0.81	254.5	92.3	0.36	276.2	221.8	58.8	69.7	89.4	5.5	2T
02	40.53	9.6	0.80	250.4	86.3	0.34	270.7	271.3	51.2	64.6	126.7	7.9	2T
03	68.32	10.3	0.82	479.5	127.6	0.27	509.5	260.7	55.4	68.5	106.2	6.6	2T
04	58.59	6.7	0.77	489.0	337.8	0.69	568.4	244.7	44.9	56.9	124.7	7.7	2T
05	79.57	6.8	0.80	544.2	83.0	0.15	563.7	217.3	50.6	61.6	167.0	10.4	2T
ZG02-01	23.20	2.5	0.71	649.0	140.3	0.22	681.9	161.0	35.0	43.1	110.6	6.9	2T
02	23.08	2.8	0.71	482.1	232.6	0.48	536.8	172.4	35.5	44.2	123.8	7.7	2T
03	10.18	2.2	0.70	203.1	177.1	0.87	244.7	145.6	35.4	42.7	154.0	9.5	2T
04	21.81	2	0.68	1012.4	366.0	0.36	1098.4	135.4	35.9	42.6	81.3	5.0	2T
Non-Mineralized Granite													
ZG03-01	84.13	6.4	0.79	1323.0	179.0	0.14	1365.0	206.7	51.1	61.5	78.3	4.9	2T
02	68.46	5.6	0.76	1295.4	249.7	0.19	1354.1	228.5	42.3	53.5	74.2	4.6	2T
03	261.39	11	0.80	4506.2	461.3	0.10	4614.7	330.7	47.5	62.3	42.2	2.6	2T
04	183.85	10.9	0.82	2939.4	329.0	0.11	3016.8	283.2	53.4	67.4	45.8	2.8	2T
ZG04-01	91.87	6.2	0.80	1922.2	673.1	0.35	2080.3	185.2	56.9	65.3	58.6	3.6	2T
02	39.25	2.8	0.73	2148.9	282.6	0.13	2215.3	153.3	39.8	47.4	51.5	3.2	2T
03	59.61	3.7	0.76	3529.6	457.5	0.13	3637.1	179.3	40.6	49.7	36.5	2.3	2T
ZG06-01	75.77	4.3	0.75	2311.5	585.6	0.25	2449.2	203.4	39.8	49.9	59.1	3.7	2T
02	58.07	3.2	0.69	3515.4	1703.2	0.48	3915.6	208.9	32.8	42.5	37.6	2.3	2T
03	27.65	3.9	0.74	410.7	299.3	0.73	481.1	190.5	40.1	49.7	118.6	7.4	2T
ZG07-01	146.91	10.1	0.82	1753.3	375.1	0.21	1841.4	238.1	59.9	71.8	64.8	4.0	2T
02	170.51	7.2	0.78	2164.3	277.1	0.13	2229.5	267.5	43.7	56.3	86.2	5.3	2T
03	377.98	24.5	0.85	2913.9	172.4	0.06	2954.4	442.0	61.1	80.5	42.7	2.6	2T
04	140.00	6.7	0.77	2824.4	578.9	0.20	2960.4	277.0	40.7	53.2	57.8	3.6	2T
ZG08-01	194.65	15.8	0.84	1633.4	258.3	0.16	1694.1	302.1	63.7	78.9	59.5	3.7	2T
02	147.93	10	0.80	1832.4	173.6	0.09	1873.2	308.0	47.3	61.5	64.9	4.0	2T
03	92.94	11.2	0.81	384.1	77.2	0.20	402.3	315.2	49.8	64.5	167.0	10.4	2T

Table 2. Cont.

Grain No.	^4He (ncc)	Mass (μg)	F_T	U (ppm)	Th (ppm)	Th/U	eU (ppm)	Grain Length (μm)	Grain Half-Width (μm)	R_s (μm)	Corrected Age (Ma)	Error $\pm 1\sigma$ (Ma)	Crystal Morphology
Mineralized Granite													
ZG05-01	170.43	14.8	0.81	1155.9	194.8	0.17	1201.7	281.6	53.1	67.0	78.5	4.9	0T
02	57.29	4.4	0.75	1251.7	633.9	0.51	1400.7	196.2	42.0	51.9	75.3	4.7	2T
03	160.68	7.3	0.80	2893.5	1330.2	0.46	3206.1	219.0	52.5	63.5	56.1	3.5	2T
ZG11-01	180.97	6.4	0.79	2475.3	540.9	0.22	2602.4	201.3	52.5	62.5	88.7	5.5	2T
02	191.83	6.8	0.80	2469.2	932.8	0.38	2688.4	191.2	58.7	67.4	85.9	5.3	2T
03	210.91	10.4	0.81	2629.5	498.3	0.19	2746.6	286.9	51.2	65.2	60.6	3.8	2T
04	372.25	17.7	0.84	3601.0	410.2	0.11	3697.4	366.6	58.1	75.2	46.5	2.9	2T
Fish Canyon Tuff Standard													
FCT-01	3.883	2.3	0.70	435.6	219.9	0.50	487.3	160.6	33.5	41.6	28.0	1.7	2T
02	10.926	5.6	0.77	470.7	405.5	0.86	566.0	218.6	44.4	55.4	28.0	1.7	2T
03	7.489	4.9	0.77	401.3	256.5	0.64	461.6	204.2	43.0	53.2	27.4	1.7	2T
04	3.897	2.2	0.71	482.7	242.2	0.50	539.6	130.9	39.8	45.8	27.5	1.7	2T

Note: F_T is the α -ejection correction after Farley et al. [46], eU is the effective uranium content [U ppm + 0.235 * Th ppm] [52]. R_s (equivalent spherical radius) = $[3 \cdot L \cdot R] / [2 \cdot (L + R)]$, where L = grain length and R = grain half-width [53]; Crystal morphology: 0T = no crystal terminations and 2T = two crystal terminations.

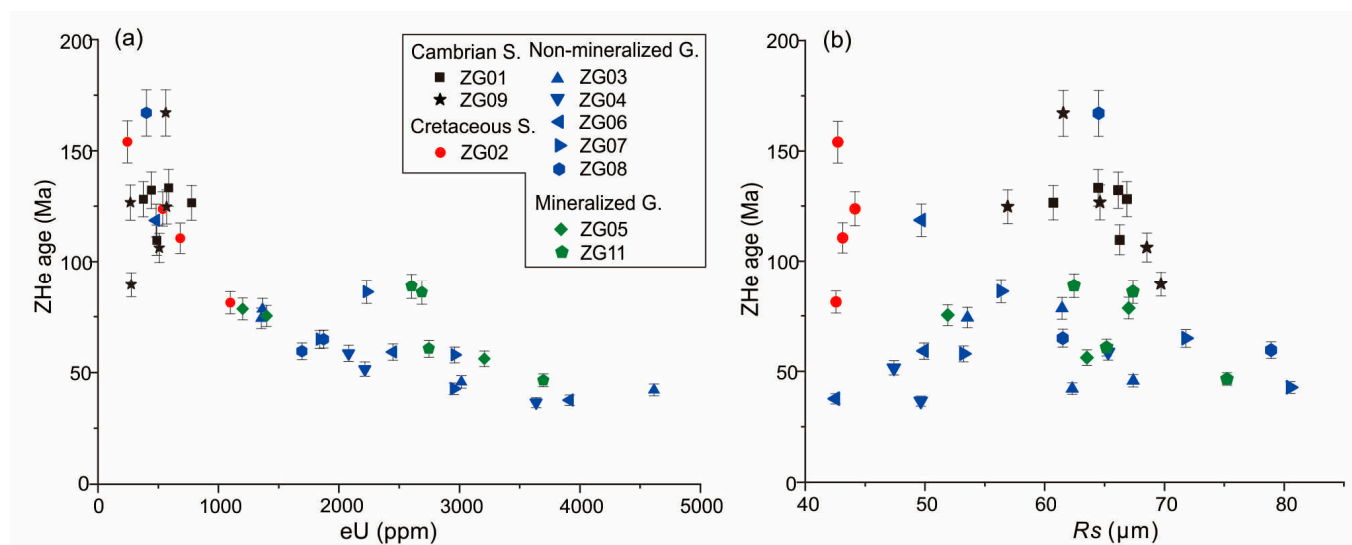


Figure 3. (a) Plots of ZHe age versus effective uranium (eU) content and (b) equivalent spherical radius (R_s) for the Lujing uranium ore field samples. S. = sandstone, G. = granite.

4.2. Apatite Fission Track Data

AFT data were acquired from two Cambrian sandstones and three Triassic granite samples (including mineralized sample ZG11), with at least 25 grains counted and >80 confined track lengths measured for each sample (Table 3, Figure 4 and supplementary material, Table S1). All central ages fall within a relatively restricted range (61.5–54.8 Ma) (Table 3). Mean track lengths (MTL) of c-axis projected confined fission tracks range from 12.84 ± 0.15 to 13.68 ± 0.14 μm (see Figure 2 inset) and display negatively skewed unimodal distribution patterns, with standard deviations ranging between 1.39 and 1.69 μm (Table 3 and Figure 4). The mean Dpar (etch-pit widths) values of measured samples range from 1.72 to 1.93 μm, suggesting little compositional variation between samples (e.g., [54]). Single-grain AFT ages do not show any relationship with Dpar values or U content (Figure 4). Despite having single-grain AFT age populations that appear to spread between ~80 and ~45 Ma (Figure 4), all samples pass the chi-square test ($P(\chi^2) > 5\%$), statistically consistent with their ages belonging to a single age population. AFT ages are generally younger than their corresponding ZHe ages, but older than or equal to (sample ZG08) AHe ages described below.

Table 3. Apatite fission track data from the Lujing uranium ore field region, South China.

Sample	No. Grains (n)	N _s (n)	ρ_s (10 ⁵ .cm ⁻²)	²³⁸ U (ppm)	Mean Dpar (Range) (μ m)	P (χ^2)	Central Age (Ma $\pm$ 1 σ)	N _{length}	Mean Track Length (μ m) $\pm$ std Error	Standard Deviation
Sandstone										
ZG01	26	911	7.49	26.73	1.75 (1.61–2.01)	0.15	57.3 $\pm$ 2.6	84	13.21 $\pm$ 0.16	1.44
ZG09	36	908	5.99	21.30	1.93 (1.67–2.18)	0.44	58.1 $\pm$ 2.4	102	13.59 $\pm$ 0.12	1.24
Non-Mineralized Granite										
ZG07	36	1385	11.24	39.70	1.74 (1.59–1.87)	0.45	58.1 $\pm$ 1.9	102	13.36 $\pm$ 0.14	1.39
ZG08	33	2005	15.01	54.46	1.72 (1.41–2.09)	0.13	54.8 $\pm$ 1.6	121	13.68 $\pm$ 0.14	1.56
Mineralized Granite										
ZG11	31	1339	14.16	46.45	1.78 (1.63–1.95)	0.49	61.5 $\pm$ 2.0	110	12.84 $\pm$ 0.15	1.57

Note: N_s is the number of spontaneous tracks counted; ρ_s is the spontaneous track density; Dpar is the long axis of track etch pit parallel to the crystallographic c-axis; P(χ^2) is the P-value of χ^2 for (n–1) degrees of freedom; N_{length} is the number of lengths measured. The ξ calibration factor used here for LA-ICP-MS AFT analysis, equivalent to the conventional zeta-calibration approach, was $2.07 \pm 0.07 \times 10^{-3}$, identical to that reported by Gleadow et al. [48].

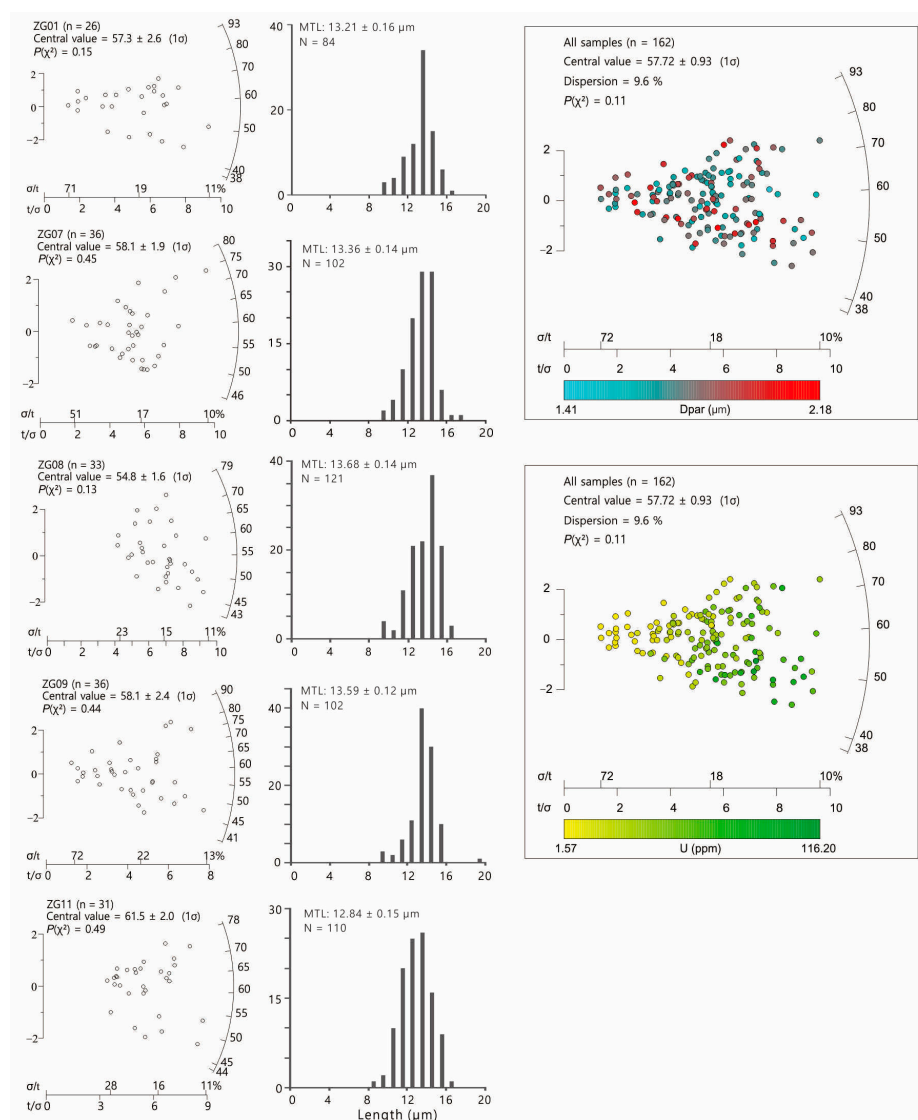


Figure 4. Radial plots of single-grain apatite fission track ages and confined fission track length distributions for Lujing uranium ore field samples. Right-hand images show radial plots for ages versus Dpar and U content. Radial plots were created with RadialPlotter [55]. MTL = mean track length, n = number of apatite grains, N = number of track lengths measured.

4.3. Apatite (U-Th-Sm)/He Data

Thirty-one single-grain AHe data from eight samples yielded dispersed ages ranging from 168 to 18 Ma (Table 4 and Figure 5a). The equivalent spherical radius (R_s), a proxy for grain size that allows for the direct comparison of 0-, 1-, and 2-termination crystals, and eU concentrations fall in the range of 45.8–107.5 μm and 2–78 ppm, respectively (Figure 5b). Cambrian (ZG01 and 09) and Upper Cretaceous (ZG02) sandstone samples yielded AHe ages between 46 and 19 Ma, with relatively little intra-sample age dispersion. Indosinian granite samples ZG03, 07, and 08 yielded AHe ages between 66 and 34 Ma, except for one older single-grain age from sample ZG08 (166 ± 10.3 Ma) with markedly high ^4He content (Table 4). AHe ages are younger than their corresponding ZHe results, a relationship consistent with the expected nominal temperature sensitivities of the ZHe and AHe systems. In contrast, samples ZG05 and 11 collected from mineralized Indosinian granites of the Niuweiling and Jinjiling uranium deposits yield seemingly anomalous AHe ages, ranging from 168 to 82 Ma (Table 4), which are substantially older than their corresponding ZHe ages and, in some cases, are older than the maximum age of LUOF mineralization.

Table 4. Apatite (U-Th-Sm)/He data from the Lujing uranium ore field region, South China.

Grain No.	⁴ He (ncc)	Mass (μg)	<i>F_T</i>	U (ppm)	Th (ppm)	Sm (ppm)	Th/U	eU (ppm)	Grain Length (μm)	Grain Half-Width (μm)	<i>R_s</i> (μm)	Corrected Age (Ma)	Error ± 1σ (Ma)	Crystal Morphology
Sandstone														
ZG01-01	0.164	5.39	0.75	5.7	7.2	29.1	1.26	7.4	169.6	56.2	63.3	44.6	2.8	0T
02	0.140	3.84	0.72	10.0	14.7	46.3	1.47	13.5	163.6	48.3	56.0	30.8	1.9	0T
03	0.122	6.98	0.78	4.9	3.4	38.9	0.69	5.7	173.4	63.3	69.6	32.0	2.0	0T
04	0.693	7.39	0.80	35.2	6.8	63.3	0.19	36.8	151.3	69.7	71.6	26.2	1.6	0T
05	0.282	4.21	0.73	16.8	26.1	266.4	1.56	22.9	153.2	52.3	58.5	32.3	2.0	0T
ZG09-01	0.052	8.55	0.79	1.3	2.8	77.3	2.19	2.0	169.6	70.8	74.9	31.0	1.9	0T
02	0.193	4.68	0.74	10.7	10.9	86.4	1.02	13.3	172.8	51.9	59.9	33.9	2.1	0T
03	0.099	3.05	0.74	9.6	8.0	76.5	0.83	11.5	150.9	57.0	62.0	31.1	1.9	1T
04	1.582	9.78	0.77	23.6	92.1	135.5	3.90	45.2	258.3	67.5	80.2	37.7	2.3	2T
05	0.321	8.18	0.80	7.8	3.7	125.4	0.48	8.7	183.6	66.6	73.3	45.9	2.8	0T
ZG02-01	0.066	2.42	0.65	9.8	35.6	81.6	3.64	18.2	168.4	37.8	46.3	18.9	1.2	0T
02	0.158	1.96	0.61	19.0	88.3	109.5	4.65	39.8	161.6	38.2	46.3	27.4	1.7	2T
03	0.281	5.52	0.76	17.4	30.4	34.9	1.74	24.5	155.1	59.5	64.5	22.5	1.4	0T
04	1.044	8.28	0.79	41.2	33.3	149.4	0.81	49.0	289.4	63.5	78.1	26.5	1.6	1T
05	0.237	3.64	0.70	15.0	60.1	103.5	4.00	29.1	186.3	44.1	53.5	26.2	1.6	0T
Non-Mineralized Granite														
ZG03-01	0.622	12.53	0.82	6.8	3.9	102.1	0.57	7.7	221.4	75.0	84.0	62.8	3.9	0T
02	4.440	14.21	0.83	43.8	16.1	306.3	0.37	47.6	229.1	78.6	87.7	64.2	4.0	0T
03	2.922	15.28	0.83	28.8	24.4	408.6	0.85	34.5	241.6	79.3	89.6	53.9	3.3	0T
04	0.567	8.72	0.80	9.2	5.0	108.6	0.54	10.4	216.5	63.3	73.5	63.9	4.0	0T
ZG07-01	1.314	5.27	0.75	55.8	28.2	322.1	0.51	62.4	206.4	50.4	60.8	43.2	2.7	0T
02	0.387	2.68	0.67	43.9	30.7	392.7	0.70	51.1	209.4	35.7	45.8	34.3	2.1	0T
03	0.429	2.81	0.69	38.7	24.1	289.9	0.62	44.4	164.9	41.2	49.5	40.2	2.5	0T
04	0.586	3.49	0.73	24.3	15.1	262.9	0.62	27.8	125.3	52.7	55.6	66.8	4.1	0T
ZG08-01	7.933	6.45	0.77	49.4	121.7	332.7	2.46	78.0	251.1	60.7	73.3	166.0	10.3	1T
02	1.965	7.58	0.79	47.4	13.6	285.4	0.29	50.6	193.8	62.4	70.8	52.6	3.3	0T
03	1.259	2.79	0.74	71.2	32.5	452.0	0.46	78.8	148.4	54.8	60.0	63.1	3.9	1T
Mineralized Granite														
ZG05-01	8.507	26.62	0.86	17.8	9.1	225.7	0.51	19.9	295.6	94.6	107.5	148.9	9.2	0T
02	1.730	4.42	0.74	24.9	21.4	313.3	0.86	29.9	183.9	48.9	57.9	143.2	8.9	0T
ZG11-01	6.955	10.09	0.80	35.2	24.2	438.9	0.69	40.9	220.8	67.4	77.5	168.2	10.4	0T
02	3.152	7.88	0.79	21.2	15.6	267.7	0.73	24.9	173.8	67.2	72.7	163.4	10.1	0T
03	1.103	3.63	0.71	34.7	33.2	393.1	0.96	42.5	198.4	42.7	52.7	81.7	5.1	0T
Durango Apatite Standard														
Durango	4.111	-	1.00	-	-	-	21.45	-	-	-	-	31.0	1.9	-
Durango	3.921	-	1.00	-	-	-	22.28	-	-	-	-	31.9	2.0	-
Durango	7.102	-	1.00	-	-	-	21.64	-	-	-	-	31.6	2.0	-

Note: *F_T* is the α-ejection correction after [46], eU is Effective uranium content [U ppm + 0.235 * Th ppm] [52]. *R_s* (equivalent spherical radius) = $[3 \cdot L \cdot R] / [2 \cdot (L + R)]$, where L = grain length and R = grain half-width [53]; Crystal morphology: 0T = no crystal terminations, 1T = one crystal termination and 2T = two crystal terminations.

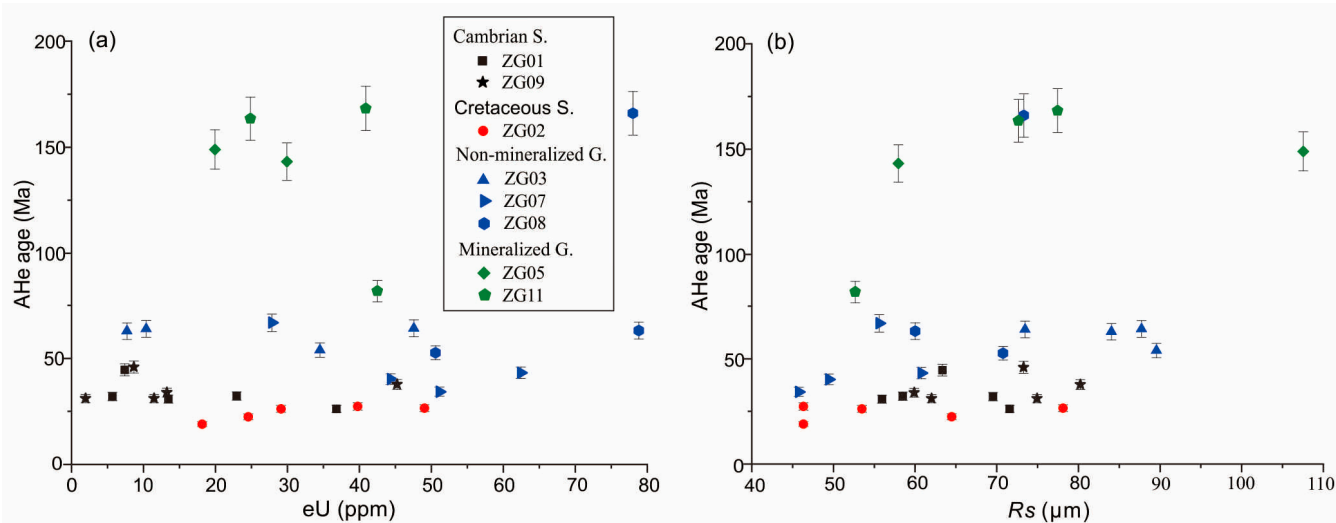


Figure 5. (a) Plots of AHe ages versus effective uranium (eU) content and (b) equivalent spherical radius (R_s) for Lujing uranium ore field samples. S. = sandstone, G. = granite.

5. Discussion

5.1. Dispersion of (U-Th)/He Data

5.1.1. ZHe Age Dispersion and Radiation Damage Effects on He Diffusion

Many of the ZHe intra-sample single-grain ages are dispersed (well beyond the $\pm 2\sigma$ error limit of the mean age). Such dispersion may be attributed to several possible factors including the effects of radiation damage on He diffusivity, He-rich fluid inclusions, variation in crystal size, and heterogeneous intra-grain eU distribution (e.g., [52,56]). Grains from the two Cambrian sandstone samples, ZG01 and 09, define a cluster of ZHe ages (mostly within a restricted age range of ~133–106 Ma), with no evident correlation between age and eU. The remaining 28 analyses, however, show a strong negative relationship between age and eU (Figure 3a) that is consistent with an increase in He diffusivity, even among different grains in the same sample, due to higher levels of radiation damage (e.g., [20,52,57]). This negative ZHe age–eU relationship implies that the LUOF region experienced a protracted thermal history at temperature regimes below which alpha radiation damage anneals [58].

As indicated in previous studies, there is good evidence that zircon crystals with a high degree of accumulated radiation damage often exhibit higher He diffusivity, resulting in closure temperatures (T_c) far lower (<50 °C absolute temperature) than that typically cited for low radiation damage grains (~180–200 °C) [20,52,57–59]. Our consistent AFT dataset can help to explain the effective temperature sensitivities of the analyzed zircons. All zircons from Cambrian and Cretaceous sandstones with eU concentrations <1100 ppm (Table 2) yield ZHe ages distinctly older than their corresponding AFT ages. However, two ZHe ages from samples ZG07 and 11, with elevated eU values of 2954 and 3697 ppm, yield considerably younger ages of ~43 and 46 Ma, even compared to their respective AFT results. Additionally, several zircon grains from granites ZG03, 04, and 06 with >3600 ppm eU yield younger ages of 45–36 Ma. This “inverted” ZHe–AFT age relationship demonstrates that the accumulation of radiation damage in the ZHe system may result in the temperature sensitivity (and the nominal T_c) being lower than that of the AFT system. The negative ZHe age–eU pattern could be more pronounced if samples underwent slow cooling, resulting in prolonged residence at temperatures lower than required for the annealing of alpha damage in zircon, and/or a subsequent reheating episode with partial age resetting (e.g., [58,60]). In our samples, the relatively flat relationship between most ZHe

ages with $eU > 2000$ ppm (Figure 3a) suggests that these zircons experienced comparatively rapid cooling through a relatively low closure temperature at $\sim 48 \pm 12$ Ma [58,61,62].

5.1.2. AHe Age Dispersion

AHe data from the sandstone and non-mineralized granite samples exhibit intra-sample reproducibility and do not show any clear relationships with either eU or R_s (Figure 5). This, together with the fact that AHe ages from ZG01, 07, 08, and 09 are younger than their corresponding AFT results, suggests that these samples cooled rapidly through the entire AHe partial retention zone (~ 80 – 30 °C) [60]. In contrast to the ZHe and AFT data, AHe ages for non-mineralized granitic samples show a generally positive linear relationship over ~ 250 m of elevation (Supplementary Material, Figure S1) that is consistent with a record of denudational cooling.

By contrast, AHe data from mineralized granite samples are concordant (excluding one grain from sample ZG11; see Table 4) and considerably older than their coexisting AFT and ZHe ages and the age range reported for uranium ore formation. These “inverted” AHe ages, with respect to coexisting AFT ages and many ZHe ages, may be attributed to a number of possible factors not quantified by the applied analytical protocol, excluding differences in grain size which show no consistent relationship with AHe age [63] (Figure 5). Some of these factors have been summarized by Fitzgerald et al. [64] and Wildman et al. [65] and include possible factors such as eU zonation (e.g., [66,67]), grain fragmentation [53], He implantation from neighboring grains within the host rock [68], U-Th rich micro-inclusions [60], He trapping or impediment of He diffusion due to strained crystals [69], crystallographic micro-voids (e.g., [70,71]), or some combination of these factors. We are not able to attribute a specific cause/s to the present AHe age pattern. Consequently, these AHe data were not included in any thermal history modeling.

5.2. Thermal History Modeling

5.2.1. Individual Sample Models

Samples were first modeled on an individual basis, initially using solely AFT data, as AFT annealing kinetics are better understood than He diffusion processes in zircon and apatite (e.g., [72]). Next, samples were remodeled, first with the addition of AHe and then ZHe data, or only modeled with ZHe and/or AHe data if no AFT data were available. These results were then compared with one another for further assessment.

In the case of Cambrian sandstone samples ZG01 and 09, inverse thermal history models which include Late Cretaceous near-surface temperature constraints were better able to fit the observed age and track length data than their counterparts with no Late Cretaceous constraint (Figure 6). Namely, their predicted confined fission track distributions exhibit narrower peaks that are consistent with the observed apatite track length data. The best-fit t - T paths for these models are nearly identical and are characterized by post-Cambrian heating to elevated temperatures (>170 °C) by the Early Cretaceous, followed by Late Cretaceous rapid cooling to near-surface temperatures. This is immediately followed by a second reheating phase during the Late Cretaceous to between ~ 80 and 130 °C and a final phase of monotonic cooling to present-day surface temperature.

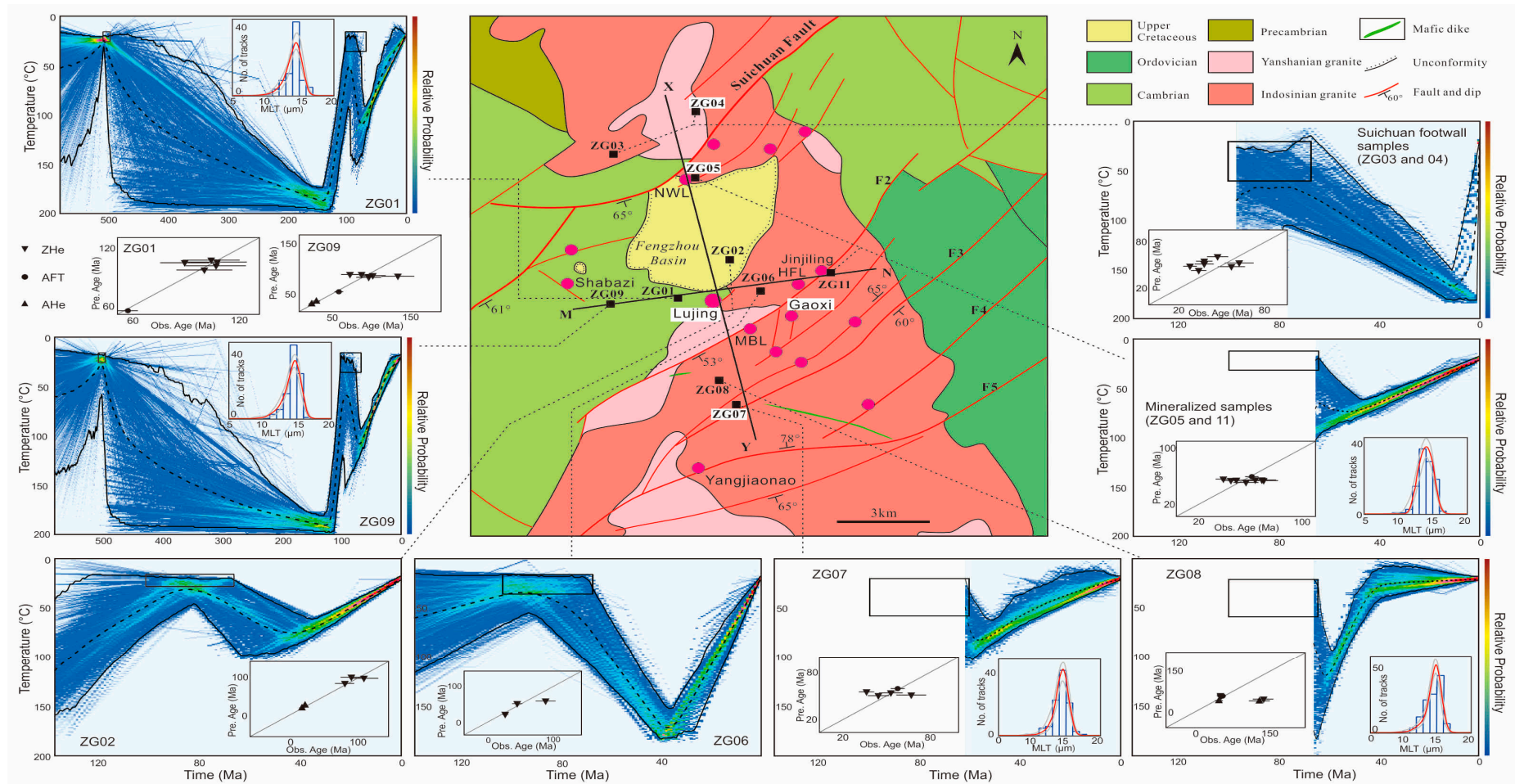


Figure 6. Inverse time–temperature (t–T) reconstructions for Lujing uranium ore field samples, generated using QTQt [49]. Note the wider temperature range of Cambrian sample t–T models. All other models were adjusted to share a common x-axis scale to facilitate visual comparison; however, QTQt did not generate pre-latest Cretaceous t–T paths for samples ZG03, 04, 05, 07, 08, and 11. See Section 3 for the thermal history modeling protocol. Black boxes represent applied t–T constraints corresponding to Cambrian and Late Cretaceous sedimentation. Black dashed lines are the best fit t–T paths and black solid lines represent the 95% confidence interval limits. Panels show corresponding observed versus predicted age and confined track distribution plots, with AFT, AHe, and ZHe ages represented by circles, triangles, and inverted triangles, respectively, and observed and predicted confined track distributions illustrated by blue bins and red curves $\pm$ the 95% confidence interval limits (light grey curves), respectively. Pre. = predicted, Obs. = observed.

The inverse thermal history model of the Late Cretaceous sandstone sample ZG02 exhibits post-depositional Late Cretaceous to Paleogene heating to temperatures well within or above the AHe partial retention zone (PRZ), followed by monotonic Paleogene to Recent cooling to surface temperatures, as constrained by its modeled Oligocene AHe ages.

Inverse thermal history models of ZHe data from non-mineralized granite samples ZG03 and 04 (0-termination AHe ages were unable to be modeled) exhibit Late Cretaceous–Neogene reheating from near-surface temperatures to between ~130 and 180 °C, followed by rapid cooling to surface temperature by the present-day (Figure 6). Note that the pre-Late Cretaceous reheating and cooling paths of these thermal history models, while relatively consistent with other modeling results in this study with respect to time and temperature, are not constrained by AFT and AHe data. The remaining non-mineralized samples ZG06, 07, and 08 produce similar thermal history models and exhibit a Late Cretaceous–Paleogene reheating phase, with the maximum temperature reached varying between 60 and 180 °C (Figure 6). This would require burial beneath a Late Cretaceous–Paleogene sequence of significant thickness and/or of low thermal conductivity to produce a blanketing effect, which would reduce the amount of burial required [73]. However, the degree of reheating may be exaggerated by the thermal history model due to the currently imperfect ZRDAAM model of Guenther et al. [52]. Although there may be other factors at play, as outlined in Section 5.1.1, ZRDAAM often underestimates He retentivity and fails to lower the effective temperature sensitivity of high to moderate eU grains (i.e., over predicting ZHe ages) (e.g., [59,62,74]). These models then exhibit gradual cooling to near-surface temperatures by the Late Paleogene–Neogene.

Mineralized granite sample ZG11 yields a t-T model exhibiting subtle Late Cretaceous–Paleocene reheating into the lower AFT partial annealing zone (PAZ), followed by gradual cooling to surface temperature by the present day. As with samples ZG01, 07, 08, and 09, such a reheating event is consistent with its negatively skewed confined fission track length distributions and single-grain AFT age population that spreads from older Late Cretaceous ages to younger Paleogene ages. By contrast, the best-fit t-T path for ZG05 exhibits Late Cretaceous–Recent thermal stability at near-surface temperatures. However, a number of its acceptable t-T paths (within the 95% confidence interval) exhibit a Late Cretaceous–Paleogene reheating pulse into the lowermost AFT PAZ, similar to the best-fit model of ZG11, suggesting that the data of ZG05 are also statistically compatible with such a thermal history. For both models, the pre-Late Cretaceous portion is not particularly well constrained by the data.

5.2.2. Multi-Sample Model

After modeling was carried out on an individual basis, samples were grouped together where possible and modeled jointly to both test whether the low-temperature thermal evolutions of various sample groups were controlled by their depositional, structural, or mineralization histories and to increase the robustness of the modeling results. This was deemed suitable for samples of similar formation age, such as for Cambrian sandstone samples (ZG01 and 09), or samples from the same structural block, such as those from the Suichuan Fault footwall (ZG03 and 04). Mineralized samples ZG05 and 11, which produced similar individual thermal history reconstructions, were also jointly modeled. While QTQt was unable to produce a joint inverse thermal history reconstruction for the Cambrian sandstone samples, their near identical individual model results strongly suggest that they shared a very similar thermal history (Figure 6).

The joint t-T reconstruction of samples ZG03 and 04 (ZHe data only) from the Suichuan footwall exhibits Late Cretaceous to Neogene reheating followed by rapid cooling to near-surface temperatures from ~10 Ma to the present (Figure 6). However, the imperfect reproducibility of the observed spread in ZHe ages by the joint inverse t-T model and a lack of accompanying AFT data in these samples allow for the possibility of an alternative latest Cretaceous–Recent low-temperature thermal evolution for the Suichuan footwall block. Unfortunately, AHe data from samples in the immediate Suichuan footwall (ZG03)

and hanging wall (ZG05) were unable to be modeled due to their 0-termination morphology. Nevertheless, significant differences in AHe ages across the fault (54–64 Ma versus 143–149 Ma in the footwall and hanging wall, respectively) suggest that the Suichuan footwall may have experienced marked earliest Paleocene cooling through the AHe PRZ during Fengzhou Basin formation relative to the hanging wall. This scenario might be expected for footwall uplift and concurrent hanging wall subsidence due to normal faulting and associated Fengzhou Basin development.

The joint inverse model of mineralized samples ZG05 and 11 yields a t-T reconstruction exhibiting subtle Late Cretaceous–Paleocene reheating into the lower AFT PAZ, followed by gradual cooling to surface temperature by the present day, consistent with the individual inverse thermal history models for these samples (Figure 6).

5.3. Geological Implications

5.3.1. Tectono-Thermal Evolution of the LUOF

The low-temperature thermochronology data and inverse thermal history modeling results presented in this study suggest that outcropping Cambrian and Cretaceous sedimentary rocks and Triassic–Jurassic granites from the LUOF shared a broadly similar Late Cretaceous–Recent tectono-thermal evolution, with respect to the applied ZHe, AFT, and AHe systems (Figure 7). For many samples, the pre-Late Cretaceous thermal history is poorly constrained by the observed data. Low eU Cretaceous ZHe ages from samples ZG01 and 09, along with AFT ages and t-T models for these samples, are consistent with the LUOF having experienced a relatively rapid Early Cretaceous (~130–105 Ma) cooling event, consistent with previously reported zircon fission track, ZHe, and AFT data in eastern South China [75–78]. This is interpreted as recording pronounced regional uplift and denudation that led to the development of the unconformity between Cambrian and Upper Cretaceous strata (Figure 2). This regional-scale exhumation episode is thought to have resulted from NW-SE-directed compression related to the northwestward subduction of the paleo-Pacific plate [30] and the ESE-directed retreat and subsequent WNW-oriented subduction of the Pacific slab [42,79].

Thermochronology data and t-T models for all samples to the southeast of the SE-dipping Suichuan normal fault record a subsequent latest Early Cretaceous–Late Cretaceous (~105–75 Ma) period of reheating into the lowermost PAZ to between ~80 and 150 °C (Figure 7). Due to variations in the onset of subsequent cooling to near-surface temperatures displayed in different thermal history reconstructions, the exact duration of the reheating phase cannot be readily resolved. This is attributed to some samples exhibiting significant ZHe and AHe age dispersion and not having coexisting AFT data (see Section 5.1). While inverse thermal history modeling of ZHe data from the Suichuan Fault footwall allow for a similar reheating phase, a significant jump in AHe ages across the fault from earliest Paleocene to latest Jurassic–earliest Cretaceous is consistent with the Suichuan footwall having experienced earliest Paleocene cooling through the AHe PRZ (~80–30 °C) coeval with hanging wall reheating. An earlier onset of Suichuan footwall cooling from higher temperatures cannot be ruled out due to a lack of AFT data for those samples. Such a contrast in low-temperature thermal evolution across the Suichuan Fault is consistent with paired footwall uplift and hanging wall subsidence due to normal faulting and associated basin formation.

A concurrent reheating phase recorded throughout much of South China is interpreted to record burial during a widespread period of Late Cretaceous–Paleogene extension and related basin formation [3,80]. Similarly, concurrent reheating of the LUOF southeast of the Suichuan Fault is interpreted to have resulted from the formation and burial beneath a once more extensive Late Cretaceous–Paleogene Fengzhou Basin that covered much of the LUOF, as testified by the preservation of red detritus well beyond the present-day extent of the basin [43]. Slight differences in the magnitude of reheating observed in the t-T reconstructions may be attributed to lateral variations in paleo-Fengzhou Basin thickness and thermal blanketing effects, as well as differences in modern sample elevations.

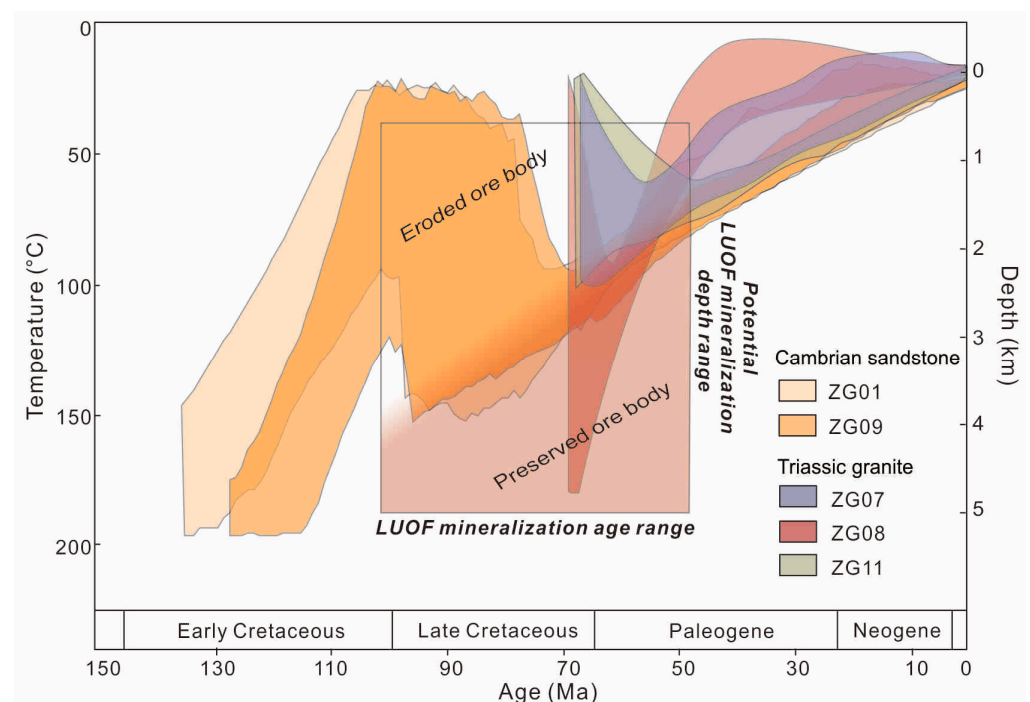


Figure 7. Cretaceous–Recent time–temperature (t–T) path envelopes consistent with low-temperature thermochronology data from the Luojing uranium ore field (LUOF) presented herein overlain by the time–temperature window of LUOF U mineralization [3,10,11]. LUOF uranium mineralization pressures of 152–507 bars [10] allow for possible ore formation depths between ~0.6 and ~5 km, depending on whether paleo-pressure conditions were more akin to lithostatic (100 bars/km) or hydrostatic (250 bars/km) [3]. Thermal history models were generated using QTQt [49] following the modeling protocol described in Section 3. Only inverse thermal history models of samples that also yielded AFT data are presented here, as they are better constrained. The t–T path envelopes suggest that the LUOF experienced a phase of pronounced denudational cooling commencing in the latest Late Cretaceous to early Paleogene (~75–50 Ma) from between ~180 and 60 °C, followed by continual cooling to surface temperatures by the present day. This is consistent with the removal of a maximum ~1.2–4.8 km of section (assuming a paleo-geothermal gradient of 33 °C/km [81]). However, the thickness of removed overburden may be less due to any thermal blanketing effect that may have accompanied sedimentation [73]. As a result of regional denudation, a moderate to significant portion of the LUOF ore body was likely removed, with the degree of preservation dependent upon the exact timing and pressure conditions (and hence depth) of U-mineralization with respect to the onset of Late Cretaceous–early Paleogene exhumation.

Commencing at some time since the latest Late Cretaceous (~75 Ma), the LUOF experienced a phase of moderate but pronounced exhumation and cooling (Figure 7). This cooling is observed in a broad region from central South China to the southeast coastal area [75,78]. It is interpreted to have occurred in response to a Late Paleogene to recent compressional regime in South China that resulted from a combination of paleo-Pacific plate subduction, India–Asia collision, and associated uplift and eastward extrusion of the Tibetan Plateau [28,75,76,81].

5.3.2. Implications for Fengzhou Basin Formation

The Upper Cretaceous Fengzhou Basin section comprises conglomerates containing pebble-sized clasts of granite and metamorphosed sandstone (Figure 8) and formed during a phase of regional intra-continental extension recorded throughout South China [1,4]. Three of four single-grain ZHe ages from the Fengzhou Basin (ZG02) predate Late Cretaceous sedimentation, as well as all granitoid ZHe ages in the LUOF, suggesting that Fengzhou detritus may have been sourced from nearby Cambrian sandstones that pro-

duced similar Jurassic–Early Cretaceous ZHe ages. The fourth and youngest single-grain ZHe age (81 Ma) may have instead been sourced from the Indosinian granite, which yielded similar Late Cretaceous ZHe ages (Table 2). However, we also note that this grain has a considerably higher eU content (~1100 ppm). Nevertheless, the detrital ZHe age spectra, composition, angular habit of clasts, and poor sorting of the gravels support the notion that the Fengzhou Basin conglomerates were deposited via the rapid accumulation of locally sourced sedimentary and intrusive rocks, as previously suggested for similarly aged basins throughout South China [80].

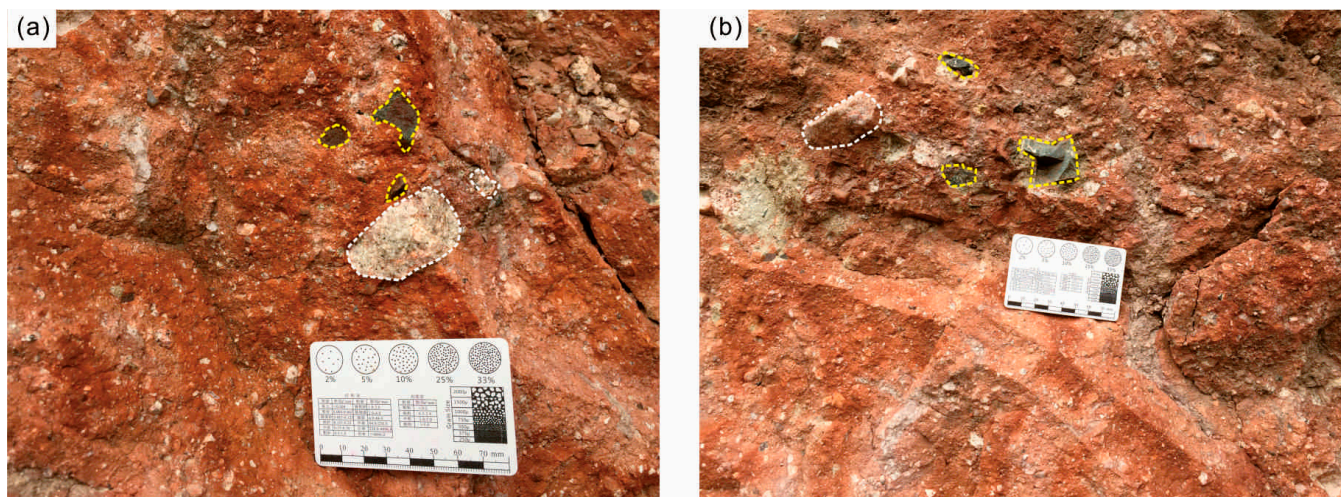


Figure 8. Field photographs of Upper Cretaceous Fengzhou Basin conglomerates from two locations, (a,b), in the Lujing uranium ore field. Several large clasts of metamorphosed sandstone and granite are highlighted by the yellow and white dashed lines, respectively. Scale bar on card in both photographs is 8 cm in length.

Thermal history models best-fit t-T paths for samples southeast of the Suichuan Fault which yielded AFT data (ZG01, 07, 08, 09, and 11) and are thus better constrained exhibit between ~30 and 105 °C of total Late Cretaceous reheating (Figure 6). Assuming that the observed reheating was caused solely by burial and using a paleo-geothermal gradient of 33 °C/km [82] and a paleo-surface temperature of 20 ± 5 °C, then a paleo-stratigraphic thickness of ~0.9–3.2 km is estimated for the Fengzhou Basin. This is similar to previous paleo-thickness estimates for the Upper Cretaceous (1.3–2.0 km) and Paleogene (0.8–2.0 km) series in South China [80]. However, the amount of burial required to have caused the observed reheating would be lowered by any thermal blanketing effect that may have accompanied the deposition of potentially low thermal conductivity sediments [73].

5.3.3. Implications for Uranium Exploration

The low-temperature thermochronology data presented in this study do not provide constraints for the timing of uranium mineralization in the LUOF, which previous studies suggested to have occurred at temperatures in the range of 150 to 270 °C during phases between 105 and 47 Ma [11]. While ZHe ages from mineralized granites of the Niuweiling and Jinjiling uranium deposits (ZG05 and 11) overlap with in-situ U-Pb ages (~75–60 Ma) from granite-related hydrothermal uranium deposits ~30 km south of the LUOF [7,83], thermal history models indicate that neither mineralized sample returned to elevated temperatures (>150 °C) during the Late Cretaceous–Recent. Therefore, either uranium mineralization in these samples occurred prior to ~90 Ma or subsequent heating caused by the influx of hydrothermal fluids was either too short-lived and/or too distal for the grains analyzed to be recorded by the low-temperature thermochronology systems studied.

According to conditions previously reported, uranium ore formation in the LUOF region possibly occurred at depths up to ~5 km. Assuming a paleo-geothermal gradient of 33 °C/km, thermal history reconstructions suggest that post-latest Late Cretaceous (~75 Ma) denudation ranged between a maximum of ~1.2 and 4.8 km, corresponding to the upper and lower Late Cretaceous paleo-temperatures of the path envelopes, 60 and 180 °C, respectively (Figure 7). These, however, are maximum estimates as paleo-geothermal gradients may have once been higher in the Fengzhou Basin due to the possible presence of lower thermal conductivity sediments, which have since been removed [73]. Nevertheless, the thermochronology data presented herein suggest that uranium ore bodies in the LUOF may have been moderately to significantly eroded due to regional Late Cretaceous–Recent exhumation, with the degree of LUOF ore body removal dependent upon the exact timing of uranium mineralization with respect to the onset of Late Cretaceous denudation. However, currently, the timing of LUOF uranium mineralization remains loosely constrained between 105 and 47 Ma [11].

6. Conclusions

Newly acquired ZHe, AFT, and AHe analyses of sandstone and granite samples provide low-temperature thermochronological constraints for the Cretaceous–Recent tectono-thermal evolution of the LUOF, South China. Thermal history modeling of these data indicates that the LUOF area experienced pronounced Early Cretaceous cooling, thought to have resulted from NW-SE-directed compression and associated denudation related to the northwestward subduction of the paleo-Pacific plate. This was followed by a period of latest Early Cretaceous–Late Cretaceous reheating recorded throughout the study area due to burial beneath a more extensive Fengzhou Basin that once blanketed much of the LUOF. Detrital ZHe age spectra and the presence of meta-sandstone and granite angular pebble clasts are consistent with surrounding metasedimentary and granitic rocks having supplied sediment to the Late Cretaceous section of the Fengzhou Basin. A final period of latest Late Cretaceous–Recent denudation recorded in the LUOF is regarded as a response to regional compression related to concurrent subduction of the paleo-Pacific plate, India–Asia collision, and associated uplift and eastward extrusion of the Tibetan Plateau. Maximum denudation estimates range from ~1.2 to 4.8 km, suggesting that any LUOF uranium ore bodies which may have formed prior to the Late Cretaceous may have been moderately to significantly eroded.

Supplementary Materials: The following material is available online at <https://www.mdpi.com/2075-163X/11/2/116/s1>, Table S1: Detailed AFT data of individual sample. Figure S1: Plot of ZHe, AHe and AFT ages versus sample elevation.

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