

Supplementary material
First report of geo- and thermochronological results of the Cordillera Central, Luzon,
Philippines

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Supplementary material A: Description of rock samples used for dating

In this section, we report the petrographic signatures of the rock samples for geo- and thermochronological dating. Mineral abbreviation follows that of Whitney and Evans (2010).

Sample CC19-01

This medium-grained biotite hornblende diorite was collected from the roadside outcrop (Fig. S-A1) on the left bank of the Chico River. The mineral assemblage is Qtz+Pl+Bt+Hbl (Fig. S-A2) with secondary Chl, Ep, and Cal. Accessory minerals are Kfs+Mag+Ilm+Zrn+Ap. The rock shows a granular texture without any foliation and lineation. Coarse Pl and Hbl show obvious chemical zoning and enclose numerous inclusions in its core and mantle.

Sample CC19-04

This hornblende diorite was collected from the roadside outcrop (Fig. S-A3) near the Lagben River. Although the outcrops are located near the Abra River fault on the geologic map, no actual shear structures were observed in the outcrops. The outcrop is somehow weathered (Fig. S-A3) and may have been sheared by the activity of the Abra River fault. The rock shows a granular texture without any foliation and lineation. The mineral assemblage is Qtz+Pl+Hbl (Fig. S-A4) with secondary Chl. Accessory minerals are Kfs+Mag+Py+Ilm+Zrn+Ap. Pl is coarse-grained relative to other minerals, with significant twinning and zoning, and encloses numerous inclusions in its core. Colorless Hbl encloses numerous inclusions in its core.

Sample CC19-06

This porphyritic hornblende diorite was collected from the roadside outcrop (Fig. S-A5) on the mountain ridge between Baguio-Sayangan. The mineral assemblage is Qtz+Pl+Hbl with

secondary Chl. Accessory minerals are Py+Mg+Ilm+Ap+Zrn. Coarse-grained Pl, Hbl (Fig. S-A6), and minor Ap phenocrysts occur. Pl shows obvious chemical zoning, and some grains enclose numerous inclusions in its core. Hbl shows ambiguous oscillatory zoning. Secondary Py is seen throughout the thin section.

Sample CC19-08

This biotite hornblende granodiorite was collected from the roadside outcrop (Fig. S-A7) on the right bank of the Agno River. The rock shows a granular texture without any foliation and lineation. The mineral assemblage is Qtz+Pl+Kfs+Bt+Hbl (Fig. S-A8) with secondary Chl and Ep. Accessory minerals are Mg+Ilm+Zrn+Ap. Coarse Pl and Hbl show obvious chemical zoning. Most Bt is altered by secondary Chl. Besides Chl replacing other minerals, anhedral Chl fills in grain boundary.

Sample CC19-09

This biotite hornblende diorite was collected from the roadside outcrop (Fig. S-A9) on the mountain ridge between Benguet and Nueva. The rock shows a granular texture, and some clots composed of fine-grained Hbl+Chl+Pl+Mag (Fig. S-A10) are observed. The mineral assemblage is Qtz+Pl+Kfs+Bt+Hbl with secondary Chl and Ep. Accessory minerals are Mg+Ilm+Zrn+Ap. Coarse Pl and Hbl show obvious chemical zoning. Hbl shows patchy chemical zoning, and some domains are replaced by secondary Chl.



Figure S-A1. Outcrop photograph from which sample CC19-01 was collected.



Figure S-A2. Slab photograph of sample CC19-01.



Figure S-A3. Outcrop photograph from which sample CC19-04 was collected.



Figure S-A4. Slab photograph of sample CC19-04.



Figure S-A5. Outcrop photograph from which sample CC19-06 was collected. The small window in the figure is a larger image of the sample collection point. A hammer for scale.



Figure S-A6. Slab photograph of sample CC19-06.



Figure S-A7. Outcrop photograph from which sample CC19-08 was collected.



Figure S-A8. Slab photograph of sample CC19-08.



Figure S-A9. Outcrop photograph from which sample CC19-09 was collected.



Figure S-A10. Slab photograph of sample CC19-09.

Supplementary material B: Methodology and result of zircon U–Pb dating

Zircon U–Pb dating was carried out at Tono Geoscience Center, Japan Atomic Energy Agency (JAEA). Zircon grains embedded in resin were polished, and cathodoluminescence (CL) images were obtained by field-emission electron probe microanalyzer JXA-8530F (JEOL, Japan) at Tono Geoscience Center. Dating of U–Pb zircon was performed using a multi-collector inductively coupled plasma mass spectrometer *Neptune-Plus* (Thermo Fisher Scientific, Germany) equipped with an excimer laser system *Analyte G2* (Photon Machines, USA). The 91500 zircon (Wiedenbeck et al., 1995) was used as the primary standard material for corrections of Pb/U and Th/U isotopes, and the OD-3 zircon (Iwano et al., 2013) was used as the secondary standard material for quality control. Details of the analysis conditions and settings are shown in Table S-B1.

The weighted average of $^{206}\text{Pb}/^{238}\text{U}$ date for OD-3 zircon determined in this study, yielding 33.29 ± 0.66 Ma (2σ ; $N = 18$; $\text{MSWD} = 0.113$; $\text{Probability} = 1.000$), is consistent with the reference age of 33.0 ± 0.1 Ma reported by (Iwano et al., 2013). Details of isotopes and dates for OD-3 are shown in Table S-B2. Results of isotope measurement of the unknown samples are summarized in Table S-B3–7. Utilizing microscopic observations and taking into account the apparent signal variation during the integration interval, we excluded data from the isotopically inhomogeneous domain and contaminated domain by inclusions or resin from the age calculation.

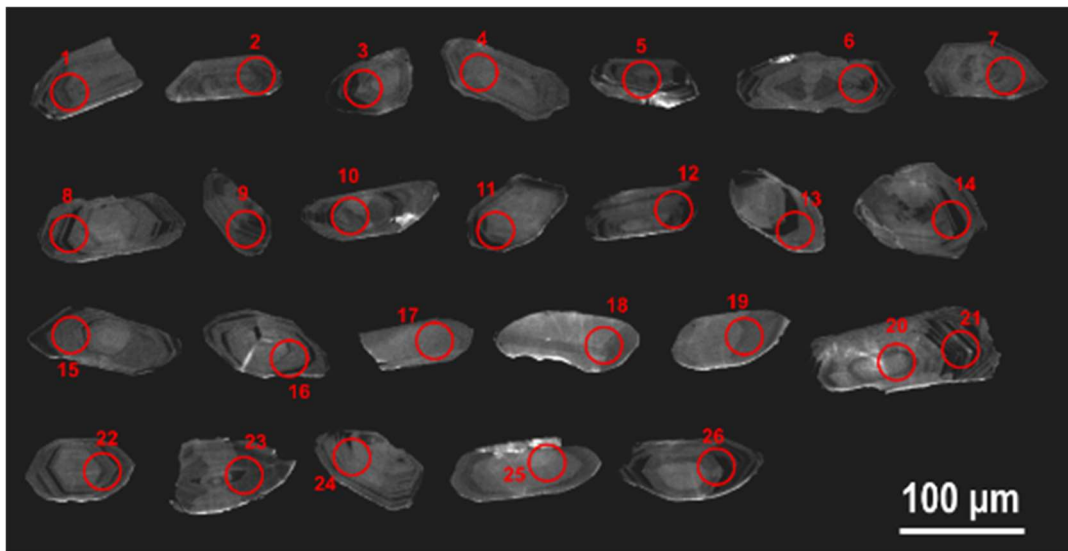


Figure S-B1. CL images of zircon grains separated from sample CC19-01. Red circles represent locations of U–Pb spot analyses by laser ablation inductively coupled plasma mass spectrometer (LA–ICP–MS) system. Numbers correspond to the Table S-B2–7. This figure was created by stacking the images of the CL images of grains used in the measurements.

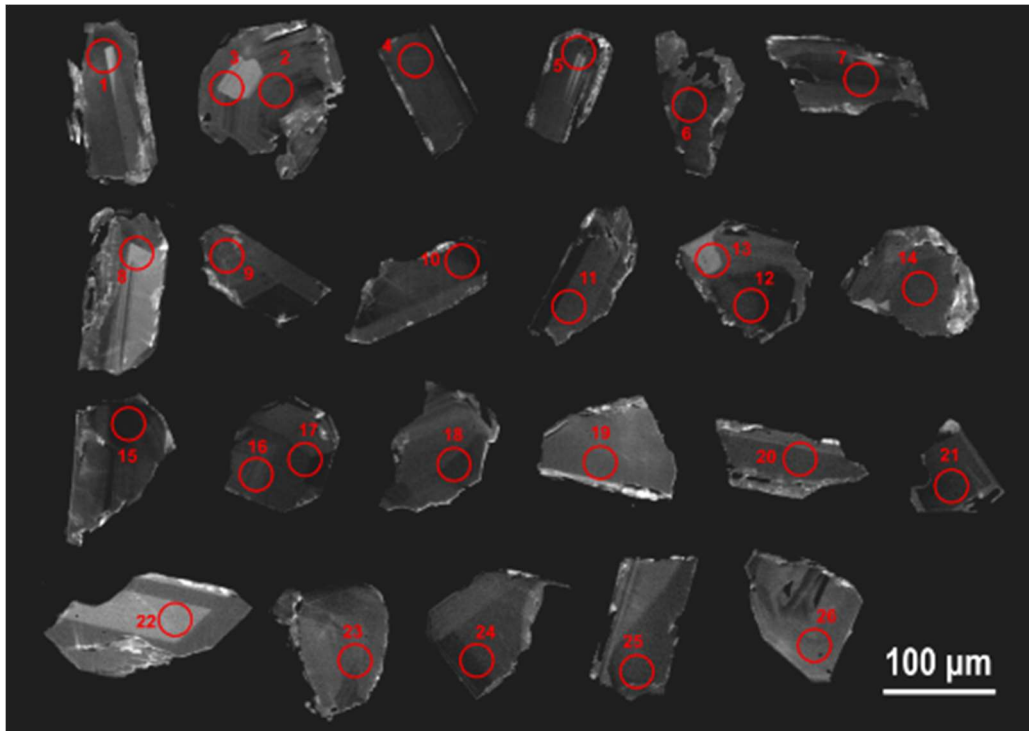


Figure S-B2. CL images of zircon grains separated from sample CC19-04.

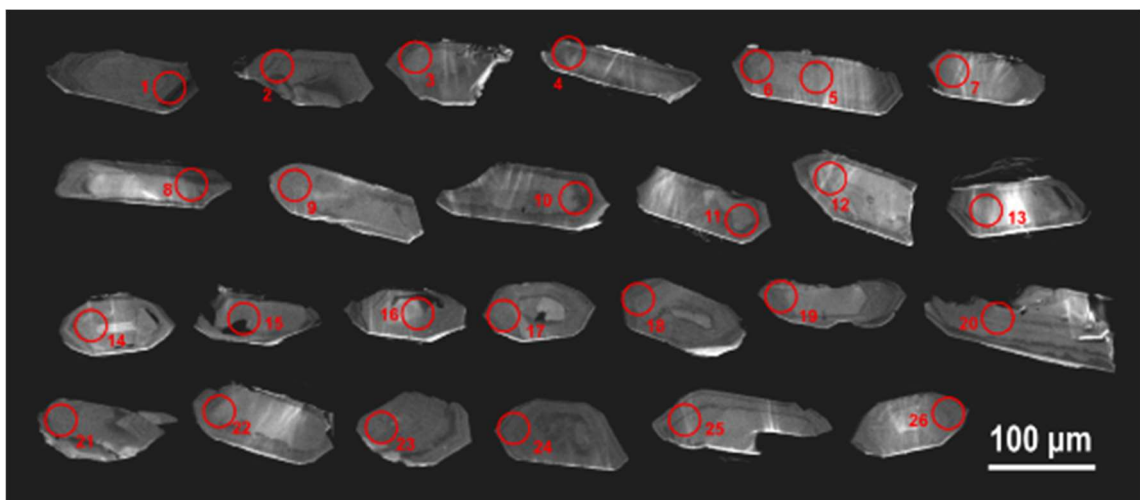


Figure S-B3. CL images of zircon grains separated from sample CC19-06.

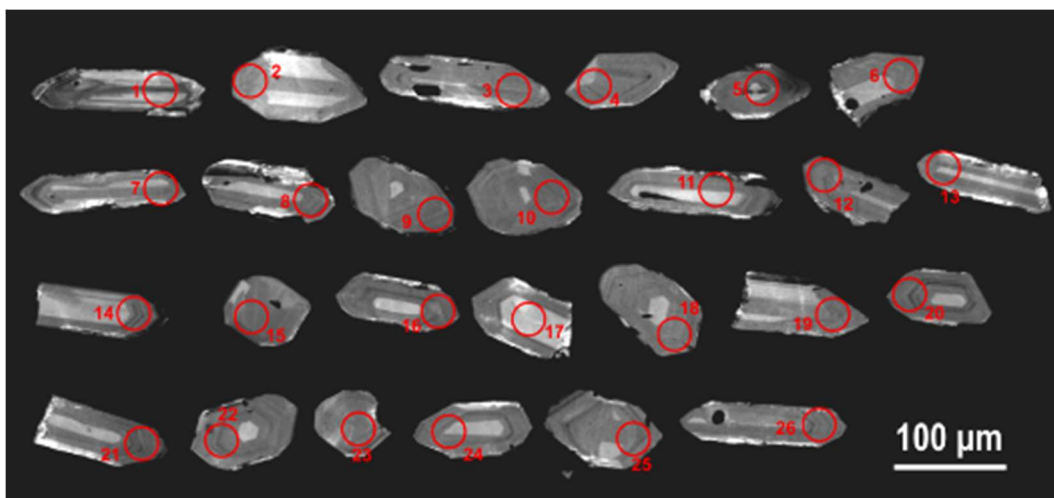


Figure S-B4. CL images of zircon grains separated from sample CC19-08.

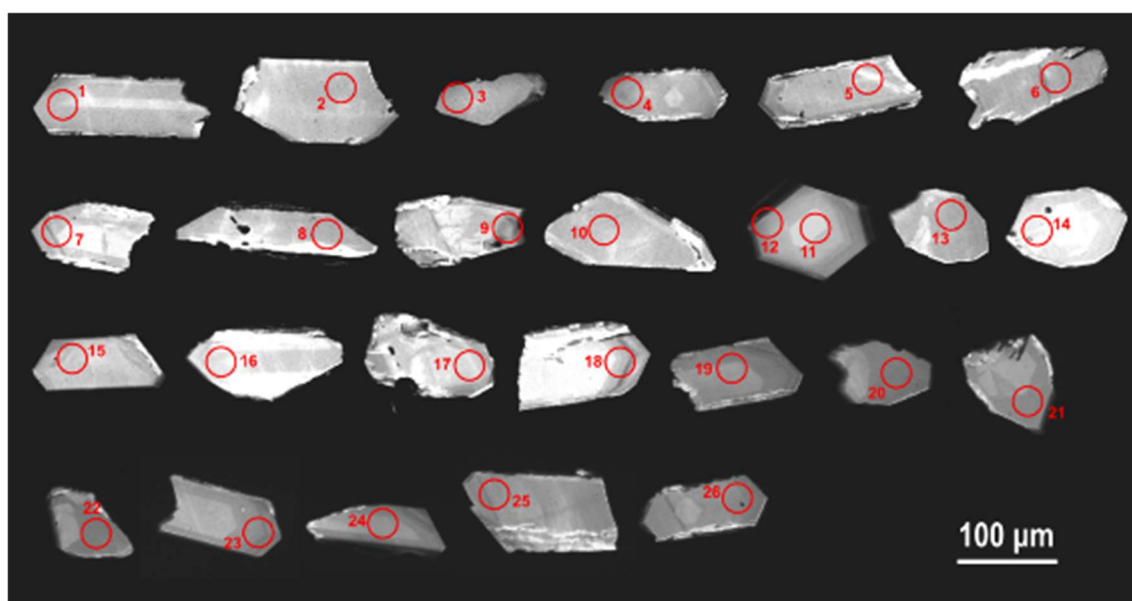


Figure S-B5. CL images of zircon grains separated from sample CC19-09.

Table S-B1. Analytical setting for zircon U–Pb dating.

Laser ablation system	
Model	Analyte G2 excimer laser (Photon Machines, USA)
Wave length	193 nm
Energy	3.0 J/cm ²
Pulse rate	10 Hz
Shot count	200 shots
Spot size	30 µm diameter
Herium gas flow rate	MFC1: 0.5 L/min, MFC2: 0.1 L/min
Mutiple collector inductively coupled plasma mass spectrometry system	
Model	Neptune- <i>Plus</i> (Thermo Fisher Scientific, Germany)
RF power	1200 W
Guard electrode	ON
Skimmer-sampling cones	H-Normal cone
Argon gas flow rate	1.065-1.098 L/min (Aux: 0.50-0.55)
Data processing	
Primary standard	91500 zircon (Wiedenbeck et al., 1995)
Secondary standard	OD-3 zircon (Iwano et al., 2013)
Common lead correction	Not made

Table S-B2. U–Pb isotopes and dates of the OD-3.

Sample code	isotopes						dates (Ma)				note
	²⁰⁷ Pb/ ²⁰⁶ Pb	SD	²⁰⁷ Pb/ ²³⁵ U	SD	²⁰⁶ Pb/ ²³⁸ U	SD	²⁰⁷ Pb/ ²³⁵ U	SD	²⁰⁶ Pb/ ²³⁸ U	SD	
20211213-OD-3-01	0.054442	0.01323	0.039697	0.010022	0.005288	0.000362	39.53	9.79	34.00	2.32	
20211213-OD-3-02	0.046787	0.00703	0.033274	0.005696	0.005158	0.000424	33.24	5.60	33.17	2.72	
20211213-OD-3-03	0.046727	0.00719	0.033407	0.005632	0.005185	0.000356	33.37	5.53	33.34	2.28	
20211213-OD-3-04	0.048644	0.00808	0.034168	0.006313	0.005094	0.000413	34.11	6.20	32.75	2.65	
20211213-OD-3-05	0.046390	0.00991	0.032393	0.007574	0.005064	0.000482	32.37	7.45	32.56	3.09	
20211213-OD-3-06	0.047322	0.00935	0.033399	0.007204	0.005119	0.000444	33.36	7.08	32.92	2.85	
20211214-OD-3-01	0.052771	0.01507	0.038056	0.011428	0.005230	0.000487	37.90	11.20	33.63	3.12	
20211214-OD-3-02	0.046911	0.00612	0.033145	0.005154	0.005124	0.000433	33.11	5.07	32.95	2.78	
20211214-OD-3-03	0.047110	0.00635	0.033393	0.005034	0.005141	0.000347	33.35	4.95	33.06	2.23	
20211214-OD-3-04	0.046702	0.00758	0.032948	0.006063	0.005117	0.000445	32.92	5.96	32.90	2.85	
20211214-OD-3-05	0.047070	0.00946	0.034762	0.007500	0.005356	0.000420	34.70	7.36	34.43	2.69	
20211214-OD-3-06	0.046653	0.00864	0.033401	0.006796	0.005192	0.000437	33.36	6.68	33.38	2.80	
20211215-OD-3-01	0.047202	0.00621	0.034040	0.005485	0.005230	0.000487	33.99	5.39	33.63	3.12	
20211215-OD-3-02	0.046490	0.01107	0.033175	0.008521	0.005175	0.000497	33.14	8.37	33.27	3.19	
20211215-OD-3-03	0.047099	0.00671	0.033309	0.005337	0.005129	0.000376	33.27	5.24	32.98	2.41	
20211215-OD-3-04	0.046575	0.00892	0.033506	0.007129	0.005218	0.000483	33.46	7.00	33.55	3.10	
20211215-OD-3-05	0.047728	0.01801	0.034073	0.013299	0.005178	0.000515	34.00	13.10	33.29	3.30	
20211215-OD-3-06	0.047026	0.01017	0.033470	0.008116	0.005162	0.000566	33.43	7.97	33.19	3.63	

Table S-B3. U–Pb isotopes and dates of sample CC19-01.

Sample code	isotopes						dates (Ma)				note
	$^{207}\text{Pb}/^{206}\text{Pb}$	SD	$^{207}\text{Pb}/^{235}\text{U}$	SD	$^{206}\text{Pb}/^{238}\text{U}$	SD	$^{207}\text{Pb}/^{235}\text{U}$	SD	$^{206}\text{Pb}/^{238}\text{U}$	SD	
CC19-01-1	0.044881	0.014792	0.005716	0.001915	0.000924	0.000055	5.79	1.93	5.95	0.35	
CC19-01-2	0.048350	0.014752	0.006750	0.002123	0.001013	0.000077	6.83	2.14	6.53	0.50	
CC19-01-3	0.047763	0.012627	0.005941	0.001640	0.000902	0.000072	6.01	1.66	5.81	0.46	
CC19-01-4	0.112559	0.052822	0.015720	0.007480	0.001013	0.000080	15.84	7.48	6.53	0.52	
CC19-01-5	0.046432	0.018627	0.006108	0.002489	0.000954	0.000068	6.18	2.51	6.15	0.44	
CC19-01-6	0.047472	0.012071	0.006281	0.001717	0.000960	0.000096	6.36	1.73	6.19	0.62	
CC19-01-7	0.047448	0.011216	0.006357	0.001555	0.000972	0.000061	6.43	1.57	6.26	0.39	
CC19-01-8	0.066721	0.034351	0.008628	0.004496	0.000938	0.000075	8.72	4.53	6.04	0.48	
CC19-01-9	0.048114	0.010111	0.006160	0.001328	0.000928	0.000045	6.24	1.34	5.98	0.29	
CC19-01-10	0.046119	0.013457	0.006110	0.001818	0.000961	0.000056	6.19	1.83	6.19	0.36	
CC19-01-11	0.045569	0.010556	0.005880	0.001401	0.000936	0.000052	5.95	1.41	6.03	0.33	
CC19-01-12	0.047462	0.011949	0.006540	0.001683	0.000999	0.000053	6.62	1.70	6.44	0.34	
CC19-01-13	0.100257	0.063514	0.013736	0.008871	0.000994	0.000125	13.85	8.89	6.40	0.81	
CC19-01-14	0.047432	0.009177	0.006433	0.001291	0.000984	0.000053	6.51	1.30	6.34	0.34	
CC19-01-15	0.051586	0.011037	0.006789	0.001502	0.000954	0.000054	6.87	1.51	6.15	0.35	
CC19-01-16	0.046004	0.010747	0.005930	0.001432	0.000935	0.000057	6.00	1.45	6.02	0.37	
CC19-01-17	0.048631	0.013819	0.006256	0.001821	0.000933	0.000059	6.33	1.84	6.01	0.38	
CC19-01-18	0.153074	0.092398	0.023528	0.014774	0.001115	0.000193	23.61	14.66	7.18	1.24	rejected
CC19-01-19	0.044962	0.013180	0.005680	0.001703	0.000916	0.000058	5.75	1.72	5.90	0.37	
CC19-01-20	0.054849	0.032121	0.007217	0.004298	0.000954	0.000103	7.30	4.33	6.15	0.66	
CC19-01-21	0.047857	0.007605	0.006219	0.001036	0.000942	0.000047	6.30	1.05	6.07	0.30	
CC19-01-22	0.048550	0.013307	0.006358	0.001816	0.000950	0.000076	6.44	1.83	6.12	0.49	
CC19-01-23	0.048107	0.008451	0.006215	0.001147	0.000937	0.000053	6.29	1.16	6.04	0.34	
CC19-01-24	0.047393	0.013979	0.006108	0.001840	0.000935	0.000057	6.18	1.86	6.02	0.37	
CC19-01-25	0.045988	0.017396	0.006054	0.002331	0.000955	0.000069	6.13	2.35	6.15	0.44	
CC19-01-26	0.050394	0.013273	0.006619	0.001787	0.000953	0.000057	6.70	1.80	6.14	0.37	

Table S-B4. U–Pb isotopes and dates of sample CC19-04.

Sample code	isotopes						dates (Ma)				note
	²⁰⁷ Pb/ ²⁰⁶ Pb	SD	²⁰⁷ Pb/ ²³⁵ U	SD	²⁰⁶ Pb/ ²³⁸ U	SD	²⁰⁷ Pb/ ²³⁵ U	SD	²⁰⁶ Pb/ ²³⁸ U	SD	
CC19-04-1	0.116339	0.025975	0.017492	0.004118	0.001090	0.000081	17.61	4.11	7.02	0.52	rejected
CC19-04-2	0.049296	0.021741	0.007041	0.003156	0.001036	0.000083	7.12	3.18	6.68	0.53	
CC19-04-3	0.047334	0.030328	0.006627	0.004292	0.001015	0.000095	6.71	4.33	6.54	0.61	
CC19-04-4	0.044975	0.013965	0.006262	0.001985	0.001010	0.000064	6.34	2.00	6.51	0.41	
CC19-04-5	0.055644	0.017797	0.008027	0.002610	0.001046	0.000061	8.12	2.63	6.74	0.39	
CC19-04-6	0.042732	0.012921	0.005896	0.001846	0.001001	0.000081	5.97	1.86	6.45	0.52	
CC19-04-7	0.044480	0.018274	0.006188	0.002581	0.001009	0.000073	6.26	2.60	6.50	0.47	
CC19-04-8	0.050471	0.025837	0.007227	0.003749	0.001039	0.000087	7.31	3.78	6.69	0.56	
CC19-04-9	0.047348	0.014721	0.006608	0.002114	0.001012	0.000076	6.69	2.13	6.52	0.49	
CC19-04-10	0.047762	0.011404	0.006832	0.001693	0.001037	0.000069	6.91	1.71	6.68	0.44	
CC19-04-11	0.048257	0.015223	0.006765	0.002182	0.001017	0.000068	6.85	2.20	6.55	0.44	rejected
CC19-04-12	0.045353	0.011650	0.006331	0.001664	0.001012	0.000057	6.41	1.68	6.52	0.37	
CC19-04-13	0.048424	0.017026	0.006699	0.002398	0.001003	0.000067	6.78	2.42	6.46	0.43	
CC19-04-14	0.045303	0.015205	0.006278	0.002151	0.001005	0.000070	6.35	2.17	6.48	0.45	
CC19-04-15	0.047963	0.010347	0.006545	0.001462	0.000990	0.000057	6.62	1.47	6.38	0.37	
CC19-04-16	0.048662	0.013476	0.006789	0.001927	0.001012	0.000063	6.87	1.94	6.52	0.41	
CC19-04-17	0.047318	0.007646	0.006509	0.001102	0.000998	0.000050	6.59	1.11	6.43	0.32	
CC19-04-18	0.041056	0.014829	0.005636	0.002069	0.000996	0.000065	5.71	2.09	6.42	0.42	
CC19-04-19	0.053812	0.018584	0.007494	0.002633	0.001010	0.000065	7.58	2.65	6.51	0.42	
CC19-04-20	0.046708	0.010494	0.006410	0.001499	0.000995	0.000065	6.49	1.51	6.41	0.42	
CC19-04-21	0.045902	0.012098	0.006377	0.001725	0.001008	0.000062	6.45	1.74	6.49	0.40	
CC19-04-22	0.203941	0.105105	0.036100	0.019231	0.001284	0.000173	36.01	18.85	8.27	1.11	
CC19-04-23	0.045739	0.011389	0.006285	0.001608	0.000997	0.000058	6.36	1.62	6.42	0.37	
CC19-04-24	0.046836	0.009209	0.006400	0.001305	0.000991	0.000054	6.48	1.32	6.39	0.35	
CC19-04-25	0.046632	0.009977	0.006474	0.001423	0.001007	0.000051	6.55	1.44	6.49	0.33	
CC19-04-26	0.046511	0.013666	0.006426	0.001940	0.001002	0.000069	6.50	1.96	6.46	0.44	

Table S-B5. U–Pb isotopes and dates of sample CC19-06.

Sample code	isotopes						dates (Ma)				note
	²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		
		SD		SD		SD		SD		SD	
CC19-06-1	0.048163	0.008687	0.014058	0.002638	0.002117	0.000110	14.17	2.64	13.63	0.71	
CC19-06-2	0.060671	0.025576	0.017177	0.007403	0.002053	0.000184	17.29	7.39	13.22	1.18	
CC19-06-3	0.047584	0.016140	0.013169	0.004555	0.002007	0.000136	13.28	4.56	12.93	0.88	
CC19-06-4	0.062603	0.016714	0.018175	0.004926	0.002106	0.000098	18.29	4.91	13.56	0.63	
CC19-06-5	0.046939	0.020147	0.013597	0.005935	0.002101	0.000167	13.71	5.95	13.53	1.07	
CC19-06-6	0.081752	0.041675	0.024628	0.012901	0.002185	0.000263	24.70	12.78	14.07	1.69	
CC19-06-7	0.045734	0.013337	0.012734	0.003823	0.002019	0.000144	12.85	3.83	13.00	0.93	
CC19-06-8	0.048097	0.012210	0.013495	0.003524	0.002035	0.000125	13.61	3.53	13.11	0.80	
CC19-06-9	0.047400	0.015510	0.013468	0.004530	0.002061	0.000160	13.58	4.54	13.27	1.03	
CC19-06-10	0.046465	0.013689	0.013609	0.004101	0.002124	0.000134	13.73	4.11	13.68	0.86	
CC19-06-11	0.046827	0.012059	0.013774	0.003638	0.002133	0.000125	13.89	3.64	13.74	0.80	
CC19-06-12	0.047072	0.011657	0.013944	0.003573	0.002148	0.000141	14.06	3.58	13.83	0.91	
CC19-06-13	0.044538	0.012075	0.013036	0.003606	0.002123	0.000116	13.15	3.61	13.67	0.75	
CC19-06-14	0.049602	0.013676	0.021765	0.006179	0.003182	0.000215	21.86	6.14	20.48	1.38	old core (autocryst?)
CC19-06-15	0.046172	0.007322	0.033723	0.006502	0.005297	0.000581	33.68	6.39	34.06	3.73	old core (autocryst?)
CC19-06-16	0.047267	0.006067	0.034625	0.004943	0.005313	0.000332	34.56	4.85	34.16	2.13	old core (autocryst?)
CC19-06-17	0.046376	0.010244	0.016752	0.004469	0.002620	0.000392	16.87	4.46	16.87	2.52	
CC19-06-18	0.051067	0.017653	0.014816	0.005223	0.002104	0.000146	14.93	5.23	13.55	0.94	
CC19-06-19	0.049650	0.013273	0.014126	0.003906	0.002064	0.000146	14.24	3.91	13.29	0.94	
CC19-06-20	0.044574	0.013092	0.012470	0.003784	0.002029	0.000155	12.58	3.79	13.07	1.00	
CC19-06-21	0.048659	0.016190	0.014088	0.004803	0.002100	0.000156	14.20	4.81	13.52	1.00	
CC19-06-22	0.048230	0.012727	0.013727	0.003727	0.002064	0.000132	13.84	3.73	13.29	0.85	
CC19-06-23	0.048841	0.031937	0.018728	0.013260	0.002781	0.000755	18.84	13.22	17.90	4.85	
CC19-06-24	0.046466	0.011933	0.012917	0.003428	0.002016	0.000135	13.03	3.44	12.98	0.87	
CC19-06-25	0.045146	0.014296	0.013168	0.004350	0.002115	0.000199	13.28	4.36	13.62	1.28	
CC19-06-26	0.047886	0.009975	0.013647	0.002990	0.002067	0.000141	13.76	3.00	13.31	0.91	

Table S-B6. U–Pb isotopes and dates of sample CC19-08.

Sample code	isotopes						dates (Ma)				note
	$^{207}\text{Pb}/^{206}\text{Pb}$	SD	$^{207}\text{Pb}/^{235}\text{U}$	SD	$^{206}\text{Pb}/^{238}\text{U}$	SD	$^{207}\text{Pb}/^{235}\text{U}$	SD	$^{206}\text{Pb}/^{238}\text{U}$	SD	
CC19-08-1	0.050480	0.010012	0.034742	0.007240	0.004991	0.000319	34.68	7.10	32.09	2.05	
CC19-08-2	0.051425	0.012105	0.036913	0.009030	0.005206	0.000347	36.81	8.84	33.47	2.23	
CC19-08-3	0.046265	0.009799	0.032771	0.007223	0.005137	0.000313	32.74	7.10	33.03	2.01	
CC19-08-4	0.066294	0.023647	0.048151	0.017812	0.005268	0.000516	47.75	17.26	33.87	3.31	
CC19-08-5	0.047149	0.009241	0.032761	0.006618	0.005040	0.000247	32.73	6.51	32.41	1.58	
CC19-08-6	0.047273	0.007035	0.032929	0.005159	0.005052	0.000247	32.90	5.07	32.49	1.58	
CC19-08-7	0.066675	0.015393	0.045474	0.010803	0.004946	0.000277	45.15	10.49	31.81	1.78	
CC19-08-8	0.048723	0.006971	0.033713	0.005024	0.005018	0.000209	33.67	4.93	32.27	1.34	
CC19-08-9	0.047657	0.007880	0.032806	0.005723	0.004993	0.000277	32.78	5.63	32.11	1.78	
CC19-08-10	0.046658	0.007107	0.032086	0.005091	0.004988	0.000221	32.07	5.01	32.07	1.42	
CC19-08-11	0.059587	0.013174	0.043337	0.010027	0.005275	0.000360	43.08	9.76	33.92	2.31	
CC19-08-12	0.046802	0.007452	0.032919	0.005582	0.005101	0.000298	32.89	5.49	32.80	1.91	
CC19-08-13	0.046920	0.008161	0.032512	0.005861	0.005025	0.000238	32.49	5.76	32.31	1.53	
CC19-08-14	0.050613	0.008705	0.037601	0.007164	0.005388	0.000442	37.48	7.01	34.64	2.83	
CC19-08-15	0.047383	0.012324	0.033261	0.008931	0.005091	0.000340	33.22	8.78	32.74	2.18	
CC19-08-16	0.067266	0.030374	0.048957	0.022317	0.005278	0.000330	48.53	21.60	33.93	2.12	
CC19-08-17	0.046553	0.014916	0.035270	0.011706	0.005495	0.000476	35.20	11.48	35.33	3.05	
CC19-08-18	0.045758	0.008428	0.032257	0.006138	0.005113	0.000245	32.24	6.04	32.88	1.57	
CC19-08-19	0.049432	0.008314	0.034400	0.006078	0.005047	0.000273	34.34	5.97	32.45	1.75	
CC19-08-20	0.046319	0.005925	0.033187	0.005069	0.005196	0.000434	33.15	4.98	33.41	2.78	
CC19-08-21	0.046952	0.005157	0.032355	0.003767	0.004998	0.000193	32.33	3.71	32.14	1.24	
CC19-08-22	0.048709	0.010714	0.035263	0.007984	0.005251	0.000282	35.19	7.83	33.76	1.81	
CC19-08-23	0.048669	0.012313	0.034518	0.009063	0.005144	0.000361	34.46	8.90	33.08	2.32	
CC19-08-24	0.045672	0.011401	0.031529	0.008035	0.005007	0.000257	31.52	7.91	32.20	1.65	
CC19-08-25	0.097472	0.060679	0.071040	0.044819	0.005286	0.000541	69.69	42.49	33.99	3.47	
CC19-08-26	0.068486	0.012523	0.046130	0.008621	0.004885	0.000189	45.79	8.37	31.41	1.21	rejected

Table S-B7. U–Pb isotopes and dates of sample CC19-09.

Sample code	isotopes						dates (Ma)				note
	$^{207}\text{Pb}/^{206}\text{Pb}$	SD	$^{207}\text{Pb}/^{235}\text{U}$	SD	$^{206}\text{Pb}/^{238}\text{U}$	SD	$^{207}\text{Pb}/^{235}\text{U}$	SD	$^{206}\text{Pb}/^{238}\text{U}$	SD	
CC19-09-1	0.043569	0.012224	0.026435	0.007565	0.004400	0.000248	26.49	7.48	28.30	3.20	
CC19-09-2	0.046611	0.056287	0.027425	0.033354	0.004267	0.000616	27.47	32.96	27.45	7.94	
CC19-09-3	0.048168	0.014803	0.029747	0.009278	0.004479	0.000238	29.76	9.15	28.81	3.07	
CC19-09-4	0.045587	0.012543	0.027568	0.007779	0.004386	0.000275	27.61	7.69	28.21	3.54	
CC19-09-5	0.046814	0.016088	0.028383	0.009983	0.004397	0.000330	28.42	9.86	28.28	4.25	
CC19-09-6	0.047016	0.015930	0.026557	0.009301	0.004097	0.000364	26.61	9.20	26.35	4.69	
CC19-09-7	0.045414	0.017458	0.026005	0.010191	0.004153	0.000316	26.07	10.09	26.72	4.07	
CC19-09-8	0.049571	0.018359	0.028772	0.010890	0.004210	0.000328	28.80	10.75	27.08	4.23	
CC19-09-9	0.046743	0.018223	0.027481	0.010991	0.004264	0.000380	27.53	10.86	27.43	4.90	
CC19-09-10	0.047280	0.013496	0.026904	0.007906	0.004127	0.000288	26.96	7.82	26.55	3.72	
CC19-09-11	0.054605	0.006680	0.034878	0.005093	0.004632	0.000370	34.81	5.00	29.79	4.76	rejected
CC19-09-12	0.049890	0.024372	0.030358	0.015081	0.004413	0.000398	30.37	14.86	28.39	5.13	
CC19-09-13	0.044572	0.014889	0.026434	0.009032	0.004301	0.000310	26.49	8.93	27.67	3.99	
CC19-09-14	0.044634	0.015865	0.026219	0.009516	0.004260	0.000313	26.28	9.42	27.41	4.03	
CC19-09-15	0.047467	0.013545	0.027768	0.008115	0.004243	0.000268	27.81	8.02	27.29	3.45	
CC19-09-16	0.045832	0.017241	0.026586	0.010250	0.004207	0.000356	26.64	10.14	27.06	4.59	
CC19-09-17	0.046164	0.010374	0.027515	0.006393	0.004323	0.000255	27.56	6.32	27.81	3.29	
CC19-09-18	0.046574	0.011268	0.027947	0.006979	0.004352	0.000269	27.99	6.89	27.99	3.47	
CC19-09-19	0.046163	0.015302	0.027364	0.009254	0.004299	0.000287	27.41	9.15	27.65	3.71	
CC19-09-20	0.047117	0.012423	0.027554	0.007453	0.004241	0.000256	27.60	7.36	27.28	3.30	
CC19-09-21	0.051042	0.016521	0.030164	0.010015	0.004286	0.000317	30.18	9.87	27.57	4.09	
CC19-09-22	0.046829	0.012683	0.027813	0.007736	0.004307	0.000273	27.86	7.64	27.71	3.52	
CC19-09-23	0.045917	0.010358	0.027473	0.006402	0.004339	0.000254	27.52	6.33	27.91	3.27	
CC19-09-24	0.045614	0.017453	0.026491	0.010346	0.004212	0.000330	26.55	10.23	27.10	4.25	
CC19-09-25	0.048176	0.011945	0.028679	0.007377	0.004317	0.000296	28.71	7.28	27.77	3.81	
CC19-09-26	0.046636	0.011907	0.027925	0.007337	0.004343	0.000269	27.97	7.25	27.94	3.47	

Supplementary material C: Methodology and result of zircon fission-track dating

Zircon fission-track (ZFT) dating was carried out at Tono Geoscience Center. Zircon grains separated from 5 rock samples (100 grains each) were mounted on a Teflon sheet and polished to obtain 4π polished surface. ZFT were etched by a eutectic melt of sodium hydroxide-potassium hydroxide (NaOH–KOH) at 225–228 °C for 105.5–134.0 h depending on etching progression of each sample (etching times are summarized in table S-C1–5).

ZFT density count was conducted by TrakScan Plus Professional (Autoscan System). About 25–30 suitable areas were selected, and the spontaneous tracks were subsequently counted using manual mode of TrakScan.

The ^{238}U concentration was determined using a quadrupole ICP–MS (Agilent 7700, Agilent Technologies, UK) coupled with an excimer laser system Analyte G2 (Photon Machines, USA). Ion counts of ^{238}U were normalized by ^{29}Si as an internal standard. External standard materials (NIST SRM 610 glass: Pearce et al., 1996; 91500 zircon: Wiedenbeck et al., 1995) were analyzed with unknown samples to correct the ^{238}U concentration and monitor a measurement error. Age standard zircons from the Fish Canyon Tuff (Hurford and Watkins 1987; Gleadow et al. 2015; Iwano et al. 2018) were analyzed under the same experimental condition. The absolute calibration method (Hasebe et al., 2004) was adopted to obtain the single-grain ages and the pooled ZFT age (etching factor: 1.0; geometry factor: 1.0; equivalent isotropic track length: 11.0; mineral density: 4.7).

Pooled ZFT age of the Fish Canyon Tuff zircon determined in this study (26.4 ± 0.8 Ma) is consistent with the reference age (28.3 ± 0.3 Ma: Gleadow et al., 2015; Iwano et al., 2018). Result of the ZFT dating of 5 samples are shown in the radial plot and kernel density plot on figure S-C-a and summarized in table S-C1–6.

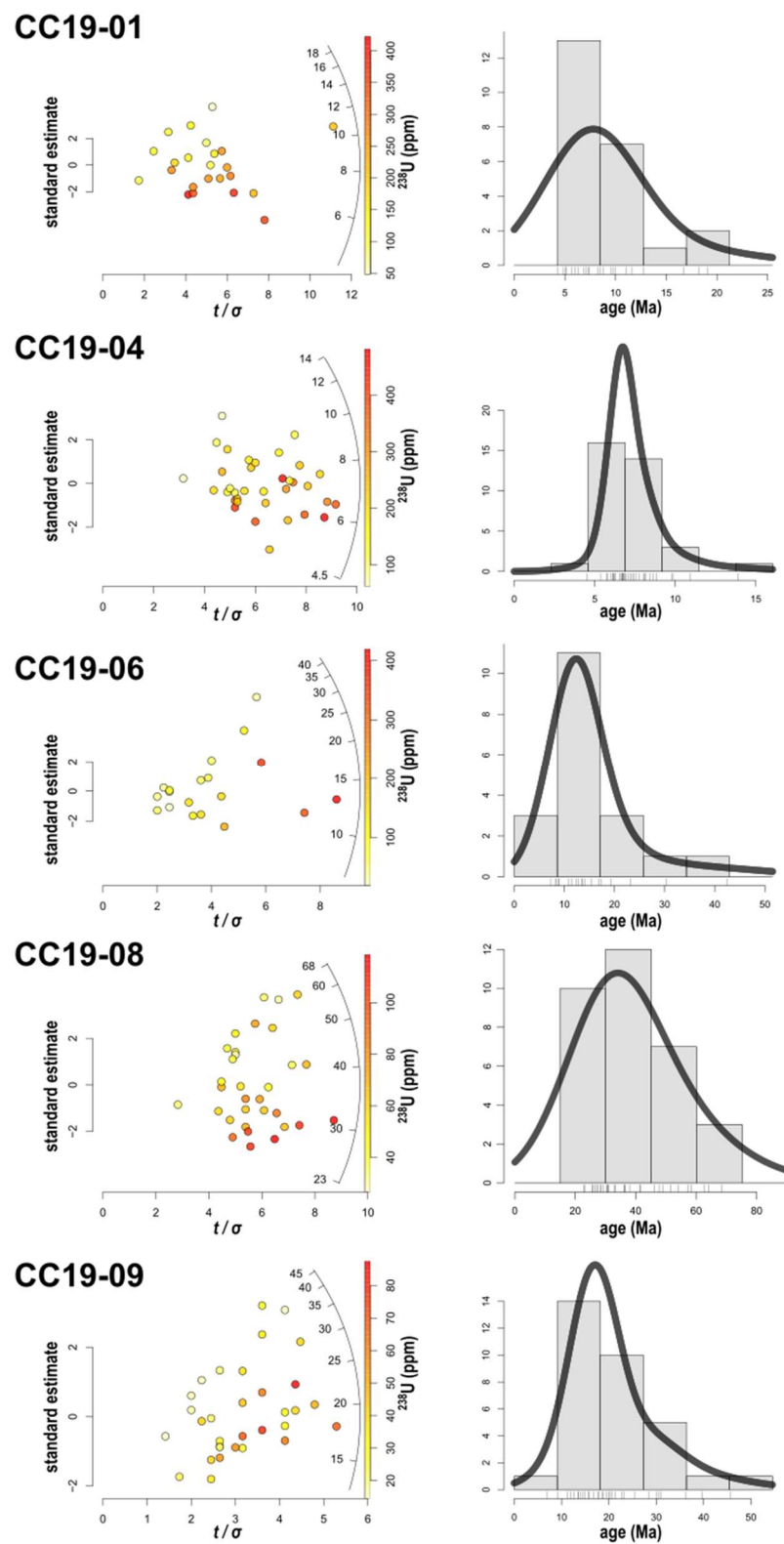


Figure S-C1. Radial plots and age histograms with kernel density estimate the smooth zircon fission-track data produced using IsoplotR (Vermeesch 2018).

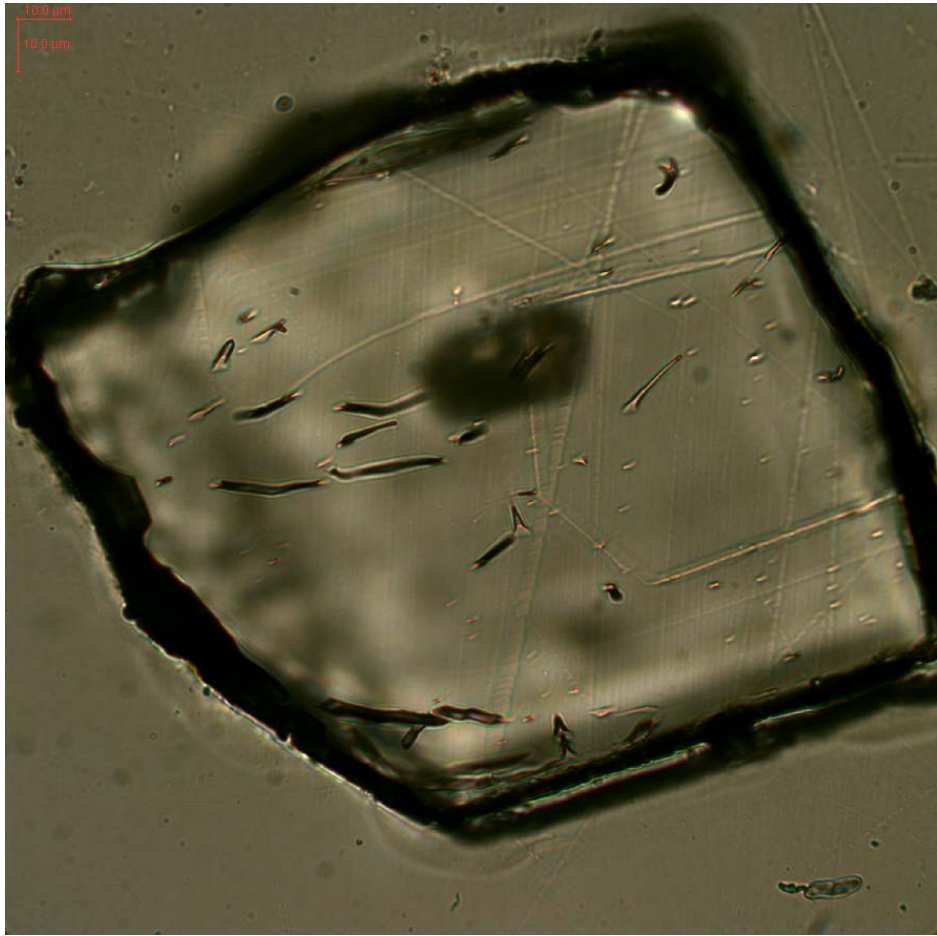


Figure S-C2. Etched dislocation structure of apatite (CC19-01).

Table S-C1. Summary of the zircon FT dating of CC19-01

sample No.	etching time	grain color	pooled FT age (Ma)		1SE (Ma)
CC19-01	134 h	yellowish-pink, orange	7.75		0.30

Grain No.	N_j	A_j (μm^2)	ρ_j (μm^{-2})	$^{238}\text{U}_j$ (ppm)	error [$^{238}\text{U}_j$] (ppm)	t_j (Ma)	σ_j (Ma)
CC19-01 tefl No.1	6	681	0.009	124.93	0.34	12.74	5.20
CC19-01 tefl No.2	3	1213	0.002	104.10	0.32	4.29	2.48
CC19-01 tefl No.3	10	866	0.012	114.14	0.35	18.25	5.77
CC19-01 tefl No.4	18	1434	0.013	135.13	0.37	16.77	3.95
CC19-01 tefl No.5	40	3219	0.012	374.55	0.64	5.99	0.95
CC19-01 tefl No.6	36	3288	0.011	244.55	0.50	8.09	1.35
CC19-01 tefl No.7	11	997	0.011	268.00	0.50	7.43	2.24
CC19-01 tefl No.8	25	4294	0.006	90.35	0.30	11.63	2.33
CC19-01 tefl No.9	17	1544	0.011	408.38	0.62	4.87	1.18
CC19-01 tefl No.10	19	1992	0.010	336.07	0.58	5.13	1.18
CC19-01 tefl No.11	61	6450	0.009	347.74	0.58	4.91	0.63
CC19-01 tefl No.12	32	3496	0.009	237.09	0.48	6.97	1.23
CC19-01 tefl No.13	19	2189	0.009	274.66	0.53	5.71	1.31
CC19-01 tefl No.14	26	2675	0.010	257.31	0.52	6.82	1.34
CC19-01 tefl No.15	38	3294	0.012	285.58	0.53	7.30	1.18
CC19-01 tefl No.16	29	3546	0.008	151.37	0.39	9.76	1.81
CC19-01 tefl No.17	33	2287	0.014	260.69	0.52	10.00	1.74
CC19-01 tefl No.18	27	5650	0.005	103.68	0.32	8.32	1.60
CC19-01 tefl No.19	17	2497	0.007	129.18	0.36	9.52	2.31
CC19-01 tefl No.20	28	4267	0.007	62.31	0.25	19.00	3.59
CC19-01 tefl No.21	124	10028	0.012	206.76	0.44	10.80	0.97
CC19-01 tefl No.22	53	7027	0.008	218.79	0.47	6.23	0.86
CC19-01 tefl No.23	12	1342	0.009	184.05	0.41	8.77	2.53

 N_j = the number of spontaneous tracks counted for the j^{th} grain A_j = the counted area for the j^{th} grain ρ_j = spontaneous FT density at the observed surface of the j^{th} grain $^{238}\text{U}_j$ = ^{238}U concentration of the j^{th} grain t_j = FT age of the j^{th} grain σ_j = error of the j^{th} grain age

Table S-C2. Summary of the zircon FT dating of CC19-04

sample No.	etching time	grain color	pooled FT age (Ma)		1SE (Ma)		
CC19-04	116 h	yellowish-pink, orange	6.91		0.18		

Grain No.	N_j	A_j (μm^2)	ρ_j (μm^{-2})	$^{238}\text{U}_j$ (ppm)	error [$^{238}\text{U}_j$] (ppm)	t_j (Ma)	σ_j (Ma)
CC19-04 tefl No.1	24	4317	0.006	151.48	0.41	6.63	1.35
CC19-04 tefl No.2	27	6065	0.004	121.50	0.37	6.62	1.27
CC19-04 tefl No.3	27	2250	0.012	351.09	0.62	6.18	1.19
CC19-04 tefl No.4	22	1868	0.012	263.98	0.55	8.06	1.72
CC19-04 tefl No.5	56	4182	0.013	334.30	0.62	7.23	0.97
CC19-04 tefl No.6	20	2862	0.007	115.42	0.38	10.93	2.44
CC19-04 tefl No.7	10	3013	0.003	77.49	0.32	7.74	2.45
CC19-04 tefl No.8	36	3170	0.011	382.14	0.72	5.37	0.89
CC19-04 tefl No.9	24	2127	0.011	206.03	0.52	9.89	2.02
CC19-04 tefl No.10	41	4938	0.008	240.22	0.55	6.24	0.98
CC19-04 tefl No.11	34	3237	0.011	233.09	0.52	8.14	1.40
CC19-04 tefl No.12	28	3291	0.009	244.65	0.54	6.28	1.19
CC19-04 tefl No.13	27	2060	0.013	407.39	0.70	5.81	1.12
CC19-04 tefl No.14	28	3681	0.008	224.13	0.51	6.13	1.16
CC19-04 tefl No.15	50	2684	0.019	453.56	0.72	7.42	1.05
CC19-04 tefl No.16	40	5747	0.007	185.39	0.49	6.78	1.07
CC19-04 tefl No.17	25	5656	0.004	116.22	0.35	6.87	1.37
CC19-04 tefl No.18	60	5856	0.010	231.36	0.52	8.00	1.03
CC19-04 tefl No.19	19	2479	0.008	206.97	0.48	6.69	1.53
CC19-04 tefl No.20	22	3598	0.006	79.38	0.29	13.91	2.97
CC19-04 tefl No.21	36	3762	0.010	205.30	0.49	8.42	1.40
CC19-04 tefl No.22	48	6026	0.008	163.24	0.43	8.81	1.27
CC19-04 tefl No.23	33	3657	0.009	188.09	0.48	8.66	1.51
CC19-04 tefl No.24	73	8183	0.009	213.36	0.52	7.55	0.88
CC19-04 tefl No.25	76	4900	0.016	466.14	0.77	6.01	0.69
CC19-04 tefl No.26	84	6249	0.013	375.24	0.68	6.47	0.71
CC19-04 tefl No.27	57	8374	0.007	127.33	0.40	9.65	1.28
CC19-04 tefl No.28	52	4626	0.011	292.69	0.63	6.94	0.96
CC19-04 tefl No.29	31	4109	0.008	201.56	0.52	6.76	1.21
CC19-04 tefl No.30	78	6871	0.011	314.00	0.66	6.53	0.74
CC19-04 tefl No.31	63	5102	0.012	371.72	0.71	6.00	0.76
CC19-04 tefl No.32	65	7220	0.009	229.69	0.56	7.08	0.88
CC19-04 tefl No.33	54	9579	0.006	139.31	0.43	7.31	0.99
CC19-04 tefl No.34	53	6888	0.008	243.97	0.60	5.70	0.78
CC19-04 tefl No.35	43	7366	0.006	232.88	0.56	4.53	0.69

Table S-C3. Summary of the zircon FT dating of CC19-06

sample No.	etching time	grain color	pooled FT age (Ma)		1SE (Ma)		
CC19-06	106 h	colorless, yellowish-pink	13.88		0.72		

Grain No.	N_j	A_j (μm^2)	ρ_j (μm^{-2})	$^{238}\text{U}_j$ (ppm)	error [$^{238}\text{U}_j$] (ppm)	t_j (Ma)	σ_j (Ma)
CC19-06 tefl No.1	6	1386	0.004	57.48	0.32	13.59	5.55
CC19-06 tefl No.2	5	1138	0.004	51.64	0.26	15.36	6.87
CC19-06 tefl No.3	55	2718	0.020	321.19	0.66	11.38	1.53
CC19-06 tefl No.4	6	3628	0.002	33.55	0.21	8.90	3.63
CC19-06 tefl No.5	4	1459	0.003	68.12	0.31	7.27	3.63
CC19-06 tefl No.6	16	1882	0.009	66.01	0.29	23.23	5.81
CC19-06 tefl No.7	15	2073	0.007	75.23	0.33	17.36	4.48
CC19-06 tefl No.8	74	2548	0.029	404.66	0.78	12.96	1.51
CC19-06 tefl No.9	19	1710	0.011	157.32	0.46	12.75	2.93
CC19-06 tefl No.10	20	2072	0.010	214.07	0.54	8.14	1.82
CC19-06 tefl No.11	4	1138	0.004	55.14	0.28	11.51	5.76
CC19-06 tefl No.12	13	1983	0.007	70.01	0.29	16.90	4.69
CC19-06 tefl No.13	13	1671	0.008	156.66	0.44	8.97	2.49
CC19-06 tefl No.14	34	902	0.038	352.70	0.65	19.29	3.31
CC19-06 tefl No.15	27	1260	0.021	127.14	0.43	30.38	5.85
CC19-06 tefl No.16	32	3015	0.011	45.23	0.24	42.28	7.48
CC19-06 tefl No.17	11	1831	0.006	128.61	0.42	8.43	2.54
CC19-06 tefl No.18	10	1114	0.009	148.77	0.45	10.89	3.44
CC19-06 tefl No.19	6	818	0.007	93.54	0.35	14.15	5.78

Table S-C4. Summary of the zircon FT dating of CC19-08

sample No.	etching time	grain color	pooled FT age (Ma)		1SE (Ma)		
CC19-08	110 h	colorless, yellowish-pink	35.63		1.08		

Grain No.	N_j	A_j (μm^2)	ρ_j (μm^{-2})	$^{238}\text{U}_j$ (ppm)	error [$^{238}\text{U}_j$] (ppm)	t_j (Ma)	σ_j (Ma)
CC19-08 tefl No.1	54	2517	0.021	61.67	0.29	62.55	8.52
CC19-08 tefl No.2	59	3706	0.016	69.38	0.30	41.34	5.38
CC19-08 tefl No.3	20	1424	0.014	70.06	0.29	36.13	8.08
CC19-08 tefl No.4	47	4510	0.010	66.29	0.30	28.35	4.14
CC19-08 tefl No.5	22	1731	0.013	44.38	0.24	51.53	10.99
CC19-08 tefl No.6	27	2419	0.011	55.18	0.27	36.45	7.02
CC19-08 tefl No.7	43	2917	0.015	86.68	0.33	30.66	4.68
CC19-08 tefl No.8	19	2015	0.009	59.71	0.28	28.47	6.53
CC19-08 tefl No.9	33	1355	0.024	75.14	0.32	58.32	10.16
CC19-08 tefl No.10	51	5569	0.009	39.69	0.23	41.57	5.83
CC19-08 tefl No.12	37	3436	0.011	63.01	0.28	30.81	5.07
CC19-08 tefl No.13	31	2311	0.013	105.50	0.38	22.93	4.12
CC19-08 tefl No.17	8	1438	0.006	36.67	0.22	27.35	9.67
CC19-08 tefl No.20	39	4151	0.009	46.64	0.23	36.31	5.82
CC19-08 tefl No.21	25	2108	0.012	43.68	0.24	48.89	9.78
CC19-08 tefl No.22	42	2549	0.016	115.37	0.38	25.76	3.98
CC19-08 tefl No.23	29	1925	0.015	82.26	0.32	33.02	6.13
CC19-08 tefl No.24	76	3894	0.020	113.54	0.38	30.99	3.56
CC19-08 tefl No.25	44	3783	0.012	32.62	0.20	64.11	9.67
CC19-08 tefl No.26	41	2263	0.018	60.31	0.28	54.06	8.45
CC19-08 tefl No.27	25	3159	0.008	29.83	0.18	47.78	9.56
CC19-08 tefl No.28	23	2496	0.009	61.65	0.28	26.95	5.62
CC19-08 tefl No.29	55	3221	0.017	105.47	0.37	29.19	3.94
CC19-08 tefl No.30	37	2572	0.014	37.78	0.23	68.45	11.26
CC19-08 tefl No.31	20	1963	0.010	48.23	0.24	38.07	8.52
CC19-08 tefl No.33	24	2174	0.011	43.00	0.23	46.23	9.44
CC19-08 tefl No.34	29	2691	0.011	64.05	0.30	30.34	5.64
CC19-08 tefl No.35	29	2859	0.010	69.32	0.31	26.39	4.90
CC19-08 tefl No.36	35	2523	0.014	75.17	0.31	33.26	5.62
CC19-08 tefl No.37	24	2060	0.012	90.14	0.36	23.31	4.76
CC19-08 tefl No.38	30	2067	0.015	102.29	0.37	25.59	4.67
CC19-08 tefl No.39	25	1482	0.017	52.91	0.26	57.37	11.48

Table S-C5. Summary of the zircon FT dating of CC19-09

sample No.	etching time	grain color	pooled FT age (Ma)		1SE (Ma)		
CC19-09	120 h	colorless, yellowish-pink	19.08		1.02		
Grain No.	N_j	A_j (μm^2)	ρ_j (μm^{-2})	$^{238}U_j$ (ppm)	error [$^{238}U_j$] (ppm)	t_j (Ma)	σ_j (Ma)
CC19-01 tefl No.1	2	1673	0.001	17.17	0.15	12.58	8.89
CC19-01 tefl No.2	13	1795	0.007	77.55	0.32	16.85	4.67
CC19-01 tefl No.3	3	3262	0.001	24.07	0.18	6.90	3.98
CC19-01 tefl No.4	7	2187	0.003	42.58	0.24	13.57	5.13
CC19-01 tefl No.5	7	1921	0.004	54.89	0.27	11.99	4.53
CC19-01 tefl No.6	10	1876	0.005	45.16	0.24	21.30	6.74
CC19-01 tefl No.7	6	2572	0.002	22.88	0.16	18.40	7.51
CC19-01 tefl No.8	23	4173	0.006	49.28	0.24	20.18	4.21
CC19-01 tefl No.9	10	1632	0.006	38.82	0.22	28.46	9.00
CC19-01 tefl No.10	13	1828	0.007	35.40	0.21	36.20	10.04
CC19-01 tefl No.11	4	1846	0.002	18.93	0.15	20.65	10.32
CC19-01 tefl No.12	4	1527	0.003	18.61	0.16	25.39	12.70
CC19-01 tefl No.13	6	2293	0.003	41.84	0.23	11.29	4.61
CC19-01 tefl No.14	13	1698	0.008	60.64	0.29	22.78	6.32
CC19-01 tefl No.15	13	1715	0.008	29.91	0.20	45.62	12.66
CC19-01 tefl No.16	17	5043	0.003	31.42	0.21	19.36	4.70
CC19-01 tefl No.17	5	1722	0.003	17.44	0.15	30.02	13.43
CC19-01 tefl No.18	6	3334	0.002	36.10	0.23	9.00	3.68
CC19-01 tefl No.19	20	2916	0.007	40.66	0.26	30.41	6.80
CC19-01 tefl No.20	5	1209	0.004	42.16	0.24	17.70	7.92
CC19-01 tefl No.21	17	4389	0.004	17.63	0.15	39.59	9.61
CC19-01 tefl No.22	7	2995	0.002	29.33	0.19	14.38	5.44
CC19-01 tefl No.23	7	1852	0.004	21.92	0.16	31.09	11.75
CC19-01 tefl No.24	10	4291	0.002	29.84	0.19	14.10	4.46
CC19-01 tefl No.25	9	2030	0.004	57.30	0.28	13.97	4.66
CC19-01 tefl No.26	17	3123	0.005	61.89	0.29	15.87	3.85
CC19-01 tefl No.27	7	4429	0.002	21.18	0.17	13.47	5.09
CC19-01 tefl No.28	10	1671	0.006	68.76	0.29	15.71	4.97
CC19-01 tefl No.29	17	5434	0.003	32.09	0.21	17.60	4.27
CC19-01 tefl No.30	19	4342	0.004	40.38	0.25	19.55	4.49
CC19-01 tefl No.31	19	1738	0.011	84.85	0.36	23.23	5.33
CC19-01 tefl No.32	28	4204	0.007	67.55	0.34	17.80	3.36

Table S-C6. Summary of the zircon FT dating of Fish Canyon Tuff zircon

sample No.	etching time	grain color	pooled FT age (Ma)		1SE (Ma)
FC3_210721	46.5 h	pink, orange	26.44		0.38

Grain No.	N_j	A_j (μm^2)	ρ_j (μm^{-2})	$^{238}U_j$ (ppm)	error [$^{238}U_j$] (ppm)	t_j (Ma)	σ_j (Ma)
FC3_210721 No.1	365	7095	0.051	265.47	0.55	34.93	1.83
FC3_210721 No.2	229	10312	0.022	187.41	0.47	21.38	1.41
FC3_210721 No.3	214	8038	0.027	151.08	0.44	31.77	2.17
FC3_210721 No.4	408	8689	0.047	386.22	0.67	21.93	1.09
FC3_210721 No.5	259	9916	0.026	326.86	0.64	14.43	0.90
FC3_210721 No.6	262	8548	0.031	158.27	0.43	34.90	2.16
FC3_210721 No.7	247	9755	0.025	163.03	0.43	28.01	1.78
FC3_210721 No.8	308	6306	0.049	396.18	0.63	22.24	1.27
FC3_210721 No.9	231	5347	0.043	476.45	0.69	16.37	1.08
FC3_210721 No.10	221	5444	0.041	267.03	0.53	27.41	1.84
FC3_210721 No.11	213	9542	0.022	87.81	0.30	45.78	3.14
FC3_210721 No.12	1017	18847	0.054	323.56	0.63	30.07	0.94
FC3_210721 No.13	154	4337	0.036	377.04	0.67	17.00	1.37
FC3_210721 No.14	141	5217	0.027	109.94	0.35	44.28	3.73
FC3_210721 No.15	515	10638	0.048	274.98	0.54	31.74	1.40
FC3_210721 No.16	273	8790	0.031	154.06	0.39	36.33	2.20

Supplementary material D: Methodology and result of zircon and apatite U-Th(-Sm)/He dating

U–Th(-Sm)/He analyses were conducted at the University of Melbourne, Australia. Five grains were handpicked under a binocular microscope using the following criteria: grain width of 75 up to 200 μm , transparent and authigenic shapes, and no visible inclusions. Grain geometries were recorded using ImageJ software to calculate the FT correction (Farley et al., 1996) for calibrating the alpha-ejection in each crystal. After measuring grain sizes, single grain of apatite and zircon were put into small acid-treated platinum capsules. Experimental protocols of He content measurement were based on House et al. (2000) using a laser extraction system. Single grains were outgassed for ^4He under vacuum using a laser set on a wavelength of 820 nm with fiber-optic coupling to the sample chamber. Conditions of laser ablation heating were $\sim 900\text{ }^\circ\text{C}$ for 5 min for apatite, and for $\sim 1300\text{ }^\circ\text{C}$ for 20 min for zircon. A re-extraction measurement was also conducted to ensure total degassing of ^4He after each gas extraction. He concentrations were determined using isotope dilution against a pure ^3He spike, calibrated against an independent ^4He standard. Second, dissolving the degassed grains and analyzing parent isotopes were performed after all Pt packets were removed from the sample stage. For dissolving apatite grains, whole Pt capsules were immersed into HNO_3 to measure ^{238}U , ^{235}U , ^{232}Th , and ^{147}Sm concentrations using solution ICP–MS. While in zircon, degassed grains were removed from their Pt capsules and transferred to where they were spiked with ^{233}U and ^{229}Th and digested in small volumes (0.3–0.5 ml) at $240\text{ }^\circ\text{C}$ for 40 h in HF. Standard solutions containing the same spike amounts as samples were treated identically, as were a series of unspiked reagent blanks. A second bombing in HCl for 24 h at $200\text{ }^\circ\text{C}$ ensured dissolution of fluoride salts. Zircon solutions were then dried down, dissolved in HNO_3 and diluted in H_2O to 5% acidity for analysis of ^{238}U , ^{235}U and ^{232}Th by solution ICP–MS. For checking analytical accuracy, we simultaneously measured age standard samples as unknown samples. In this case, we used Durango apatite (McDowell et al., 2005) and Fish Canyon Tuff zircon (Gleadow et al., 2015) as standards.

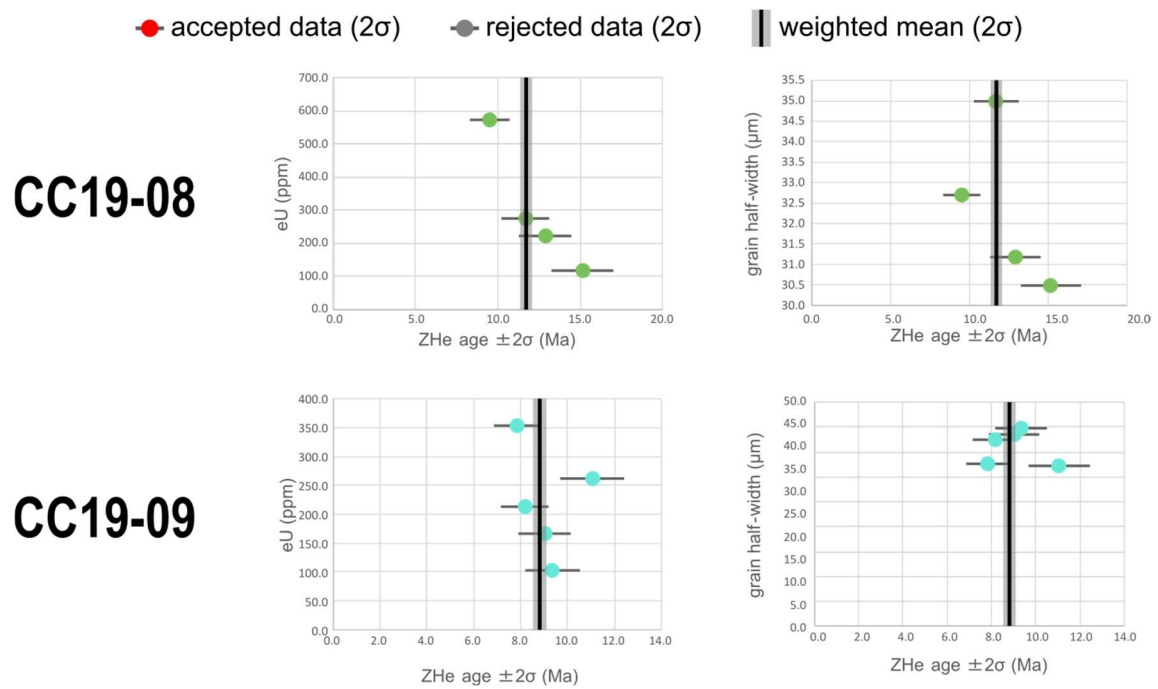


Figure S-D1. ZHe grain age versus effective U concentration (eU) and grain half-width.

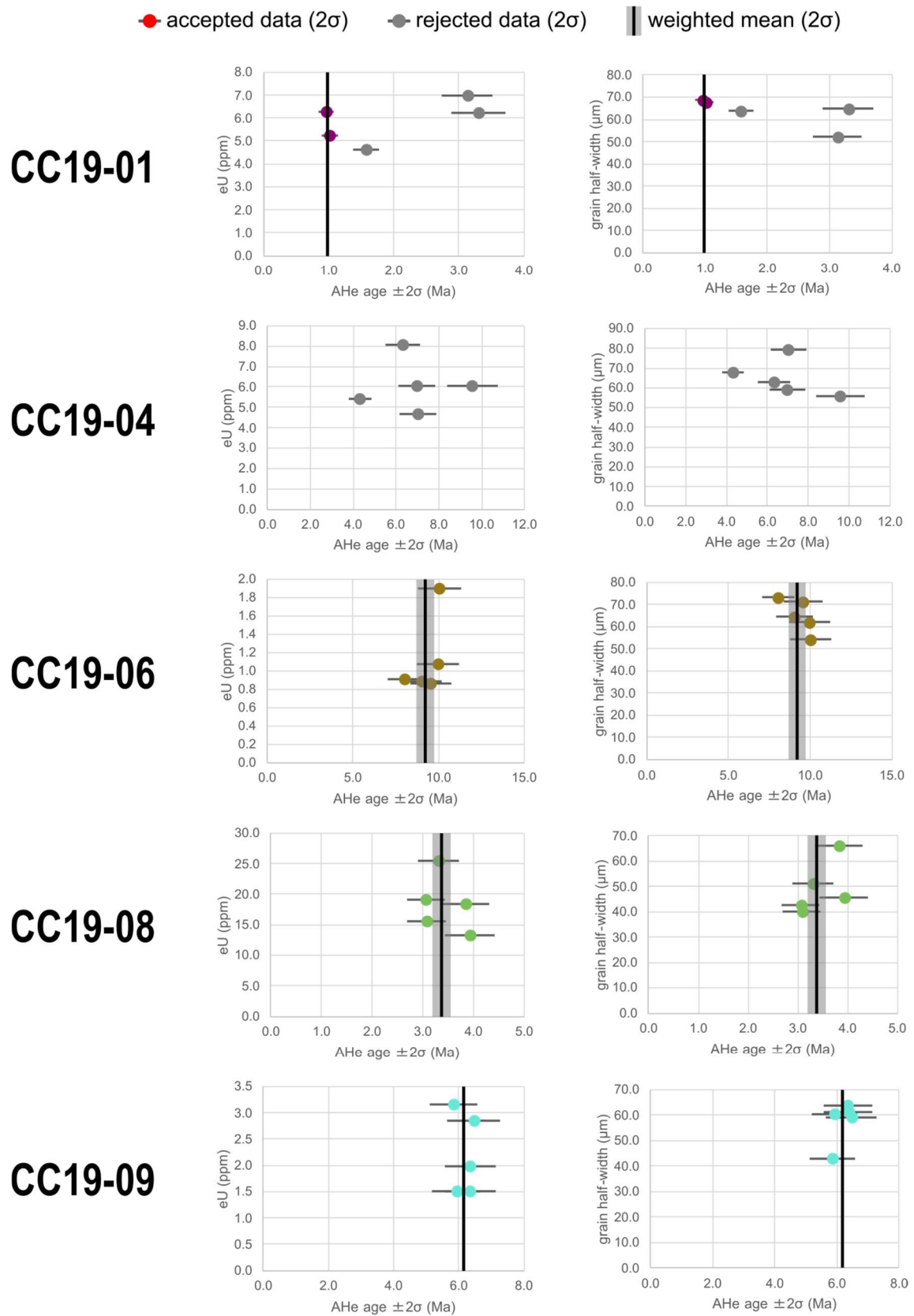


Figure S-D2. AHe grain age versus effective U concentration (eU) and grain half-width.

Table S-D1. Single grain apatite (U-Th-Sm)/He data.

Sample No.	Analysis No.	He#	⁴ He gas ncc	Mass (mg)	² Mean FT	U ppm	Th ppm	Sm ppm	Th/U	^b [eU] ppm	Uncorrected Age (Ma)	Corrected Age (Ma)	Error ±1σ (Ma)	Grain length (μm)	Grain half-width (μm)	^c Grain morphology
CC19-01	23741	80416	0.006	0.00975	0.79	4.0	9.7	56.6	2.39	6.3	0.8	0.96	0.06	206.2	68.6	0T
CC19-01	23742	80419	0.009	0.01202	0.80	2.8	7.7	46.1	2.78	4.6	1.3	1.57	0.10	291.9	64.0	0T
CC19-01	23743	80422	0.018	0.00901	0.79	4.0	9.4	57.4	2.36	6.2	2.6	3.30	0.20	212.5	65.0	0T
CC19-01	23744	80425	0.005	0.00933	0.79	3.5	7.4	40.5	2.11	5.2	0.8	1.01	0.06	200.4	68.1	0T
CC19-01	23745	80428	0.010	0.00507	0.74	3.8	13.5	63.7	3.57	7.0	2.3	3.13	0.19	183.2	52.5	0T
CC19-04	23751	80446	0.019	0.00465	0.75	3.1	12.5	302.2	3.99	6.0	5.2	6.97	0.43	198.5	59.3	1T
CC19-04	23752	80449	0.023	0.00456	0.76	4.4	15.7	301.0	3.55	8.1	4.8	6.32	0.39	181.0	62.8	1T
CC19-04	23753	80452	0.028	0.00510	0.72	3.1	12.5	288.7	3.97	6.0	6.9	9.56	0.59	197.6	55.7	2T
CC19-04	23754	80455	0.015	0.00648	0.75	2.7	11.6	237.0	4.36	5.4	3.2	4.31	0.27	170.4	67.7	2T
CC19-04	23755	80458	0.041	0.01195	0.80	2.5	9.3	233.0	3.69	4.7	5.6	7.03	0.44	228.0	79.4	2T
CC19-06	23756	80461	0.007	0.00919	0.79	0.7	0.8	26.9	1.14	0.9	7.2	9.05	0.56	220.1	64.4	0T
CC19-06	23757	80464	0.008	0.00897	0.79	0.6	1.1	26.7	1.69	0.9	7.6	9.57	0.59	175.7	71.3	0T
CC19-06	23758	80467	0.008	0.00771	0.78	0.7	1.6	26.2	2.34	1.1	7.7	9.98	0.62	198.1	62.2	0T
CC19-06	23759	80470	0.012	0.00678	0.76	1.4	2.1	63.1	1.55	1.9	7.7	10.05	0.62	230.1	54.1	0T
CC19-06	23760	80473	0.009	0.01160	0.81	0.6	1.3	42.5	2.05	0.9	6.5	8.04	0.50	215.8	73.1	0T
CC19-08	23761	80476	0.014	0.00285	0.69	14.9	17.6	126.9	1.18	19.0	2.1	3.06	0.19	156.2	42.6	0T
CC19-08	23762	80479	0.016	0.00344	0.71	10.1	13.5	143.6	1.33	13.3	2.8	3.93	0.24	164.6	45.6	0T
CC19-08	23763	80482	0.048	0.00621	0.76	20.6	20.7	132.4	1.00	25.5	2.5	3.31	0.21	235.5	51.2	0T
CC19-08	23764	80485	0.045	0.00671	0.78	14.3	17.1	131.1	1.19	18.3	3.0	3.83	0.24	153.9	65.9	0T
CC19-08	23765	80488	0.010	0.00244	0.67	12.2	14.0	126.1	1.15	15.5	2.1	3.08	0.19	151.1	40.0	0T
CC19-09	23766	80491	0.009	0.00530	0.73	1.8	4.5	114.5	2.53	2.9	4.7	6.46	0.40	184.0	58.9	2T
CC19-09	23767	80494	0.006	0.00642	0.75	1.0	2.2	148.5	2.10	1.5	4.4	5.92	0.37	211.0	60.5	2T
CC19-09	23768	80497	0.007	0.00662	0.75	1.0	2.2	210.8	2.28	1.5	4.8	6.35	0.39	197.2	63.6	2T
CC19-09	23770	80503	0.005	0.00289	0.68	1.6	6.6	201.3	4.17	3.2	4.0	5.85	0.36	218.3	42.8	1T
CC19-09	23892	80911	0.004	0.00344	0.74	0.90	4.6	164.9	5.34	2.0	4.7	6.35	0.39	151.4	61.2	1T
<i>Durango apatite standard</i>																
Durango	23534	79591	2.623	-	1.00	-	-	-	16.0	-	31.8	31.8	2.0	-	-	-
Durango	23535	79594	3.234	-	1.00	-	-	-	22.2	-	31.9	31.9	2.0	-	-	-
Durango	23834	80521	3.274	-	1.00	-	-	-	19.0	-	32.4	32.4	2.0	-	-	-
Durango	23893	80914	2.077	-	1.00	-	-	-	18.83	-	32.0	32.0	2.0	-	-	-

^aF_T is the a-ejection correction after Farley et al. (1996).^bEffective uranium concentration (U ppm + 0.235 Th ppm).^cGrain morphology - 0T = no terminations, 1T = one termination, 2T = 2 terminations.

Table S-D2. Single grain zircon (U-Th)/He data.

Sample No.	Analysis No.	He#	⁴ He (ncc)	Mass (mg)	^a F _T	U ppm	Th ppm	Th/U ratio	^b [eU] ppm	Corrected age (Ma)	Error (±1s)	Grain length (μm)	Grain half width (μm)	^c Crystal morphology
CC19-08	25959	88593	0.289	0.0007	0.64	256.2	69.9	0.27	272.6	11.7	0.7	94.6	35.0	2T
CC19-08	25960	88596	0.354	0.0010	0.66	206.6	70.1	0.34	223.1	12.9	0.8	120.1	31.2	2T
CC19-08	25961	88599	0.570	0.0009	0.65	540.3	136.7	0.25	572.4	9.5	0.6	105.5	32.7	2T
CC19-08	25962	88602	0.167	0.0008	0.62	106.5	43.8	0.41	116.8	15.2	0.9	104.3	30.5	2T
CC19-09	25963	88605	0.329	0.0016	0.71	196.6	71.8	0.37	213.4	8.2	0.5	124.9	41.7	2T
CC19-09	25964	88608	0.385	0.0011	0.67	241.8	81.3	0.34	260.9	11.1	0.7	113.7	35.7	2T
CC19-09	25965	88611	0.626	0.0019	0.71	328.8	106.2	0.32	353.7	7.8	0.5	154.6	36.2	2T
CC19-09	25966	88614	0.229	0.0020	0.73	96.5	26.3	0.27	102.6	9.3	0.6	136.2	44.3	2T
CC19-09	25967	88617	0.272	0.0015	0.72	155.8	43.0	0.28	165.9	9.0	0.6	120.8	42.8	2T
<i>Fish Canyon Tuff standard</i>														
FCT	25939	88450	10.248	0.0050	0.79	487.7	265.2	0.54	550.0	30.4	1.9	211.8	51.4	2T
FCT	25940	88453	8.425	0.0058	0.80	386.5	219.9	0.57	438.2	27.3	1.7	243.7	49.1	2T
FCT	25942	88532	4.703	0.0035	0.76	341.1	206.8	0.61	389.7	28.7	1.8	194.8	43.4	2T
FCT	26097	88894	10.958	0.0100	0.85	263.2	156.8	0.60	300.1	30.0	1.9	237.2	74.8	2T
FCT	25941	88529	10.068	0.0059	0.79	394.5	188.2	0.48	438.7	31.9	2.0	253.4	48.1	2T

^aF_T is the α-ejection correction after Farley *et al.* (1996).^b Effective uranium concentration (U ppm+0.235 Th ppm).^c Grain morphology - 0T = no terminations, 1T = one termination, 2T = 2 terminations.

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