GSA Data Repository 2016232

Pleistocene onset of rapid, punctuated exhumation in the eastern Central Range of the Taiwan orogenic belt

Hsu et al.

(U-Th)/He method and data

Samples from the two transects were crushed, and zircon grains were separated using sieving, magnetic and heavy liquid mineral separation techniques. Ten samples yielded zircon of sufficient quality for analysis. All crystals from the ten samples for (U-Th)/He analyses were hand-picked using a 184x binocular microscope to ensure the grains were selected on the basis of appropriate size, euhedral habit, clarity, and the presence of as few inclusions as possible. The grains were loaded in niobium micro-crucibles and their helium isotopic analyses of individual grains were measured by diode laser gas extraction and quadrupole mass spectrometry in the Group 18 Laboratories at Arizona State University (ASU). After helium extraction the grains were dissolved using standard dissolution procedures (Evans et al., 2005; Reiners, 2005; Reiners et al., 2002) and U and Th concentrations were measured by inductively coupled plasma-source mass spectrometry (ICPMS) at Group 18 Laboratories at ASU. A complete description of the (U-Th)/He dating procedures in Group 18 Laboratories can be found in Van Soest et al. (2011). An alpha particle ejection correction (Ft) was applied to (U-Th)/He dates calculated from the measurements to derive a corrected (U-Th)/He age (Farley et al., 1996; Hourigan et al., 2005). For each sample from which at least two grains could be dated successfully, we calculated inverse variance-weighted mean dates for all grains and the standard deviation of that weighted mean (σ_{WM}). We also calculated the mean squared weighted deviation (MSWD) of the weighted mean (Wendt and Carl, 1991), which is a measure of the degree of dispersion of the data around the weighted mean. As is often the case for (U-Th)/He data, the MSWD for our samples were frequently of sufficient magnitude to indicate that the data scatter exceeded that which could be explained by analytical uncertainty alone. An established way to present more realistic uncertainties in the weighted means for such samples is to multiply σ_{WM} by the square-root of the MSWD to arrive at an adjusted uncertainty ($\sigma_{WMadjusted}$) (Ludwig, 2003). In the data tables and our data modeling and interpretations, we report and use uncertainties of $2\sigma_{WM}$ for inverse variance-weighted means when the data are not over-dispersed, and $2\sigma_{WMadjusted}$ when they are.

For sample C04-40 (see p12, Beyssac et al., 2007) (Fig. 2A), we excluded one individual grain age from the mean calculation because it was substantially older than the rest of the replicates for that sample.A summary of new ApHe, ZrnHe and ZrnFT ages are presented in Table DRA1, DRA2 and DRA3.

Inverse modeling

We modeled the exhumation histories interpreted from the age-elevation data and zero-age interpretations using the Monte Carlo inversion algorithm of HeFTy v.1.8.3 program (Ketcham, 2005). To evaluate variations in the time-temperature histories along strike in the Central Range (i.e., the collision propagation model) we selected samples from lowest elevation sites in the northern and southern transects. For the northern transect we used modeled samples LS9019 (ZrnFT) and C04-47 (ZrnHe) and for southern transect we modeled sample C64, which contains three different thermochronometers: ZrnFT, ZrnHe and ApHe.

The range of possible thermal histories was constrained by two geologic events (boxes in Fig DR 4): (1) the depositional age of the sample from the northern site (td) and (2) relatively wide temperature window (300°C to 450°C) for peak metamorphism at 5 to 1 Ma (tb). The samples at the lowest elevation at the southern site are Eocene, so deposition is constrained to be no later than late Eocene (~34-38 Ma). Samples from northern the site are from the Tananao Complex, which is interpreted be separated from the Eocene sediments by an angular unconformity; the complex was also therefore at or near the Earth's surface in the Eocene. The peak metamorphism is based on illite crystallinity (Chen, 1994; Tsao, 1996) and Raman spectroscopy of carbonaceous materials (Beyssac et al., 2007) and peak temperatures are interpreted to have been achieved in the passive margin setting just prior to exhumation (e.g., Lee et al., 2015; Lo and Onstott, 1995; Wintsch et al., 2011). We therefore set the time of peak temperatures between 5 Ma to 1 Ma.

Each model had monotonic path segments with four half-segments evenly spaced between adjacent constraints and the models were run until there were 100 "good" goodness of fits (GOF). The number of model runs ranged from 28800 to 1459000. For every run, the program determined "acceptable" GOF (i.e., >0.05), "good" GOF (i.e., >0.5) and a weighted mean fit.

Our inverse model, as shown in Fig. 3 and Fig. DR4, suggest three cooling periods: (1) prior to 2-2.5 Ma; (2) 2 to 0.5 Ma and (3) 0.5-0 Ma.

Table DR1. Zircon (U-Th)/He Data Obtained Along the Southern transect of eastern Central Range and Mt. Yu transects in Central and Southern Taiwan

Sample	Rep.	Longitude	Latitude	Elevation	[U]	1s	[Th]	1s	[He]	1s	Th/^{238}U	Raw Age	1s	Mean l	Mean r	Mean F_T	Age $F_{T\ corr}$	1s	WM Age	2s
				(m)	pmole	pmole	pmole	pmole	pmole	pmole		Ma	Ma	µm	µm		Ma	Ma	Ma	Ma
									Southern transect											
C64	z01	120.99	22.71	540	4.084	0.035	0.749	0.006	0.00217	0.00011	0.185	0.40	0.02	137.7	32.6	0.678	**0.586**	**0.031**		
	z02				0.757	0.008	0.424	0.004	0.00045	0.00002	0.565	0.41	0.02	119.1	31.7	0.661	**0.621**	**0.030**		
	z03				1.387	0.012	0.544	0.004	0.00048	0.00002	0.395	0.25	0.01	119.0	28.6	0.640	**0.387**	**0.014**		
	z04				2.955	0.025	2.031	0.013	0.00110	0.00004	0.692	0.25	0.01	119.2	28.1	0.640	**0.390**	**0.013**		
	mean																		**0.425**	**0.094**
K05	*z01*	120.94	22.73	674	*1.517*	*0.016*	*0.803*	*0.006*	*1.28383*	*0.01549*	*0.534*	*559.55*	*8.98*	*151.4*	*41.2*	*0.725*	***771.8***	***12.4***		
	z02				*11.066*	*0.092*	*6.962*	*0.046*	*0.04627*	*0.00058*	*0.634*	*2.85*	*0.04*	*190.8*	*46.9*	*0.767*	***3.714***	***0.054***		
	z03				*5.485*	*0.046*	*3.130*	*0.019*	*0.58848*	*0.00715*	*0.575*	*73.47*	*1.05*	*146.1*	*31.5*	*0.681*	***107.8***	***1.5***		
	z04				*7.823*	*0.070*	*5.576*	*0.040*	*3.65467*	*0.04334*	*0.718*	*304.80*	*4.43*	*168.5*	*40.0*	*0.726*	***419.7***	***6.1***		
	z05				9.703	0.083	2.087	0.016	0.00485	0.00012	0.217	0.37	0.01	233.7	36.3	0.742	**0.500**	**0.013**		
	mean																		**0.5**	**0.013**
K02	z01	120.93	22.73	810	2.859	0.024	1.060	0.008	0.00115	0.00002	0.373	0.29	0.01	245.8	60.5	0.818	**0.353**	**0.007**		
	z02				5.793	0.049	4.597	0.029	0.00389	0.00008	0.799	0.44	0.01	209.7	42.8	0.763	**0.580**	**0.013**		
	z03				*6.409*	*0.053*	*3.351*	*0.023*	*3.26507*	*0.04097*	*0.527*	*343.96*	*5.18*	*362.5*	*33.3*	*0.731*	***470.3***	***7.1***		
	z04				*7.095*	*0.063*	*4.629*	*0.030*	*4.14060*	*0.05026*	*0.657*	*382.63*	*5.69*	*238.7*	*46.5*	*0.779*	***491.5***	***7.3***		
	z05				*3.753*	*0.033*	*2.187*	*0.014*	*2.03279*	*0.02446*	*0.587*	*360.81*	*5.35*	*225.7*	*30.4*	*0.698*	***516.6***	***7.7***		
	mean																		**0.41**	**0.20**
K14	z01	120.92	22.70	1224	16.195	0.160	2.886	0.019	0.01097	0.00017	0.180	0.51	0.01	215.6	45.8	0.775	**0.655**	**0.012**		

	z02				2.464	0.025	1.905	0.012	0.00133	0.00006	0.779	0.36	0.02	151.1	30.9	0.673	**0.530**	**0.023**		
	z03				12.705	0.124	9.265	0.059	0.00856	0.00013	0.735	0.45	0.01	203.5	47.3	0.771	**0.583**	**0.010**		
	z04				19.210	0.192	5.935	0.038	0.01738	0.00028	0.311	0.66	0.01	262.7	58.7	0.819	**0.805**	**0.015**		
	z05				5.110	0.050	3.060	0.019	0.00430	0.00008	0.603	0.58	0.01	170.8	40.5	0.741	**0.778**	**0.016**		
	mean																		**0.661**	**0.093**
OT16	z01	120.87	22.74	1810	3.983	0.033	4.023	0.030	0.00582	0.00025	1.017	0.92	0.04	172.5	42.8	0.752	**1.227**	**0.054**		
	z02				2.842	0.024	2.169	0.014	0.00351	0.00018	0.769	0.82	0.04	160.7	30.4	0.682	**1.203**	**0.064**		
	z03				5.757	0.048	2.744	0.019	0.00499	0.00009	0.480	0.61	0.01	152.3	35.4	0.704	**0.865**	**0.017**		
	z04				3.417	0.030	0.956	0.006	0.00294	0.00006	0.282	0.63	0.01	138.4	32.2	0.685	**0.920**	**0.020**		
	z05				1.130	0.010	0.688	0.005	0.00100	0.00004	0.613	0.60	0.02	110.8	31.8	0.658	**0.915**	**0.034**		
	mean																		**0.916**	**0.092**
OT11	z03	120.90	22.72	2020	3.479	0.034	3.502	0.024	0.00429	0.00009	1.014	0.78	0.02	204.3	35.0	0.723	**1.080**	**0.024**		
	z04				5.051	0.050	5.655	0.039	0.00549	0.00009	1.128	0.67	0.01	181.4	35.7	0.713	**0.945**	**0.017**		
	z05				4.038	0.039	1.352	0.009	0.00330	0.00007	0.337	0.59	0.01	167.8	46.0	0.762	**0.775**	**0.018**		
	mean																		**0.91**	**0.16**
										Mt. Yu transect										
YS-20	*z01*	120.92	23.53	900	*8.914*	*0.123*	*4.255*	*0.080*	*0.02993*	*0.00036*	*0.470*	*2.34*	*0.041*	*185.1*	*46.0*	*0.749*	***3.127***	***0.055***		
	z02				*4.858*	*0.075*	*3.279*	*0.061*	*0.00812*	*0.00010*	*0.670*	*1.12*	*0.021*	*163.4*	*41.6*	*0.749*	***1.497***	***0.028***		
	z03				2.911	0.042	1.598	0.033	0.00252	0.00004	0.550	0.60	0.013	130.0	28.5	0.657	**0.907**	**0.020**		
	z05				2.835	0.045	1.754	0.032	0.00296	0.00004	0.610	0.71	0.014	125.0	23.9	0.610	**1.159**	**0.024**		
	z06				2.340	0.039	0.747	0.018	0.00241	0.00004	0.320	0.74	0.017	136.7	31.5	0.646	**1.151**	**0.027**		
	z07				3.276	0.047	1.740	0.034	0.00323	0.00005	0.530	0.68	0.014	146.0	30.5	0.680	**1.002**	**0.020**		
	mean																		**1.03**	**0.13**

Rainbow	*z01*	120.94	23.57	1550	*17.456*	*0.234*	*11.312*	*0.232*	*0.01498*	*0.00042*	*0.640*	*0.58*	*0.02*	*229.8*	*42.3*	*0.767*	***0.754***	***0.023***		
	z02				14.873	0.186	8.247	0.139	0.02510	0.00049	0.550	1.16	0.03	297.3	58.0	0.823	**1.409**	**0.032**		
	z03				6.306	0.100	3.987	0.095	0.00980	0.00040	0.630	1.05	0.05	219.6	52.4	0.800	**1.314**	**0.056**		
	z04				3.356	0.046	3.020	0.056	0.00617	0.00008	0.890	1.18	0.02	257.7	42.2	0.768	**1.537**	**0.027**		
	z05				3.779	0.060	3.482	0.069	0.00533	0.00007	0.910	0.90	0.02	207.5	43.8	0.763	**1.182**	**0.022**		
	mean																		**1.34**	**0.22**
YS-06	z01	120.92	23.47	2880	2.509	0.036	1.454	0.026	0.00392	0.00007	0.580	1.07	0.023	151.3	30.3	0.679	**1.573**	**0.035**		
	z02				*3.320*	*0.051*	*1.371*	*0.030*	*0.04771*	*0.00057*	*0.410*	*10.16*	*0.19*	*133.5*	*30.8*	*0.680*	***14.940***	***0.280***		
	z03				*10.621*	*0.136*	*6.986*	*0.117*	*0.08654*	*0.00109*	*0.650*	*5.48*	*0.093*	*246.5*	*50.3*	*0.799*	***6.860***	***0.120***		
	z04				*4.022*	*0.070*	*3.368*	*0.052*	*0.30115*	*0.00358*	*0.830*	*48.45*	*0.91*	*190.7*	*39.7*	*0.740*	***65.400***	***1.200***		
	z05				*9.153*	*0.137*	*12.574*	*0.209*	*0.04147*	*0.00050*	*1.360*	*2.67*	*0.045*	*183.4*	*32.9*	*0.697*	***3.825***	***0.066***		
	mean																		**1.57**	**0.07**
YS-02	z01	120.96	23.47	3952	4.488	0.068	0.785	0.023	0.00985	0.00012	0.170	1.64	0.032	145.6	31.45	0.687	**2.378**	**0.046**		
	z02				*1.387*	*0.030*	*1.511*	*0.035*	*0.01902*	*0.00024*	*1.080*	*8.49*	*0.19*	*99.0*	*28.9*	*0.625*	***13.590***	***0.300***		
	z03				*0.993*	*0.016*	*0.601*	*0.015*	*0.01183*	*0.00015*	*0.600*	*8.10*	*0.16*	*107.4*	*18.7*	*0.502*	***16.130***	***0.330***		
	z04				0.983	0.016	0.317	0.014	0.00117	0.00003	0.320	0.86	0.024	109.7	21.65	0.568	**1.516**	**0.042**		
	z05				*2.055*	*0.039*	*1.206*	*0.029*	*0.03334*	*0.00041*	*0.580*	*11.06*	*0.23*	*113.0*	*20.75*	*0.549*	***20.150***	***0.430***		
	z06				1.044	0.018	0.803	0.020	0.00150	0.00003	0.760	0.95	0.022	104.2	22.2	0.566	**1.675**	**0.040**		
	mean																		**1.82**	**0.51**

For each sample, sample position (WGS84 system) and elevation (m) are given. For each replicate, we provide concentrations in U, Th and He, mass of the grain, Ft, mean radius and mean length, and raw and corrected ages. Italics are excluded calculating mean age.

Table DR2. Aptite (U-Th)/He Data Obtained in the Southern transect of the eastern Central Range.

Southern transect																				
Sample	Rep.	Longitude	Latitude	Elevation	[U]	1s	[Th]	1s	[He]	1s	mean r	mean l	Mean F_T	Age $F_{T\ corr}$	1s	[^{238}U]	[^{232}Th]	[eU]	WM Age	2s
				(m)	pmole	pmole	pmole	pmole	fmole	fmole	µm	µm		Ma	Ma	ppm	ppm	ppm	Ma	Ma
C64	*a01*	120.99	22.71	540	*0.0671*	*0.0007*	*0.6684*	*0.0081*	*1.418*	*0.034*	*44.4*	*132.1*	*0.656*	***7.53***	***0.19***	*7.3*	*71.8*	*24*		
	a02				0.1372	0.0013	0.6985	0.0085	0.064	0.013	36.6	98.3	0.592	**0.28**	**0.06**	29.7	148.3	65		
	a03				0.1206	0.0011	0.9915	0.0100	0.052	0.012	36.4	155.9	0.618	**0.19**	**0.04**	16.6	133.8	48		
	a04				0.3789	0.0031	1.4762	0.0130	0.139	0.013	43.6	148.0	0.669	**0.22**	**0.02**	38.2	146.1	73		
	a05				0.1026	0.0009	1.8208	0.0157	0.137	0.012	51.0	139.2	0.687	**0.29**	**0.03**	8.0	140.1	41		
	mean																		**0.25**	**0.03**

For each sample, sample position (WGS84 system) and elevation (m) are given. For each replicate, we provide concentrations in U, Th and He, mass of the grain, Ft, mean radius and mean length, and raw and corrected ages. Italics are excluded calculating mean age.

Table DR3. Zircon Fission Track Data Obtained Along the Southern transect of eastern Central Range and Mt. Yu Transects in Central and Southern Taiwan

Sample	Longitude	Latitude	Elevation(m)	Zeta	Crystal	RhoS	(Ns)	RhoI	(Ni)	RhoD	(Nd)	Pooled Age	± 1s	Mean Age	± 1s	Central Age	± 1s
								Southern transect									
C64	120.99	22.71	540	26.33	20	1.422	69	30.039	1458	12	4798	1.5	0.2	1.7	0.2	1.5	0.2
K014	120.92	22.70	1224	26.33	20	1.926	106	26.594	1464	12	4798	2.3	0.3	2.5	0.2	2.3	0.3
OT16	120.87	22.74	1810	26.33	21	3.518	245	38.5	2681	12	4798	2.9	0.2	3	0.3	2.9	0.2
OT11	120.90	22.72	2020	26.33	20	1.733	108	24.57	1531	12	4798	2.2	0.3	2.3	0.1	2.2	0.3
								Mt. Yu transect									
ys-04	120.94	23.46	3300	26.33	7	0.048	128	0.172	462	9.1	4798	3.7	0.4	3.7	0.4		
ys-05	120.93	23.46	3100	26.33	5	0.046	46	0.157	158	9.1	4798	3.8	0.7	4	0.3		
Ran Bow	120.94	23.57	1550	26.33	23	0.032	216	0.276	1848	1.295	4238	2.2	0.2	2.2	0.1		
ys-17	120.96	23.53	1450	26.33	11	0.001	108	0.01	978	1.4	4123	2.2	0.3	2.2	0.2		

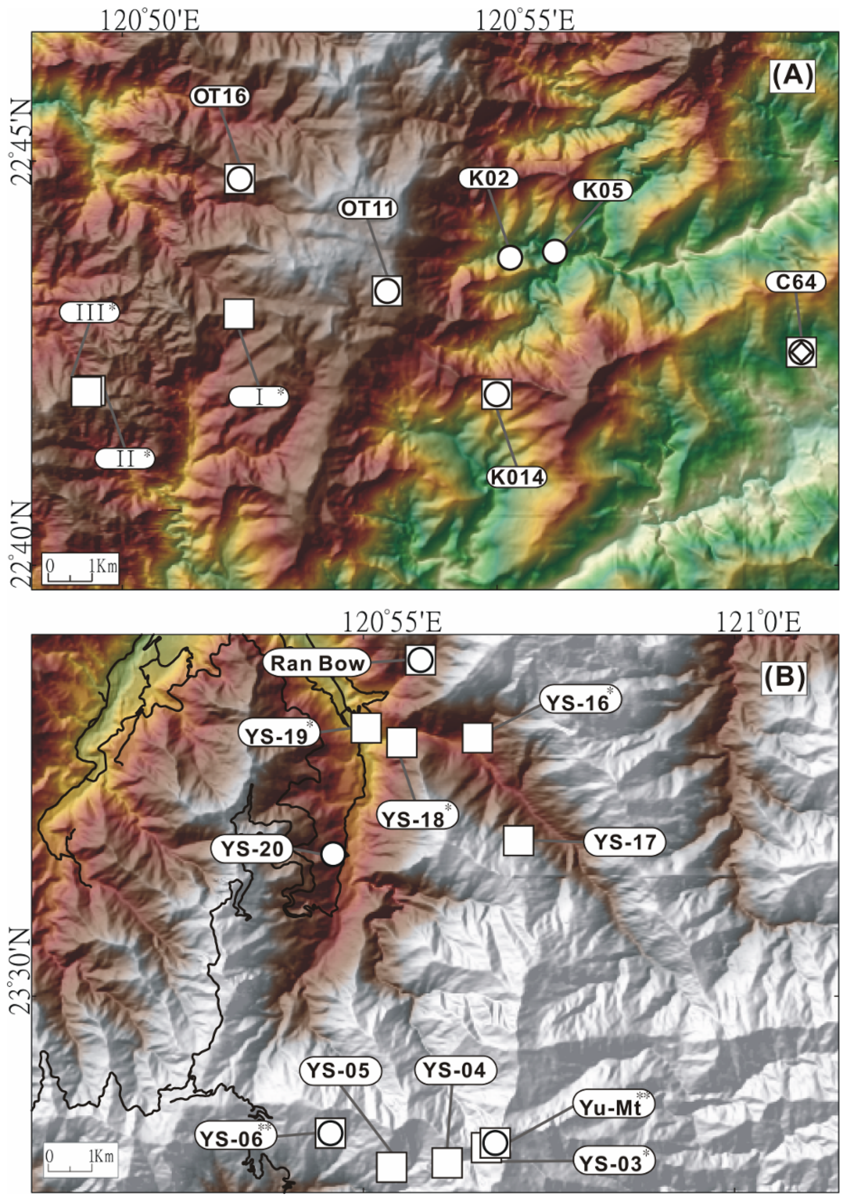

Figure DR1. Sample location maps for southern transect (A) and Mt. Yu (B). Diamond: ApHe age; Square: ZrnHe age; Circle: ZrnFT age (* previously ZrnFT age reported by Lee et al. (2006) and Lee et al. (2015); ** new ZrnHe age and previously ZrnFT age reported by Lee et al. (2015)).

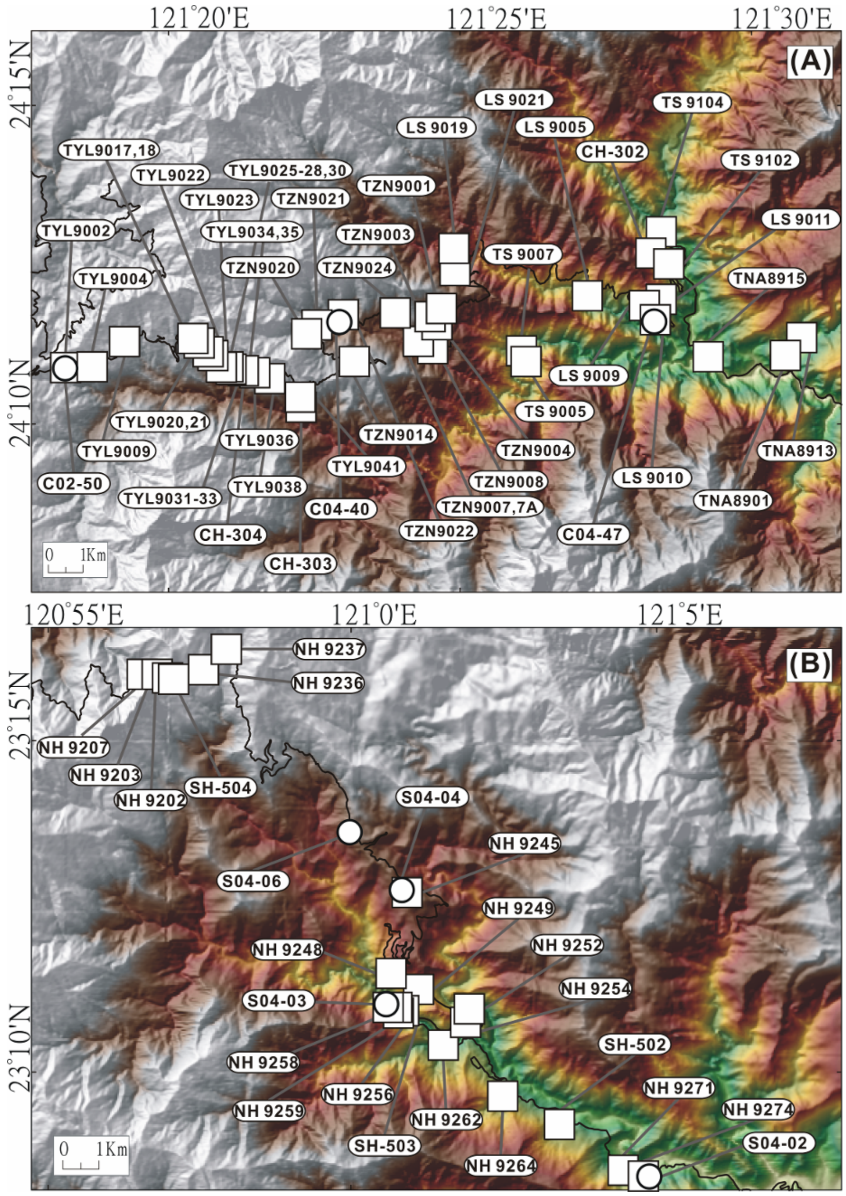

Figure DR2. Sample location maps for northern transect (A) and middle transect (B).
Square: ZrnFT age published by Tsao et al. (1992); Tsao (1996); Liu et al. (2001).
Circle: ZrnHe age reported by Beyssac et al. (2007).

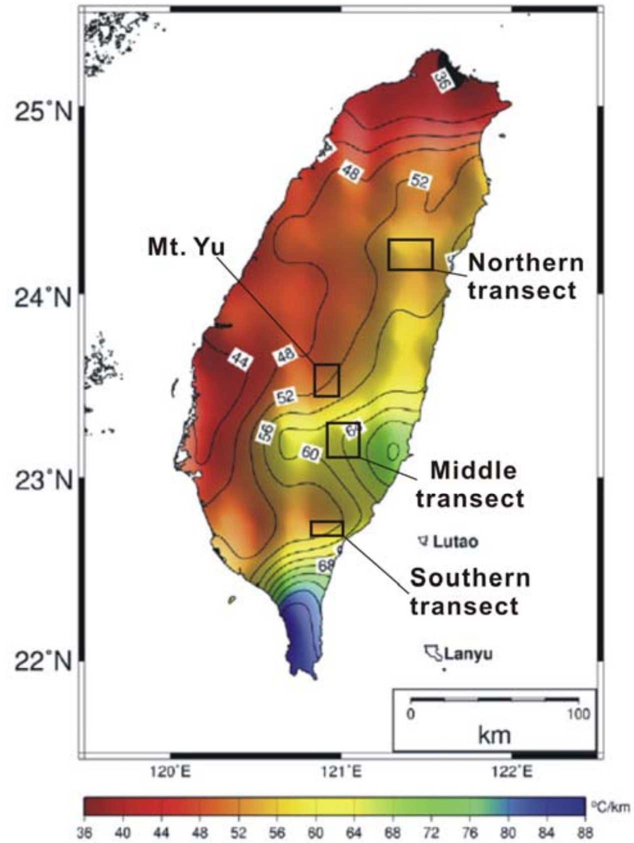

Figure DR3. Thermal gradient map derived from Curie point depth map (Curie temperature 580°C) (From Hsieh et al. (2014)).

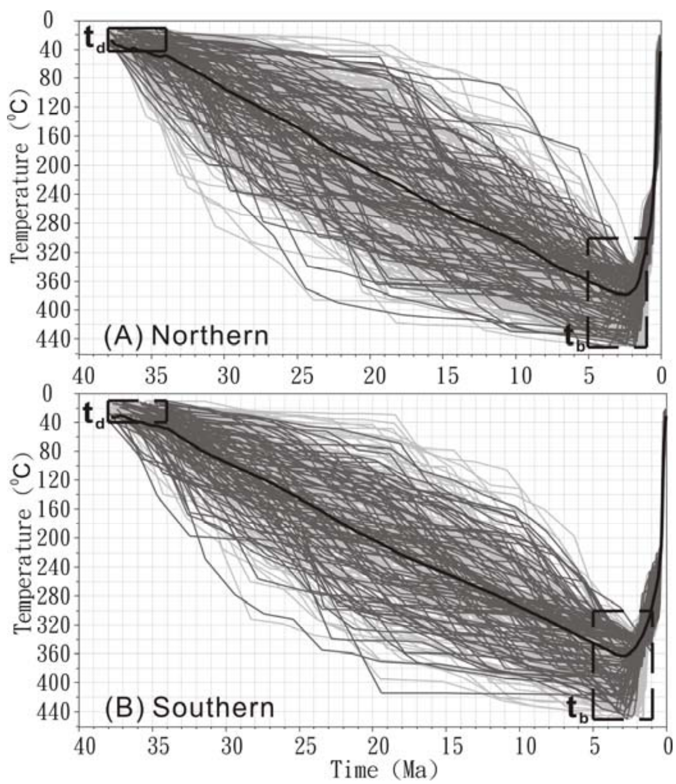

Figure DR4. Time–temperature model results for selected samples from the northern (A) and southern (B) transects using HeFTy (Ketcham, 2005). The acceptable goodness of fit (GOF) >0.05 are represented by light gray paths and good GOF >0.5 by dark gray paths. Black dashed boxes indicate additional constraints : the depositional age (t d) and range of plausible post-depositional burial heating histories (t b) based on illite crystallinity and RSCM temperatures. The thick black line is the weighted mean fit t-T path.

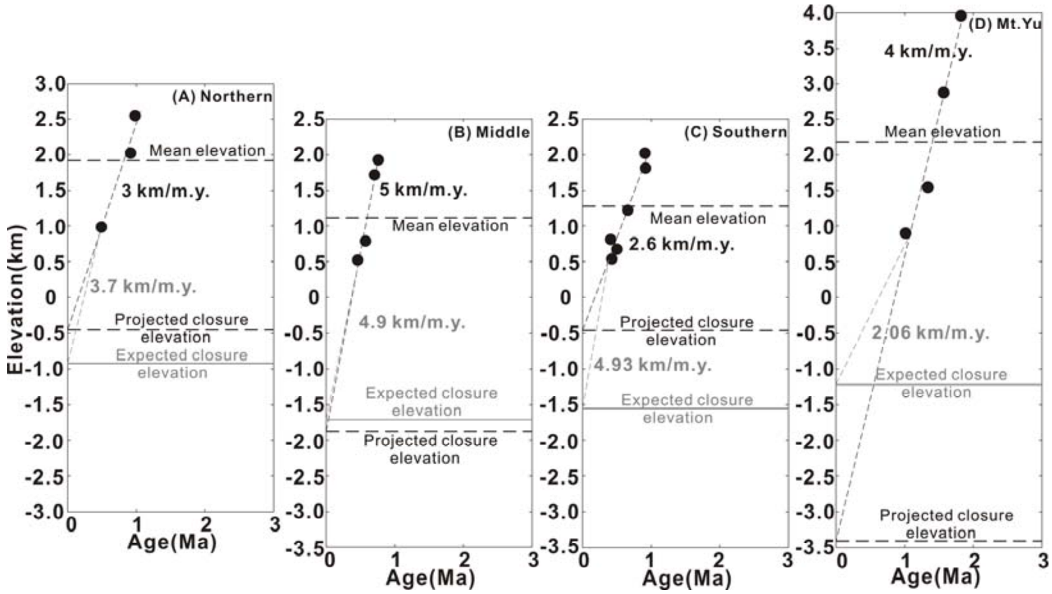

Figure DR5. Zircon (U-Th)/He ages versus elevation from northern transect (A), middle transect (B), southern transect (C) and Mt. Yu (D) showing 1) expected closure depth beneath the present mean elevation estimated by the modern thermal gradient and 2) projected closure depth assuming no exhumation since about 0.6 Ma, 0.8 Ma, 0.5 Ma and 1.3 Ma (time of closure for rocks at the mean elevation) respectively. Difference between expected and projected depths requires an increase in the rate of exhumation in the southern area but a decrease in the rate of exhumation in Mt. Yu (Reiners and Brandon, 2006).

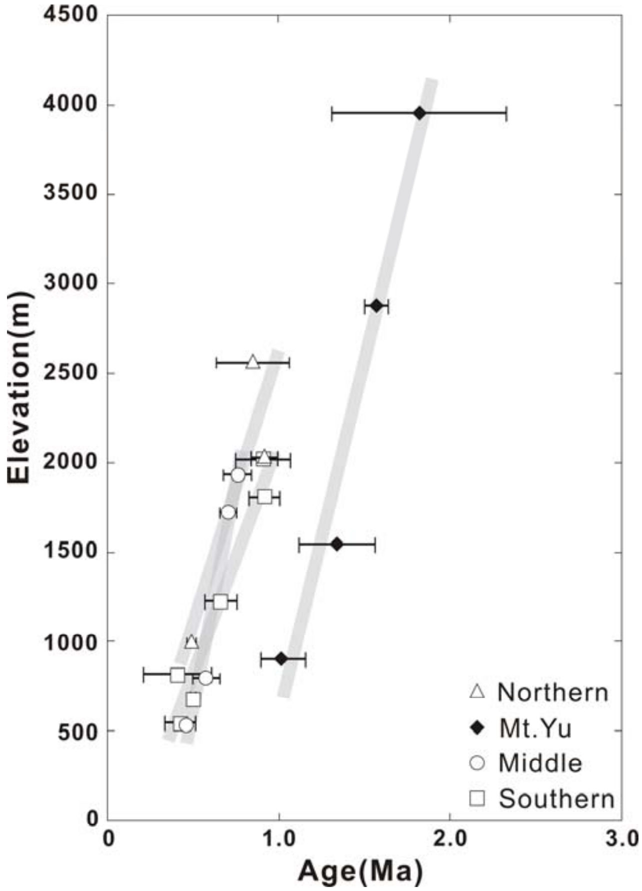

Figure DR6. Composite plots of ZrnHe mean cooling ages versus elevation for all transects. The plots show high rates of cooling at all four areas (~3–5 km/m.y.).

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