Supporting Information

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SI Text

The calculated weighed mean $^{206}Pb/^{238}U$ dates from this study are younger than dates on the same ash beds published in ref. 1 by up to 0.2% (Table S1 and Fig. S2). This difference is 7–9 times the uncertainty associated with each weighted mean date. Here we explore possible explanations. To eliminate any potential issues with sample heterogeneity, we used the same mineral separates that were analyzed for ref. 1 and chose morphologically similar, high aspect ratio zircons. Both studies yield a similar distribution of single grain dates with an approximately normal distribution of errors [mean square of weighted deviates (MSWD) ≅ 1] when the few outliers interpreted to be the result of inheritance (n = 10/61) are excluded, and it is assumed that chemical abrasion effectively eliminates Pb loss in most cases. We consider it unlikely that the younger weighted mean dates seen in this work are the result of a selection bias or systematic Pb loss in multiple populations of zircon.

The data for ref. 1 were acquired in 2006, in the early stages of the EARTHTIME initiative. Since that time, there have been significant changes in the way U-Pb data are acquired and reduced at Massachusetts Institute of Technology and in other laboratories. These changes include the following. (*i*) New values for the isotopic compositions and purity of U and Pb standards used to calibrate the EARTHTIME tracer solution and new algorithms to determine this composition, which improves the accuracy of the solution calibration relative to the MIT1L calibration by ref. 2 and used in ref. 1. The new calibration reflects the ∼5 permil change in the $^{238}U/^{235}U$ values for CRM112a determined by ref. 3, which leads overall to a decrease in a single $^{206}Pb/^{238}U$ date of ∼0.05%. (*ii*) As a result of tracer calibration, we refined the $^{18}O/^{16}O$ ratio used for UO_2 measurements, which results in a value ∼2.5% greater than that used to reduce the data in ref. 1 and a 0.025% decrease (∼60 ka) in a typical single-grain $^{206}Pb/^{238}U$ date. (*iii*) Refined estimates of the isotopic composition and dispersion in the laboratory blank, which includes additional measurements and a revised algorithm to calculate composition, indicate that the composition used in ref. 1 was not as accurate as the values used in this study and that the uncertainties were underestimated. For example, applying the composition and uncertainty used by ref. 1 to data from bed 25 generated for this study results in an increase of the weighted mean $^{206}Pb/^{238}Pb$ date by 35 ka, with a 27% decrease in analytical uncertainty. (*iv*) New algorithms were used for point by point interference correction on masses 201–205. (*v*) Point by point fractionation corrections for Pb were used using the EARTHTIME 202-205-233-238 tracer rather than application of a single value for α-Pb based on long-term monitoring of National Bureau of Standards 981, 982, and synthetic zircon solutions with ET535 added, which was done in ref. 1. We suggest that the fractionation correction used in this study likely reduces scatter in $^{206}Pb/^{238}U$ dates caused by assuming a constant value and uncertainty. (*vi*) New algorithms were used for determining and propagating uncertainties into a weighted mean date (4, 5). The dates in ref. 1 cannot simply be recalculated to independently incorporate one or all of the above changes, and thus the relative effects of each cannot be evaluated.

The nonlinear difference between dates also suggests that the subjectivity of data reduction and other factors such as the response of zircon to chemical abrasion and/or subtle, unaccounted for interference corrections, may play a role. Application of these improvements yield significantly improved accuracy and precision on the weighted mean and interpolated dates (Fig. S2 and Table S2). This improvement is particularly evident for bed 33, on which no mean was calculated by ref. 1 due to excess scatter, which is likely due to residual Pb-loss (Fig. S2).

1. Shen SZ, et al. (2011) Calibrating the end-Permian mass extinction. *Science* 334(6061): 1367–1372.
2. Schoene B, Crowley JL, Condon DJ, Schmitz MD, Bowring SA (2006) Reassessing the uranium decay constants for geochronology using ID-TIMS U–Pb data. *Geochim Cosmochim Acta* 70(2):426–445.
3. Condon DJ, McLean N, Noble SR, Bowring SA (2010) Isotopic composition (238U/235U) of some commonly used uranium reference materials. *Geochim Cosmochim Acta* 74 (24):7127–7143.
4. McLean N, Bowring J, Bowring S (2011) An algorithm for U-Pb isotope dilution data reduction and uncertainty propagation. *Geochem Geophys Geosyst* 12(6):1–26.
5. Bowring JF, McLean NM, Bowring SA (2011) Engineering cyber infrastructure for U-Pb geochronology: Tripoli and U-Pb_Redux. *Geochem Geophys Geosyst* 12(6): 1–19.

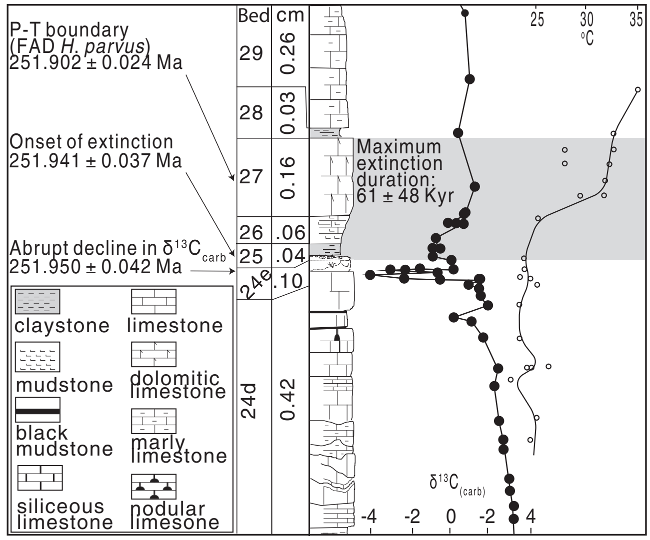

Fig. S1. Stratigraphy, geochronology, carbonate carbon isotopic composition, and composite ocean paleotemperature for the extinction interval at the Global Stratotype Section and Point (GSSP), Meishan, China. Stratigraphy and carbonate carbon isotopic composition are from Cao et al. (1). Paleotemperature is from Joachimski et al. (2).

1. Cao C, et al. (2009) Biogeochemical evidence for euxinic oceans and ecological disturbance presaging the end-Permian mass extinction event. *Earth Planet Sci Lett* 281(3-4):188–201.
2. Joachimski MM, et al. (2012) Climate warming in the latest Permian and the Permian-Triassic mass extinction. *Geology* 40(3):195–198.

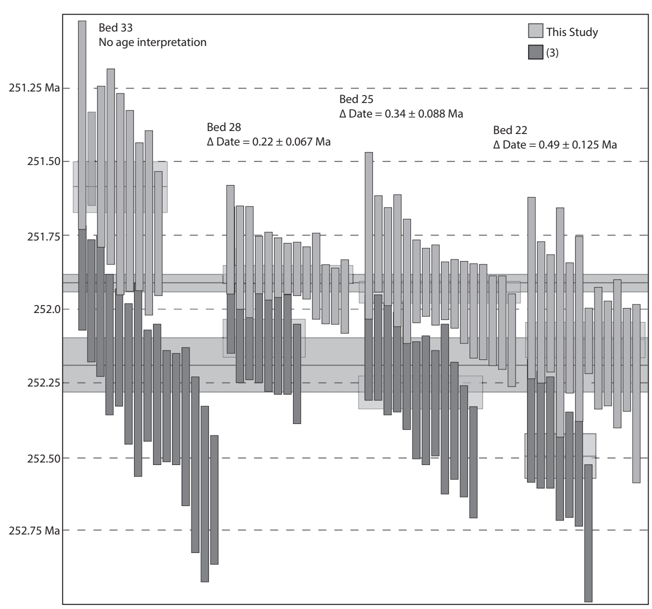

Fig. S2. Comparison of single-grain zircon analysis from beds 22, 25, 28, and 33. Dates from ref. 1 are in dark gray and from this study are in light gray. Each vertical bar represents a single zircon analysis, the height of which is proportional to the 2σ analytical uncertainty on that analysis. The thin horizontal bar through the middle of each population of analysis represents the weighted mean calculated date for that bed, which is surrounded by the 2σ analytical uncertainty on this date. Thick horizontal lines passing through the diagram are the calculated maximum extinction duration (beds 25–28) and are keyed by color to the respective study.

1. Shen SZ, et al. (2011) Calibrating the end-Permian mass extinction. *Science* 334(6061):1367–1372.

Table S1. Difference in $^{206}Pb/^{238}U$ weighted mean dates for Meishan ash beds from this study and from ref. 1

Sample	Shen et al. 2011	*n*; MSWD	Mya*	*n*; MSWD	ΔDate (Mya)
Bed 22-MZ96 (−4.3)	252.50 ± 0.11	(8; 0.8)	252.104 ± 0.060/0.28	(12, 0.50)	0.49 ± 0.125
Bed 25-MBE0203	252.28 ± 0.08	(13; 1.9)	251.941 ± 0.037/0.28	(16; 1.3)	0.34 ± 0.088
Bed 28-MBE0205	252.10 ± 0.06	(7; 1.4)	251.880 ± 0.031/0.28	(13; 0.76)	0.22 ± 0.067
Bed 33-MD99-33u	No age interpretation	Not applicable	251.583 ± 0.086/0.29	(9, 0.86)	None

*Uncertainty reported is 2σ internal (analytical)/external. External uncertainty includes uncertainty associated with tracer calibration and ^{238}U decay constant. Uncertainty on differences is added in quadrature from 2σ analytical uncertainty on dated beds.

1. Condon DJ, McLean N, Noble SR, Bowring SA (2010) Isotopic composition (238U/235U) of some commonly used uranium reference materials. *Geochim Cosmochim Acta* 74:7127–7143.

Table S2. U-Pb isotopic data and single-grain zircon dates

Sample and fraction	Composition			Isotopic ratios									Dates (Mya)				
	Pb* (pg)[†]	Pbc (pg)[‡]	Th/U[§]	206Pb/ 204Pb[¶]	208Pb/ 206Pb[‖]	206Pb/ 238U[‖]	±2s %	207Pb/ 235U[‖]	±2s %	207Pb/ 206Pb[‖]	±2s %	Correlation coefficient	206Pb/238U <Th>**f	±2s absolute[††]	207Pb/ 235U[‡‡]	±2s absolute[††]	Correlation coefficient
MD99-33u (bed 33)																	
z1	10.277	0.813	0.742	730.807	0.235	0.040	0.111	0.284	1.260	0.052	1.238	0.240	251.513	0.275	253.561	2.828	0.240
z2	9.475	0.839	0.592	679.826	0.187	0.040	0.125	0.283	1.351	0.052	1.329	0.221	251.630	0.309	252.952	3.025	0.221
z4	9.275	0.663	0.827	790.601	0.262	0.040	0.102	0.281	1.164	0.051	1.145	0.226	251.684	0.252	251.842	2.595	0.226
z5	5.586	0.552	0.644	603.426	0.204	0.040	0.135	0.280	1.531	0.051	1.505	0.238	251.513	0.334	251.029	3.406	0.238
z6	5.995	0.617	0.730	568.289	0.231	0.040	0.139	0.281	1.631	0.051	1.606	0.221	251.607	0.344	251.619	3.636	0.221
z9	12.836	0.523	0.717	1411.322	0.227	0.040	0.065	0.282	0.644	0.051	0.631	0.244	251.486	0.159	252.017	1.437	0.244
z11	8.236	0.745	0.655	655.293	0.207	0.040	0.128	0.284	1.392	0.052	1.370	0.221	251.705	0.315	253.751	3.126	0.221
z16	8.950	0.567	0.683	922.383	0.216	0.040	0.086	0.283	0.984	0.052	0.967	0.231	251.741	0.212	253.161	2.204	0.231
z17	7.186	0.762	0.733	551.292	0.232	0.040	0.144	0.279	1.689	0.051	1.658	0.253	251.371	0.356	249.986	3.743	0.253
MBE0205 (bed 28)																	
z1	95.822	0.313	0.478	18513.842	0.151	0.040	0.051	0.282	0.085	0.051	0.059	0.709	251.956	0.126	251.993	0.190	0.709
z4	12.658	0.442	0.723	1641.269	0.228	0.040	0.059	0.282	0.558	0.051	0.548	0.220	251.886	0.147	252.277	1.247	0.220
z6	18.890	0.958	0.592	1172.719	0.187	0.040	0.071	0.282	0.776	0.051	0.763	0.226	251.823	0.176	251.903	1.730	0.226
z8	37.429	0.562	0.607	3904.118	0.192	0.040	0.037	0.282	0.237	0.051	0.232	0.216	251.862	0.091	251.996	0.530	0.216
z11	27.572	0.530	0.684	2997.531	0.216	0.040	0.036	0.281	0.305	0.051	0.299	0.208	251.875	0.089	251.842	0.680	0.208
z12	11.461	0.574	0.731	1147.501	0.231	0.040	0.075	0.281	0.796	0.051	0.781	0.248	251.762	0.186	251.586	1.774	0.248
z13	17.787	0.983	0.465	1114.532	0.147	0.040	0.077	0.281	0.821	0.051	0.808	0.213	251.838	0.190	251.845	1.830	0.213
z16	23.831	0.578	0.548	2460.545	0.173	0.040	0.041	0.282	0.368	0.051	0.361	0.204	251.948	0.101	252.389	0.822	0.204
z17	26.153	0.529	0.500	2987.040	0.158	0.040	0.039	0.282	0.302	0.051	0.299	0.149	251.955	0.096	252.295	0.676	0.149
z18	19.001	0.388	0.660	2840.031	0.209	0.040	0.040	0.282	0.322	0.051	0.316	0.216	251.848	0.098	252.266	0.720	0.216
z21	23.401	0.415	0.524	3382.454	0.166	0.040	0.035	0.282	0.269	0.051	0.263	0.218	251.861	0.087	252.137	0.600	0.218
z23	41.944	1.133	0.629	2165.926	0.199	0.040	0.047	0.282	0.419	0.051	0.411	0.225	251.852	0.116	252.206	0.936	0.225
z25	22.163	0.528	0.526	2521.836	0.166	0.040	0.041	0.282	0.363	0.051	0.355	0.256	251.857	0.102	251.936	0.810	0.256
MBE0203 (bed 25)																	
z5	11.974	0.520	0.626	1355.706	0.198	0.040	0.062	0.283	0.670	0.052	0.658	0.226	252.038	0.153	253.146	1.500	0.226
z6	16.591	0.579	0.680	1659.969	0.215	0.040	0.057	0.282	0.546	0.051	0.537	0.215	251.976	0.140	252.106	1.220	0.215
z7	35.158	0.894	0.594	2321.304	0.188	0.040	0.047	0.282	0.390	0.051	0.381	0.236	251.947	0.117	252.501	0.872	0.236
z8	24.082	0.584	0.647	2398.111	0.205	0.040	0.055	0.282	0.384	0.051	0.374	0.244	251.917	0.137	252.477	0.859	0.244
z11	24.813	0.413	0.634	3503.291	0.201	0.040	0.040	0.282	0.263	0.051	0.256	0.232	251.936	0.099	252.195	0.588	0.232
z12	22.225	1.046	0.663	1240.030	0.210	0.040	0.066	0.283	0.727	0.051	0.716	0.220	252.009	0.163	252.744	1.627	0.220
z14	12.232	0.424	0.608	1700.375	0.192	0.040	0.115	0.281	0.563	0.051	0.535	0.336	251.748	0.284	251.503	1.254	0.336
z16	30.500	0.469	0.596	3822.666	0.189	0.040	0.047	0.281	0.256	0.051	0.246	0.295	251.907	0.116	251.733	0.571	0.295

Table S2. Cont.

Sample and fraction	Composition			Isotopic ratios									Dates (Mya)				
	Pb* (pg)[†]	Pbc (pg)[‡]	Th/U[§]	206Pb/ 204Pb[¶]	208Pb/ 206Pb[‖]	206Pb/ 238U[‖]	±2s %	207Pb/ 235U[‖]	±2s %	207Pb/ 206Pb[‖]	±2s %	Correlation coefficient	206Pb/238U <Th>**f	±2s absolute[††]	207Pb/ 235U[‡‡]	±2s absolute[††]	Correlation coefficient
z21	11.767	0.397	0.564	1766.638	0.178	0.040	0.067	0.282	0.517	0.051	0.508	0.208	251.776	0.165	251.913	1.154	0.208
z22	10.698	0.251	0.718	2433.824	0.227	0.040	0.065	0.283	0.409	0.052	0.399	0.222	252.005	0.161	253.275	0.916	0.222
z23	20.597	0.303	0.831	3763.472	0.263	0.040	0.064	0.282	0.277	0.051	0.267	0.265	252.045	0.160	252.109	0.619	0.265
z24	29.528	0.279	0.502	6363.726	0.159	0.040	0.091	0.282	0.193	0.051	0.164	0.527	251.833	0.225	252.184	0.432	0.527
z25	28.759	0.907	0.604	1870.738	0.191	0.040	0.064	0.282	0.490	0.051	0.479	0.234	252.105	0.158	252.142	1.095	0.234
z26	10.264	0.475	0.619	1276.525	0.196	0.040	0.086	0.282	0.754	0.051	0.736	0.257	251.904	0.212	252.468	1.685	0.257
z31	19.637	0.304	0.651	3742.086	0.206	0.040	0.053	0.284	0.276	0.052	0.265	0.283	252.766	0.131	253.648	0.619	0.283
z32	12.619	0.357	0.687	2041.178	0.217	0.040	0.079	0.282	0.473	0.051	0.464	0.190	252.717	0.195	252.501	1.056	0.190
z33	17.971	0.410	0.656	2543.477	0.207	0.040	0.057	0.282	0.375	0.051	0.368	0.185	251.904	0.141	252.193	0.837	0.185
z34	10.251	0.310	0.535	1986.473	0.169	0.040	0.068	0.282	0.484	0.051	0.477	0.182	251.820	0.167	252.533	1.083	0.182
z35	6.590	0.321	0.649	1203.960	0.205	0.040	0.095	0.283	0.821	0.051	0.803	0.246	252.534	0.234	252.923	1.839	0.246
MZ96 (−4.3) (bed 22)																	
z1	9.070	0.558	0.507	991.047	0.160	0.040	0.084	0.287	0.920	0.052	0.903	0.236	254.321	0.208	256.400	2.084	0.236
z2	19.219	0.495	0.423	2397.833	0.134	0.040	0.045	0.283	0.377	0.051	0.372	0.165	252.107	0.112	252.959	0.844	0.165
z3	8.175	0.597	0.504	839.435	0.159	0.040	0.102	0.283	1.088	0.052	1.069	0.229	252.151	0.253	253.409	2.440	0.229
z5	9.489	0.504	0.502	1146.177	0.158	0.052	0.074	0.385	0.767	0.054	0.757	0.175	326.432	0.237	330.723	2.164	0.175
z6	7.170	0.595	0.570	727.912	0.180	0.040	0.098	0.282	1.253	0.051	1.245	0.119	252.010	0.241	252.274	2.799	0.119
z7	5.595	0.463	0.416	759.359	0.131	0.040	0.125	0.282	1.214	0.051	1.192	0.231	251.927	0.310	252.314	2.713	0.231
z8	5.379	0.481	0.751	648.381	0.237	0.040	0.158	0.281	1.462	0.051	1.420	0.313	252.044	0.391	251.080	3.252	0.313
z9	1.922	0.651	0.448	2042.101	0.137	0.148	0.198	1.455	0.386	0.071	0.325	0.538	889.717	1.648	912.127	2.322	0.538
z10	9.062	0.655	0.458	857.181	0.145	0.040	0.090	0.283	1.063	0.052	1.045	0.236	252.063	0.222	253.086	2.381	0.236
z14	10.793	0.589	0.549	1103.944	0.174	0.040	0.081	0.278	0.860	0.051	0.838	0.307	252.013	0.200	249.129	1.899	0.307
z16	10.097	0.264	0.630	2241.185	0.199	0.040	0.072	0.282	0.456	0.051	0.438	0.318	252.150	0.179	252.035	1.017	0.318
z17	7.648	0.286	0.191	1763.883	0.061	0.040	0.084	0.282	0.615	0.051	0.589	0.369	252.132	0.208	252.225	1.373	0.369
z18	9.148	0.257	0.497	2154.042	0.157	0.040	0.071	0.282	0.446	0.051	0.443	0.128	252.172	0.176	252.478	0.998	0.128
z21	17.438	0.306	0.543	3390.630	0.171	0.059	0.091	0.446	0.377	0.055	0.357	0.323	370.678	0.329	374.652	1.180	0.323
z22	4.697	0.329	0.516	870.075	0.163	0.040	0.128	0.281	1.110	0.051	1.086	0.238	252.066	0.316	251.214	2.469	0.238
z23	5.777	0.446	0.677	759.931	0.214	0.040	0.123	0.284	1.207	0.052	1.191	0.180	252.287	0.305	253.836	2.711	0.180
MSB 34–2 (bed 34)																	
z9	27.946	0.399	0.676	4037.644	0.214	0.040	0.099	0.281	0.263	0.051	0.237	0.432	251.435	0.245	251.822	0.586	0.432
z10	6.985	0.879	0.672	474.147	0.212	0.040	0.185	0.283	2.025	0.052	1.973	0.320	251.662	0.455	253.362	4.540	0.320
z11	10.737	0.445	0.672	1404.695	0.212	0.040	0.168	0.281	0.693	0.051	0.661	0.304	251.421	0.415	251.567	1.544	0.304
z12	34.641	0.500	0.689	3974.906	0.218	0.040	0.066	0.281	0.260	0.051	0.247	0.311	251.478	0.164	251.385	0.579	0.311
z13	31.633	0.571	0.662	3207.811	0.209	0.040	0.054	0.281	0.309	0.051	0.296	0.322	251.497	0.133	251.582	0.688	0.322

Table S2. Cont.

Sample and fraction	Composition: Pb* (pg)†	Composition: Pbc (pg)‡	Th/U§	Isotopic ratios: 206Pb/204Pb¶	208Pb/206Pb‖	206Pb/238U‖	±2s %	207Pb/235U‖	±2s %	207Pb/206Pb‖	±2s %	Correlation coefficient	Dates (Mya): 206Pb/238U <Th>**f	±2s absolute††	207Pb/235U‡‡	±2s absolute††	Correlation coefficient
z15	17.101	1.216	0.666	826.874	0.211	0.040	0.113	0.282	1.150	0.051	1.114	0.364	251.620	0.279	252.266	2.569	0.364
z16	7.036	0.607	0.735	672.915	0.232	0.040	0.115	0.281	1.386	0.051	1.363	0.240	251.577	0.284	251.759	3.090	0.240
z17	10.339	0.356	0.680	1679.481	0.215	0.040	0.064	0.282	0.574	0.051	0.565	0.195	251.796	0.159	251.968	1.282	0.195
z18	13.277	0.421	0.688	1822.853	0.218	0.040	0.055	0.282	0.512	0.051	0.501	0.238	251.738	0.135	252.339	1.143	0.238
z21	9.031	0.303	0.646	1738.759	0.204	0.040	0.071	0.283	0.543	0.051	0.529	0.252	252.199	0.175	252.671	1.214	0.252
z22	8.823	0.319	0.691	1598.787	0.218	0.040	0.078	0.281	0.578	0.051	0.565	0.225	251.502	0.193	251.742	1.288	0.225
z24	5.638	0.461	0.758	705.476	0.240	0.040	0.121	0.281	1.334	0.051	1.313	0.216	251.471	0.300	251.540	2.973	0.216
z25	10.546	0.801	0.613	785.193	0.194	0.040	0.104	0.282	1.169	0.051	1.148	0.243	251.435	0.255	252.072	2.609	0.243
z26	12.856	0.439	0.661	1704.160	0.209	0.040	0.062	0.282	0.544	0.051	0.535	0.203	251.482	0.154	252.107	1.215	0.203

Analyses highlighted in gray are not included in the weighted mean calculation.
†Total mass of radiogenic Pb.
‡Total mass of common Pb.
§Th contents calculated from radiogenic ^{208}Pb and the ^{207}Pb/^{206}Pb date of the sample, assuming concordance between U-Th and Pb systems.
¶Ratio of radiogenic Pb (including ^{208}Pb) to common Pb.
‖Measured ratio corrected for fractionation and spike contribution only.
**Measured ratios corrected for fractionation, tracer, and blank.
††Isotopic dates calculated using the decay constants λ^{238} = 1.55125E−10 and λ^{235} = 9.8485E−10 (1).
‡‡Corrected for initial Th/U disequilibrium using radiogenic 208Pb and Th/U[magma] = 3.00000.

1. Jaffey A, Flynn K, Glendenin L, Bentley W, Essling A (1971) Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U. *Phys Rev C Nucl Phys* 4:1889–1906.