DATA REPOSITORY

Additional explanation of analytical methods

Zircon was mounted in epoxy, polished, and imaged for cathodoluminescence (CL) with an accelerating voltage of 15 KeV and beam current of 10 nA on a JEOL 733 Superprobe electron microprobe (EMP) with the secondary electron detector mounted in place of the optical microscope ocular. The grains were also imaged with backscattered electrons (BSE) at similar settings on the EMP. Zr, Si, Hf, Th, and U were measured with the EMP at a beam current of 200 nA. Natural and synthetic standards were used. Measurement times on peak were 240 seconds on Th, 120 seconds on Zr, Hf , and U, and 16 seconds on Si. Measurement times on background were the same, split between both sides of the peak. Background positions were carefully chosen to avoid secondary peak interferences and the detectors were optimally set for pulse-height analysis. Raw data were corrected for matrix effects with the CITZAF program (Armstrong, 1995). The 1σ standard deviations of counts were 0.3% for Si, 1.0% for Zr, 0.5% for Hf, 1-4% for Th-rich domains, 5-15% for Th-poor domains, 2-3% for U-rich domains, and 5-20% for U-poor domains.

Armstrong, J.T., 1995, CITZAF—a package of correction programs for the quantitative electron microbeam X-ray analysis of thick polished materials, thin-films and particles: Microbeam Analysis, v. 4, p. 177–200.

Error propagation for the initial Th/U disequilibrium correction

The theoretical background for initial $^{230}Th/^{238}U$ disequilibrium and methodology for correcting $^{206}Pb/^{238}U$ dates is given in Schärer (1984) and Parrish (1990). Because $^{206}Pb/^{238}U$ dates in young zircon are especially sensitive to these corrections and the uncertainties have not been formally treated in the literature, we derived the error propagation for the Th/U disequilibrium correction and that of the Th/U[zircon] calculation. Schärer (1984) showed that the disequilibrium corrected $^{206}Pb/^{238}U$ ($R68dc$) can be related to the measured $^{206}Pb/^{238}U$ ($R68o$), the ratio of the Th/U[zircon] (TUz) and the Th/U[magma] (TUm), and the ratio of the decay constants of ^{238}U and ^{230}Th (λ_{238} and λ_{230}, respectively) in the equation:

$$R68dc = R68o - \left[\left(\frac{\lambda_{238}}{\lambda_{230}}\right)\cdot\left(\frac{TUz}{TUm} - 1\right)\right]$$

The uncertainty in the corrected ratio can be calculated using standard error propagation techniques related to the partial derivatives of the expression relative to the corrected ratio and assuming a Gaussian distribution of errors.

$$\sigma^2_{R68dc} = \sigma^2_{R68o}\cdot\left(\frac{\partial R68dc}{\partial R68o}\right)^2 + \sigma^2_{\lambda 238}\cdot\left(\frac{\partial R68dc}{\partial \lambda_{238}}\right)^2 + \sigma^2_{\lambda 230}\cdot\left(\frac{\partial R68dc}{\partial \lambda_{230}}\right)^2 + \sigma^2_{TUz}\cdot\left(\frac{\partial R68dc}{\partial TUz}\right)^2 + \sigma^2_{TUm}\cdot\left(\frac{\partial R68dc}{\partial TUm}\right)^2$$

where σ denotes the uncertainty in the variable in its subscript. It is a good assumption in this case that none of these errors are correlated, so those terms are excluded. The uncertainties in λ_{238} and λ_{230} are treated as systematic errors and not propagated into individual zircon analyses.

The derivatives are:

$$\left(\frac{\partial R68dc}{\partial R68o}\right)=1$$
$$\left(\frac{\partial R68dc}{\partial \lambda 238}\right)=\frac{1}{\lambda_{230}}\cdot\left(1-\frac{TUz}{TUm}\right)$$
$$\left(\frac{\partial R68dc}{\partial \lambda 230}\right)=\frac{\lambda_{238}}{\lambda_{230}^2}\cdot\left(\frac{TUz}{TUm}-1\right)$$
$$\left(\frac{\partial R68dc}{\partial TUz}\right)=-\left(\frac{\lambda_{238}}{\lambda_{230}}\cdot\left(\frac{1}{TUm}\right)\right)$$
$$\left(\frac{\partial R68dc}{\partial TUm}\right)=\left(\frac{\lambda_{238}}{\lambda_{230}}\cdot\left(\frac{TUz}{TUm^2}\right)\right)$$

The Th/U[magma] is estimated (in this case) from melt inclusions in quartz phenocrysts from the Bishop Tuff (Anderson et al., 2000) and the Th/U[zircon] is calculated as follows. The amount of ^{232}Th in the zircon is estimated by calculating the amount (in moles) of radiogenic ^{208}Pb (*Pb*208*r*) in the zircon using algorithms identical in derivation to those presented for *Pb*206*r* and *Pb*207*r* in Schmitz and Schoene (in press) and assuming concordance with the ^{206}Pb/^{238}U date:

$$Th232=\frac{Pb208r}{[\exp(age\cdot\lambda_{232})-1]},$$

where *Th*232 is the amount (in moles) of ^{232}Th in the zircon, *age* is the ^{206}Pb/^{238}U date, and λ_{232} is the decay constant for ^{232}Th. The uncertainty in the amount of ^{232}Th, assuming no correlations between errors, is:

$$\sigma_{Th232}^2=\left[\sigma_{Pb208r}\left(\frac{\partial Th232}{\partial Pb208r}\right)\right]^2+\left[\sigma_{age}\left(\frac{\partial Th232}{\partial age}\right)\right]^2+\left[\sigma_{\lambda_{232}}\left(\frac{\partial Th232}{\partial \lambda_{232}}\right)\right]^2$$

The uncertainty in λ_{232} is a systematic error and not propagated into individual zircons. The partial derivatives are:

$$\left(\frac{\partial Th232}{\partial Pb208r}\right)=\frac{1}{[\exp(age\cdot\lambda_{232})-1]}$$
$$\left(\frac{\partial Th232}{\partial age}\right)=\frac{-Pb208r}{[\exp(age\cdot\lambda_{232})-1]^2}\cdot\exp(age\cdot\lambda_{232})\cdot\lambda_{232}$$
$$\left(\frac{\partial Th232}{\partial \lambda_{232}}\right)=\frac{-Pb208r}{[\exp(age\cdot\lambda_{232})-1]^2}\cdot\exp(age\cdot\lambda_{232})\cdot age$$

The uncertainty in the Th/U[zircon] is calculated by propagating the uncertainties in the calculated amounts of ^{232}Th and U (again assuming errors are uncorrelated):

$$\sigma_{TUz} = TUz \cdot \sqrt{\left(\frac{\sigma_{Th232}}{Th232}\right)^2 + \left(\frac{\sigma_U}{U}\right)^2}$$

We note that this is the present day Th/U[zircon], but because of the young age of the Bishop Tuff, this number has not changed substantially since the time of eruption. In old samples, the Th/U[zircon] and Th/U[magma] at the time of crystallization will be different from that calculated above, and may need to be corrected for radioactive decay for maximum accuracy.

Because the Th/U[zircon] is calculated using the ^{206}Pb/^{238}U date, which is turn used to recalculate this date, a few iterations are necessary to converge.

Table 1. U-Pb isotopic data from the Bishop Tuff.

						Isotopic ratios											Dates					
Sample	Pb*	Pb_c (pg)	Pb*/Pb_c	Th/U	±	$^{206}Pb/^{204}Pb$	$\%^{206}Pb$	$\%^{207}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	% err	$^{207}Pb/^{235}U$	% err	$^{207}Pb/^{206}Pb$	% err	corr. coef.	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(j)	(k)	(j)	(k)	(j)	(k)		(l)	(m)	(l)	(m)	(n)	(o)
z2 ET, CA	1.70	0.37	4.6	0.52	0.01	291	93.7	49.5	0.197	0.0001190	0.36	0.0008138	2.55	0.05609	2.39	0.888	766.8	2.8	826.0	21.1	456	53
z3 ET, CA	2.29	0.42	5.5	0.58	0.01	337	94.6	53.2	0.215	0.0001189	0.37	0.0008084	1.65	0.05556	1.55	0.795	766.6	2.8	820.5	13.5	435	35
z7 ET, CA	2.13	0.31	6.8	0.57	0.01	414	95.6	58.7	0.213	0.0001186	0.37	0.0008135	1.36	0.05610	1.28	0.687	764.7	2.8	825.7	11.2	456	28
z10 ET, CA	1.98	0.46	4.3	0.60	0.01	266	93.1	46.8	0.225	0.0001187	0.39	0.0008037	2.56	0.05529	2.45	0.707	765.2	3.0	815.7	20.9	424	55
z11 ET, CA	1.54	0.74	2.1	0.57	0.01	140	86.9	30.3	0.217	0.0001194	0.40	0.0008147	6.91	0.05578	6.84	0.372	769.5	3.1	826.9	57.1	443	152
z12 ET, CA	1.84	0.37	5.0	0.55	0.02	311	94.1	50.4	0.208	0.0001193	0.40	0.0007890	3.88	0.05413	3.69	0.804	768.9	3.1	800.8	31.0	376	83
z14 ET	1.63	0.33	4.9	0.56	0.01	304	94.0	50.5	0.211	0.0001186	0.37	0.0008071	2.18	0.05567	2.05	0.859	764.7	2.9	819.2	17.8	439	46
z15 ET	1.77	0.88	2.0	0.61	0.01	133	86.3	29.4	0.230	0.0001191	0.41	0.0008242	3.48	0.05642	3.34	0.741	767.9	3.2	836.5	29.1	469	74
z16 ET	1.88	0.87	2.2	0.59	0.01	143	87.3	30.8	0.219	0.0001186	0.40	0.0008060	3.09	0.05553	2.94	0.795	764.6	3.0	818.1	25.3	434	65
z18 ET	1.66	0.69	2.4	0.58	0.01	158	88.4	33.4	0.220	0.0001189	0.41	0.0008121	3.60	0.05582	3.44	0.773	766.3	3.1	824.2	29.7	445	77
z19 IMG, MIT, CA	1.73	0.44	4.0	0.52	0.01	252	92.8	45.5	0.201	0.0001191	0.36	0.0008058	1.90	0.05549	1.77	0.780	767.5	2.7	817.8	15.6	432	40
z21 IMG, CD, MIT, CA	2.30	0.37	6.2	0.54	0.01	381	95.2	56.1	0.202	0.0001194	0.36	0.0008003	1.19	0.05488	1.11	0.584	769.7	2.8	812.3	9.7	407	25
z22 IMG, CD, MIT, CA	1.44	0.94	1.5	0.51	0.02	109	83.2	24.4	0.197	0.0001192	0.43	0.0008061	3.87	0.05546	3.63	0.788	768.5	3.3	818.2	31.7	431	81
z23 IMG, CD, MIT, CA	1.81	0.36	5.1	0.55	0.01	315	94.2	51.3	0.208	0.0001190	0.41	0.0008059	1.45	0.05545	1.35	0.474	766.9	3.1	818.0	11.9	430	30
z24 IMG, ET, CA	0.87	0.41	2.1	0.45	0.02	146	87.5	31.5	0.180	0.0001209	0.45	0.0008269	7.98	0.05619	7.72	0.680	779.4	3.5	839.2	66.9	460	171
z25 IMG, ET, CA	0.97	0.64	1.5	0.47	0.02	110	83.4	24.8	0.186	0.0001189	0.40	0.0008146	5.75	0.05633	5.54	0.711	766.7	3.1	826.8	47.5	465	123
z26 IMG, ET, CA	1.39	0.51	2.7	0.58	0.01	176	89.6	36.3	0.219	0.0001193	0.41	0.0008198	3.90	0.05616	3.78	0.546	768.9	3.2	832.1	32.5	459	84
z27 IMG, CD, ET, CA	1.72	0.66	2.6	0.59	0.01	169	89.2	34.6	0.221	0.0001191	0.41	0.0008008	2.94	0.05493	2.78	0.788	767.5	3.1	812.8	23.9	409	62
z28 IMG, CD, ET, CA	1.57	0.43	3.6	0.57	0.01	229	92.0	42.7	0.213	0.0001199	0.37	0.0008092	2.14	0.05515	2.02	0.835	772.7	2.9	821.3	17.6	418	45

(a) z2, z3 etc. are labels for fractions; IMG = grain was CL and BSE imaged; CD = central domain seen in CL image; ET = EARTHTIME tracer solution; MIT = MIT tracer solution; CA = grain was treated with the chemical abrasion method.

(b) Weight of radiogenic Pb.

(c) Weight of common Pb.

(d) Ratio of radiogenic Pb to common Pb.

(e) Model Th/U ratio calculated from radiogenic 208Pb/206Pb ratio and 206Pb/238U date corrected for initial disequilibrium in Th/U.

(f) Error is 2 sigma.

(g) Measured ratio corrected for spike and fractionation only. Fractionation correction of 0.25 ± 0.04%/amu (atomic mass unit) was applied to Daly analyses performed on the Sector-54 mass spectrometer, based on analysis of NBS-981.

(h) % of 206Pb that is radiogenic Pb.

(i) % of 207Pb that is radiogenic Pb.

(j) Corrected for fractionation, spike, and procedural blank. All common Pb is assigned to procedural blank. Measured procedural blank composition is 206Pb/204Pb = 18.27 ± 0.18, 207Pb/204Pb = 15.59 ± 0.16, 208Pb/204Pb = 38.12 ± 0.38 (2 sigma). 206Pb/238U and 208/206 ratios corrected for initial disequilibrium in Th/U using Th/U [magma] = 2.81 ± 0.32 (2 sigma).

(k) Error is 2 sigma, propagated using the algorithms of Schmitz and Schoene (in press). 206Pb/238U error includes uncertainty associated with initial disequilibrium in Th/U.

(l) Date in Ka based on decay constants of Jaffey et al. (1971). 206Pb/238U date corrected for initial disequilibrium in Th/U using Th/U [magma] = 2.81 ± 0.32 (2 sigma).

(m) Error in Ka is 2 sigma. 206Pb/238U error includes uncertainty associated with initial disequilibrium in Th/U.

(n) Date in Ma based on decay constants of Jaffey et al. (1971).

(o) Error in Ma is 2 sigma.

Table 2. Chemical compositions of zircon from the Bishop Tuff.

z20

Electron microprobe results (wt. %)							
Position[1]	ED	ED	ED	ED	CD	CD	CD
Si	15.34	15.33	15.33	15.31	15.30	15.30	15.30
Zr	48.22	48.19	48.18	48.19	48.20	48.21	48.20
Hf	1.23	1.14	1.13	1.06	1.02	1.03	1.03
U	0.24	0.30	0.37	0.25	0.16	0.14	0.16
Th	0.09	0.21	0.24	0.15	0.08	0.05	0.08
O	34.61	34.58	34.58	34.54	34.53	34.53	34.53
Total	99.73	99.76	99.83	99.51	99.29	99.25	99.30
Th/U	0.38	0.69	0.64	0.60	0.47	0.37	0.50

Grain 4

Electron microprobe results (wt. %)								
Position[1]	ED	ED	ED	ED	CD	CD	CD	CD
Si	15.34	15.34	15.32	15.33	15.31	15.30	15.30	15.30
Zr	48.20	48.18	48.20	48.19	48.22	48.22	48.21	48.22
Hf	1.19	1.15	1.11	1.12	1.09	1.05	1.05	1.04
U	0.31	0.39	0.23	0.29	0.10	0.07	0.10	0.07
Th	0.14	0.31	0.11	0.21	0.05	0.04	0.04	0.03
O	34.60	34.58	34.56	34.57	34.55	34.54	34.54	34.53
Total	99.78	99.94	99.53	99.71	99.32	99.22	99.24	99.20
Th/U	0.45	0.80	0.49	0.74	0.53	0.53	0.41	0.43

z22

Electron microprobe results (wt. %)										
Position[1]	ED	ED	ED	ED	ED	ED	ED	CD	CD	CD
Si	15.34	15.34	15.35	15.33	15.32	15.31	15.31	15.28	15.28	15.28
Zr	48.19	48.17	48.15	48.20	48.20	48.17	48.17	48.20	48.20	48.20
Hf	1.15	1.16	1.14	1.13	1.09	0.99	1.01	0.93	0.93	0.91
U	0.40	0.45	0.53	0.27	0.25	0.32	0.31	0.07	0.08	0.04
Th	0.19	0.37	0.45	0.13	0.12	0.29	0.30	0.03	0.03	0.01
O	34.58	34.59	34.58	34.57	34.55	34.52	34.52	34.49	34.49	34.48
Total	99.85	100.08	100.19	99.63	99.53	99.60	99.63	99.00	99.01	98.92
Th/U	0.47	0.82	0.85	0.49	0.49	0.92	0.96	0.51	0.37	0.20

z28

Electron microprobe results (wt. %)									
Position[1]	ED	ED	ED	ED	ED	ED	CD	CD	CD
Si	15.35	15.34	15.33	15.33	15.33	15.33	15.31	15.31	15.31
Zr	48.18	48.20	48.19	48.18	48.17	48.18	48.20	48.20	48.20
Hf	1.20	1.17	1.13	1.12	1.11	1.12	1.05	1.04	1.05
U	0.43	0.35	0.37	0.35	0.39	0.34	0.17	0.19	0.18
Th	0.27	0.16	0.22	0.24	0.30	0.23	0.08	0.08	0.07
O	34.60	34.59	34.57	34.57	34.56	34.57	34.54	34.53	34.54

Total	100.03	99.81	99.81	99.79	99.87	99.78	99.33	99.35	99.35
Th/U	0.62	0.47	0.61	0.69	0.78	0.68	0.47	0.41	0.39

[1] CD = central domain, ED = external domain.