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- Astronomical age for the Bishop Tuff
- Intercalibration of orbital and radiometric ages
- Single crystal $^{40}Ar/^{39}Ar$ age for the Bishop Tuff

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An astronomical age for the Bishop Tuff and concordance with radioisotopic dates

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Abstract The Bishop Tuff forms a key stratigraphic horizon for synchronization of Quaternary sedimentary records in North America. The unit stratigraphically overlies the Matuyama-Brunhes geomagnetic polarity reversal by several thousand years; high-precision dating of this tuff may be valuable for regional and global correlation of records. The Quaternary time scale is anchored by $^{40}Ar/^{39}Ar$ ages on lava flows and ash layers where available, with stage boundaries and geomagnetic reversals including astronomically tuned records. However, astronomical dating has not yet validated the high-precision $^{238}U/^{206}Pb$ zircon and $^{40}Ar/^{39}Ar$ sanidine ages of the Bishop Tuff. We have identified the Bishop Tuff within the marine sedimentary record and derived an astronomical age of 0.765 ± 0.008 Ma by correlation to the LR04 $\delta^{18}O$ global benthic stack and its age model. This age is consistent with Bishop Tuff radioisotopic ages, including new single crystal $^{40}Ar/^{39}Ar$ sanidine fusion analyses presented here, which demonstrates that concordance through multiple dating techniques is achievable within the Quaternary.

1. Introduction

Intercalibration of ages from different geochronometers is of vital importance to the construction of the geologic timescale. $^{40}Ar/^{39}Ar$ and $^{238}U/^{206}Pb$ dating are often used on minerals extracted from tephra layers and may combine radioisotopic ages with orbitally tuned ages [*Kuiper et al*., 2008; *Meyers et al*., 2012; see also *Gradstein et al*., 2012 and *Singer*, 2013; *Rivera et al*., 2011]. The Bishop Tuff was erupted from the Long Valley caldera in eastern California (Figure 1a). Recently, an $^{40}Ar/^{39}Ar$ sanidine age (0.7674 ± 0.0022 Ma) [*Rivera et al*., 2011], determined relative to the Fish Canyon Tuff sanidine and the astronomically dated A1 Tephra sanidine, and a $^{238}U/^{206}Pb$ zircon date of 0.7666 ± 0.0031 Ma which is the weighted mean of 166 zircon rim ages determined by secondary ion mass spectrometry [*Chamberlain et al*., 2014] were shown to agree with an earlier $^{238}U/^{206}Pb$ zircon age determined using thermal ionization mass spectrometry (0.7671 ± 0.0019 Ma) [*Crowley et al*., 2007]. However, *Simon et al*. [2014] determined an $^{40}Ar/^{39}Ar$ sanidine age (0.780 ± 0.002 Ma, relative to the Fish Canyon optimization age of *Renne et al*. [2011] that is significantly older than those reported by *Chamberlain et al*. [2014], *Crowley et al*. [2007], and *Rivera et al*. [2011]. As the Bishop Tuff, which stratigraphically overlies the Matuyama-Brunhes geomagnetic polarity reversal by several thousand years, can be used as a regional stratigraphic marker, an astronomical age for the Bishop Tuff will assist in resolving the discrepancies between various reported radioisotopic ages. Here we report an astronomical age for the Bishop Tuff that we have identified in marine sediments in cores from Ocean Drilling Program (ODP) Leg 167 drilled offshore from the California margin (Figure 1a) along with new single crystal $^{40}Ar/^{39}Ar$ sanidine analyses on sample BT-79G94 [*Sarna-Wojcicki et al*., 2000] that support previously determined radioisotopic ages for the Bishop Tuff [*Chamberlain et al*., 2014; *Crowley et al*., 2007; *Rivera et al*., 2011]. Our results demonstrate that the three geochronometers yield consistent ages within uncertainty for this important Quaternary supereruption.

2. Methods and Results

2.1. Fingerprinting the Bishop Tuff

The Initial Reports of ODP Leg 167 [*Lyle et al*., 1997] indicate that an ash layer occurs stratigraphically above the Matuyama-Brunhes boundary at ODP Sites 1012 and 1013. Five samples of this ash were collected from four ODP Leg 167 holes (1012A, 1012B, 1013A, and 1013C; Figure 1a). Glass shards were extracted from each sample and chemically characterized by electron probe microanalysis at Washington State University's GeoAnalytical

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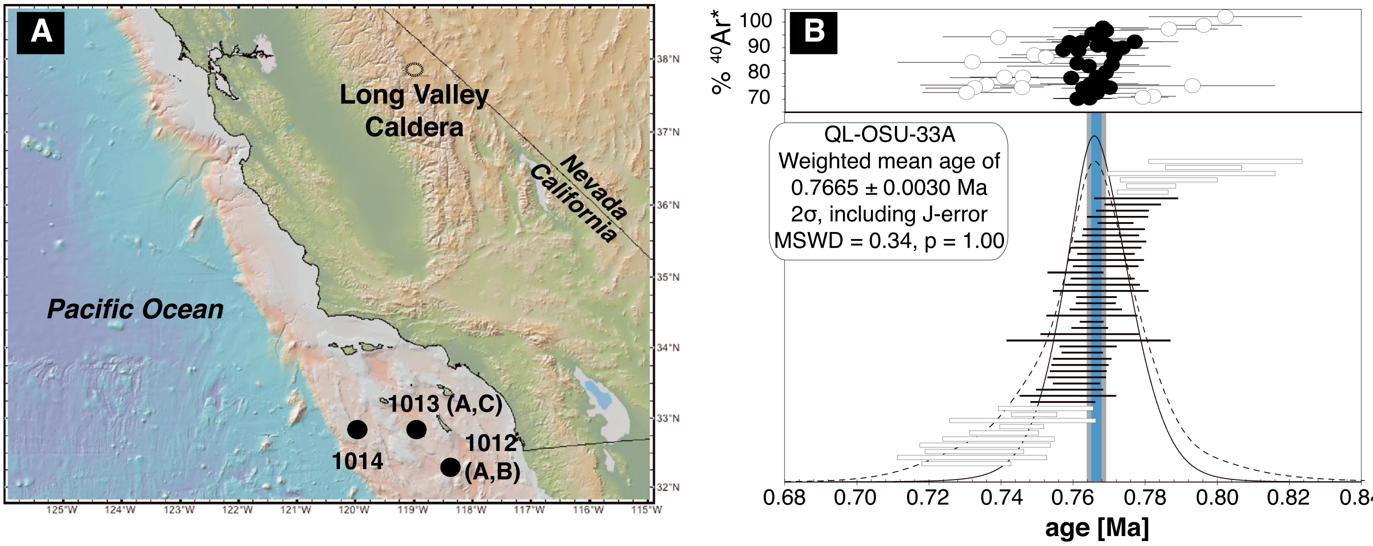

Figure 1. (a) Long Valley caldera and ODP Leg 167 Site locations (base map generated with GeoMapApp); (b) single crystal $^{40}Ar/^{39}Ar$ Bishop Tuff sanidine analyses with $\%^{40}Ar^*$ shown with 2σ analytical uncertainties including J. Outliers represented by open symbols. Probability function of all analyses shown as broken line; solid line represents distribution of analyses used to calculate the weighted mean. Weighted mean indicated as blue bar—width of bar represents 1σ uncertainty—gray area is 2σ uncertainty.

Lab (WSU; Table 1). The five samples were identified as being derived from the same volcanic deposit and then compared with other known ashes within the WSU tephra database. Based on major element geochemical similarities, the samples were correlated to either the Bishop Tuff [*Knott et al*., 1999; *Sarna-Wojcicki et al*., 1985] or the Glass Mountain Ash Bed [*Reheis et al*., 1993]. However, the Glass Mountain Ash occurs within the Matuyama reversed polarity chron [*Reheis et al*., 1993; *Simon et al*., 2014], deeming it too old and not the source of our samples. We conclude that the tephra sampled at Sites 1012 and 1013 is the Bishop Tuff.

2.2. Single Crystal $^{40}Ar/^{39}Ar$ Sanidine Analyses

Handpicked Bishop Tuff sanidine grains (≤1 mm) are from sample BT-79G94 [*Sarna-Wojcicki et al*., 2000] and experiments utilize the astronomically dated A1 Tephra sanidine (A1Ts; 6.943 ± 0.005 Ma; *Rivera et al*., 2011) as the neutron fluence monitor. All Bishop Tuff and A1Ts fusion analyses were measured as single crystals and were determined with the ^{40}K partial decay constants of *Min et al.* [2000]. Argon isotopic analyses were performed on a Nu Instruments Noblesse multicollector mass spectrometer at the Quaternary Dating Laboratory (QUADLAB) following procedures similar to those previously published [*Brumm et al*., 2010; *Rivera et al*., 2011]. Refer to the supporting information for additional $^{40}Ar/^{39}Ar$ method details and full argon isotopic data.

We carried out 50 single crystal total fusion $^{40}Ar/^{39}Ar$ analyses of Bishop Tuff sanidine, which yield a weighted mean $^{40}Ar/^{39}Ar$ age of 0.7665 ± 0.0030/0.0032 Ma (2 sigma including error on *J*/with decay constant uncertainty, Figure 1b), supported by an inverse isochron age of 0.7684 ± 0.0046 Ma with trapped argon of atmospheric composition (295.1 ± 7.2; within error of *Lee et al*. [2006]). The weighted mean $^{40}Ar/^{39}Ar$ age for the Bishop Tuff obtained by single crystal experiments is nearly identical to our previously reported multigrain fusion $^{40}Ar/^{39}Ar$ sanidine age of 0.7667 ± 0.0030 Ma relative to the A1Ts monitor [*Rivera et al*., 2011]. However, the dispersion in the single crystal dates, with 16 of 50 analyses identified as outliers following a predefined statistical filtering process [*Powell et al*., 2002; *Kuiper et al*., 2008; *Rivera et al*., 2011; *Ellis et al*., 2012], suggests that some grains may suffer from either excess ^{40}Ar or argon loss, although no correlation is seen between age, signal size, $\%^{40}Ar^*$, or Ca/K. Because there is an indication of antecrystic or disturbed grains in sample BT-79G94, our preferred $^{40}Ar/^{39}Ar$ age for the BT is represented by the single crystal data presented here (0.7665 ± 0.0032 Ma) rather than the limited number of multicrystal analyses presented in *Rivera et al*. [2011]. This age is equivalent to 0.7673 Ma or 0.7699 Ma when calibrated the Fish Canyon Tuff sanidine (FCTs) monitor age of *Kuiper et al*. [2008] or *Renne et al*. [2011], respectively. We note that this calibrated $^{40}Ar/^{39}Ar$ age is in excellent agreement with a high-precision $^{238}U/^{206}Pb$ CA-TIMS zircon age of

Table 1. EPMA Analyses of Glass Shards from Tephras Extracted From ODP Leg 167

Sample (Hole-Core-Section, Depth)	n[a]	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	Cl	Total[c]	Probable Source	Correlation Coefficient[d]
1012A-7H-1W, 79–83 cm	18	77.51(0.16)[b]	12.66(0.13)	0.76(0.06)	0.07(0.04)	3.40(0.17)	5.01(0.30)	0.04(0.02)	0.47(0.04)	0.08(0.02)	100	Bishop Ash Bed or Glass Mtn Ash Bed	0.98
1012A-7H-1W, 89–93 cm	18	77.57(0.18)	12.63(0.12)	0.75(0.05)	0.06(0.03)	3.44(0.21)	4.94(0.21)	0.04(0.02)	0.47(0.04)	0.10(0.01)	100	Bishop Ash Bed or Glass Mtn Ash Bed	0.98
1012B-6H-6W, 87.5–89.5 cm	20	77.60(0.16)	12.68(0.10)	0.73(0.04)	0.06(0.02)	3.40(0.21)	4.93(0.30)	0.03(0.01)	0.48(0.04)	0.09(0.02)	100	Bishop Ash Bed or Glass Mtn Ash Bed	0.98
1013A-6H-7W, 6–10 cm	20	77.43(0.15)	12.72(0.14)	0.73(0.04)	0.06(0.04)	3.37(0.21)	5.10(0.30)	0.04(0.02)	0.46(0.04)	0.09(0.02)	100	Bishop Ash Bed	0.99
1013C-6H-5W, 48–50 cm	20	77.40(0.17)	12.73(0.12)	0.73(0.03)	0.07(0.03)	3.45(0.21)	5.04(0.30)	0.04(0.02)	0.46(0.04)	0.08(0.01)	100	Bishop Ash Bed or Glass Mtn Ash Bed	0.98

[a]Number of glass shards analyzed.
[b]Standard deviations of the analyses given in parentheses.
[c]Analyses normalized to 100 wt.%.
[d]*Borchardt et al.* [1972];Na, Ca, Si, Al, Fe, K = unit weighting, Mg, Ti = 0.25 weighting.

0.7671 ± 0.0019 Ma for the Bishop Tuff [*Crowley et al.*, 2007] and a sensitive high-resolution ion microprobe, reverse geometry (SHRIMP-RG) $^{238}U/^{206}Pb$ zircon age of 0.7666 ± 0.0031 Ma [*Chamberlain et al.*, 2014] as determined on zircon rims representing late-stage growth prior to eruption.

Additionally, our new single crystal age for the Bishop Tuff just overlaps at 2σ with the older multicrystal age determined by *Sarna-Wojcicki et al*. [2000] when the data are treated in the same manner. In a reevaluation of the *Sarna-Wojcicki et al*. [2000] data for only sample 79G94 (aliquots A–C), we have omitted all analyses yielding less than 70% $^{40}Ar^*$, consistent with the filtering processes used within this and other studies. The new age for the Bishop Tuff, relative to the original monitor Taylor Creek Rhyolite of 27.92 Ma, is 0.7622 ± 0.0084 Ma (2 s analytical uncertainty), which recalculates to 0.7785 ± 0.0084 Ma relative to FCTs of *Kuiper et al*. [2008]. When placed in context of a common filtering process and monitor value the ages reported for sample 79G94 by *Sarna-Wojcicki et al*. [2000] and in this study are consistent at 2σ. The slightly older age of *Sarna-Wojcicki et al*. [2000] may be due to inclusion of antecrystic grains within their multicrystal approach. This is suggested by the larger dispersion of ages within the 79G94(A) aliquot (mean square weighted deviate = 2.7) [*Sarna-Wojcicki et al*., 2000, Table 3b] and the tail to slightly older ages shown within the single crystal data of this study (Figure 1), which could account for the slight offset of their result with our single crystal $^{40}Ar/^{39}Ar$ fusion date and the $^{238}U/^{206}Pb$ zircon ages of both *Crowley et al*. [2007] and *Chamberlain et al.* [2013].

2.3. Astronomical Isotope Age of the Bishop Tuff

To determine an astronomical age for the Bishop Tuff, we have chosen to use the method of correlating the published benthic oxygen isotope ($\delta^{18}O$) record of Site 1014B [*deMenocal and Baker*, 2000] to the LR04 global benthic $\delta^{18}O$ stack age model [*Lisiecki and Raymo*, 2005], which represents an astronomical age as it derived from an ice volume model forced by insolation [*Lisiecki and Raymo*, 2005]. The original age model for Site 1014 is based on a combination of bioevents and magnetostratigraphy [*Lyle et al*., 1997]. The Bishop Tuff was identified as a distinct minimum within the magnetic susceptibility data of Site 1012B at 55.0–55.2 m below sea floor (mbsf), likely due to the diamagnetic minerals of the ash. This susceptibility low is also present at Site 1014B, allowing for a direct correlation between the two cores (Figure 2a). We construct a revised mbsf* for Site 1014B (Figure 2b) by assuming that the sedimentary cores 167-1014B-7H and 167-1014B-8H do not have a gap and can be connected as a continuous section. This is necessary

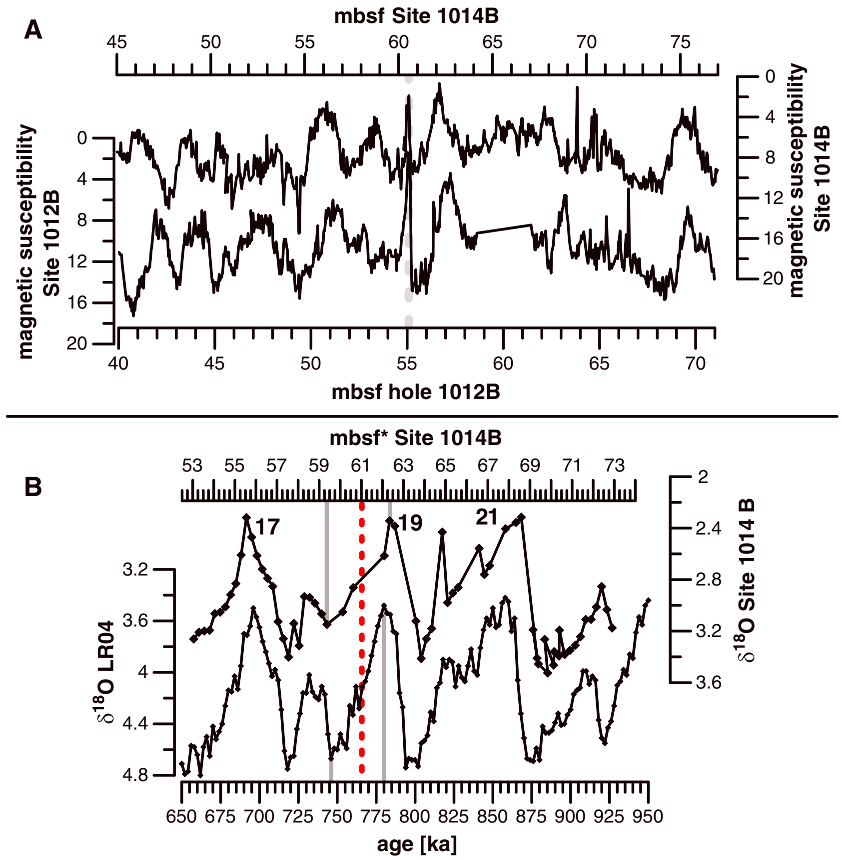

Figure 2. (a) Correlation of the magnetic susceptibility minimum associated with the Bishop Tuff (gray broken line) from ODP Site 1012 to Site 1014. (b) Correlating the relative position of the Bishop Tuff (red-dashed line, indicative) from ODP Site 1014B to the LR04 global benthic stack on its age scale (bottom). Correlative points (grey lines) and marine isotope stages are indicated (17, 19, and 20).

because the cored sediment expanded exceeding the length of the mbsf during coring and recovery, and the end of core 167-1014B-7H has a mbsf lower than the top of core 167-1014B-8H. The correlative position of the Bishop Tuff at Site 1014B corresponds to 61.04 mbsf* and is close to one isotope measurement at 60.62 mbsf in 167-1014B-7-CC, above the correlative position of the Bishop Tuff. Correlating the δ^{18}O stratigraphy from Site 1014B [*deMenocal and Baker*, 2000] to the LR04 global benthic stack [*Lisiecki and Raymo*, 2005] (Figure 2b) is restricted by the limited amount of δ^{18}O data available in this interval; sedimentation rates seem to be semiconstant. As the Bishop Tuff is positioned between the lowest δ^{18}O values of MIS 19 at 0.78 Ma and the highest values at ~ 0.746 Ma, we use these tie points in the LR04 and the Site 1014 oxygen isotope stratigraphies (indicated in Figure 2b). Using these, and associated uncertainties (for stratigraphic position, age, and also for additional or missing sediment; see the R [*R Core Team*, 2013] script in the supporting information), we obtain an age range from 0.7612 Ma to 0.7692 Ma, corresponding to a mean value of 0.7652 ± 0.004 Ma. Adding the potentially systematic uncertainty of the LR04 stack (±4 ka) [*Lisiecki and Raymo*, 2005], an age of 0.7652 ± 0.008 Ma (2 sigma), based on correlation correctness, validity of the LR04 age model and data, continuity of the section, and uncertainty in the correlation points, is obtained for the Bishop Tuff.

3. Discussion

3.1. Timescale Construction

The δ^{18}O data from Site 1014 are not directly correlated to an orbital target curve but to the LR04 [*Lisiecki and Raymo*, 2005] benthic δ^{18}O age model based on the timescale of the *Imbrie and Imbrie* [1980] ice volume model. The LR04 age model uses the summer insolation of the 1993 orbital solution [*Laskar et al.*, 1993] as input; therefore, the LR04 age model indirectly represents an orbital timescale. Benthic δ^{18}O values are generally thought to represent a signal comprising both global ice volume and deep sea temperatures, and are not directly (without any time delay) responding to changes in insolation. Therefore, this correlation target including a time delay and nonlinearity is more justified than a direct tuning to insolation or a combination of orbital parameters. A higher-resolution benthic $\delta^{18}O$ record of Site 1012 or 1014 may allow for a more precise Bishop Tuff age in the future.

3.2. Intercalibration

The age based on ODP Leg 167 is consistent with our $^{40}Ar/^{39}Ar$ single crystal sanidine and $^{238}U/^{206}Pb$ zircon ages [*Crowley et al*., 2007; *Chamberlain et al*., 2014] determined for the Bishop Tuff. Similarly, a study on the Alder Creek Rhyolite (northern California) [*Rivera et al*., 2013] demonstrated that multichronometer consistency is achievable for Quaternary units when (1) $^{40}Ar/^{39}Ar$ age experiments utilize an astronomically dated monitor (or one that is astronomically calibrated) and (2) $^{238}U/^{206}Pb$ age experiments utilize the chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) method coupled with the EARTHTIME isotopic tracer solutions [*Condon et al*., 2007].

The Bishop Tuff $^{40}Ar/^{39}Ar$ age presented here (0.7665 ± 0.0032 Ma) is in remarkable agreement with an age of 0.7666 ± 0.0031 Ma, representing late-stage rim growth on Bishop Tuff zircon and interpreted by *Chamberlain et al*. [2014] as an eruption age. However, both are statistically distinct from that reported by *Renne et al*. [2011] (0.7781 ± 0.0074 Ma) as determined through recalculation of ages by *Sarna-Wojcicki et al*. [2000] and *Simon et al*. [2014] (0.780 ± 0.002 Ma) following the Ar-U/Pb (R, τ) pair optimization approach, equivalent to an FCTs age of 28.294 Ma. The older $^{40}Ar/^{39}Ar$ ages are problematic because it is geologically unlikely that the CA-TIMS zircon ages [*Crowley et al*., 2007], typically detailing preeruptive crystallization, would be younger than the eruption-recording sanidine ages. This discrepancy has often been attributed to the accuracy of the $^{238}U/^{206}Pb$ zircon date, in part due to the Th/U disequilibrium correction applied [*Simon et al*., 2014; *Renne et al*., 2010]. *Crowley et al*. [2007] justify their use of Th/U measured within quartz-hosted melt inclusions by arguing that these values represent the magmatic composition during late-stage crystallization, as do the $^{238}U/^{206}Pb$ zircon dates. Similarly, *Chamberlain et al*. [2014] use Th/U measured on coexisting glass to appropriately correct each of their sample dates for ^{230}Th disequilibrium. Although addressing the various proposed Th/U ratios used for disequilibrium correction is beyond the scope of this paper, a brief discussion is necessary in order to examine potential resolutions to the discrepancy between the numerous radioisotopic ages. A $Th/U_{[magma]}$ correction value > 4.5 is required to align the $^{238}U/^{206}Pb$ zircon date of *Crowley et al*. [2007] with the ~ 0.780 Ma $^{40}Ar/^{39}Ar$ sanidine ages of *Renne et al*. [2011] and *Simon et al*. [2014]. However, such high Th/U ratios have not been recorded from Bishop Tuff quartz-hosted melt inclusions (average of 2.37 ± 0.64) [e.g., *Schmitt and Simon*, 2004]. Rather, *Simon et al*. [2014] argue for the use of Bishop Tuff pumice clast Th/U values as representative of the disequilibrium correction in an attempt to reconcile the $^{238}U/^{206}Pb$ zircon dates of *Crowley et al*. [2007] with their older $^{40}Ar/^{39}Ar$ age; however, this is problematic because it may overestimate $Th/U_{[melt]}$ at the time of zircon nucleation and growth. As pumice clasts are a mixture of melt and crystals, including zircon- and Th-enriched accessory phases such as allanite or chevkinite, Th/U of pumice may not truly represent the magmatic Th/U that was in equilibrium with the crystallizing zircon.

Nevertheless, the proposed $^{40}Ar/^{39}Ar$ age of 0.780 ± 0.002 Ma [*Simon et al*., 2014] can be reconciled with the age presented here (0.7665 ± 0.0030 Ma) through the adjustment of the age of the Alder Creek Rhyolite sanidine neutron fluence monitor used by *Simon et al*. [2014]. As *Rivera et al*. [2013] showed, zircon crystallization within the Alder Creek Rhyolite magma batch occurred as recently as 1.1978 ± 0.0046 Ma, with a proposed $^{40}Ar/^{39}Ar$ sanidine eruption age of 1.1850 ± 0.0016 Ma. The use of 1.193 Ma [*Nomade et al*., 2005]; or 1.2056 Ma as determined by the *Renne et al*., 2011 calibration) for the $^{40}Ar/^{39}Ar$ age of Alder Creek Rhyolite as the standard in the *Simon et al*. [2014] study clearly results in a Bishop Tuff eruptive age older than the youngest zircon crystallization age. Rather, a recalculation of the *Simon et al*. [2014] date of 0.780 ± 0.002 Ma to the Alder Creek Rhyolite standard age of *Rivera et al*. [2013] results in an age of the Bishop Tuff of 0.7673 ± 0.002 Ma (uncertainty retained) and thus consistent with both the $^{40}Ar/^{39}Ar$ date presented here and in *Rivera et al*. [2011], the astronomical/isotope stratigraphic age determined in this study, and the $^{238}U/^{206}Pb$ zircon date of *Crowley et al*. [2007].

While the Bishop Tuff is stratigraphically close to the Matuyama-Brunhes geomagnetic polarity reversal, no precise age for the boundary can be provided at the offshore location studied here due to complications in the paleomagnetic behavior of ODP Leg 167 sediments [*Heider et al.*, 2000]. Previous work has suggested that the temporal offset between the reversal and the deposition of the tuff was circa 15 ka [*Sarna-Wojcicki et al.*, 2000]. However, the records used in the earlier calibration were mostly lacustrine and alluvial sections, and the assumption of (semi) constant sedimentation rates over tens of meters seems tentative. Inaccuracies given by *Sarna-Wojcicki et al.* [2000] do not include potentially nonconstant sedimentation rates and may therefore result in a greater or smaller offset between the reversal and deposition of the tuff, depending sedimentation rates.

4. Conclusions

Here we present an astronomical age for the Bishop Tuff of 0.7652 ± 0.008 (2 sigma) Ma based on the LR04 age model, which represents a benthic global $\delta^{18}O$ stack tuned to an ice model. A quantitative correlation procedure including the uncertainty in correlation points is applied; the result depends on the assumptions of correlation correctness, validity of the LR04 age model and data, continuity of the section, and uncertainty in correlation points. Bishop Tuff $^{40}Ar/^{39}Ar$ single crystal sanidine experiments result in a weighted mean age of 0.7673 ± 0.0032 Ma relative to FCT = 28.201 Ma [*Kuiper et al.*, 2008] or 0.7665 ± 0.0032 Ma (2 sigma, including systematic uncertainties, relative to the astronomically dated A1 tephra sanidine (A1Ts; 6.943 ± 0.005 Ma) [*Rivera et al.*, 2011], consistent with both $^{238}U/^{206}Pb$ zircon analyses and the proposed astronomical age. This work demonstrates the ability to achieve internally consistent ages for a Quaternary tephra utilizing a multichronometer approach that incorporates an astronomically dated $^{40}Ar/^{39}Ar$ neutron fluence monitor and the CA-ID-TIMS method for $^{238}U/^{206}Pb$ zircon dating.

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