1 **Implications of two Holocene time-dependent geomagnetic models for**
2 **cosmogenic nuclide production rate scaling**

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9 **Abstract**

10 The geomagnetic field is a major influence on in situ cosmogenic nuclide production rates at
11 a given location (in addition to atmospheric pressure and, to a lesser extent, solar modulation
12 effects). A better understanding of how past fluctuations in these influences affected production
13 rates should allow more accurate application of cosmogenic nuclides. As such, this work
14 explores the cosmogenic nuclide production rate scaling implications of two recent time-
15 dependent spherical harmonic geomagnetic models spanning the Holocene. Korte and Constable
16 (2011, *Phys. Earth Planet. Int.* **188**, 247–259) and Korte et al. (2011, *Earth Planet. Sci. Lett.*
17 **312**, 497–505) recently updated earlier spherical harmonic paleomagnetic models with new
18 paleomagnetic data from sediment cores in addition to new archeomagnetic and volcanic data.
19 These updated models offer improved resolution and accuracy over the previous versions, in part
20 to due to increased temporal and spatial data coverage. In addition, Pavón-Carrasco et al. (2014,
21 *Earth Planet. Sci. Lett.* **388**, 98–109) developed another time-dependent spherical harmonic
22 model of the Holocene geomagnetic field, based solely on archeomagnetic and volcanic
23 paleomagnetic data from the same underlying paleomagnetic database as the Korte et al. models,
24 but extending to 14 ka.

25 With the new models as input, trajectory-traced estimates of effective vertical cutoff rigidity
26 (R_C - the standard method for ordering cosmic ray data) yield significantly different time-
27 integrated scaling predictions when compared to each other and to results using the earlier
28 models. In addition, predictions of each new model using R_C are tested empirically using recently
29 published production rate calibration data for both ^{10}Be and ^3He , and compared to predictions
30 using corresponding time-varying geocentric dipolar R_C formulations and a static geocentric
31 axial dipole (GAD) model. Results for the few calibration sites from geomagnetically sensitive

regions suggest that the Pavón-Carrasco et al. (2014) time-varying dipolar model tends to predict sea level, high latitude production rates more in line with those from calibration sites not affected by geomagnetic variations. This suggests that uncertainties arising from hemispheric and temporal sampling biases in the Holocene spherical harmonic models considered here, combined with the currently limited spatial and temporal distribution of production rate calibration sites as empirical tests, limit the robustness of the non-dipole aspects of these models for production rate scaling. These analyses should be revisited as such models improve and additional calibration sites become available.

Keywords

Geomagnetic field; spherical harmonic; cutoff rigidity; scaling factor; dipole

1.0 Introduction

The geomagnetic field is a key influence on the distribution of charged primary cosmic ray particles incident on the Earth's atmosphere. This spatial variation is reflected in the resulting atmospheric cascade of secondary cosmic rays, some of which interact with terrestrial materials to yield in situ cosmogenic nuclides. Models of how the production rates of these nuclides vary in time and space therefore must account for both geographic variability associated with position within the geomagnetic field and variability arising from time-dependent changes in field strength.

Early representations of the geomagnetic field in cosmic ray and cosmogenic nuclide research relied on static dipolar approximations to the field (e.g., Lal, 1958; Lal, 1991; Lal and Peters, 1967; Rose et al., 1956; Simpson, 1951), since the dipole component comprises ca. 90% of the modern field (Butler, 1992). Nishiizumi et al. (1989) recognized the need to account for

time-dependent geomagnetic effects on estimating in situ cosmogenic ^{10}Be and ^{26}Al production rates from their measured concentrations, but assumed simple dipolar intensity changes. Subsequent models accounted for time-dependent geomagnetic variation using various geocentric dipolar models driven by separate records of paleointensity and paleomagnetic pole position (e.g., Ohno and Hamano, 1992). Dunai (2000) presented a model for scaling in situ cosmogenic nuclide production rates with altitude and latitude that attempted to include non-dipole field effects by adapting a dipolar field approximation incorporating modern geomagnetic inclination measurements. Dunai (2001) expanded on that with a time-varying model adapted to use paleo-inclination records (to approximate non-dipole field effects) and virtual axial dipole moment (VADM) reconstructions (e.g., Guyodo and Valet, 1999; Yang et al., 2000).

Desilets and Zreda (2003) and Lifton et al. (2005) subsequently published in situ cosmogenic nuclide production rate scaling models that accommodated both dipole and non-dipole field effects on cosmic rays using numerically derived effective vertical cutoff rigidities (R_C), a measure of the energy required for primary cosmic rays to penetrate the geomagnetic field to interact with the atmosphere at a given location (see discussion in Lifton et al., 2008). R_C values are computed by numerically tracing the paths of vertically incident antiprotons outward from the Earth's surface to infinity using high-order, static spherical harmonic representations of the modern geomagnetic field, to identify plausible trajectories vs. physically impossible trajectories that arise due to the presence of the solid Earth – a process known as trajectory tracing (e.g., Cooke et al., 1991; Shea et al., 1968). R_C is widely accepted as one of the most accurate means of ordering cosmic-ray measurements (e.g., Grieder, 2001). Still, these scaling models relied on dipolar representations to model time-dependent fluctuations in the paleo-geomagnetic field – in

large part because millennial-scale, time-dependent, high-order spherical harmonic models were lacking.

This changed when Korte and Constable (2003) first developed such a model (CALS3k.1) spanning the last 3,000 years, based on a global paleomagnetic dataset comprising lake sediment and archeomagnetic time series. The model combined a spatial spherical harmonic inversion with a temporal cubic B-spline fit. Using a newer and larger global data compilation (Korte et al., 2005), Korte and Constable (2005a) subsequently extended their original model to cover 0-7 ka (CALS7k.2). Lifton et al. (2008) used this model to generate global trajectory-traced R_C grids at 500-year intervals over that period. Contrary to the common assumption in cosmogenic nuclide studies that non-dipole effects are transient and average out relatively rapidly (e.g., Gosse and Phillips, 2001), that study indicated that time-integrated non-dipole effects could persist for millennia – a significant finding since a prominent application for in situ cosmogenic nuclides is surface exposure dating over the past ca. 20 ka. This work builds on that study and compares the implications for cosmogenic nuclide scaling of two new spherical harmonic paleomagnetic models that span the Holocene, along with corresponding time-dependent dipolar implementations derived from those models as well as a static dipolar model.

1.1 Geomagnetic records commonly in use

The CRONUS online calculator (Balco et al., 2008) is one of the most commonly used tools to calculate surface exposure ages and/or steady-state erosion rates from in situ cosmogenic nuclide measurements. The geomagnetic framework in that calculator utilizes the CALS7k.2 R_C grids from Lifton et al. (2008) from 0-7 ka, coupled with global geocentric axial dipolar (GAD) R_C models for older ages (Balco et al., 2008; Elsasser et al., 1956). From 7-12 ka, the Virtual Dipole Moment (VDM) model of Yang et al. (2000), based on volcanic and archeomagnetic

paleointensity and directional data, is used to drive a GAD R_C model. From 12 ka- 800 ka, on the other hand, the calculator drives a GAD R_C model using the SINT-800 global Virtual Axial Dipole Moment (VADM) model (Guyodo and Valet, 1999). VADMs differ from VDMs in that VADMs are derived only from paleointensity data, while VDMs include directional information as well. SINT-800 is based on 33 stacked paleointensity records from broadly distributed oceanic sediment cores, providing global coverage.

Lifton et al. (2014) updated this framework to include a newer continuous geomagnetic model with significantly higher temporal and spatial resolution, covering the last 3 ka (CALS3k.3) (Korte et al., 2009). They generated global grids of R_C values at 100-year intervals from CALS3k.3 from 0-3 ka, as well as from CALS7k.2 from 3-7 ka, in contrast to the 500-year intervals utilized by Lifton et al. (2008) and Balco et al. (2008) (Figure 1). While the geomagnetic records are referenced to the 0 ka of radiocarbon dating (“present” being 1950 CE), Lifton et al. (2014) expanded that time series to allow for recent *in situ* cosmogenic sampling by adding R_C grids generated from decadal Definitive Geomagnetic Reference Fields (DGRFs) covering 1950-2010 (Finlay et al., 2010).

Rather than use a simple dipolar R_C model beyond 7 ka (e.g., Elsasser et al., 1956), Lifton et al. (2014) generated trajectory-traced R_C values using a GAD field with variable dipole moment, fit by a 6th-order polynomial of latitudinal cosines – an approach similar to that of Desilets and Zreda (2003). This formulation was then driven by a hybrid paleointensity reconstruction based on GLOPIS-75 (Laj et al., 2004) and PADM2M (Ziegler et al., 2011). GLOPIS-75 is a high-resolution global VADM model from 0-75 ka that is calibrated with the Yang et al. (2000) data and other volcanic paleointensities <20 ka. Lifton et al. (2014) used GLOPIS-75 from 7-18 ka, at which point the long-term dipole moment record was switched to PADM2M since both records

exhibited similar values and trends at 18 ka. PADM2M was selected over long-term VADM models such as SINT-800 (Guyodo and Valet, 1999) or SINT-2000 (Valet et al., 2005) because it was designed to address bias in recovering geomagnetic variability from VADM datasets.

This geomagnetic framework drives the new CRONUScalc online calculator (Marrero et al., 2015, <http://web1.itc.ku.edu:8888/1.0/>). Differences between time-integrated scaling factors generated using the LSD flux-based scaling model of Lifton et al. (2014) and this framework, relative to those predicted with LSD using a static trajectory-traced modern GAD model (Lifton et al., 2014), are presented in Figure 1 for comparison, assuming time-integrated exposures at sea level of 2, 5, 8, and 12 ka. Common to the Lifton et al. (2014) framework and the GAD are atmospheric conditions based on the ERA-40 re-analysis of mean sea level pressure and 1000-mb temperature (Uppala et al., 2005), and solar modulation effects modeled following Lifton et al. (2014).

The resulting framework predicts a couple of notable persistent features relative to the GAD model (Figure 1). First, sea level scaling factors in the Northern Hemisphere mid- and low latitudes are typically lower than those predicted by the GAD. This effect is particularly pronounced in the Northern Hemisphere in the north Pacific Ocean, Middle East, and north Atlantic Ocean, and is strongest in times of a strong dipolar field (Figure 2), when scaling factor differences of greater than 15% are predicted relative to a GAD. This trough-like pattern is generally stable throughout the 12 ka modeled period, but decreases in magnitude as the time-integrated effects of a lower dipole moment in the early to middle Holocene are factored in. The weaker dipole moment in the early to middle Holocene also leads to prediction of a corresponding ridge-like pattern at Southern Hemisphere low to mid-latitudes – for 8 ka exposures the Lifton et al. (2014) scaling factors in those regions exceed those of a GAD by > 5-

10%, whereas for a strong dipole over 2 ka of exposure the Lifton et al. (2014) model generally predicts scaling factors less than a GAD by a similar amount at those latitudes. An additional persistent feature of interest is a relative scaling factor high found in the southern Pacific over New Zealand – it is most prominent when the dipole is weaker in the 8 ka model grid.

2.0 New Geomagnetic Records

Recently, two new time-dependent spherical harmonic models have been published that extend through the Holocene (Korte and Constable, 2011; Korte et al., 2011; Pavón-Carrasco et al., 2014). Both are based on the GEOMAGIA50v2 database of archeomagnetic and volcanic paleomagnetic measurements (Donadini et al., 2009; Korhonen et al., 2008), but Korte and Constable (2011) and Korte et al. (2011) extend this with numerous sedimentary paleomagnetic records from lacustrine and oceanic cores. Pavón-Carrasco et al. (2014) exclude sedimentary records from their model, but add in more recent volcanic and archeomagnetic datasets.

2.1 CALS3k.4 and CALS10k.1b

Building on the modeling approach of CALS3k.3 (Korte et al., 2009) and CALS7k.2 (2005a), the new CALS3k.4 (Korte and Constable, 2011) and CALS10k.1b (Korte et al., 2011) models of the Holocene geomagnetic field extend the earlier models significantly, with improved data coverage and more sophisticated modeling techniques. Both new models are based on the same compilation (Korte and Constable, 2011) from 0-12 ka, incorporating archeomagnetic/volcanic records extended with sedimentary paleomagnetic datasets. Almost 80% of the data are from the 0-3 ka time period – CALS3k.4 is based on this subset, incorporating ca. 4800 more sediment data than CALS3k.3, and 163 more archeomagnetic data. The predominance of the data from that time interval enables a higher resolution model < 3 ka,

compared to CALS10k.1b that spans 0-10 ka. To boost data coverage for ages > 3 ka, CALS10k.1b also incorporates 75 sedimentary paleomagnetic records, vs. 42 for CALS7k.2. Although the compilation extends to 12 ka, the model stops at 10 ka to mitigate boundary effects in the inversion (Korte et al., 2011).

2.2 SHA.DIF.14k (Pavón-Carrasco et al., 2014)

Pavón-Carrasco et al. (2014) present an alternative model to CALS10k.1b that extends to 14 ka. They follow a modeling approach similar to that of Korte et al. (2011) but restrict their analysis to purely archeomagnetic and volcanic paleointensity data from GEOMAGIA50v2, updated with 311 additional data published since Donadini et al. (2009). The resulting compilation, comprising over 13,000 data points, is even more strongly biased to young ages than CALS10k.1b – ca. 83% of the data are from 0-3 ka, and only 3% of the data are from >8 ka. The data were inverted using a spherical harmonic model in space and a temporal B-spline fit over the last 14 ka – the resulting model is known as SHA.DIF.14k.

2.3 Time-dependent R_C framework

The implications of each of these models for in situ cosmogenic nuclide production rate scaling were investigated using the LSD flux-based model and a framework modified from that of Lifton et al. (2014). For the Korte et al. models, CALS3k.4 was used for the period 0-3 ka, while CALS10k.1b was used from 3-10 ka; SHA.DIF.14k was used from 0-14 ka. Spherical harmonic coefficients were generated at 100-year intervals from 0-3 ka (0 ka corresponding to radiocarbon Modern, or 1950) to capture the higher resolution of each model in that time span, with 200-year intervals beyond that to 10 ka for CALS10k.1b or 14 ka for SHA.DIF.14k. GLOPIS-75 VADM's were used at 200-year intervals to 75 ka, followed by PADM2M at 1000-

year intervals to 800 ka, and 2000-year intervals to 2 Ma. The interval spacing was adjusted from that of Lifton et al. (2014) to improve computational speed while remaining faithful to the temporal variability in each model (considering the time-integrated nature of in situ cosmogenic nuclide inventories), and the GLOPIS-75/PADM2M transition point was shifted to incorporate the higher temporal resolution of GLOPIS-75 (relative to that of PADM2M) throughout its duration.

R_C values for each time step were generated on a global 5° latitude (85° to -85°) by 15° longitude (0° to 360°) grid from the spherical harmonic coefficients for 0-10 ka (CALS3k.4/CALS10k.1b) and 0-14 ka (SHA.DIF.14k) using trajectory-tracing software, following Lifton et al. (2014; 2008). For comparison with each spherical harmonic model (Section 3), corresponding time-varying geocentric dipolar R_C (R_{CD}) values were calculated by first calculating dipole moments and paleopole positions from the respective spherical harmonic coefficients at the time steps specified above (Figure 2). Geomagnetic latitudes of sites of interest were calculated from the paleopole positions, and the trajectory-traced geocentric dipole model (not a GAD in this case since the pole doesn't necessarily coincide with the Earth's spin axis) of Lifton et al. (2014) was then used to generate R_{CD} values for the time series. R_{CD} values for times beyond the end of each spherical harmonic (or time-dependent dipolar) model were calculated using the GAD formulation of Lifton et al. (2014), geographic latitude, and the GLOPIS-75/PADM2M VADM record.

2.3.1 Dipole moment variation

One issue that occurs at the transition from the spherical harmonic CALS7k.2 model to the VADM models is that there is a step increase in dipole moment at that point, from the former to the latter (e.g., Balco et al., 2008) (Figure 2). Korte and Constable (2005b) argued that the

CALS7k.2 dipole moment is lower than the VADM-derived dipole moment because some of the spectral power of the geomagnetic field is able to be partitioned into higher order harmonics in CALS7k.2 and other spherical harmonic models, whereas the entire geomagnetic power spectrum is collapsed onto the dipole in the VADMs. Due to the lesser geomagnetic influences on scaling at middle and high latitudes, and the time-integrated nature of in situ cosmogenic nuclide production, the effect of this step is typically small unless the age range of interest is proximal to the step.

Nonetheless, a discontinuity can be an issue any time two models/records are combined. The youngest portion of GLOPIS-75 (< 20 ka) is based on the Yang et al. (2000) dataset augmented by additional volcanic paleomagnetic records. As such, the value of the VADM side of the step should remain similar to that observed in Balco et al. (2008) in the current analysis. Figure 2 presents the temporal variation of dipole moment predicted by each of the spherical harmonic models considered here (quadratic sum of g^1_0 , g^1_1 , and h^1_1 terms) as well as a compilation from VADMs calculated from the GEOMAGIA50v1 database for 0-10 ka (Knudsen et al., 2008; Korhonen et al., 2008). Comparison of each model indicates general agreement over the last 3 ka between CALS3k.3, CALS7k.2, CALS10k.1b, and SHA.DIF.14k, while CALS3k.4 predicts somewhat lower dipole moments than the others from ca. 0.5-1.5 ka. Korte and Constable (2011) attribute this latter effect to increased data coverage in the newer model that allows greater spectral power to reside in non-dipole aspects of the field. All predict generally lower values than the VADM record from 1-3 ka. Prior to 3 ka, CALS10k.1b and SHA.DIF.14k generally agree with the VADMs until ca. 7.5 ka, at which point CALS10k.1b predicts ca. 10% lower values than the VADMs until 10 ka. SHA.DIF.14k tends to follow the VADM record the most closely of models over the 10 ka period, although with oscillations of higher frequency and amplitude.

CALS7k.2 tends to deviate significantly below the other two Holocene models and the VADM, likely due to the lack of sufficient data prior to 3 ka in the earlier model (Korte et al., 2011). At any rate, the previously noted dipole moment discontinuity between the new models and the VADM is greatly reduced compared to CALS7k.2 (Figure 2). The general consistency between dipole moments predicted by CALS10k.1b, SHA.DIF.14k, and the VADM is likely due to each being based on essentially the same underlying dataset (GEOMAGIA50v1 or v2). On the other hand, disparities between CALS10k.1b and SHA.DIF.14k can be attributed to the inclusion of numerous sedimentary records in the former (Korte et al., 2011), as well as differences in modeling techniques.

2.4 Holocene R_C variation effects on scaling

Predicted time-integrated scaling effects of the global R_C grids generated for sea level using each new model were compared to those of static GAD models through the Holocene, as in Figure 1. Results indicate significant differences between the Lifton et al. (2014) geomagnetic framework and each new model, as well as between the new models themselves (Figures 3 and 4). Scaling predictions using the new Korte and Constable framework show generally similar patterns to those using the Lifton et al. (2014) framework, but with shallower negative predictions relative to the GAD and correspondingly higher positive estimates, particularly in the Southern Hemisphere (Figures 1a and 3a). Overall, the amplitude of the variations using the CALS3k.4/CALS10k.1b framework relative to those of a GAD are greater and more persistent temporally than those using the Lifton et al. (2014) framework (Figures 1 and 3). For example, the magnitude of the early to mid-Holocene relative scaling factor high in the vicinity of New Zealand suggested in the 8 ka panel of Figure 1c is significantly greater in the new framework, and extends more prominently across the equator into southern China and Tibet. This feature is

significant enough that it persists into the earliest Holocene as indicated on the time-integrated 12 ka panel of Figure 3d. On the other hand, this feature is not present in the scaling predictions of the SHA.DIF.14k framework (Figure 4). In general the pattern of time-integrated scaling factors relative to a GAD for that framework is more similar to that of Lifton et al. (2014) in the late Holocene than those using the CALS3k.4/CALS10k.1b framework, but with a broader and more pronounced relative low in the north Pacific mid-latitudes. In fact, most of the predicted relative time-integrated scaling factors throughout the Holocene for SHA.DIF.14k are less than those using a GAD, and the global pattern has much less structure than that of CALS3k.4/CALS10k.1b. This likely reflects the lack of the additional sedimentary paleomagnetic datasets of the more recent CALS models in the SHA.DIF.14k model (see below).

3.0 Discussion

Given the different scaling predictions derived using alternative geomagnetic models, the next logical step is to attempt to evaluate which model yields the most globally consistent results. Implementing alternative geomagnetic models in a flexible cosmogenic nuclide scaling framework such as that of Lifton et al. (2014) enables empirical tests of each model's efficacy. In principle, one could use a set of globally distributed, high-quality production rate calibration sites spanning a range of exposure ages as such a test. In that case, the best-performing framework would be the one that reduces the production rate derived from each site to a single reference value (within uncertainties), assuming other site-specific parameters (i.e., atmospheric pressure, erosion, etc.) are adequately described. A number of such calibration sites have been published recently for in situ cosmogenic ^{10}Be (Table 1) (Balco et al., 2009; Ballantyne and Stone, 2012; Claude et al., 2014; Fenton et al., 2011; Goehring et al., 2012; Kaplan et al., 2011; Kelly et al., 2015; Lifton et al., 2015; Martin et al., 2015; Putnam et al., 2010; Young et al.,

2013). Furthermore, recent additions to the ^3He calibration dataset previously compiled by Goehring et al. (2010) extend its geographic and temporal range, making it an attractive option for this purpose as well (Table 2) (Ackert et al., 2003; Amidon and Farley, 2011; Blard et al., 2006; Blard et al., 2013; Cerling and Craig, 1994; Dunai and Wijbrans, 2000; Eaves et al., 2015; Foeken et al., 2012; Goehring et al., 2010; Kurz et al., 1990; Licciardi et al., 1999; Licciardi et al., 2006).

One of the criteria suggested by the CRONUS-Earth project for well-characterized calibration sites was that there be multiple samples analyzed at each site to account for possible geological variability (e.g. Kelly et al., 2015; Lifton et al., 2015). Calibration sites with only single sample measurements were thus excluded from this analysis, comprising 2 sites for the ^{10}Be dataset and 13 sites for ^3He dataset (see notes on Tables 1 and 2).

Reference production rates at sea level and high latitude (SLHL) were calculated for each remaining site separately using CALS3k.4/CALS10k.1b and SHA.DIF.14k, for both R_C and R_{CD} formulations, as well as for a static GAD R_{CD} model, using the respective nuclide-specific form of the LSD scaling model (Lifton et al., 2014) (Tables 1 and 2) and MATLAB code modified from Balco et al. (2008), referenced to 2010. Corrections for topographic shielding, snow cover, and erosion followed the original publications. Predicted SLHL production rates for each geomagnetic framework and each nuclide were subsequently screened for outliers using Peirce's Criterion (Ross, 2003), a more robust version of Chauvenet's Criterion that allows for multiple outliers. For the ^{10}Be calibrations, this analysis indicated that one site, the Grotlandsura site of Fenton et al. (2011), was consistent with the entire dataset for the CALS3k.4/CALS10k.1b R_C scenario, but was inconsistent with the results from the other scenarios, even with all corrections suggested by those authors. As such, it was kept for consideration for the former scenario but

excluded from the latter ones. Similarly, predicted ^3He production rates for the Pohina and Awawa Kahao flows from Kurz et al. (1990) were rejected as inconsistent with the dataset as a whole – in this case for all temporally varying scenarios (only the Awawa Kahao flow was rejected from the static GAD case).

Both arithmetic and inverse error-weighted means were subsequently calculated from each dataset for comparison. Uncertainties in the weighted means were calculated as the greater of either the error in the weighted mean (Bevington and Robinson, 2003, Eq. 4.19) or the weighted average variance (Bevington and Robinson, 2003, Eqs. 4.22 and 4.23). All uncertainties are quoted as 1σ . Normal kernel density estimates (“camelplots”) for each nuclide were calculated for each framework, and are presented in the Supplemental Material (Figure S1- ^{10}Be and Figure S2- ^3He). Given the scatter among sites (particularly for ^3He), the arithmetic mean and standard deviation is preferred here. The ranges (maximum – minimum) of production rate values derived with each framework are also presented on Tables 1 and 2.

The resulting trimmed datasets for each geomagnetic scenario yielded mean SLHL production rates that exhibited small but systematic differences from each other, for both nuclides. Mean production rates calculated using CALS3k.4/CALS10k.1b were generally slightly lower than those based on SHA.DIF.14k, and those calculated using R_C were somewhat less than those incorporating R_{CD} values. Each geomagnetic scenario yielded datasets that were generally internally consistent, and arithmetic means were essentially indistinguishable from each other within 1σ standard deviation.

For ^{10}Be , arithmetic mean values ranged from 3.91 ± 0.20 at $\text{g}^{-1} \text{y}^{-1}$ (CALS3k.4/CALS10k.1b, R_C) to 3.99 ± 0.17 at $\text{g}^{-1} \text{y}^{-1}$ (SHA.DIF.14k, R_{CD}), with corresponding coefficient of variations (CoV's) of 5.2 and 4.2%, respectively (Table 1). Inverse error-weighted means showed a similar

pattern, ranging from 3.90 ± 0.06 at $\text{g}^{-1} \text{y}^{-1}$ to 4.04 ± 0.04 at $\text{g}^{-1} \text{y}^{-1}$, respectively – distinct at 1σ . Much of the agreement between the different geomagnetic frameworks in this case is likely due to the fact that most of the ^{10}Be calibration sites (15 of 18) considered here are from middle and high latitude regions that are typically insensitive to geomagnetic influences. Three sites, however, are particularly sensitive to predictions made by the competing frameworks: the New Zealand site of Putnam et al. (2010), Peruvian site of Kelly et al. (2015), and the Bolivian site of Martin et al. (2015) (Figures 3 and 4, Table 1). In those cases, the SHA.DIF.14k model framework yielded results much closer to both the arithmetic and weighted means, and the R_{CD} formulation yielded slightly better results than the R_C framework (note the predicted ranges). This pattern is also reflected in the CoV for each dataset relative to those of the CALS3k.4/CALS10k.1b frameworks (Table 1). Interestingly, the static GAD model also yielded an overall fit with this dataset comparable to the time-varying SHA.DIF.14k R_{CD} framework, but was not as successful as the latter in aligning the sensitive sites (Table 1).

Another way to visualize how each geomagnetic framework performed with this calibration dataset is to plot the normalized production rate residuals (relative to the arithmetic mean in this case: $P_{\text{Site}}/P_{\text{Mean}} - 1$) for each site for each framework (Figure 5). For most mid- and high latitude sites, inter-site scatter is relatively evenly distributed overall above and below the mean, and each of the frameworks predicts similar results. For the sensitive sites, though, significant differences among frameworks are apparent, particularly for the Putnam et al. (2010) and Kelly et al. (2015) sites.

The ^3He results exhibited significantly higher inter-site scatter than the ^{10}Be datasets, but still with similar patterns (Table 2, Figure 6). One should note that this calibration site dataset includes a few sites with ages >100 ka, in which the effects of erosion and the potential for

geographic biases in the long-term geomagnetic records may contribute to the scatter. Only olivine samples were included, except as indicated on Table 2. Arithmetic mean values ranged from 114.0 ± 16.3 at $\text{g}^{-1} \text{y}^{-1}$ (CALS3k.4/CALS10k.1b, R_C) to 116.4 ± 16.2 at $\text{g}^{-1} \text{y}^{-1}$ (SHA.DIF.14k, R_{CD}), with corresponding CoV's of 14.3 and 13.9%, respectively – approximately 3x those for ^{10}Be (Table 2). Inverse error-weighted means showed a similar pattern, spanning 118.5 ± 2.5 at $\text{g}^{-1} \text{y}^{-1}$ to 120.8 ± 2.6 at $\text{g}^{-1} \text{y}^{-1}$, respectively – but were not distinguishable at 1σ . The pattern for ^3He using the R_C models was similar to those of ^{10}Be in that SHA.DIF.14k had a slightly lower CoV than the CALS3k.4/CALS10k.1b results for each cutoff formulation, yet the CoV for the time-varying R_{CD} model with CALS3k.4/CALS10k.1b was slightly better than the corresponding SHA.DIF.14k version (but not significantly so). Both SHA.DIF.14k models predicted smaller production rate ranges than the corresponding CALS3k.4/CALS10k.1b frameworks; the SHA.DIF.14k R_C model yielded the lowest range (still 82 at $\text{g}^{-1} \text{y}^{-1}$!). Overall, the static GAD results are more discrepant than those of the time-dependent models.

For these datasets, the Hawaiian sites of Kurz et al. (1990) and Blard et al. (2006) might be of value in discerning the efficacy of the various models, since they lie deep within the relative production rate low (vs. a GAD) in the North Pacific, with magnitude differences particularly relevant for the 2 and 5 ka exposure times depicted in Figures 3 and 5. However, both studies exhibit significant scatter relative to the mean, decreasing their usefulness in this regard. The New Zealand site of Eaves et al. (2015) potentially can also inform this analysis – results for this site in the CALS3k.4/CALS10k.1b R_C framework agree well with the global mean for that framework, while the other frameworks perform more poorly (Figure 6). The Pocolli Fan site of Blard et al. (2013) is a third geomagnetically sensitive location in this dataset, similar to that of

Kelly et al. (2015). Production rate predictions using both the CALS3k.4/CALS10k.1b and SHA.DIF.14k R_C frameworks agree most closely with their respective global means, contrary to the ^{10}Be results – the R_{CD} results for both are inconsistent with the weighted means at 1σ as is the static R_{CD} framework.

Globally the greatest discrepancies between the time-dependent frameworks occur in the Southern Hemisphere, while each framework predicts similar SLHL values for Northern Hemisphere calibration sites (Figures 5 and 6). This likely reflects the preponderance of Holocene paleomagnetic data from the Northern Hemisphere relative to the Southern, used in constructing the spherical harmonic models (e.g., Korte et al., 2011; Nilsson et al., 2014; Panovska et al., 2015; Pavón-Carrasco et al., 2014). For example, 97% of the GEOMAGIA50v2 archeomagnetic and volcanic data used in constructing the SHA.DIF.14k model are from the Northern Hemisphere (Pavón-Carrasco et al., 2014). Temporal undersampling is also an issue in these models, particularly for the early Holocene. A new study by Panovska et al. (2015) notes that the SHA.DIF.14k model relies on only 355 values from the western coastal U.S. and Hawaii for the period 8-14 ka (i.e., both temporal *and* spatial undersampling for that period). Even though the incorporation of sediment core data improves the spatial and temporal data coverage for CALS3k.4/CALS10k.1b beyond that of GEOMAGIAv2, the Southern Hemisphere and early Holocene are still significantly under-represented (Korte et al., 2011; Panovska et al., 2015). Panovska et al. (2015) also demonstrate that modeling and inversion techniques are advancing rapidly, improving on the Holocene models considered here.

Taken together, it is clear that there are spatial and temporal shortcomings in both spherical harmonic models, as well as in the spatial and temporal distribution of (and scatter among) calibration sites that potentially could be used to test the models. Overall, the time-dependent

dipolar frameworks perform slightly better than the spherical harmonic frameworks from which they are derived, given the limited temporal and spatial distribution of the calibration sites available for each nuclide. Although the static R_{CD} framework performs well for the ^{10}Be sites, and more poorly for the ^3He dataset, the well-established temporal variation of the geomagnetic field argues against this as a preferred framework.

The small magnitudes of the differences between the models in terms of mean production rates are likely due two main sources. First, as noted previously, the preponderance of calibration sites at locations that are relatively insensitive to geomagnetic influences for both nuclides dilutes the signal from the few sensitive sites significantly in the means. In addition, considerable scatter remains in the ^3He dataset, even after excluding outliers and single-sample sites, making it more difficult to discern site-to-site differences. Placing somewhat greater weight on the higher precision ^{10}Be calibrations, the SHA.DIF.14k dipolar (R_{CD}) model framework tends to yield Holocene scaling results that are generally more consistent at geomagnetically sensitive locations with the corresponding production rate predictions from less-sensitive locations (and dataset means) than other frameworks (Figure S1).

4.0 Conclusions

This paper compares the time-integrated effects of two new time-dependent Holocene spherical harmonic geomagnetic models on cosmogenic nuclide production rate scaling. While each model represents an advance over earlier models due to increased data coverage and more sophisticated modeling techniques, each has significantly different scaling implications, and shortcomings remain. While both the CALS3k.4/CALS10k.1b composite model (Korte and Constable, 2011; Korte et al., 2011) and the SHA.DIF.14k model (Pavón-Carrasco et al., 2014) are based on the same underlying archeomagnetic/volcanic paleomagnetic dataset, the CALS

models include additional sediment core paleomagnetic data to increase geographic and temporal coverage. This leads to major regional differences between the scaling predictions using the two geomagnetic frameworks and the LSD model of Lifton et al. (2014), relative to that using a GAD. These differences are manifested on global scaling factor grids mainly as a stronger and more variable structure in the new CALS models – most prominently as a region of higher scaling factors over New Zealand and southern Asia. Both models tend to predict lower than GAD scaling factors for the northern mid-latitudes, but differ in their magnitudes.

Predicted differences were tested empirically by comparing distributions of SLHL production rates for ^{10}Be and ^3He derived using the nuclide-specific version of LSD and recent calibration datasets. These in turn were compared to SLHL production rate predictions using time-dependent dipolar versions of each model and a static GAD model. Variation among the arithmetic and weighted means calculated from each model framework is low due to the dominant middle to high latitude calibration site distributions diluting local variability from regions predicted to be geomagnetically sensitive. Overall, though, the temporally varying dipolar frameworks do a slightly better job than the spherical harmonic versions in reducing inter-site SLHL production rate scatter given spatial and temporal distribution of calibration sites for each nuclide. Considering the significantly greater scatter in the ^3He calibration dataset, the ^{10}Be results are judged to be more robust in this case. Looking solely at calibrations from the sensitive regions, the dipolar SHA.DIF.14k framework does a somewhat better job overall of bringing ^{10}Be production rates from those sites into agreement with sites from areas generally unaffected by geomagnetic variation. This suggests that uncertainties arising from hemispheric and temporal sampling biases in the Holocene spherical harmonic models considered here, combined with the currently limited spatial and temporal distribution of production rate

calibration sites as empirical tests, limit the robustness of the non-dipole aspects of these models for production rate scaling purposes at present.

Moving forward, identifying additional high-quality calibration sites for multiple nuclides in locations situated to distinguish between various model predictions should be a priority. In addition, as paleomagnetic data coverage continues to improve in both time and space (particularly in the Southern Hemisphere and early Holocene) and Holocene spherical harmonic modeling and inversion techniques advance (e.g., Panovska et al., 2015), analyses such as those presented here will be worth revisiting.

One should note that this analysis does not include potential effects of time-varying atmospheric structure or vertical ground motion associated with tectonic or isostatic drivers. Given the dominance of altitudinal over latitudinal (geomagnetic) scaling effects on cosmogenic nuclide production, temporal changes in the atmospheric pressure over a sampling site could conceivably contribute to observed scatter in the calibration site data. Research into how best to account for such effects within the LSD framework is ongoing.

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Figure Captions

Figure 1 – Global grids showing the percentage differences between time-integrated LSD flux-based scaling factors predicted using R_C (effective vertical cutoff rigidity) values derived from the CALS3k.3/CALS7k.2 time-dependent geomagnetic framework relative to those using a static geocentric axial dipole (GAD). Panels A-D show results integrated over model exposure times of 2, 5, 8, and 12 ka, respectively. Note the generally low relative scaling predictions in the northern mid-latitudes in the mid- to late Holocene, and the higher relative scaling results straddling the equator and extending southward to New Zealand in the early Holocene.

Figure 2 – Comparison of Holocene dipole moment estimates for spherical harmonic paleomagnetic models discussed in the text. The virtual axial dipole moment (VADM) model of Knudsen et al. (2008) is derived from paleointensity measurements in an early version of the archeomagnetic/volcanic compilation used in the spherical harmonic models (GEOMAGIA50v1) (Korhonen et al., 2008). Note the step discontinuity (indicated by circles) between the CALS3k.3/CALS7k.2 dipole moment and that of the VADM – similar to that in both Balco et al. (2008) and Lifton et al. (2014).

Figure 3 – Global grids showing the percentage differences between time-integrated LSD flux-based scaling factors predicted using R_C values derived from the CALS3k.4/CALS10k.1b time-dependent geomagnetic framework, relative to those using a static GAD. Panels A-D show results integrated over model exposure times of 2, 5, 8, and 12 ka, respectively. Note the broadly similar hemispheric patterns

compared to CALS3k.3/CALS7k.2 in Figure 1 but with shallower negative predictions relative to a GAD and correspondingly higher positive estimates, particularly in the Southern Hemisphere. Overall a stronger, higher resolution, and more persistent structure is evident, in particular the magnitude of the late Holocene Northern Hemisphere relative scaling low and the early Holocene relative scaling high over New Zealand and southern Asia.

Figure 4 – Global grids showing the percentage differences between time-integrated LSD flux-based scaling factors predicted using R_C values derived from the SHA.DIF.14k geomagnetic framework, relative to those using a static GAD. Panels A-D show results integrated over model exposure times of 2, 5, 8, and 12 ka, respectively. Note the greater similarity to the CALS3k.3/CALS7k.2 results (Figure 1) than to those of CALS3k.4/CALS10k.1b (Figure 3). A key difference from the latter is the broader Holocene Northern Hemisphere relative scaling low and the lack of the early Holocene relative scaling high over New Zealand and southern Asia.

Figure 5 – Normalized ^{10}Be SLHL production rate residuals (relative to the arithmetic mean) for each calibration site, for all five geomagnetic framework scenarios considered. Note that significant differences between models are evident only in the Southern Hemisphere mid- and low latitude sites.

Figure 6 – Normalized ^3He SLHL production rate residuals (relative to the arithmetic mean) for each calibration site, for all five geomagnetic framework scenarios considered. Note that significant differences between time-dependent models are evident only in the Southern Hemisphere mid- and low latitude sites.

696 **Table 1 – ¹⁰Be nuclide-specific production rate calibration comparisons**

Study	Site	Latitude ⁺ (°N)	Longitude ⁺ (°E)	Altitude ⁺ (m asl)	Age (ka) [#]	Effective Vertical <i>R_C</i>		Time-varying <i>R_{CD}</i>		Static <i>R_{CD}</i>
						CALS3k.4 CALS10k.1b ⁺⁺	SHA.DIF.14k ⁺⁺	CALS3k.4 CALS10k.1b ⁺⁺	SHA.DIF.14k ⁺⁺	GAD ⁺⁺
Balco et al. (2009)*	Ashuelot	43.0146	-72.3251	182	15.07 ± 0.30	4.28 ± 0.09 (0.7)	4.28 ± 0.09 (0.7)	4.27 ± 0.09 (0.7)	4.24 ± 0.08 (0.7)	4.19 ± 0.08 (0.7)
	Baffin Island	69.8327	-70.4967	67	8.16 ± 0.25	3.72 ± 0.29 (0.4)	3.72 ± 0.29 (0.4)	3.72 ± 0.29 (0.4)	3.72 ± 0.29 (0.4)	3.72 ± 0.29 (0.4)
	Cobblestone	44.8470	-73.5891	234	13.18 ± 0.13	3.87 ± 0.29 (0.7)	3.87 ± 0.29 (0.7)	3.87 ± 0.29 (0.7)	3.84 ± 0.28 (0.7)	3.78 ± 0.28 (0.7)
	Littleton	44.3021	-71.6668	385	13.90 ± 0.25	4.21 ± 0.12 (0.1)	4.21 ± 0.12 (0.1)	4.20 ± 0.12 (0.1)	4.17 ± 0.12 (0.1)	4.10 ± 0.12 (0.1)
Ballantyne and Stone (2012)	Scottish Highlands	57.3939	-5.6678	301	11.70 ± 0.30	4.03 ± 0.14 (0.2)	4.07 ± 0.14 (0.2)	3.99 ± 0.14 (0.2)	4.04 ± 0.14 (0.2)	4.00 ± 0.14 (0.2)
Claude et al. (2014)	Chironico	46.4208	8.8505	787	13.37 ± 113	3.98 ± 0.24 (2.1)	4.04 ± 0.24 (2.1)	3.83 ± 0.23 (2.1)	3.99 ± 0.24 (2.1)	3.88 ± 0.23 (2.1)
Fenton et al. (2011)	Grotlandsura	68.9113	17.5261	53	11.42 ± 0.11	3.45 ± 0.14 (0.7)	<u>3.45 ± 0.14 (0.7)</u>	<u>3.45 ± 0.14 (0.7)</u>	<u>3.45 ± 0.14 (0.7)</u>	<u>3.45 ± 0.14 (0.7)</u>
	Russenen	69.2139	19.4722	105	10.94 ± 0.08	3.84 ± 0.19 (0.8)	3.84 ± 0.19 (0.8)	3.84 ± 0.19 (0.8)	3.84 ± 0.19 (0.8)	3.84 ± 0.19 (0.8)
Goehring et al. (2012)	Halsnøy	59.7978	5.8047	84	11.60 ± 0.20	4.08 ± 0.12 (2.0)	4.12 ± 0.12 (2.0)	4.06 ± 0.12 (2.0)	4.10 ± 0.12 (2.0)	4.06 ± 0.12 (2.0)
	Oldedalen	61.6663	6.8148	136	5.97 ± 0.06	3.93 ± 0.11 (5.0)	3.96 ± 0.11 (5.0)	3.92 ± 0.11 (5.0)	3.95 ± 0.11 (5.0)	3.92 ± 0.11 (5.0)
Kaplan et al. (2011)	Puerto Bandera	-50.2429	-72.7020	227	12.89 ± 0.24	3.87 ± 0.10 (1.3)	4.04 ± 0.11 (1.3)	3.89 ± 0.1 (1.3)	4.07 ± 0.11 (1.3)	3.90 ± 0.1 (1.3)
Kelly et al. (2015)	Huancane	-13.9473	-70.8914	4857	12.41 ± 0.11	3.59 ± 0.08 (2.5)	3.69 ± 0.08 (2.5)	3.73 ± 0.08 (2.5)	3.96 ± 0.09 (2.6)	3.90 ± 0.09 (2.5)
Lifton et al. (2015)	Promontory Point**	41.2637	-112.4755	1602	18.36 ± 0.30	4.19 ± 0.09 (1.1)	4.22 ± 0.09 (1.1)	4.29 ± 0.09 (1.1)	4.25 ± 0.09 (1.1)	4.20 ± 0.09 (1.1)
Martin et al. (2015)	Challapata	-18.9131	-66.7513	3882	16.07 ± 0.64	3.88 ± 0.22 (0.6)	3.91 ± 0.23 (0.6)	4.04 ± 0.23 (0.6)	4.16 ± 0.24 (0.6)	4.28 ± 0.25 (0.6)
Putnam et al. (2010)	Macaulay	-43.5758	170.6075	1028	9.69 ± 0.05	3.56 ± 0.08 (0.4)	3.96 ± 0.09 (0.4)	3.81 ± 0.08 (0.4)	4.10 ± 0.09 (0.4)	3.88 ± 0.08 (0.4)
Young et al. (2013)	Baffin Island	69.8327	-70.4967	67	8.16 ± 0.25	3.87 ± 0.14 (0.5)	3.87 ± 0.14 (0.5)	3.87 ± 0.14 (0.5)	3.87 ± 0.14 (0.5)	3.87 ± 0.14 (0.5)
	Marrait	69.2844	-50.7566	345	9.24 ± 0.04	3.82 ± 0.08 (0.2)	3.82 ± 0.08 (0.2)	3.82 ± 0.08 (0.2)	3.82 ± 0.08 (0.2)	3.82 ± 0.08 (0.2)
	Tasiussaq	69.1427	-51.0526	143	8.18 ± 0.46	3.75 ± 0.21 (0.1)	3.75 ± 0.21 (0.1)	3.75 ± 0.21 (0.1)	3.75 ± 0.21 (0.1)	3.75 ± 0.21 (0.1)
Arithmetic Mean ⁺⁺						3.91 ± 0.2 [5.2%]	3.96 ± 0.18 [4.5%]	3.94 ± 0.18 [4.5%]	3.99 ± 0.17 [4.2%]	3.95 ± 0.17 [4.2%]
Weighted Mean ⁺⁺						3.90 ± 0.06 [1.6%]	3.99 ± 0.05 [1.2%]	3.96 ± 0.05 [1.2%]	4.04 ± 0.04 [1.0%]	3.98 ± 0.04 [0.9%]
Range ⁺⁺						0.72	0.59	0.57	0.53	0.56

697 **Notes**

- 698 + Mean values for site
699 ++ Units of at g⁻¹ y⁻¹
700 # Referenced to 2010 CE
701 * Single-sample sites excluded: Holyoke and Perry Mountain
702 ** Means of replicate samples used for calibration
703 Italicized and underlined production rate results fail Peirce's Criterion and are excluded from the arithmetic and weighted means, and from further analysis
704 Numbers in parentheses next to site production rates are reduced χ^2 values for each fit
705 Percentages in brackets below mean values are coefficients of variation (CoV)
706

707 **Table 2 – ³He nuclide-specific production rate calibration comparisons**

Study	Site	Latitude ⁺ (°N)	Longitude ⁺ (°E)	Altitude ⁺ (m asl)	Age (ka) [#]	Effective Vertical R_C		Time-varying R_{CD}		Static R_{CD}
						CALS3k.4 CALS10k.1b ⁺⁺	SHA.DIF.14k ⁺⁺	CALS3k.4 CALS10k.1b ⁺⁺	SHA.DIF.14k ⁺⁺	GAD ⁺⁺
Ackert et al. (2003)	Cerro Volcán	-46.6463	-70.7528	448	108.70 ± 2.80	136.5 ± 1.7 (0.8)	137.3 ± 1.8 (0.8)	136.6 ± 1.8 (0.8)	137.5 ± 1.8 (0.8)	139.6 ± 1.8 (0.8)
	Rio Pinturas	-47.0680	-70.8967	902	67.80 ± 3.00	123.3 ± 1.4 (7.1)	124.4 ± 1.5 (7.1)	123.4 ± 1.4 (7.1)	124.7 ± 1.5 (7.1)	125.2 ± 1.5 (7.1)
Amidon et al. (2011)*	Bonneville Flood	42.6030	-114.4513	982	18.36 ± 0.30	125.1 ± 10.6 (0.2)	125.9 ± 10.7 (0.2)	127.1 ± 10.8 (0.2)	126.6 ± 10.7 (0.2)	124.5 ± 10.6 (0.2)
Blard et al. (2006)**	Kaunamano	19.0563	-155.5547	60	8.29 ± 0.08	167.6 ± 15.6 (0.9)	165.4 ± 15.4 (0.9)	162.4 ± 15.1 (0.9)	163.5 ± 15.2 (0.9)	161.4 ± 15 (0.9)
Blard et al. (2013)	Pocolli Fan	-19.8884	-67.6194	3814	15.26 ± 0.50	118.3 ± 3.7 (2.0)	119.5 ± 3.7 (2)	122.9 ± 3.8 (2.0)	127.0 ± 3.9 (2.0)	129.7 ± 4 (2.0)
Cerling & Craig (1994)***	Bonneville Flood	42.8556	-112.4125	1380	18.36 ± 0.30	109.5 ± 3.1 (0.8)	110.2 ± 3.2 (0.8)	111.3 ± 3.2 (0.8)	110.9 ± 3.2 (0.8)	109 ± 3.1 (0.8)
	Tabernacle Hill	38.9333	-112.5250	1455	18.26 ± 0.30	120.0 ± 2.6 (0.7)	120 ± 2.6 (0.7)	122.7 ± 2.7 (0.7)	121.0 ± 2.6 (0.7)	121.0 ± 2.6 (0.7)
	Yapoah Crater	44.2630	-121.7889	1561	2.51 ± 0.78	102.2 ± 13.1 (1.3)	103.2 ± 13.2 (1.3)	108.1 ± 13.9 (1.3)	106.4 ± 13.7 (1.3)	96.4 ± 12.4 (1.3)
Dunai & Wijbrans (2000)	Atalaya de Femes	28.9190	-13.8280	35	281.0 ± 19.0	115.4 ± 10 (0.1)	115.2 ± 10 (0.1)	115.2 ± 10 (0.1)	115.3 ± 10 (0.1)	130.9 ± 11.4 (0.1)
	Tahiche	29.0120	-13.5391	197	152.0 ± 26.0	112.9 ± 19.3 (0.1)	112.4 ± 19.3 (0.1)	112.5 ± 19.3 (0.1)	112.6 ± 19.3 (0.1)	126.0 ± 21.6 (0.1)
Eaves et al. (2015)	Murimotu	-39.1490	175.4755	826	10.50 ± 0.11	114.4 ± 3.5 (7.7)	131.2 ± 4 (7.7)	127.8 ± 3.9 (7.7)	137.3 ± 4.2 (7.7)	131.1 ± 4 (7.7)
Foeken et al. (2012)	Fogo	14.8916	24.4806	222	125.9 ± 0.7	94.5 ± 4.6 (7.3)	94.3 ± 4.6 (7.3)	94.5 ± 4.6 (7.3)	94.6 ± 4.6 (7.3)	109.6 ± 5.4 (7.4)
Goehring et al. (2010)	Tabernacle Hill	38.9302	-112.5211	1459	18.26 ± 0.30	118.3 ± 2 (1.1)	118.3 ± 2 (1.1)	121 ± 2.1 (1.1)	119.3 ± 2.1 (1.1)	119.3 ± 2.1 (1.1)
Kurz et al. (1990)****	Awawa Kahao	19.7130	-155.5254	1024	8.57 ± 0.09	<u>225.9 ± 9 (0.6)</u>	<u>222.1 ± 8.8 (0.7)</u>	<u>218.5 ± 8.7 (0.7)</u>	<u>220.6 ± 8.8 (0.7)</u>	<u>218.1 ± 8.7 (0.7)</u>
	Kaalaiki	19.1676	-155.6047	28	2.30 ± 0.12	101.1 ± 19.5 (1.9)	109.7 ± 21.2 (1.9)	100.3 ± 19.4 (1.9)	105.1 ± 20.3 (1.9)	91.2 ± 17.6 (1.9)
	Malekule	19.8139	-155.8917	2339	5.53 ± 0.13	79.8 ± 5.1 (3.3)	83.4 ± 5.3 (3.3)	79.3 ± 5 (3.3)	80.7 ± 5.1 (3.3)	72.7 ± 4.6 (3.3)
	Pohina	19.2506	-155.6478	832	0.66 ± 0.05	<u>188.4 ± 26.4 (1)</u>	<u>196.1 ± 27.5 (1)</u>	<u>190.6 ± 26.7 (1)</u>	<u>196.3 ± 27.5 (1)</u>	174.9 ± 24.5 (1.1)
Licciardi et al. (1999)	Clear Lake	44.3664	-121.9889	941	2.91 ± 0.07	111.8 ± 6.2 (1.2)	113.3 ± 6.3 (1.2)	117.7 ± 6.5 (1.2)	116.9 ± 6.5 (1.2)	103.6 ± 5.7 (1.2)
	Lava Butte	43.6812	-121.3817	1282	7.15 ± 0.13	111.8 ± 3.3 (0)	109.1 ± 3.2 (0)	116.5 ± 3.4 (0.1)	110 ± 3.2 (0)	107.3 ± 3.1 (0.1)
	South Belknap	44.2432	-121.8557	1524	2.81 ± 0.02	103.3 ± 4.3 (6.7)	104.8 ± 4.3 (6.7)	109.3 ± 4.5 (6.8)	108.1 ± 4.4 (6.7)	95.7 ± 3.9 (6.7)
	Yapoah Crater	44.2733	-121.7846	1562	2.51 ± 0.78	102.3 ± 2.7 (12.3)	103.3 ± 2.8 (12.3)	108.2 ± 2.9 (12.3)	106.6 ± 2.8 (12.3)	96.6 ± 2.6 (12.4)
Licciardi et al. (2006)	Bürfellshraun	64.0861	-21.7375	35	8.12 ± 0.12	115.3 ± 3.8 (2.9)	115.8 ± 3.8 (2.9)	115.2 ± 3.8 (2.9)	115.4 ± 3.8 (2.9)	115.2 ± 3.8 (2.9)
	Lambahraun	64.3738	-20.5540	452	4.10 ± 0.25	109.5 ± 9.3 (0.6)	109.9 ± 9.3 (0.6)	109.4 ± 9.3 (0.6)	109.6 ± 9.3 (0.6)	109.4 ± 9.3 (0.6)
	Leitahraun	63.9788	-21.4726	268	5.27 ± 0.11	118.4 ± 7.5 (1)	118.8 ± 7.6 (1)	118.3 ± 7.5 (1)	118.5 ± 7.5 (1)	118.3 ± 7.5 (1)
	Þingvallahraun	64.1604	-21.0424	124	10.39 ± 0.08	110.1 ± 4.6 (6.9)	110.6 ± 4.6 (6.9)	110 ± 4.6 (6.9)	110.3 ± 4.6 (6.9)	116.4 ± 4.9 (6.9)
Arithmetic Mean ⁺⁺						114.0 ± 16.3 [14.3%]	115.5 ± 15.8 [13.7%]	116.1 ± 15.6 [13.4%]	116.4 ± 16.2 [13.9%]	115.2 ± 18.5 [16.1%]
Weighted Mean ⁺⁺						118.5 ± 2.5 [2.1%]	119.7 ± 2.5 [2.1%]	120.8 ± 2.4 [2.0%]	120.8 ± 2.6 [2.1%]	119.3 ± 3.1 [2.6%]
Range ⁺⁺						87.8	82.0	83.0	82.9	102.2

Notes

+ Mean values for site
++ Units of $\text{at g}^{-1} \text{y}^{-1}$
Referenced to 2010 CE
* Pyroxene analyzed. All other samples are olivine.
** Single-sample sites excluded: Kapapala, Waimea
*** Single-sample sites excluded: Black Crater, Giant Crater
**** Single-sample sites excluded: Hualalai, Kipuka Nene, Ninole, Hualalai Summit, Mauna Loa picritic flow, Hainoa Crater, Waiaha, Hilo Municipal Golf Course, Puu Anahulu
Italized and underlined production rate results fail Peirce's Criterion and are excluded from the arithmetic and weighted mean, and from further analysis
Numbers in parentheses next to production rates are reduced χ^2 values for each fit
Percentages in brackets below the mean values are coefficients of variation (CoV)

719

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6