Paleomagnetism and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the Plio-Pleistocene Boring Volcanic Field: implications for the geomagnetic polarity time scale and paleosecular variation

Jonathan T. Hagstrum^{*}, Robert J. Fleck, Russell C. Evarts, and Andrew T. Calvert

U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025 USA

^{*} Corresponding author. Tel.: +1 650 329 4672; fax: +1 650 329 4936.

E-mail address: jhag@usgs.gov (J.T. Hagstrum).

A B S T R A C T

Paleomagnetic directions and $^{40}\text{Ar}/^{39}\text{Ar}$ ages have been determined for samples of lava flows from the same outcrops, where possible, for 84 eruptive units ranging in age from 3200 ka to 60 ka within the Boring volcanic field (BVF) of the Pacific Northwest, USA. This study expands upon our previous results for the BVF, and compares the combined results with the current geomagnetic polarity time scale (GPTS). Lava flows with transitional directions were found within the BVF at the Matuyama-Brunhes and Jaramillo-Matuyama polarity boundaries, and replicate ages corresponding to these and other boundaries have been newly ascertained. Although the BVF data generally agree with GPTS chronozone boundaries, they indicate that onset of the Gauss-Matuyama transition and Olduvai subchron occurred significantly earlier than given in the current time scale calibration. Additional comparisons show that the BVF results are consistent with recent statistical models of geomagnetic paleosecular variation.

Keywords: paleosecular variation; paleomagnetism; geochronology; geomagnetic field; lavas

1. Introduction

The Boring volcanic field (BVF) in western Oregon and Washington, USA, (Fig. 1) has recently been the subject of U.S. Geological Survey (USGS) investigations that included detailed geologic mapping, petrographic and geochemical analyses, and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic and paleomagnetic studies (e.g., Evarts et al., 2009; Fleck et al., 2014). A systematic determination of the BVF's eruptive history was undertaken to assess its anomalous neotectonic setting west of

the Cascade arc (e.g., Hildreth, 2007), as well as the magnitude of its concomitant volcanic hazards within the greater Portland and Vancouver metropolitan area. The BVF consists of more than eighty monogenetic volcanic centers, each of which produced relatively small volumes of basalt to low-SiO₂ andesite (Evarts et al., 2009). The duration of most eruptive events was likely no more than a few years to decades. The BVF represents a westward extension of Cascade volcanism across the Portland Basin (Hildreth, 2007), and its eastern boundary is arbitrarily placed at longitude 122°W (Allen, 1975; eastern edge of Fig. 1). In the southern and eastern part of the BVF, Boring lavas overlie low-K tholeiite flows (Evarts et al., 2009) that apparently issued from vents near the axis of the High-Cascade volcanic arc (Conrey et al., 2004).

This paper follows on that of Fleck et al. (2014) in which more than 140 ⁴⁰Ar/³⁹Ar determinations were reported for lava flows and intrusions from within the BVF having ages between ~3200 ka and ~60 ka (Table 1; Fig. 2). Paleomagnetic data were also included from an equivalent number of localities (>160) coincident with, or within the same unit proximal to, the geochronologic sampling sites. To improve age control, duplicate ⁴⁰Ar/³⁹Ar determinations were made for this study on sixteen samples (Table 2), whose ages were near or at chronozone boundaries of the geomagnetic polarity time scale (GPTS; Ogg, 2012; Singer, 2014).

This large data set provides the opportunity to compare these results to recent compilations of the GPTS, and the timing of reversals and excursions of the geomagnetic field during the Late Pliocene and Pleistocene epochs will be the main subject of this paper. Rapidly cooled lava flows can be particularly useful in documenting the ancient geomagnetic field because they provide geologically instantaneous records of the paleofield's characteristics. Moreover, the BVF data set captures transitional fields at two polarity boundaries allowing precise determinations for the timing of these reversals. Also, our data permit us to more tightly bracket

the timing of other field reversals and subchrons within this time period. In addition, we have compared the Boring lavas paleomagnetic data with current statistical models of geomagnetic paleosecular variation and previously published data sets (e.g., Constable and Parker, 1988; Tauxe and Kent, 2004; Johnson et al., 2008).

[Figure 1 near here]

2. Methods

2.1 Paleomagnetism

Oriented samples of Boring lavas and shallow intrusions were collected primarily from artificial (e.g., road, quarry) and stream cut exposures in order to obtain the freshest possible rock. At most sites eight paleomagnetic core samples were drilled and were oriented and marked, prior to removal, using an orienting tool consisting of magnetic and solar compasses and clinometer. Hand samples oriented with a magnetic compass, to be later drilled in the laboratory, were also collected at remote and inaccessible sites to determine a rock unit's polarity.

In the laboratory, usually three 2.2-cm-long specimens were cut from each core sample, and natural remanent magnetizations (NRMs) of specimens from all samples were measured using a three-axis 2G superconducting magnetometer within a magnetically shielded room. The lowermost specimen of the drill core (i.e., least-weathered) was subjected primarily to progressive alternating-field (AF) demagnetization to determine the stability and structure of the specimen's natural remanent magnetization (NRM). Initially a Schonstedt GSD-5 tumbling AF demagnetizer was used, and later AF demagnetizations were accomplished with an automated system sample handling system (Kirschvink et al., 2008). Thermal demagnetizations were done on a smaller number of representative samples, using an ASC TD-48 oven, with a residual field

≤ 10 nT, to determine the reliability of the AF treatments and to provide information on the magnetic carrier mineralogy.

The laboratory work spanned the years from 1983 to 2010, and the AF demagnetization procedure changed during this time period. Initially, one or two specimens from a given site were subjected to pilot demagnetizations of five or more steps at peak inductions of up to 100 mT, and the remaining specimens to a single or “blanket” demagnetization, usually at peak inductions between 30 to 50 mT, to remove any spurious or secondary components of magnetization identified in the pilot demagnetizations. By 2010, all specimens were being subjected to three or more demagnetization steps of up to 80 mT, and specimen-level characteristic directions were determined using a least squares method based on principal component analysis (Kirschvink, 1980; Cogné, 2003). Throughout, site-mean directions were calculated using Fisher (1953) statistics. In only one case (site 4T208; Table 1), intersecting demagnetization planes and Bingham statistics (Onstott, 1980) were used to determine the site’s mean direction. Because this site mean is of lower fidelity (Table 1), and is an outlier compared to the other means for this unit (Basalt of Canemah), it was rejected from further consideration.

Multiple sampling sites within a given mapped unit could be in a single flow, in multiple flows erupted within a restricted period of time relative to PSV (having similar directions), or in separate flows representing temporally independent paleomagnetic directions (Table 1). Unfortunately, it can be difficult to determine from field relations alone whether sites are in the same flow or in a number of related ones. A few larger centers (e.g., Mt. Scott, Larch Mountain) clearly consist of multiple flows emplaced over a period of years to centuries whereas smaller units (e.g., North Fork Rock Creek, Canemah) typically consist of a single lava flow. Significant differences in paleomagnetic directions, however, could also be due to local vent anomalies

(Baag et al., 1995) as many of the sampling sites were located proximal to their eruptive centers (Fig. 1). Groupings for PSV model comparisons were made based on individual sites, mapped units, and independent paleomagnetic directions. Independent directions were determined from non-overlapping 95% confidence limits (Table 1); those from a single unit that overlapped were averaged to a mean direction as indicated in Table 1 by blue-colored cells.

[Table 1 near here]

2.2 $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

Detailed descriptions of the $^{40}\text{Ar}/^{39}\text{Ar}$ sample collection and laboratory analyses are presented by Fleck et al. (2014) and will be outlined only briefly here. Although our initial aim was to collect paleomagnetism and geochronology samples from the same outcrops, some outcrops were deemed less suitable for $^{40}\text{Ar}/^{39}\text{Ar}$ dating due to thin-section examinations that showed fine grain-size, glassy groundmass, and/or weathering. In such cases, samples for dating were collected from other parts of the same flow as best determined by field relationships or by petrographic and geochemical analyses. $^{40}\text{Ar}/^{39}\text{Ar}$ determinations were performed between 1998 and 2015 during which the experimental procedures shifted from using crushed whole-rock samples to using groundmass separates. The incremental heating experiments were also initially conducted on samples using a 250-355 μm grain size, and later changed to a 180-250 μm size range for better removal of phenocrysts (Fleck et al., 2014). Groundmass separates were prepared by removing the most magnetic fraction with a hand magnet or a Franz isodynamic separator, and any olivine and/or coarse plagioclase phenocrysts were removed using magnetic methods, heavy liquid separation, and/or hand picking (Fleck et al., 2014).

Samples were irradiated in the USGS TRIGA reactor at Denver, Colorado, at a constant power level of 1 MW for 2 h, and were analyzed in the USGS $^{40}\text{Ar}/^{39}\text{Ar}$ laboratory at Menlo Park, California. Argon was incrementally extracted using a resistance furnace and molybdenum crucible. Temperature levels were selected to distribute the total release of Ar over at least eight steps, but in some cases a greater number of steps (>15 total) and higher temperatures were used (Fleck et al., 2014). Ar isotopic analyses were done using a MAP216 single-collector mass spectrometer, and data reduction was accomplished using routines developed in house, and using the Isoplot program developed by Ludwig (2003), with updates through 2009. The $^{40}\text{Ar}/^{39}\text{Ar}$ ages reported (Tables 1 and 2) are those interpreted to be most reliable of the weighted-mean plateau, isochron, or recoil model ages determined (Fleck et al., 2014); uncertainties in Ar analyses are given at the 1σ level, and weighted means were calculated using the inverse variance as the weighting factor.

[Figure 2 and Table 2 near here]

Sanidine from the Taylor Creek Rhyolite (TCs; Dalrymple and Duffield, 1988) was used as the neutron flux monitor during irradiation. The irradiation parameter (J) has been adjusted for all BVF samples, including those reported by Fleck et al. (2014), to give ages consistent with the age determined by Kuiper et al. (2008) for sanidine from the Fish Canyon Tuff (FCs). Those authors used a tephra collected from an astronomically tuned marine succession in Morocco to obtain an age of 28.198 ± 0.044 Ma (referred to here as the “Kuiper value” or age) for FCs using the ^{40}K decay constants recommended by Steiger and Jager (1977). If the total decay constant for ^{40}K of Min et al. (2000) is used, however, the age of FCs becomes 28.201 ± 0.046 Ma. The decay constants recommended by Steiger and Jager (1977) are used in this paper and J -values are converted to be consistent with the Kuiper value for FCs. This conversion is consistent with

the approach in the Geologic Time Scale 2012 (Gradstein et al., 2012) and facilitates both the comparison of our results to the GPTS and their adjustment to future standard calibrations. As shown by Kuiper et al. (2008), the most commonly used *total* decay constants for ^{40}K (Steiger and Jager, 1977; Min et al., 2000; Renne et al., 2010) generate an age spread of only about 0.01% for a 28.2 Ma-old sanidine, almost an order of magnitude less than the lowest analytical uncertainty currently achievable. Consequently, our use of the decay constants of Steiger and Jager (1977) has no effect on comparisons of our $^{40}\text{Ar}/^{39}\text{Ar}$ ages to those of other laboratories or to global chronology boundaries. All $^{40}\text{Ar}/^{39}\text{Ar}$ ages referenced in this paper are presented relative to an age of 28.198 Ma for FCs, unless the value is clearly identified as that from the original publication. Where an age has been recalculated to the Kuiper value, the age is marked with an asterisk and identification number (e.g., *¹) and the source and original age are reported in Appendix 1. For example, Singer et al. (2005) reported an age of 776 ± 2 ka for the Matuyama-Brunhes reversal from Haleakela on Maui (Hawai'i) relative to an age of 28.02 Ma for FCs. This is quoted in section 4.1 of this paper as $781 \pm 2^{*4}$ ka relative to the Kuiper age of 28.198 Ma for FCs.

3. Results

3.1 Paleomagnetism

The NRM intensities for samples of the Boring lavas and intrusions, measured prior to any demagnetization treatments, are on the order of 1 to 0.1 A/m. AF and thermal demagnetizations showed similar behavior (Fig. 3), and the characteristic magnetization component in each sample was usually isolated between 30 and 100 mT or 200° and 575°C. The characteristic magnetization component most often decayed univectorially towards the origin after removal of

any secondary components. Success of thermal demagnetization treatments in reducing NRM intensities to less than 10% of their initial values by 575°C (Fig. 3) indicates that the magnetic mineralogy of these rocks is most likely fine-grained, moderate to low-Ti titanomagnetite. The characteristic magnetizations are inferred to be primary thermal remanent magnetizations (TRM) acquired during initial cooling of the rock unit, and this inference is corroborated by the $^{40}\text{Ar}/^{39}\text{Ar}$ ages and general correspondence of observed paleomagnetic polarities with the GPTS (Table 1; Ogg, 2012; Fleck et al., 2014).

[Figure 3 near here]

Samples with slightly higher unblocking temperatures ($>575^\circ\text{C}$) apparently contain minor amounts of hematite, and, because they carry similar paleomagnetic directions, this mineral most likely formed early on during cooling and oxidation of the lava flows (Fig. 3b, c, e). AF and thermal demagnetization treatments show different directions for two samples from site BL8001 (Fig. 3f). Five of the eight samples from this site gave similar directions, but three gave directions that were significantly different and scattered to the ESE (Table 1). The demagnetization data for these outlier directions show that they are stable TRMs, and we suggest they could possibly be due to rapid field changes during the Olduvai subchron.

Secondary components in the Boring lavas were likely acquired during thermal overprinting by overlying lava flows or subsequent intrusions (e.g., Fig. 3g), but also could have resulted from lightning strikes or weathering. Due to the insignificant amount of measurable post-eruptive deformation in the region, no structural corrections were applied to the *in situ* site-mean directions. GPS and paleomagnetic measurements indicate that dextral shear, due to oblique subduction of the Juan de Fuca plate, has caused regional rotation rates of $\sim 1^\circ/\text{Myr}$ in the

Portland area over the last 12 Myr (McCaffrey et al., 2007; Wells et al., 1998). For the relatively young Boring lavas such rotations are within analytical error of the site-mean directions.

Individual site-mean directions for the BVF (Table 1) are shown in Figure 4a, and those grouped by mapped unit in Figure 4b. Both polarities of the geomagnetic field are represented, and normal and reversed independent directions pass the reversal test of McFadden and McElhinny (1990) at the 95% confidence level with an “A” level classification ($N = 105$; $R_{1(n)} = 45.0542$; $R_{2(r)} = 56.7103$; $\gamma_c = 4.92^\circ$; $\gamma_o = 1.77^\circ$). Virtual geomagnetic poles (VGPs) calculated for the independent paleomagnetic direction are shown in Figure 5, and the mean pole is far-sided and distinct from the geographic pole at the 95% confidence level. For the most part, dispersal of these VGPs about the long-term geographic pole was caused by paleosecular variation (PSV) of the geomagnetic field.

[Figures 4 and 5 near here]

PSV has customarily been defined by the variability of VGPs for volcanic rocks, and a common metric has been their angular dispersion or angular standard deviation (S). In order not to bias the VGP population representing “normal” PSV, outliers attributed to excursions or transitional (i.e., full reversal) behavior of the geomagnetic field are rejected. Generally in the past a threshold value of 45° has been used (e.g., McElhinny and McFadden, 1997), but more recently a recursive method developed by Vandamme (1994) has been adopted. In this method, the optimum cutoff angle is arrived at by calculating it first based on the full dataset, rejecting outliers, then recalculating the cutoff angle and again rejecting outliers until the cutoff angle encompasses all of the remaining VGPs. For the BVF, the VGPs rejected in the first round were those for the basaltic andesite at Lookout Point (T5153, BL9001) at the base of the Brunhes chron, and those for the basalt of Kaiser Road (T2295) at the top of the Jaramillo subchron

(Table 1). Also, because of their stratigraphic positions at chronozone boundaries these VGPs are considered transitional. In addition, data from the basaltic andesite of Hard Scramble Creek (T3020, $270 \pm 12^{*1}$ ka) and of Boyles Creek (T3028, $281 \pm 5^{*2}$; Table 1) were also rejected as outliers and could possibly be associated with an excursions event within the middle Brunhes chron.

3.2 $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

$^{40}\text{Ar}/^{39}\text{Ar}$ age determinations made for this study are reported in Table 2 with the calculation technique (“Interp” column) indicated as weighted-mean plateau (P), isochron (I), or recoil model ages (R) as shown in Figure 6. Plateau ages are defined as the inverse-variance-weighted mean of that part of an age spectrum composed of contiguous gas fractions representing >50% of the total ^{39}Ar released, and for which no age differences are detected between any two fractions at the 95% confidence level (Fleck et al., 1977). An isochron age is calculated using the algorithm of York (1969) with conventions adopted by Ludwig (2003). Recoil model ages, discussed below, represent the age calculated for a specified fraction of an age spectrum, based on a specific model for the origin of that pattern.

[Figure 6 and Table 2 near here]

With few exceptions, $^{40}\text{Ar}/^{39}\text{Ar}$ age-spectra in this study exhibit at least some evidence of nuclear recoil effects of ^{39}Ar and/or ^{37}Ar that are related to the fine-grained character of the lavas. The age effects due to recoil of ^{39}Ar exceed those of ^{37}Ar even in these high-Ca rock types, but most recoil effects involve redistribution of the Ar isotopes within the irradiated grain aggregates and not net loss. For either of these recoil species most samples show less than ~5% net recoil loss (Fleck et al., 2014). Nuclear recoil in $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology and the model for

and calculation of $^{40}\text{Ar}/^{39}\text{Ar}$ recoil model ages are discussed in detail in Fleck et al. (2014). Those authors define a recoil model age as “*the integrated age of contiguous temperature increments and fractions of increments in a centered fraction of the age spectrum*”. The application and usefulness of this treatment as a proxy for a plateau age is documented in that paper (Fleck et al., 2014).

4. Discussion

4.1 The geomagnetic polarity time scale (GPTS)

The GPTS for the C sequence of marine magnetic anomalies (Cenozoic: Late Cretaceous through Neogene) is constructed by fitting spreading rate models, via magnetostratigraphies, to stratigraphic sections calibrated by biostratigraphy, cyclostratigraphy, and radioisotopically-dated horizons (e.g., Cande and Kent, 1995; Ogg, 2012; Table 1). For the Quaternary Period (<2.6 Ma), paleomagnetic and paleointensity studies of radioisotopically dated volcanic rocks, as well as astrochronologically dated marine sediments have provided high-resolution ages for chronozone boundaries as well as shorter-term excursions (e.g., Channell et al., 2010; Singer, 2014). In the following we discuss the BVF paleomagnetic and geochronologic data with respect to current temporal representations of the GPTS.

$^{40}\text{Ar}/^{39}\text{Ar}$ estimates for the timing of the Matuyama-Brunhes (M-B) reversal have come from transitionally magnetized lava flows on Maui, Hawai'i (Baksi et al., 1992; Coe et al., 2004; Singer et al., 2005), on the Canary Islands (Singer and Pringle, 1996), in Chile (Singer and Pringle, 1996; Brown et al., 2004), and from Tahiti (Singer and Pringle, 1996; Mochizuki et al., 2011; Camps et al., 2011). Mean ages for these lava sequences except at Haleakela on Maui tend to cluster at $798 \pm 3^{+3}_{-3}$ ka, whereas those from Haleakela have a weighted mean age of $781 \pm 2^{+4}_{-4}$

ka (Singer et al., 2005; Singer, 2014). As noted in the Methods section (2.2), these and all $^{40}\text{Ar}/^{39}\text{Ar}$ ages cited in this paper are reported relative to the Kuiper (2008) age for the FCs standard. Channell et al. (2010), however, note that this astrochronologically-based calibration is at odds with those based on North Atlantic sediment cores (FCs of 27.93 Ma compared to 28.198 Ma for Kuiper et al., 2008). Paleointensity records from marine sediments indicate a pronounced intensity drop, dubbed the “M-B precursor” and probably represented by the earlier ($798 \pm 3^{*3}$ ka) lava sequences, which apparently preceded the intensity low associated with the actual M-B field reversal (e.g., Kent and Schneider, 1995; Hartl and Tauxe, 1996; Channell et al., 2010). Comparisons of astrochronological ages for the M-B reversal from sediment cores in the North Atlantic show that it consistently occurs at the younger end of marine isotope stage 19 with a mean astronomical age of 773.1 ± 0.8 ka, as determined by correlation of $\delta^{18}\text{O}$ records of the cores to an ice volume model (Channell et al., 2010).

Our weighted mean age of $778 \pm 4^{*5}$ ka for the transitional polarity flow(s) of the basaltic andesite of Lookout Point (Fig. 7; Tables 1, 2) compares well to an age of ~ 780 ka for the M-B reversal favored by a number of sources (e.g., Cande and Kent, 1995; Shackelton et al., 1990; Horng et al., 2002; Lisiecki and Raymo, 2005; Ogg, 2012). However, our original age for the Lookout Point flow(s) of 773 ± 5 ka (Fleck et al., 2014) relative to FCs at 28.02 Ma would agree well with the 773.1 ± 0.8 ka age of Channell et al. (2010) for the M-B reversal. This demonstrates that our transitional lavas at Lookout Point are consistent with the M-B reversal regardless of the choice of astrochronologic calibrations used for FCs. Replicate $^{40}\text{Ar}/^{39}\text{Ar}$ ages for other lower Brunhes lava flows of the BVF also constrain the age for the M-B reversal: ages for the normal polarity basaltic andesite of Palmer Peak ($766 \pm 5^{*6}$ ka) and basalt of Bobs Mountain ($782 \pm 4^{*7}$ ka) indicate that they closely followed the onset of the M-B reversal.

[Figure 7 near here]

Reversals defining the Jaramillo normal subchron have previously been dated by $^{40}\text{Ar}/^{39}\text{Ar}$ determinations of transitionally magnetized lava flows in the Punaruu Valley of Tahiti. Singer et al. (1999) originally reported a weighted mean $^{40}\text{Ar}/^{39}\text{Ar}$ age of 986 ± 5 ka for flows at the end of the Jaramillo subchron, and an age of 1053 ± 6 ka on a flow at the bottom of the Jaramillo subchron. Singer (2014) recalculated these ages to the Kuiper age for FCs as 1008 ka and 1076 ka, respectively. A transitional polarity lava flow from the upper Jaramillo boundary on the Meseta del Lago Buenos Aires in Argentina gives a $^{40}\text{Ar}/^{39}\text{Ar}$ isochron age of $990 \pm 35^{*8}$ ka (2σ) (Brown et al., 2004). In the BVF, the transitional polarity basalt of Kaiser Road provides replicate ages for the termination of the Jaramillo subchron at $972 \pm 3^{*9}$ ka and 971 ± 3 ka (Table 2). No transitional flow was found within the BVF to define the onset of the Jaramillo, but this reversal is bracketed by the $1149 \pm 3^{*10}$ ka age for the reversed basalt of Sylvania and the $1072 \pm 5^{*11}$ ka age for the normally magnetized basaltic andesite of Three Corner Rock (Tables 2 & 4; Fleck et al., 2014). Although our age for the termination of the Jaramillo subchron of 972 ± 3 ka is significantly less than determined by Singer (2014) at 1008 ± 5 ka, it is more similar to the 988 ka astronomically determined age for this horizon from Horng et al. (2002) and GPTS12 (Ogg, 2012), and to the $990 \pm 35^{*8}$ ka (2σ) of Brown et al. (2004).

The Cobb Mountain normal subchron was initially identified by the transitionally magnetized rhyolite of Alder Creek in northern California (Mankinen et al., 1978), which has more recently been dated at $1201 \pm 6^{*12}$ ka (Turrin et al., 1994), $1201 \pm 1^{*13}$ ka (Normade et al., 2005), $1186.1 \pm 1.6^{*14}$ ka by Rivera et al. (2013), and at 1189 ± 2 by Singer (2014). These and many unpublished results obtained on sanidine from this unit, which has become an international $^{40}\text{Ar}/^{39}\text{Ar}$ age standard, clearly place this polarity transition prior to the 1185 to 1173 ka span

accepted by Ogg (2012) for GTS2012. We also recently determined an age of 1195.7 ± 3.9 ka on this sanidine in the Menlo Park laboratory, within the range of these reported ages and outside of the GTS2012 window. Despite the greater dispersion of the above results than quoted analytical uncertainties, these ages do fall within the range of $^{40}\text{Ar}/^{39}\text{Ar}$ laboratory age variation reported by Heizler (2008). High-resolution marine sediment and paleointensity records indicate the Cobb Mountain subchron spans 1215 to 1190 ka (Channell et al., 2002). A transitionally magnetized lava flow from the Perçsani Mountains, Romania, at the base of the subchron, has a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 1221 ± 11 ka (Panaiotu et al., 2013), supporting the older age span for the subchron. Our average $^{40}\text{Ar}/^{39}\text{Ar}$ age of $1217 \pm 4^{*15}$ ka from the reversely magnetized basaltic andesite of Hunsinger (Table 2) places this unit below the Cobb Mountain subchron (Table 1), in age agreement with the 1215 ka age of its base from marine sediment cores (Channell et al., 2002; Table 2; Fig. 7). The 1159 ± 13 ka age for the reversed-polarity basaltic andesite of Fletcher Flat represents an upper limit for the termination of this subchron. The discordant replicate ages and large uncertainty obtained for the basalt of Chamberlain Hill (Table 2), however, discount any use of its 1197 ± 26 ka age for polarity timing.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages of lava flows at Cerro del Fraile, Argentina, establish constraints on the age of the Olduvai normal subchron: an age of $1934 \pm 66^{*16}$ ka (2σ) for a transitional polarity flow defines the subchron's onset, and normal and reversed polarity flows dated at $1869 \pm 50^{*17}$ and $1798 \pm 86^{*18}$ ka (2σ), respectively, limit the age of its termination (Singer et al., 2004). Additional $^{40}\text{Ar}/^{39}\text{Ar}$ ages of $1792 \pm 26^{*19}$ ka come from a transitional flow on the island of Moorea (Baksi, 1994) and of $1772 \pm 7^{*20}$ ka from a normal-polarity tuff in Olduvai Gorge (Walter et al., 1991). Singer et al. (2014) reports combined results for these ages of 1934 ± 66 and 1787 ± 15 ka for the onset and end of the Olduvai subchron recalculated to the Kuiper age

for FCs. Our data for the BVF (Table 1; Fleck et al., 2014) suggest that the subchron began somewhat earlier, bracketed by single determinations of $1976 \pm 10^{*21}$ ka for a reversed polarity tholeiite (CLRV-1) near the Clackamas River and $1965 \pm 12^{*22}$ ka for the normal polarity basalt of Deer Creek. Replicate ages of the normal polarity basaltic andesite of Oneonta Creek (Table 2) also provide support for initiation of normal polarity prior to $1933 \pm 12^{*23}$ ka. Because of a lull in BVF eruptions between ~ 2.2 and ~ 1.7 Ma (Fig. 2) there are consequently few flows from which we could determine the Olduvai's termination (Fig. 7).

Although there exists no direct $^{40}\text{Ar}/^{39}\text{Ar}$ age for the beginning of the Matuyama chron (Singer, 2014), detailed marine magnetic anomaly profiles and high-resolution global marine oxygen isotope stratigraphy and magnetostratigraphy have provided astrochronologic ages of 2581 ka (Cande and Kent, 1995), 2600 ka (Shackleton et al., 1990), and 2608 ka (Lisiecki and Raymo, 2005). GTS2004 and GTS2012 have both used the 2581 ka value for the Gauss-Matuyama (G-M) boundary and that is shown in Table 1. The G-M reversal is bracketed by two $^{40}\text{Ar}/^{39}\text{Ar}$ -dated tuffs within lake sediments in Kenya that give an interpolated and recalculated age of 2610 ka for the boundary (Deino et al., 2006). Fleck et al. (2014) discuss results from the BVF, noting that the basalt of Canemah (replicate ages; Table 2) and at least three other early BVF lavas of reversed polarity have ages older than the 2581 ka age for the G-M reversal. As shown in Table 3, six units with reversed polarity near the initiation of the Matuyama chron yield ages greater than 2581 ka, when calculated with the monitor age of FCs (28.198 Ma) recommended by Kuiper et al. (2008) from orbitally tuned strata. The results of these studies therefore strongly support an older age of at least 2610 ka for the G-M reversal and support an age up to 2632 ± 9 ka.

[Table 3 near here]

Normal-polarity flows at the top of the Gauss chron were not found within the BVF (Table 1), but three reversed-polarity, low-potassium tholeiites with a mean age of $3074 \pm 18^{*24}$ ka and the basalt of McIntyre Ridge with an age of $3108 \pm 10^{*25}$ ka represent the Kaena subchron (Table 1). Normal-polarity low-potassium tholeiites near Bridal Veil Falls in the BVF with a mean age of 3125 ± 42 ka are consistent with the onset of the Kaena subchron given by Ogg (2012) at 3116 ka.

4.2 Statistical paleosecular variation (PSV) models

Dispersion analysis of VGP distributions has traditionally been used to investigate PSV and construct models for the geomagnetic field, in particular by calculating S values (see Results) that apparently increase with increasing latitude (McElhinny and McFadden, 1997; Tauxe and Kent, 2004). For the BVF we have calculated S_B values (using a Vandamme cutoff of 40.3°), which correct for within-site dispersion (see Johnson et al., 2008). The S_B values for various BVF VGP populations are listed in Table 4 and plotted in Figure 8. Differences between S_B values for normal and reversed polarity chrons are often observed in PSV studies, and although the global analysis of 0 to 5 Ma lava flows by Johnson et al. (2008) found a constant level of S_B with latitude for the Brunhes chron of $\sim 16^\circ$, the BVF Matuyama S_B value obtained here is $\sim 16^\circ$ while that for the Brunhes chron is higher at $\sim 21^\circ$. The combined BVF S_B value for all data of 18.8° is similar to those values predicted by the G and TK03 models (Fig. 8).

[Figure 8 and Table 4 near here]

Linder and Gilder (2012), however, demonstrated that the latitudinal variation in S is likely a mathematical artifact of the non-linear transformation between directional and VGP space. They suggest that Fisher's (1953) k value for directions is a better estimate of dispersion, and show

that the k value remains constant with respect to latitude for the modern geomagnetic field. In addition, model CP88 predicts constant S_B values with latitude (Constable and Parker, 1988), and Johnson et al. (2008) have shown that studies with poor quality data, or too few samples per site, can also contribute to the latitudinal variation in S_B .

The basic question has been whether VGPs or directions have Fisherian (circular) distributions and thus should be the subject of PSV investigations. We have calculated elongation values for our BVF directional and VGP data sets (Table 4) to determine whether one or the other is circularly distributed. Again, there is a considerable difference between the normal- and reversed-polarity data sets with the reversed directions tending to be more circularly distributed than the normal directions. (e.g., 1.11 vs. 1.54). Because of the nonlinear mapping function between directions and VGPs, the reversed-polarity VGPs tend to be more elliptical and the normal-polarity ones less so. For the BVF the number of data points for reversed-polarity lava flows ($N = 58$) is greater than that for those with normal-polarity ($N = 47$), and the more numerous data (23% greater) might better represent the full range of PSV.

5. Conclusions

$^{40}\text{Ar}/^{39}\text{Ar}$ ages determined for lava flows of the BVF, when recalculated for FCs=28.198 Ma (as given throughout this section), generally agree with the GPTS2012 (Ogg, 2012). Our direct age for the M-B transition of 778 ± 4 ka, from the transitional basalt of Lookout Point, is in good agreement with the GPTS2012 age of 781 ka (Table 5) and other astrochronological ages (see Discussion) for this chron boundary. The other direct age from a transitional flow (basalt of Kaiser Road) is 972 ± 3 ka from the top of the Jaramillo subchron zone and is more similar to the 988 ka age given in the GPTS2012 than to 1008 ± 5 ka accepted by Singer (2014). Our bracketed

age for the lower Jaramillo boundary between 1149 and 1072 ka also agrees with the equivalent age of 1072 ka from the GPTS2012.

Although we found no normal-polarity units of the Cobb subchron within the BVF, the ages of several BVF flows constrain its initiation to after 1217 ± 4 ka (Table 1). Although these ages from reversed-polarity flows permit the age range of 1185 to 1173 ka accepted by GPTS2012 (Table 5), ages from multiple laboratories cited and discussed by Singer (2014) indicate an earlier initiation. From BVF lavas, the onset of the Olduvai subchron, however, is somewhat older than the GPTS2012 age for this boundary: it began between 1976 ± 10 and 1965 ± 12 ka, whereas the GPTS2012 age is 1945 ka. Too large an eruptive gap in dated BVF flows (>200 yr) occurs at the end of the Olduvai chron for our data to have any meaningful bearing on its terminal age. $^{40}\text{Ar}/^{39}\text{Ar}$ ages at the base of the Matuyama chron also indicate that the G-M boundary is older ($>2632 \pm 9$ ka) than the GPTS2012 value of 2581 ka (2.581 Ma). Finally, the BVF ages of 3124 ± 42 and 3109 ± 9 ka bracket the GPTS2012 age of 3116 ka for the beginning of the Kaena subchron (Table 5).

[Table 5 near here]

S_B values for VGPs of the BVF Matuyama (16° ; $N = 54$) and Brunhes (21° ; $N = 39$) datasets are different, but are reversed in relative value to those determined by Johnson et al. (2008) in their compilation of paleomagnetic lava-flow data for the last 5 Ma: they calculated a consistent 16° S_B value with latitude for the Brunhes chron ($N = 1037$), and more variable and somewhat higher values in several Matuyama datasets ($N = 507$). The elongation values for the BVF Brunhes and Matuyama flows are also different with the Matuyama distribution being more circular (1.17), or Fisherian, than that of the Brunhes (1.59). This latter result indicates that our BVF Brunhes dataset possibly contains insufficient independent data points, and that the

Matuyama dataset more accurately represents PSV dispersion for this time in the Pacific Northwest.

Acknowledgments. We thank Duane Champion for contributing paleomagnetic data for five BVF sites (A3001-A3061), and Blair Bridges, James Saburomaru, and Dean Miller for technical assistance. We are also grateful to Jack Hillhouse (USGS) and two anonymous referees for constructive reviews of the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

- Allen, J.E., 1975. Volcanoes of the Portland area. *The Ore Bin* 37, 145-157.
- Baag, C., Helsley, C.E., Xu, S., Lienert, B.R., 1995. Deflection of paleomagnetic directions due to magnetization of the underlying terrain. *Journal of Geophysical Research* 100, 10,013-10,027.
- Baksi, A.K., 1994. Concordant sea-floor spreading rates obtained from geochronology, astrochronology, and space geodesy. *Geophysics Research Letters* 21, 133-136.
- Baksi, A.K., Hsu, V., McWilliams, M.O., Farrar, E. 1992. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Brunhes Matuyama geomagnetic field reversal. *Science* 256, 356-357.
- Brown, L.L., Singer, B.S., Gorrington, M., 2004. Paleosecular variation in the southern hemisphere: Paleomagnetic and geochronologic results from Meseta del Lago Buenos Aires, Patagonia, Argentina. *Geochemistry, Geophysics, Geosystems* 5, doi:10.1029/2003GC000526.
- Camps, P., Singer, B.S., Carvallo, C., Goguitchaichvili, A., Fanjat, G., Allen, B., 2011. The Kamikatsura event and the Matuyama-Brunhes reversal recorded in lavas from Tjörnes Peninsula, northern Iceland. *Earth and Planetary Science Letters* 310, 33-44.
- Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic. *Journal of Geophysical Research* 100, 6,093-6,095.
- Channell, J.E.T., Mazaud, A., Sullivan, S., Turner, S., Raymo, M.E., 2002. Geomagnetic excursions and paleointensities in the Matuyama chron at Ocean Drilling Program sites 983 and 984 (Iceland Basin). *Journal of Geophysical Research* 107, B6, 2114, doi:10.1029/2002GC000440.
- Channell, J.E.T., Hodell, D.A., Singer, B.S., Huang, C., 2010. Reconciling astrochronological and $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the Matuyama-Brunhes boundary and late Matuyama Chron. *Geochemistry, Geophysics, Geosystems*, doi:10.1029/2010GC003203.

- Coe, R.S., Singer, B.S., Pringle, M.S., Zhao, X., 2004. Matuyama-Brunhes reversal and Kamikatsura event on Maui: Paleomagnetic directions, $^{40}\text{Ar}/^{39}\text{Ar}$ ages and implications. *Earth and Planetary Science Letters* 222, 667-684.
- Cogné, J.P., 2003. PaleoMac: A MacintoshTM application for treating paleomagnetic data and making plate reconstructions. *Geochemistry, Geophysics, Geosystems* 4 (1), 1007, doi:10.1029/2001GC000227.
- Conrey, R.M., Grunder, A., Schmidt, M., 2004. State of the Cascade Arc: Stratovolcano persistence, mafic lava shields, and pyroclastic volcanism associated with intra-arc rift propagation. Oregon Department of Geol. Min. Indust. Open File Report O-04-04, 39 p.
- Constable, C.G., Parker, R.L., 1988. Statistics of the geomagnetic secular variation for the past 5 m.y. *Journal of Geophysical Research* 93, 11,569-11,581.
- Cox, A., 1969. Confidence limits for the precision parameter κ . *Geophysical Journal of the Royal Astronomical Society* 18, 545-549.
- Dalrymple, G.B., Duffield, W., 1988. High precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating of Oligocene rhyolites from the Mogollon-Datil Volcanic Field using a continuous laser system. *Geophysical Research Letters* 15, 463-466.
- Deino, A.L., Kingston, J.D., Glen, J.M., Edgar, R.K., Hill, A., 2006. Precessional forcing of lacustrine sedimentation in the late Cenozoic Chemeron Basin, Central Kenya Rift, and calibration of the Gauss/Matuyama boundary. *Earth and Planetary Science Letters* 247, 41-60.
- Engelbreton, D.C., Beck, M.E., Jr., 1978. On the shape of directional data sets. *Journal of Geophysical Research* 83 (B12), 5979-5982.
- Evarts, R.C., Conrey, R.M., Fleck, R.J., Hagstrum, J.T., 2009. The Boring volcanic field of the Portland-Vancouver area, Oregon and Washington: Tectonically anomalous forearc volcanism in an urban

- setting. In: O'Connor et al. (Eds.) *Volcanoes to vineyards: Geologic Field Trips Through the Dynamic Landscape of the Pacific Northwest*. Geological Society of America Field Trip Guide 15, 253-270.
- Fisher, R.A., 1953. Dispersion on a sphere. *Proceedings of the Royal Society of London Series A* 217, 295-305.
- Fleck, R.J., Sutter, J.F., Elliot, D.H., 1977. Interpretation of discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age-spectra from Antarctica. *Geochemica Cosmochemica Acta* 41, 15-32.
- Fleck, R.J., Hagstrum, J.T., Calvert, A.T., Evarts, R.C., Conrey, R.M., 2014. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, paleomagnetism, and evolution of the Boring volcanic field, Oregon and Washington, USA. *Geosphere* 10 (6), doi:10.1130/GES00985.1.
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., 2012. (Eds.) *The Geologic Time Scale 2012*, Elsevier, Oxford, 1144 p.
- Hartl, P., Tauxe, L., 1996. A precursor to the Matuyama/Brunhes transition-field instability as recorded in pelagic sediments. *Earth and Planetary Science Letters* 138, 121-135.
- Heizler, M., EARTHTIME Ar working group, 2008. Argon laboratory intercomparison efforts for the EARTHTIME initiative. *Geophysical Research Abstracts* 10, EGU2008-A-11478.
- Hildreth, W., 2007. Quaternary magmatism in the Cascades—A geologic perspective. U.S. Geological Survey Professional Paper 1744, 125 p.
- Horng, C.S., Lee, M.Y., Pälike, H., Wei, K.-Y., Liang, W.T., Iizuka, Y., Torii, M., 2002. Astronomically calibrated ages for geomagnetic reversals within the Matuyama Chron. *Earth Planets Space* 54, 679-690.
- Johnson, C.L., Constable, C.G., Tauxe, L., Barendregt, R., Brown, L.L., Coe, R.S., Layer, P., Mejia, V., Opdyke, N.D., Singer, R.S., Staudigel, H., Stone, D.B., 2008. Recent investigations of the 0-5 Ma

- geomagnetic field recorded by lava flows. *Geochemistry, Geophysics, Geosystems* 9 (4), doi:10.1029/2007GC001696.
- Kent, D.V., Schneider, D.A., 1995. Correlation of the paleointensity variation records in the Brunhes/Matuyama polarity transition interval. *Earth and Planetary Science Letters* 129, 135-144.
- Kirschvink, J.L., 1980. The least-squares line and plane and analysis of palaeomagnetic data. *Geophysical Journal of the Royal Astronomical Society* 62, 699-718.
- Kirschvink, J.L., Kopp, R.E., Raub, T.D., Baumgartner, C.T., Holt, J.W., 2008. Rapid, precise, and high-sensitivity acquisition of paleomagnetic and rock-magnetic data: Development of a low-noise automatic sample changing system for superconducting rock magnetometers. *Geochemistry, Geophysics, Geosystems* 9 (5), Q05Y01, doi:10.1029/2007GC001856.
- Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R., Wijbrans, J.R., 2008. Synchronizing rock clocks of Earth history. *Science* 320, 500-504.
- Linder, J., Gilder, S.A., 2012. Latitude dependency of the geomagnetic secular variation S parameter: A mathematical artifact. *Geophysical Research Letters* 39, L02308, doi:10.1029/2011GL050330.
- Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20, PA1003, doi:10.1029/2004PA001071.
- Ludwig, K.R., 2003. Isoplot: A geochronological toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publication* 4, 70 p.
- Mankinen, E.A., Donnelly, J.M., Grommé, C.S., 1978. Geomagnetic polarity event recorded at 1.1 m.y.b.p. on Cobb Mountain, Clear Lake volcanic field, California. *Geology* 6, 653-656.
- McCaffrey R., Qamar, A.I., King, R.W., Wells, R., Khazaradze, G., Williams, C.A., Stevens, C.W., Vollick, J.J., Zwick, P.C., 2007. Fault locking, block rotation and crustal deformation in the Pacific Northwest. *Geophysical Journal International* doi: 10.1111/j.1365-246X.2007.03371.

- McElhinny, M.W., McFadden, P.L., 1997. Palaeosecular variation over the past 5 Myr based on a new generalized database. *Geophysical Journal International* 131, 240-252.
- McFadden, P.L., McElhinney, M.W., 1990. Classification of the reversal test in paleomagnetism. *Geophysical Journal International* 103, 725-729.
- Min, K., Mundil, R., Renne, P.R., Ludwig, K.R., 2000. A test for systematic errors in $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology through comparison with U/PB analysis of a 1.1-Ga rhyolite. *Geochimica et Cosmochimica Acta* 64, 73-98.
- Mochizuki, N., Oda, H., Ishizuka, O., Yamazaki, T., Tsunakawa, H., 2011. Paleointensity variation across the Matuyama-Brunhes polarity transition: Observations from lavas at Punaruu Valley, Tahiti. *Journal of Geophysical Research* 116, B06103, doi:10.1029/2010JB008093.
- Nomade, S., Renne, P.R., Vogel, N., Deino, A.L., Sharp, W.D., Becker, T.A., Jaouni, A.R., Mundil, R., 2005. Alder Creek sanidine (ACs-2): A Quaternary $^{40}\text{Ar}/^{39}\text{Ar}$ dating standard tied to the Cobb Mountain geomagnetic event. *Chemical Geology* 218, 315-338.
- Ogg, J.G., 2012. Geomagnetic polarity time scale. In: Gradstein, F.M., et al. (Eds.) *The Geologic Time Scale 2012*. Elsevier, Oxford, 85-113.
- Onstott, T.C., 1980. Application of the Bingham distribution function in paleomagnetic studies. *Journal of Geophysical Research* 85, 1500-1510.
- Panaiotu, C.G., Jicha, B.R., Singer, B.S., Tugui, A., Seghedi, I., Panaiotu, A.G., Necula, C., 2013. $^{40}\text{Ar}/^{39}\text{Ar}$ chronology and paleomagnetism of Quaternary basaltic lavas from the Persani Mountains (East Carpathians). *Physics of Earth and Planetary Interiors* 221, 1-14.
- Peck, D.L., Griggs, A.B., Schlicker, H.G., Wells, F.G., Dole, H.M., 1964. Geology of the central and northern parts of the western Cascade Range in Oregon. U.S. Geological Survey Professional Paper 449, 56 p.

- Renne, P.R., Swisher, CC., III, Deino, A.L., Darner, D.B., Owens, T., DePaolo, D.J., 1988. Intercalibration of standards, absolute ages, and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Chemical Geology* 145, 117-152.
- Renne, P.R., Mundil, R., Balco, G., Min, K., Ludwig, K.R., 2010. Joint determination of ^{40}K decay constants and $^{40}\text{Ar}^*/^{40}\text{K}$ for the Fish Canyon sanidine standard, and improved accuracy for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *Geochimica et Cosmochimica Acta* 74, 5349-5367.
- Rivera, T.A., Storey, M., Schmitz, M.D., Crowley, J.L., 2013. Age intercalibration of $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine and chemically distinct U/Pb zircon populations from the Alder Creek rhyolite Quaternary geochronology standard. *Chemical Geology* 345, 87-98.
- Shackleton, N.J., Berger, J., Peltier, W.R., 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions Royal Society of Edinburgh* 81, 251-261.
- Singer, B.S., 2014. A Quaternary geomagnetic instability time scale. *Quaternary Geochronology* 21, 29-52.
- Singer, B.S., Pringle, M.S., 1996. Age and duration of the Matuyama-Brunhes geomagnetic polarity transition from $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating analyses of lavas. *Earth and Planetary Science Letters* 139, 47-61.
- Singer, B.S., Hoffman, K.A., Chauvin, A., Coe, R.S., Pringle, M.S., 1999. Dating transitionally magnetized lavas of the late Matuyama chron: Toward a new $^{40}\text{Ar}/^{39}\text{Ar}$ time scale of reversals and events. *Journal of Geophysical Research* 104, 679-693.
- Singer, B.S., Brown, L., Rabassa, J., Guillou, H., 2004. $^{40}\text{Ar}/^{39}\text{Ar}$ chronology of late Pliocene and Early Pleistocene geomagnetic and glacial events in southern Argentina. In: Channell, J.E.T., Kent, D.V., Lowrie, W., Meert, J. (Eds.), *Timescales of the Paleomagnetic Field*. *Geophysical Monograph Series* 145. American Geophysical Union, Washington, D.C., 175-190.

- Singer, B.S., Hoffman, K.A., Coe, R.S., Brown, L.L., Jicha, B.R., Pringle, M.S., Chauvin, A., 2005. Structural and temporal requirements for geomagnetic field reversal deduced from lava flows. *Nature* 434, 633-636.
- Steiger, R.J., Jager, E., 1977. Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmo-chronology. *Earth and Planetary Science Letters* 36, 359-362.
- Tauxe, L., Kent, D.V., 2004. A simplified statistical model for the geomagnetic field and the direction of shallow bias in paleomagnetic inclinations: Was the ancient geomagnetic field dipolar? In: Channell, J.E.T., Kent, D.V., Lowrie, W., Meert, J. (Eds.), *Timescales of the Paleomagnetic Field*. Geophysical Monograph Series 145. American Geophysical Union, Washington, D.C., 101-116.
- Turrin, B.D., Donnelly-Nolan, J.M., Hearn Jr., B.C., 1994. $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Rhyolite of Alder Creek, California: Age of the Cobb Mountain normal polarity subchron revisited. *Geology* 22, 251-254.
- Vandamme, D., 1994. A new method to determine paleosecular variation. *Physics of Earth and Planetary Interiors* 85, 131-142.
- Walter, R.C., Manega, P.C., Hay, R.L., Drake, R.E., Curtis, G.H., 1991. Laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating of Bed I, Olduvai Gorge, Tanzania. *Nature* 354, 145-149.
- Wells, R.E., Weaver, C.S., Blakely, R.J., 1998. Fore arc migration in Cascadia and its neotectonic significance. *Geology* 26, 759-762.
- York, D., 1969. Least squares fitting of a straight line with correlated errors. *Earth and Planetary Science Letters* 5, 320-324.

Fig. 1. Map showing Boring volcanic rocks in pinkish-orange color, low-potassium tholeiite flows originating in the Cascade arc to the east in purple, as well as major geographic and cultural features of the region. Symbols: green circles, locations of $^{40}\text{Ar}/^{39}\text{Ar}$ and paleomagnetic sampling sites; orange circles, $^{40}\text{Ar}/^{39}\text{Ar}$ sampling sites; blue circles, paleomagnetic sampling sites; and red triangles, mapped volcanic vents.

Fig. 2. Histogram of age distribution for the Boring volcanic field lava flows listed in Table 1. Our $^{40}\text{Ar}/^{39}\text{Ar}$ data indicate that the periods of lowest volcanic activity occurred between 2200 and 1700 ka and 500 and 350 ka.

Fig. 3. Orthogonal vector plots of alternating field (black) and thermal (red) demagnetization results for Boring lava samples from different polarity intervals (see Table 1). Solid circles indicate projection onto the horizontal plane and open circles onto the vertical plane. NRM is natural remanent magnetization with alternating field steps of 2.5, 5, 10, 15, 20, 30, 40, 50, 60, 70 and 80 mT, and thermal demagnetization steps of 100°, 200°, 300°, 400°, 450°, 500°, 525°, 550°, 575°, 600°, 625°, and 650°C.

Fig. 4. (a) Equal-area stereoplots of individual site-mean directions for the Boring lavas with 95% confidence limits. Normal and reversed polarity stars indicate the expected dipole field directions. (b) Directions grouped by mapped unit (see Table 1). Triangles with 95% confidence limits indicate overall mean directions for the normal and reversed polarity flows (Table 2). Filled symbols indicate positive inclinations and open symbols negative inclinations.

Fig. 5. Virtual geomagnetic poles for independent field recordings (see text) of the Boring volcanic field lavas (Table 1) plotted in common (normal) polarity. Black circles indicate normal poles and open red circles converted reversed poles. BVF indicates location of the Boring volcanic field in Oregon and Washington (Fig. 1). Triangle denotes mean VGP within 95% confidence circle in green.

Fig. 6. Plots are examples of $^{40}\text{Ar}/^{39}\text{Ar}$ (a) plateau, (b) isochron, and (c) recoil model age diagrams for sample QV03-167 (summary data shown in Table 2). Recoil model ages are described in detail in Fleck et al. (2014).

Fig. 7. Magnetostratigraphy of the Boring lava field showing (a) inclination and (b) declination plots versus age (Table 1). Black dots indicate ages, and red bars indicate 1σ error values; where replicate ages are available, the mean age is used (Table 2). Listed ages of polarity boundaries are from Ogg (2012).

Fig. 8. Angular dispersion of virtual geomagnetic poles (S_B) with lower (lS_B) and upper (uS_B) 95% confidence limits (Cox, 1969) as a function of latitude for the various populations listed in Table 4 (closed circles, normal polarity; open circles, reversed polarity; triangle, combined), compared with Model TK03 (Tauxe and Kent, 2004) and Model G (McElhinny and McFadden, 1997). Also shown at lower right are ellipses representing the elongation estimates for the normal-polarity (1.54) and reversed-polarity (1.11), and Brunhes (1.59) and Matuyama (1.17), directional distributions (Table 4).

Table 1. Paleomagnetic directions and virtual geomagnetic poles for lava flows of the Boring Volcanic Field

Chron	Event	Unit Name/location ¹	Unit Age ² (ka)	PM ID ³	LAT ⁴	LON ⁴	INC ⁵	DEC ⁵	N/N _o ⁶	r ⁷	k ⁷	α ₉₅ ⁷	VGP ⁸		Pol ⁹		
					NAD 83								LAT	LON			
Brunhes		BA of Beacon Rock	59±6	T3374		45.62640	-122.01970	72.0	27.3	9/9	8.9597	198	3.7	69.7	284.2		
		B of Trout Creek Hill	95±9	BL8097		45.75478	-122.83220	53.6	314.4	8/8	7.9482	135	4.8	53.7	145.9		
		B of Barnes Road	108±6	T2287		45.51255	-122.78637	48.9	357.7	8/8	7.9808	365	2.9	74.2	64.6		
				4T064		45.49375	-122.77808	38.8	333.3	7/8	6.9195	75	7.0	57.9	108.9		
				Mean		-----	-----	44.5	344.5	2/2	1.9691	-----	-----	67.0	95.3		
		B of Battle Ground	108±15*	T8065		45.82920	-122.52155	70.3	0.4	8/8	7.9658	205	3.9	81.5	238.9		
		BA of Canyon Creek	116±9	T5049		45.59511	-122.19312	44.4	2.5	8/8	7.9880	584	2.3	70.4	51.1		
		BA of Elk Point	122±15	T2319		45.50620	-122.75328	45.5	354.5	8/8	7.9381	113	5.2	71.0	72.4		
		B of Texas Creek	128±6	T3004		45.66917	-122.19527	32.1	1.4	8/8	7.8882	63	7.1	61.7	55.0		
				T3012		45.66800	-122.19437	47.1	29.2	8/8	7.9673	214	3.8	61.1	354.8		
				Mean		-----	-----	40.4	13.8	2/2	1.9490	-----	-----	64.8	26.9		
		BA of Rocky Butte	≤134	T0260		45.53950	-122.56347	59.1	1.8	7/8	6.9971	2047	1.3	84.2	43.8		
		BA of Vogel Creek	135±7	T0276		45.63568	-122.21387	48.0	5.1	9/9	8.9644	225	3.4	72.9	42.4		
		BA of Aschoff Buttes	214±4	T6169		45.41607	-121.98534	66.1	354.9	8/8	7.9730	260	3.4	85.4	190.9		
				T6161		45.39957	-122.02237	60.1	349.5	8/8	7.9899		2.1	81.2	121.8		
				Mean		-----	-----	63.1	351.9	2/2	1.9968	-----	-----	84.2	143.0		
		A of Multnomah Basin	246±4	BL8017		45.56775	-122.09228	45.4	355.3	8/8	7.9881	588	2.3	70.9	70.8		
		BA of N Fork Rock Creek	246±4	T7074		45.75863	-122.00984	75.7	358.6	8/8	7.9814	376	2.9	72.8	235.9		
				T7066		45.75869	-122.01049	76.8	350.8	8/8	7.9509	143	4.7	70.2	226.4		
				T7058		45.76809	-122.02254	74.9	18.6	8/8	7.9796	342	3.0	70.8	265.5		
				Mean		-----	-----	76.1	3.2	3/3	2.9960	496	5.5	72.0	242.6		
		BA of Hard Scramble Creek	270±12	T3020		45.66953	-122.12520	61.5	290.9	8/8	7.9706	238	3.6	41.9	170.4		
				T3052		45.65593	-122.13570	80.6	355.8	8/8	7.8830	60	7.2	61.6	222.2		
				T3044		45.66109	-122.12719	71.5	303.6	8/8	7.8841	60	7.2	54.0	185.8		
				T5033		45.66937	-122.13872	77.9	308.8	7/8	6.9872	470	2.8	56.1	204.2		
				Mean		-----	-----	73.9	305.9	4/4	3.9458	55	12.5	55.5	192.3		
		A of McCloskey Creek	272±11	T0285		45.63057	-122.13798	67.9	307.4	7/8	6.9764	254	3.8	55.4	176.2		
		BA of Boyles Creek	281±5	T3028		45.66358	-122.16030	84.6	102.8	8/8	7.9811	370	2.9	42.4	252.0		
				4T056		45.65207	-122.16010	79.0	310.7	8/8	7.9396	116	5.2	56.3	208.2		
				T5017		45.64583	-122.14993	80.7	308.0	7/8	6.9127	69	7.3	54.5	212.9		
				T5025		45.66498	-122.14882	77.6	306.8	8/8	7.9728	258	3.5	55.4	203.3		
				T5041		45.64948	-122.14365	76.1	307.5	8/8	7.9672	214	3.8	56.1	198.8		
				Mean		-----	-----	78.4	308.2	4/5	3.9982	1653	2.3	56.5	205.0		
		B of Carver	339±3	BL8073		45.39722	-122.49577	60.4	5.1	7/8	6.9802	303	3.5	84.5	13.2		
		B of Powell Butte	344±5	T2271		45.48988	-122.51613	50.4	10.0	8/8	7.9731	260	3.4	73.7	25.5		
		B of Little Beacon Rock		T3383		45.63361	-122.02183	54.7	353.6	8/8	7.9061	75	6.5	78.5	85.4		
				T6319		45.64670	-122.03120	64.9	12.6	8/8	7.9653	202	3.9	81.2	315.5		

Brunhes		501±7	Mean	-----	-----	60.1	1.6	2/2	1.9854	-----	-----	85.3	42.9	
	BA of Green Mountain	607±22*	T8073	45.65483	-122.46772	58.4	349.1	8/8	7.9815	377	2.9	79.6	112.0	
	A of Latourelle Prairie	611±28	T5294	45.49482	-122.05312	56.1	335.5	8/8	7.9415	120	5.1	69.6	130.9	
	BA of Mount Pleasant	616±21*	T8089	45.56620	-122.21872	40.2	10.3	9/9	8.9142	93	5.4	65.9	34.1	
	BA of Dougan Creek	643±10	4T025	45.68007	-122.13822	72.8	9.0	7/7	6.9293	85	6.6	76.4	258.3	
	BA E of N Fork Bull Run River	662±8	BL8129	45.50347	-122.02320	53.0	335.9	8/8	7.9866	522	2.4	68.0	123.5	
			T5302	45.50376	-122.01145	65.5	352.2	8/8	7.9796	343	3.0	84.2	173.0	
			Mean	-----	-----	59.5	342.5	2/2	1.9831	-----	-----	76.2	132.1	
	BA of Rodlun Road	675±18	T3080	45.46300	-122.45030	41.9	14.1	4/8	3.9895	286	5.5	65.8	24.7	
			A3001	45.46900	-122.41900	39.7	6.8	12/12	11.9877	897	1.5	66.4	41.7	
			Mean	-----	-----	40.9	10.4	2/2	1.9973	-----	-----	66.4	33.2	
	B of Borges Road	676±63	T3072	45.45403	-122.46305	74.0	13.1	8/8	7.9917	847	1.9	73.4	260.6	
	BA of Hardscrabble quarry	678±22	A3013	45.38978	-122.45602	39.3	12.6	12/12	11.9756	451	2.1	64.7	29.4	
	A of Mount Norway	697±9	T6231	45.60612	-122.25223	38.1	2.6	8/8	7.9193	87	6.0	65.9	51.8	
	BA of Damascus	717±26	A3025	45.41178	-122.48623	39.8	8.3	12/12	11.9810	578	1.8	66.2	38.3	
	BA of Prune Hill	≤745	T0268	45.58628	-122.48092	49.2	22.8	7/8	6.9699	199	4.3	66.4	0.6	
	BA of Palmer Peak	766±5	BL8113	45.54838	-122.01772	64.4	3.6	8/8	7.9888	628	2.2	87.4	311.7	
T5278			45.55767	-122.02328	70.3	15.3	8/8	7.9692	227	3.7	76.8	280.5		
Mean			-----	-----	67.5	8.7	2/2	1.9958	-----	-----	82.5	285.7		
B of Bobs Mountain	782±4	T6119	45.65765	-122.19605	63.9	340.0	8/8	7.9598	174	4.2	76.1	154.7		
BA of Winston Road	≤833	A3061	45.43448	-122.46865	78.6	4.1	11/12	10.9705	339	2.5	67.3	241.5		
BA of Lookout Point	778±4	T5153	45.49375	-122.13793	55.0	195.5	8/8	7.9524	147	4.6	7.8	45.2		
		BL9001	45.46212	-122.12987	62.3	179.5	9/9	8.9272	110	4.9	0.9	58.2		
		Mean	-----	-----	58.9	188.3	2/2	1.9908	-----	-----	4.5	51.4		
Matuyama														781
	BA of Mount Talbert	875±6	4T104	45.42167	-122.55867	-51.0	189.4	8/8	7.9952	1451	1.5	74.4	26.2	
	BA of Duncan Creek	880±17*	4T040	45.65117	-122.09190	-66.4	174.9	8/8	7.9801	352	3.0	85.3	192.7	
	B of Tote Road	935±7	4T032	45.63533	-122.17635	-37.5	167.3	8/8	7.9653	202	3.9	63.2	85.0	
	BA of Yeon Mountain	951±5	BL9026	45.58488	-122.02623	-64.2	169.2	8/8	7.9623	186	4.1	82.5	154.8	
	BA of Devils Rest	967±13	BL8041	45.56373	-122.15192	-54.5	153.3	8/8	7.7729	31	11.8	67.2	129.7	
	B of Kaiser Road	972±3	T2295	45.55938	-122.83238	-71.7	273.7	7/8	6.9922	769	2.2	34.8	260.7	988
	BA of Kelly Butte	1011±28*	4T256	45.49920	-122.56333	65.8	306.9	8/8	7.9882	593	2.3	54.3	171.2	
	BA of Wildboy Creek	≤1031	T6225	45.65785	-122.20112	54.9	0.7	4/8	3.8920	28	17.7	79.8	54.6	
			T5073	45.65765	-122.19838	43.4	11.0	6/8	5.9770	218	4.6	67.8	30.6	
			Mean	-----	-----	49.3	6.5	2/2	1.9866	-----	-----	73.7	37.6	
BA of Burnside Road	1034±8	4T088	45.51892	-122.72322	68.0	320.3	6/8	5.9834	300	3.9	63.4	173.9		
BA of Woodward Creek	1063±9	T6217	45.68325	-122.05423	48.5	28.1	8/8	7.9785	326	3.1	62.7	354.6		
BA of Three Corner Rock	1072±5	4T048	45.73237	-122.04950	46.8	19.9	7/8	6.7788	27	11.8	66.3	9.6	1072	

Matuyama		B of Mount Sylvania	1149±3	4T192	45.46742	-122.73247	-64.4	164.7	8/8	7.9729	258	3.5	79.3	156.8	
				4T001	45.41325	-122.72458	-82.6	149.5	8/8	7.9607	178	4.2	57.3	223.7	
				4T017	45.44783	-122.72892	-65.5	159.4	7/8	6.9811	318	3.4	75.7	163.3	
				4T096	45.43825	-122.69133	-58.9	152.2	8/8	7.9561	159	4.4	68.8	141.4	
				Mean	-----	-----	-63.0	158.4	3/4	2.9936	313	7.0	74.7	151.5	
		BA of Bonney Slope	1149±14	4T080	45.52653	-122.79958	-45.7	189.3	8/8	7.9910	776	2.0	70.1	32.1	
				4T072	45.49788	-122.75588	-44.7	191.3	7/8	6.9561	137	5.2	68.8	28.2	
				Mean	-----	-----	-45.2	190.3	2/2	1.9998	-----	-----	69.5	30.1	
		BA of Fletcher Flat	1159±13	T3036	45.62987	-122.13410	-55.3	178.5	8/8	7.9603	176	4.2	80.1	65.0	
		B of Chamberlain Hill	1197±26*	T5105	45.52715	-122.33872	-57.9	182.7	8/8	7.9812	373	2.9	82.7	40.8	
	Cobb														1173
		(No Representative Units)													
															1185
		BA of Hunsinger	1217±4	T2231	45.34625	-122.53055	-56.2	168.7	7/8	6.9734	226	4.0	77.9	73.8	
				T3088	45.36695	-122.52338	-75.9	171.8	8/8	7.8127	37	9.2	71.5	225.8	
				4T128	45.33962	-122.53640	-45.7	163.4	4/8	3.9937	477	4.2	67.5	99.2	
				Mean	-----	-----	-51.0	165.8	2/3	1.9908	-----	-----	72.4	101.4	
		BA of Bear Prairie	1228±8	T8081	45.62813	-122.22443	-58.5	180.9	8/8	7.9891	643	2.2	83.6	51.5	
				T0293	45.61653	-122.30115	-67.7	195.3	7/8	6.9853	408	3.0	78.6	295.7	
				Mean	-----	-----	-63.3	187.0	2/2	1.9904	-----	-----	85.0	334.7	
		BA of Outlook	1230±10	A3049	45.39108	-122.49932	-56.1	161.6	12/12	11.9883	940	1.4	73.7	121.7	
		BA of Holcomb Creek	1286±24	4T200	45.36825	-122.54288	-60.4	154.2	8/8	7.9351	108	5.4	70.9	144.5	
		B of Pepper Mountain	1290±9	4T152	45.52335	-122.18273	-60.8	201.7	6/7	5.9637	138	5.7	73.9	333.4	
		BA of Broughton Bluff	1300±19	T2279	45.53982	-122.37568	-54.6	193.0	8/8	7.9847	459	2.6	75.6	115.1	
		B of S Fork Gordon Creek	1390±8	T5145	45.50155	-122.14167	-52.9	186.3	7/8	6.9898	588	2.5	77.0	33.7	
		BA of Trout Creek	1422±21	T5184	45.44830	-122.16795	-65.7	193.0	8/8	7.9300	100	5.6	80.8	307.9	
				T5169	45.47690	-122.26923	-62.5	166.0	6/8	5.9836	306	3.8	79.9	144.5	
				T3280	45.48848	-122.31010	-59.4	189.9	8/8	7.9888	623	2.2	81.0	0.3	
				Mean	-----	-----	-63.1	182.9	3/3	2.9832	119	11.4	87.7	351.6	
		BA of Gordon Creek	1464±10	T5129	45.50302	-122.17793	-57.1	175.6	8/8	7.9892	648	2.2	81.5	82.3	
		BA E of Angels Rest	1513±8	BL8049	45.56732	-122.14252	-47.8	184.7	8/8	7.9771	306	3.2	72.9	43.7	
		A of Larch Mountain	1514±8	T5121	45.55387	-122.12427	-47.1	190.3	7/8	6.9826	345	3.2	70.9	29.1	
				4T159	45.53732	-122.11537	-49.3	181.7	7/8	6.9759	249	3.8	74.5	52.4	
				Mean	-----	-----	-48.3	186.1	2/2	1.9971	-----	-----	73.1	39.4	
		B of Mount Scott	1585±16	T3256	45.41113	-122.54305	-53.2	184.1	8/8	7.9638	193	4.0	77.9	41.0	
				T3060	45.45562	-122.56605	-49.9	199.9	7/8	6.9925	804	2.1	68.6	4.3	
				T3068	45.45562	-122.56605	-58.4	194.8	4/4	3.9735	113	8.7	77.4	352.5	
				4T240	45.44025	-122.56797	-54.2	177.4	8/8	7.9951	1418	1.5	79.1	68.7	
				4T248	45.46888	-122.55993	-43.2	165.9	7/8	6.9830	353	3.2	66.8	91.5	
				T2255	45.41275	-122.52422	-54.7	205.7	8/8	7.9962	1844	1.3	68.1	193.9	
				4T112	45.44317	-122.54905	-57.8	170.8	8/8	7.9658	205	3.9	80.2	104.9	

Matuyama				Mean	-----	-----	-53.9	185.0	7/7	6.8990	59	7.9	78.4	36.4	
		B of Sycamore	1632±43	T2263	45.47697	-122.50722	-71.8	173.6	8/8	7.9929	979	1.8	78.1	220.2	
				T3264	45.42742	-122.49277	-57.3	192.6	8/8	7.9424	122	5.1	78.0	1.6	
				Mean	-----	-----	-64.8	185.7	2/2	1.9794	-----	-----	85.9	306.7	
		BA E of Larch Mountain	1685±6	BL8105	45.53522	-122.02672	-54.1	207.7	8/8	7.8118	37	9.2	66.3	345.7	
				BL9018	45.52447	-122.04292	-55.8	195.4	8/8	7.9510	143	4.7	75.2	1.0	
				Mean	-----	-----	-55.1	201.7	2/2	1.9960	-----	-----	70.9	351.5	
		BA of Bell Creek	1694±13	T6279	45.54211	-122.02963	-63.7	196.5	8/8	7.9850	466	2.6	78.4	323.1	
		BA of N Fork Bull Run River	1702±8	BL9010	45.53690	-122.01217	-57.8	211.8	8/8	7.9573	164	4.3	65.5	333.5	
															1778
	Olduvai	B of Tumalt Creek	1908±5	BL1005	45.58653	-122.06148	76.6	330.4	1/1	1.0000	-----	-----	65.0	207.7	
		B of Horsetail Creek	1910±15	BL1008	45.57942	-122.00028	75.2	324.7	1/1	1.0000	-----	-----	63.9	200.1	
				Mean	-----	-----	75.9	327.4	2/2	1.9997	-----	-----	64.5	203.7	
		BA of Oneonta Creek	1933±12	BL8001	45.56325	-122.09387	53.5	0.6	5/8	4.9944	708	2.9	78.5	55.4	
		B of Deer Creek	1965±12	BL1010	45.52225	-122.03177	51.8	12.4	1/1	1.0000	-----	-----	73.8	17.5	
				Mean	-----	-----	53.3	2.6	6/9	5.9875	-----	-----	78.2	47.4	
															1945
		Low-K tholeiite	1976±10	T5208	45.17912	-122.15208	-73.0	166.8	5/8	4.9676	123	6.9	74.4	211.6	
		B of N Fork Gordon Creek	2236±32	4T167	45.52977	-122.15297	-61.6	172.3	7/8	6.9618	157	4.8	83.8	123.8	
				T5137	45.50142	-122.13893	-58.6	174.0	8/8	7.9938	1129	1.7	82.4	95.6	
				Mean	-----	-----	-60.1	173.2	2/2	1.9993	-----	-----	83.3	108.0	
		B of Bridal Veil Creek	2291±10	4T136	45.54118	-122.17337	-61.4	181.4	8/8	7.9495	139	4.7	86.4	41.3	
				T7146	45.54543	-122.14182	-55.2	189.9	7/8	6.9839	374	3.1	77.7	17.1	
				4T272	45.51882	-122.25687	-64.0	174.6	8/8	7.9317	102	5.5	86.2	153.0	
				Mean	-----	-----	-60.4	182.7	3/3	2.9893	187	9.0	85.3	32.5	
		BA of Multnomah Basin Rd	2299±12	BL8033	45.56562	-122.09945	-62.7	177.7	8/8	7.9680	219	3.8	87.8	106.5	
		BA of Fischers Mill	2447±20	4T232	45.31117	-122.47582	-62.8	182.4	7/8	6.9571	140	5.1	87.9	1.1	
				T6009	45.32217	-122.46547	-57.4	184.7	8/8	7.9470	132	4.8	81.9	30.3	
				T3161	45.33983	-122.43963	-38.2	198.5	7/8	6.9563	137	5.2	61.7	19.0	
				Mean	-----	-----	-60.1	183.6	2/3	1.9977	-----	-----	84.9	24.6	
		BA of Root Creek	2530±14	T2223	45.27245	-122.50463	-53.0	184.4	8/8	7.9613	181	4.1	77.8	140.1	
		Low-K tholeiite	2575±47	T6185	45.46178	-122.04728	-67.9	179.0	8/8	7.9803	355	2.9	84.5	231.4	
		BA of Four Corners	2585±10	4T224	45.30445	-122.49235	-51.0	171.3	4/8	3.9755	122	8.3	74.8	87.0	
				T3169	45.32098	-122.48060	-56.6	195.5	8/8	7.9615	182	4.1	75.8	357.0	
				Mean	-----	-----	-54.4	182.6	2/2	1.9823	-----	-----	79.4	45.9	
		BA of Fallsview	2596±19	T3112	45.23045	-122.58430	-58.8	193.7	7/8	6.9872	468	2.8	78.4	352.1	
				T5081	45.25188	-122.52190	-61.3	163.9	8/8	7.9705	237	3.6	78.1	139.7	
				T3120	45.22933	-122.52848	-55.0	192.7	8/9	7.9392	115	5.2	76.3	8.3	
				Mean	-----	-----	-59.1	184.3	3/3	2.9745	78	14.0	83.7	25.3	
		BA of Highland Butte	2611±18	T3145	45.26148	-122.40537	-60.4	203.0	8/8	7.9771	305	3.2	72.9	332.5	
				T3129	45.24662	-122.45303	-53.7	198.6	8/8	7.9368	111	5.3	72.0	359.0	

Matuyama		BA of Beaver Creek	2618±57	Mean	-----	-----	-57.1	200.6	2/2	1.9962	-----	-----	72.9	346.6			
				T3153	45.28578	-122.45218	-55.7	206.5	6/8	5.9667	150	5.5	68.2	342.6			
				T5089	45.28292	-122.49823	-41.6	181.6	7/8	6.9682	188	4.4	68.6	53.6			
			A of Tong Road	2623±42	Mean	-----	-----	-49.3	192.3	2/2	1.9650	-----	-----	72.1	20.8		
					4T120	45.39770	-122.47523	-56.2	178.7	8/8	7.9753	283	3.3	81.3	64.7		
					T2247	45.39678	-122.47898	-59.0	177.3	7/8	6.9649	171	4.6	84.0	102.4		
			B of Canemah	2632±9	Mean	-----	-----	-57.6	178.0	2/2	1.9994	-----	-----	82.7	69.8		
					T3096	45.28787	-122.54222	-52.1	184.5	8/8	7.9621	185	4.1	77.0	40.4		
					T3137	45.26212	-122.47612	-52.8	190.5	8/8	7.9730	259	3.5	75.6	19.6		
		4T208			45.17958	-122.50173	-31.0	162.8	8/8	[-32,-3]	[6.9,17.3]	-----	58.1	89.9			
		T2239			45.34883	-122.60997	-51.5	192.1	8/8	7.9899	693	2.1	73.8	162.0			
		T3104	45.24237	-122.58547	-52.7	189.9	8/8	7.9581	167	4.3	75.8	21.7					
		Mean	-----	-----	-52.3	189.3	4/5	3.9980	1472	2.4	75.7	24.2					
		Gauss	Kaena														2581
				(No Representative Units)													
Low-K tholeiite	3074±18			T3185	45.22295	-122.36257	-56.9	223.7	8/8	7.9751	281	3.3	56.7	325.3	3032		
				4T216	45.19698	-122.33115	-61.5	198.2	8/8	7.9877	569	2.3	76.7	332.2			
				T5192	45.41087	-122.21388	-81.2	182.6	8/8	7.9941	1184	1.6	62.6	239.5			
				Mean	-----	-----	-59.8	211.8	2/3	1.9857	-----	-----	66.4	327.4			
	B of McIntyre Ridge			3109±9	T6017	45.31750	-122.05792	-60.4	195.6	8/8	7.9768	302	3.2	78.0		341.7	
Low-K tholeiite	3124±42			4T175	45.54498	-122.16970	54.5	10.9	5/9	4.9648	114	7.2	76.6	15.9	3116		
				T5113	45.54078	-122.17037	54.3	2.2	7/8	6.9777	269	3.7	79.1	48.2			
				Mean	-----	-----	54.5	6.5	2/2	1.9981	-----	-----	78.4	30.3			
	Low-K tholeiite			3249±25	T3217	45.44015	-122.22379	57.0	29.6	8/8	7.9706	238	3.6	66.7		337.0	

¹A is andesite; B is basaltic, BA is basaltic andesite, K is potassium, N is north, S is south, and E is east.

²Unit age, calculated relative to FCs monitor age of 28.198 Ma, is the weighted mean age of multiple samples. Asterisk (*) indicates significant age discordance.

³PM ID is paleomagnetism site identifier; following blue cell indicates that the site was not used in final calculations (see text).

⁴Latitude (LAT) and longitude (LON) in degrees of site location; NAD 83 datum used.

⁵Inclination (INC) and declination (DEC) in degrees of site-mean paleomagnetic direction.

⁶Number of samples analyzed (N) over number of samples collected (N₀).

⁷r is the vector sum of N unit vectors, k is the concentration parameter of Fisher (1953), and α₉₅ is the radius of 95% confidence in degrees.

⁸VGP is virtual geomagnetic pole with its latitude (LAT) and longitude (LON) in degrees. VGPs for reversed-polarity directions are transformed to the northern hemisphere.

⁹Pol is magnetic polarity: black where normal, vertically lined (green text) where transitional, and white (red text) where reversed. Ages of polarity boundaries are from Oaq (2012).

Table 2. Boring Lavas replicate ages

Unit Name/location ¹	Polarity chron ²	LAT ³	LON ³	PM ID ⁴	Ar ID ⁵	Reported Age (ka) ⁶	Tech ⁷	Replicate Age (ka) ⁸	Tech ⁷	Mean Age (ka) ⁹
		NAD 83								
BA of Rocky Butte	Brunhes	45.53950	-122.56347	T0260	QV99-18	≤134 ± 26	RM	≤133 ± 57	RM	≤134±23
BA of Damascus	lower Brunhes	45.41178	-122.48623	A3025	RC02-134	775 ± 50	RM	705 ± 23	RM	717±26
BA of Palmer Peak	lower Brunhes	45.54838	-122.01772	BL8113	03BV-G152	768 ± 5	P	751 ± 44	I	766±5
					07BV-G997	775 ± 5	P	760 ± 17	RM	
					09BV-G1318	751 ± 6	P	--	--	
B of Bobs Mountain	lower Brunhes	45.65765	-122.19605	T6119	QV00-25B	775 ± 10	P	784 ± 4	P	782±4
BA of Lookout Point	Matuyama/Brunhes	45.49375	-122.13793	T5153	QV03-167	789 ± 22	RM	782 ± 9	P	778±4
		45.46212	-122.12987	BL9001	RC03-122	777 ± 5	P	770 ± 12	P	
B of Kaiser Road	Jaramillo/Matuyama	45.55938	-122.83238	T2295	QV01-34	979 ± 6	P	971 ± 3	P	972±3
BA of Kelly Butte	upper Jaramillo	45.49920	-122.56333	4T256	QV02-48B	974 ± 8	P	1031 ± 6	P	1011±28
BA of Woodward Creek	lower Jaramillo	45.67910	-122.05332	-----	05BV-G345	1075 ± 8	P	1057 ± 6	P	1063±9
BA of Three Corner Rock	lower Jaramillo	45.73237	-122.04950	4T048	02BV-G10A	1071 ± 6	P	1073 ± 11	P	1072±5
BA of Fletcher Flat	Matuyama (above Cobb)	45.62987	-122.13410	T3036	QV01-38	1169 ± 27	RM	1155 ± 19	RM	1159±13
		45.62990	-122.13513	-----	04BV-G310	1158 ± 24	RM	--	--	
B of Chamberlain Hill	Matuyama (above Cobb)	45.52715	-122.33872	T5105	03CM-T250	1167 ± 14	P	1220 ± 12	P	1197±26
BA of Hunsinger	Matuyama (below Cobb)	45.34625	-122.53055	T2231	QV02-59	1236 ± 10	P	--	--	1217±4
						1226 ± 10	P	1209 ± 6	P	
		45.33962	-122.53640	4T128	QV03-154	1211 ± 6	P	1221 ± 5	P	
BA of Oneonta Creek	Olduvai	45.56300	-122.07945	-----	07BV-G871	1939 ± 4	P	1908 ± 8	P	1933±12
BA of Highland Butte	lower Matuyama	45.26148	-122.40537	T3145	QV02-80	2608 ± 29	P	2600 ± 28	RM	2611±18
		45.24662	-122.45303	T3129	RC02-338	2640 ± 42	RM	--	--	
B of Canemah	lower Matuyama	45.24678	-122.49148	-----	QV02-99	2625 ± 19 ^c	P	--	--	2632±9
		45.30517	-122.56548	-----	QV02-83	2625 ± 13	P	2643 ± 14	P	

¹ B is basaltic, BA is basaltic andesite.

² Black text indicates normal polarity; red text, reversed polarity; and green text, transitional polarity (as in Table 1).

³ Paleomagnetism sampling site latitude (LAT) and longitude (LON) in degrees.

⁴ PM ID is paleomagnetism site identifier; no PM ID indicates that Ar sample was taken at a different, more suitable, location in the same unit (see Fig. 1).

⁵ Ar ID is ⁴⁰Ar/³⁹Ar sample identifier.

⁶ Age reported by Fleck et al. (2014) with estimated 1-sigma (1σ) error, converted to monitor age equivalent to FCs = 28.198 Ma (^c = corrected).

⁷ Interp is interpreted age; I is isochron, P is plateau, and RM is recoil model (see Fig. 2).

⁸ Replicate ages reported herein with standard error (with monitor age adjusted to FCs = 28.198 Ma).
⁹ Weighted mean of reported and replicate ages with weighted standard error of the mean.
^c Original data corrected.

Table 3. Ages of Matuyama volcanic rocks of the Boring Volcanic Field near the Gauss-Matuyama chron boundary							
Unit Name/Volcanic Center	Unit Age (ka) ¹	Paleomagnetic Samples			Ar Sample ²	Polarity ³	Age (ka) ⁴
		ID	Lat 83	Long 83			
Basaltic andesite of Root Creek	2530±14	T2223	45.27245	-122.50463	QV03-210B	R	2530±14
Low-potassium Tholeiite	2575±47	T6185	45.46178	-122.04728	RC05-30	R	2575±47
Basaltic andesite of Four Corners	2585±10				QV03-144B	R	2585±10
		4T224	45.30445	-122.49235		R	
		T3169	45.32098	-122.48060		R	
Basaltic andesite of Fallsview	2596±19	T3112	45.23045	-122.58430		R	
		T5081	45.25188	-122.52190		R	
		T3120	45.22933	-122.52848	QV02-94	R	2596±19
Basaltic andesite of Highland Butte	2611±18	T3145	45.26148	-122.40537	QV02-80 Run 1	R	2608±29
		T3145	45.26148	-122.40537	QV02-80 Run 2	R	2600±28
		T3129	45.24662	-122.45303	RC02-338	R	2640±42
Basaltic andesite of Beaver Creek	2618±57				QV03-206	R	2618±57
		T5089	45.28292	-122.49823		R	
Andesite of Tong Road	2623±42	4T120	45.39770	-122.47523	QV02-55C	R	2623±42
		T2247	45.39678	-122.47898		R	
Basalt of Canemah	2632±9				QV02-99	R	2625±19
					QV02-83 Run 1	R	2625±13
					QV02-83 Run 2	R	2643±14
		T3096	45.28787	-122.54222		R	
		T3137	45.26212	-122.47612		R	
		4T208	45.17958	-122.50173		R	
		T2239	45.34883	-122.60997		R	
		T3104	45.24237	-122.58547		R	

¹ Unit age is the indicated age of single samples or the weighted mean age of multiple samples.

² Sample Locations for Ar samples are from Fleck et al. (2014). Where age and paleomagnetic ID appear on the same line, locations are the same.

³ Magnetic polarity of the samples: R = Reversed.

⁴ Ages from Fleck et al. (2014), calculated for FCs = 28.198 Ma (in ka, with 1 σ uncertainties).

Table 4. VGP dispersion and elongation estimates for BVF datasets			
---	--	--	--

Dataset	Direction		N ²	k ³	α_{95} ⁴	E ⁵	VGP		K ⁷	A ₉₅ ⁸	S _B ⁹	IS _B ¹⁰	uS _B ¹⁰	E ⁵
	INC ¹	DEC ¹					LAT ⁶	LON ⁶						
Brunhes chron	58.9	358.1	39	24	4.8	1.59	86	87.4	15	6.1	20.5	17.8	24.3	1.34
Matuyama chron	-58.1	181.9	54	47	2.9	1.17	84.9	57.6	28	3.8	15.8	14.0	18.2	1.25
Normal polarity	58.6	359.7	47	24	4.4	1.54	85.9	71.9	14	5.7	21.1	18.5	24.5	1.42
Normal polarity (grouped)	59.0	359.4	41	24	4.6	1.78	86.2	77.2	14	6.1	-----	-----	-----	1.62
Reversed polarity	-58.7	183.1	58	44	2.8	1.11	85.6	44.2	25	3.8	16.4	14.5	18.8	1.19
Reversed polarity (grouped)	-58.1	183.2	40	66	2.8	1.08	84.0	45.8	38	3.7	-----	-----	-----	1.47
All polarities combined	58.7	1.7	105	32	2.5	1.48	85.9	55.8	19	3.3	18.8	17.2	20.8	1.47
All polarities (grouped)	58.5	1.3	81	35	2.7	1.49	85.3	57.9	21	3.5	-----	-----	-----	1.45

¹ Mean inclination (INC) and declination (DEC), in degrees, of paleomagnetic directions (see Fig. 5).

²Number of temporally independent flows sampled (see text); and of data grouped by mapped unit (grouped; Table 1).

³Fisher (1953) concentration parameter, in degrees, for directions.

⁴Radius of 95% cone of confidence, in degrees, for mean directions.

⁵ E is ratio of major to minor axes (elongation) for elliptical data sets (see Engebretson and Beck, 1978).

⁶Latitude (LAT) and longitude (LON), in degrees, of virtual geomagnetic poles (VGP; see Fig. 6).

⁷ Fisher (1953) concentration parameter, in degrees, for poles.

^aRadius of 95% cone of confidence, in degrees, for poles.

^a Between-site dispersion of VGPs, in degrees, with respect to the geographic pole, corrected for within-site dispersion (see Johnson et al., 2008).

¹⁰ Lower (IS_B) and upper (uS_B) 95% confidence limits, in degrees, for S_B values (see Cox, 1969).

Table 5. Revised chron/subchron boundaries				
Polarity reversal	Age of Polarity Transition (ka)			
	This study¹	Horng et al.²	GPTS12³	GITS⁴
Matuyama-Brunhes	778±4	781±3	781	773
Jaramillo termination	972±3	988±3	988	1008
Jaramillo onset	≥1072±5	1072±2	1072	1076
Cobb Mtn onset	<1217±4	1185±5	1185	1221
Olduvai onset	1976±10 to 1965±12	1945±4	1945	1934
Gauss-Matuyama	>2632±9	-----	2581	2610
Keana onset	3124±42 to 3109±9	-----	3116	-----

¹ GPTS constraints from the Boring volcanic field. Ages ($\pm 1\sigma$).

² Ages from Horng et al. (2002). Ages ($\pm 1\sigma$).

³ Ages from Ogg (2012).

⁴ Ages from Singer (2014).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8