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The pre-AD 585 extension of the U.S. Southwest archaeomagnetic reference curve

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ABSTRACT

A set of 104 independently dated archaeomagnetic directions was used to extend the U.S. Southwest reference curve back to 375 cal BC and to calculate isolated mean VGPs centered on 960 cal BC and 2390 cal BC. Prior to this study, most U.S. Southwest reference curves extended to only ca. AD 585. This study employed Sternberg's moving window technique with variably sized windows, rather than fixed windows, to smooth the dataset into a continuous curve. The size of each averaging window was determined by the density of data captured by the window, such that each window had a minimum data density of 5.0 and a minimum window size of 50 years. This approach differs from previous studies in the U.S. Southwest, which have applied a uniformly sized averaging window to a dataset regardless of the temporal distribution of the data.

1. Introduction

Archaeomagnetic dating is a chronometric technique that uses changes in the earth's magnetic field through time to date specific archaeological features. Typically, researchers focus on dating archaeological thermal features, such as hearths, roasting pits, and kilns, which acquire a thermoremanent magnetization (TRM) parallel to the existing magnetic field when heated and cooled through normal use. A date is obtained for this heating and cooling event by comparing the archaeomagnetic direction recovered from the feature with a calibrated record of the regional geomagnetic secular variation to determine when the feature was magnetized. Often, this regional secular variation record is presented as an archaeomagnetic reference curve, and it typically is calculated from a set of independently dated magnetic directions that have been recovered from sources such as archaeological thermal features (e.g., hearths, roasting pits) (Schnepp and Lanos, 2005, 2006; Zananiri et al., 2007), lava flows (Hagstrum and Champion, 2002; Arrighi et al., 2006), and/or historical observations of the magnetic field (Jackson et al., 2000). Furthermore, these independently dated archaeomagnetic directions should be recovered from within an area 1000 km diameter in order to avoid introducing errors from regional perturbations in the magnetic field (Batt, 1997; Casas and Incoronato, 2007; Noël and Batt, 1990; Schnepp and Lanos, 2006; Sternberg, 1997; but see Hagstrum and Blinman, 2010). This geographic limitation is the reason that regional curves must be created from local datasets and cannot be used to accurately date archaeological features from other areas (Lengyel, 2004)

Over the past several decades, archaeomagnetic dating has been utilized routinely to date archaeological features in the U.S. Southwest. However, as the scope of archaeological research has shifted to include earlier periods of occupation in this region, the temporal restrictions of the existing archaeomagnetic reference curve have hampered efforts to date these sites. Currently, the most commonly used reference curves for the U.S. Southwest, SWCV595 (LaBelle and Eighmy, 1997) and SWCV2000 (Lengyel and Eighmy, 2002), cover the temporal period between AD 585 and the present. A number of projects in central and southern Arizona, however, have focused on archaeological features and sites that were utilized before AD 585. Fortunately, many researchers have chosen to collect archaeomagnetic samples from these earlier features, along with related independent dating samples (e.g., radiocarbon samples), and the inventory of independently dated, early archaeomagnetic samples has grown to the point that it is possible to extend the Southwest dating curve to earlier time periods. Therefore, the goal of this study was simply to compile an archaeomagnetic reference curve for the U.S. Southwest that covered as much of the period prior to AD 585 as was warranted by the available data. This was accomplished by first populating the study dataset according to specific precision criteria, and then smoothing this dataset into a spatially and temporally averaged curve through the moving window method developed by Sternberg

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(Sternberg, 1982, 1989; Sternberg and McGuire, 1990a) with a modified sliding-window approach (e.g., Hagstrum and Blinman, 2010; Le Goff et al., 2002; Zananiri et al., 2007). The details of this study are presented below.

2. The reference curve dataset

The dataset amassed for this study consisted of 104 independently dated archaeomagnetic samples recovered from archaeological sites across the U.S. Southwest (Supplemental Material). The majority of these samples predated the existing curves for this region, although the study did include samples that overlapped with the earliest portion of these curves, between ca. AD 585 and 675. While existing curves ostensibly cover the period back to AD 585, the earliest portion of these datasets tends to be poorly represented (e.g., Eighmy and LaBelle, 1995), and it seemed prudent to try to augment and strengthen these existing data as part of the larger goal of expanding the temporal coverage of the regional reference curve. This approach had the added benefit of facilitating the articulation of the curve extension developed through this study with the early end of previously developed curves (see Section 4).

While the majority of samples utilized in this study were compiled specifically for this project, eighteen of the samples have been included in previous curve-building efforts. Four of these were included in a newly published reference curve developed for the western U.S. (Hagstrum and Blinman, 2010), and all four date to the period between AD 400 and 600. The other fourteen samples were included in the SWCV595/2000 reference curve dataset (Eighmy and LaBelle, 1995), and they contributed almost exclusively to the earliest three mean VGPs calculated for those curves (i.e., the AD 600, 625 and 650 mean VGPs). For clarity, it should be noted that the two curves, SWCV595 and SWCV2000, are based on the same dataset but depict slightly different paths of secular variation. The curve SWCV595 is a statistically calculated curve constructed through Sternberg's moving windows method, whereas SWCV2000 is a modification of that curve that corrects for specific shortcomings of the averaging calculations (see Lengyel and Eighmy, 2002 for a full discussion).

2.1. Magnetic data

The archaeomagnetic samples included in this study were collected from archaeological thermal features (e.g., hearths and roasting pits) using the methods outlined in Eighmy (1990), and each sample consisted of 6–12 individually oriented cubes recovered from a single feature. These samples were processed in one of six laboratories, and the resulting data were made available through published project reports (e.g., Clark, 2000; Rogge, 2009) and/or laboratory technical series (e.g., Dubois, 2008; Eighmy and Klein, 1988, 1990; Eighmy and LaBelle, 1995; Eighmy et al., 1987). Laboratories contributing to this study include the former Colorado State University (CSU), University of Arizona (UA) and Statistical Research Inc. (SRI) archaeomagnetic laboratories, Robert Dubois' laboratories at the University of Arizona and the University of Oklahoma, the New Mexico Office of Archaeological Studies (NMOAS) Archaeomagnetic Dating lab, and the Illinois State Museum (ISM) Archaeomagnetic Dating lab. Only the NMOAS and ISM labs are still in operation.

For the most part, the archaeomagnetic data were generated through similar laboratory procedures. Each specimen in a sample was progressively demagnetized through alternating field (AF) demagnetization, typically at 5 or 10 mT intervals (e.g., Cox and Blinman, 1999; Eighmy and LaBelle, 1995), and then the specimen data were combined to obtain the mean magnetic data for the sample. The CSU, Dubois and NMOAS labs reported mean sample data at a single, optimal level of demagnetization, usually at the NRM (natural remanent magnetism; i.e., pre-demagnetization), 5 mT or 10 mT level. In contrast, the UA, SRI and ISM laboratories used principal component analysis (Kirschvink, 1980) to calculate the mean sample data over the entire demagnetization routine (typically NRM to 40 mT). Following convention in the U.S. (e.g., Eighmy et al., 1980), the mean magnetic directions were converted to their corresponding magnetic pole positions, termed virtual geomagnetic poles (VGPs), and these VGPs were utilized in subsequent analyses. A VGP differs from the global geomagnetic pole because it reflects a single recording of the magnetic field from one location and thus includes the affects of local magnetic perturbations that are averaged out at the global scale (Butler, 1992).

2.2. Temporal calibration data

The magnetic data included in this study were temporally calibrated into calendar years through associated radiocarbon dates, tree-ring dates, or cultural information, depending on which was identified by the investigating archaeologist as providing the best age estimate for the feature. Most of the data were associated with radiocarbon dates (66%), including all of the data that predated AD 200. In most cases, the corrected radiocarbon dates were available through project publications (e.g., Clark, 2000; Elson and Swartz, 1994), and these were recalibrated into two-sigma date ranges through OxCal (v. 3.10; Bronk Ramsey, 1995, 2001) using the IntCal04 dataset (Reimer et al., 2004). The radiocarbon dates associated with the NMOAS data (Cox and Blinman, 1999) were reported only as two-sigma calibrated date ranges, and these original calibrations are retained in this study. It should be noted that only two-sigma calibrated date ranges were used in this study in order to provide the most accurate temporal calibrations for the associated magnetic data and to maintain consistency with the other independent dating techniques employed.

A much smaller subset of the data was associated with tree-ring dates (14%), and all of these post-dated AD 580. Two of the tree-ring dated samples were reported by Cox and Blinman (1999) and are new to the Southwest archaeomagnetic dataset. The remaining 13 tree-ring dated samples are included in the SWCV595/2000 reference curve dataset (Eighmy and LaBelle, 1995) and contribute to the earliest three mean VGPs calculated for those curves (LaBelle and Eighmy, 1997; Lengyel and Eighmy, 2002).

Finally, the remaining magnetic data (20%) were dated through associated cultural information (e.g., ceramics, architectural styles), including all of the Dubois data and most of the NMOAS data. The age estimates associated with four of the Dubois data were assessed and reported in a recent study of western U.S. secular variation (Hagstrum and Blinman, 2010), and those newly assessed estimates are utilized in this study. The age estimate for Dubois's data from the Connie Site was provided by Dr. Eric Blinman at the NMOAS, but the data were not incorporated into his western U.S. curve. Likewise, the archaeologically based age estimates reported for the NMOAS data (Cox and Blinman, 1999) are utilized directly in this study, but they were not incorporated into Hagstrum and Blinman's (2010) western U.S. study. The last culturally dated data point was included in the SWCV595/2000 dataset (Eighmy and LaBelle, 1995) and contributes to the early end of those curves

2.3 Study precision criteria

Two precision criteria were applied to potential data when compiling the study dataset. First, only archaeomagnetic data with time estimates of less than 300 years were included in the study.

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This range is somewhat larger than those used by many other studies in the Southwest (e.g., Eighmy, 1991:203; Eighmy et al., 1986:82, 1990:229; LaBelle and Eighmy, 1997:432) primarily because the majority of samples included in this study were calibrated through associated radiocarbon dates, rather than through dendrochronology. The less precise time-estimate criterion was needed to accommodate the larger date ranges generated through radiocarbon dating.

It should be noted that several researchers have advocated recently against using temporal precision cut-offs to filter datasets when using a curve construction procedure that takes the temporal error into account (e.g., Lanos et al., 2005; Schnepp et al., 2004). It was felt that a precision cut-off was appropriate for this study, however, in order to improve the temporal accuracy of the overall dataset. By limiting the size of acceptable two-sigma calibrated radiocarbon date ranges, this study could exclude radiocarbon samples processed under older laboratory standards and/or those that may not have been recovered in accordance with more recent archaeological methodology (e.g., Schiffer, 1986). Although the smaller two-sigma calibrated date ranges of the included samples do not necessarily ensure that the radiocarbon dates accurately reflect the age of the associated archaeomagnetic data, the presumed care with which these samples were selected improves the likelihood that the two datasets are related. Furthermore, by restricting the range of acceptable calibrated radiocarbon dates, this study limits the affects of fluctuations in the radiocarbon calibration curve on the temporal resolution of the dataset.

In addition to temporal filtering, the archaeomagnetic data were filtered to include only those with α_{95} values of less than 10°. Again, this cut-off is much larger than the 3.0° (Dubois, 2008) or 3.5° (LaBelle and Eighmy, 1997) values utilized in other Southwest archaeomagnetic studies, but it is in-line with larger values used in other recent studies (e.g., Donadini et al., 2009; Hagstrum and Blinman, 2010; Schnepp and Lanos, 2005). It could be argued that a cut-off value is unnecessary, since the data are weighted by their precision (e.g., Lanos et al., 2005; Schnepp et al., 2004); however, samples with α_{95} values larger than 10.0° tend to be magnetically unstable and typically are judged to be unreliable for dating or curve construction (e.g., Lengyel et al., 2003). The use of a 10° cut-off allowed this study to tap a larger pool of potential data while still maintaining a level of accuracy. It should be noted that in practice the largest sample α_{95} value included in the study dataset is 7.29°, and 65% of the dataset had α_{95} values of 3.5° or less (Supplemental Material).

2.4 Treatment of contexts with multiple samples

At times, researchers collected multiple archaeomagnetic and/or radiocarbon samples from individual features. In most cases, a better estimate of the archaeomagnetic direction and/or radiocarbon date associated with a particular context was obtained by averaging the respective sample data from that feature. For contexts with multiple archaeomagnetic samples, the sample data were compared first to determine whether the measurable difference between them was due to chance (McFadden and Lowes, 1981). Contexts with two or more statistically different archaeomagnetic samples were excluded from the study dataset because it was uncertain which sample provided a better estimate of the relevant archaeomagnetic data. Statistically indistinguishable data, on the other hand, were combined to calculate the mean archaeomagnetic data for the context. A total of 10 contexts met this requirement (Table 1). For six of these contexts, the archaeomagnetic data were available at the specimen level, allowing the mean context data to be calculated from the individual specimen data. For the remaining four contexts, however, only the mean sample data were available, and the context means could be calculated only at the sample level. This included the two samples recovered from Feature 1 at Ocho Metates, and after the samples were averaged it was determined that the artificially enhanced precision of the averaged sample skewed the shape of the curve (see discussion in Section 3.2). For this reason, the individual sample data were retained in the study dataset.

As with the archaeomagnetic data, the internal consistency of contextually paired radiocarbon samples was assessed statistically to ascertain whether they reflected the same true age. These calculations were conducted in OxCal (v. 3.10) following the procedures outlined in Ward and Wilson (1978, 1981). Sets of determinations found to be statistically indistinguishable at the 0.05 significance level were pooled to calculate a mean age for the feature (Table 2). For the most part, these determinations were combined according to Ward and Wilson's Type II procedure; however, in the case of Feature 25 at LA 87066, two determinations

Table 1
Mean archaeomagnetic data for contexts with multiple archaeomagnetic samples. Individual sample data can be found in the supplementary file to this study.

Site name	Site number	Feature number	Averaged samples	*n*	A_{95}	*k*	Plat	Plong
Ocho Metates, Colorado	–	Feature 1	Dubois-815 and 816	2	1.86	17938.85[d]	70.80	310.06
Hay Hollow Valley, Connie Site	–	Feature 57	Dubois-1106 and 1109	2	14.64[c]	292.92	81.97	288.28
–	LA 87066	Feature 25[a]	SRI 2283 and SRI 2284	19[b]	1.90	327.71	74.99	334.52
Square Hearth	AZ AA:12:745 (ASM)	Feature 33[a]	AZ AA:12:745(ASM)-1, AZ AA:12:745(ASM)-2, AZ AA:12:745(ASM)-3	39[b]	1.00	485.74	88.77	280.59
Santa Cruz Bend	AZ AA:12:746 (ASM)	Feature 310	AZ AA:12:746(ASM)-8, AZ AA:12:746(ASM)-9	21[b]	1.50	447.49	86.02	286.17
–	AZ-I-25-47 (NAV)	Feature 1[a]	AZ-I-25-47 (NAV)-2, AZ-I-25-47 (NAV)-1	22[b]	2.00	253.09	85.30	272.02
Pueblo Patricio	AZ T:12:42 (ASM)	Feature 162	AZ T:12:42(ASM)-7, AZ T:12:42(ASM)-8	2	2.83	7775.03	84.47	298.06
Round Valley	AZ U:3:341 (ASM)	Feature 27	SRI 2699 and SRI 2700	22[b]	0.65	2362.22	89.47	227.42
Finch Camp	AZ U:11:7 (ASM)	Feature 2215	SRI 4010 and SRI 4011	23[b]	2.79	118.68	88.81	272.04
–	5MT9168	Feature 3	CSU/5MT9168-1 (DVGP231), CSU/5MT9168-3 (DVGP232)	2	2.80	7935.66	83.92	308.04

[a] These contexts have multiple radiocarbon samples as well.
[b] These samples were averaged at the specimen level.
[c] This combined sample's large α_{95} value reflects the distance between the averaged samples; the individual sample α_{95} values meet the precision criterion.
[d] Due to the extremely large *k*-value calculated for this combination, the averaged data were not used in this study and are presented here only for reference.

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Table 2
Mean calibrated radiocarbon dates for contexts with multiple radiocarbon samples.

Site name	Site number	Feature number	Combined samples	Corrected dates	Test statistic	Mean calibrated radiocarbon date
Dairy	AZ AA:12:285 (ASM)	Feature 123	Beta-178894, Beta-178899	2800 ± 40, 2820 ± 40	$T' = 0.135 < \chi^2_{0.05} = 3.84$	1040–890 cal BC
–	AZ N:12:25 (ASM)	Feature 2	Beta-56618, Beta-56621, Beta-86350	1350 ± 90, 1550 ± 90, 1440 ± 70	$T' = 2.428 < \chi^2_{0.05} = 5.991$	AD 530–670
–	LA 87066	Feature 25[a]	Beta-178607, Beta-178608, Beta-178609	1920 ± 70, 1790 ± 40, 1820 ± 70	$T' = 0.004 < \chi^2_{0.05} = 3.841$	AD 90–320
Square Hearth	AZ AA:12:745 (ASM)	Feature 33[a]	AA-13782, AA-13783	1675 ± 65, 1810 ± 60	$T' = 2.209 < \chi^2_{0.05} = 3.841$	cal AD 220–550
–	AZ-I-25-47 (NAV)	Feature 1[a]	Beta-83941, Beta-83942	1310 ± 70, 1490 ± 60	$T' = 3.659 < \chi^2_{0.05} = 3.841$	cal AD 550–680
Pueblo Patricio	AZ T:12:42 (ASM)	Feature 89	Beta-10769, Beta-7679	1580 ± 100, 1600 ± 60	$T' = 0.019 < \chi^2_{0.05} = 3.841$	cal AD 340–580
Eagle Ridge, Locus B	AZ V:5:104 (ASM)	Feature 68	AA-11960, AA-13690	1760 ± 75, 1725 ± 65	$T' = 0.126 < \chi^2_{0.05} = 3.841$	cal AD 130–420
Boatyard	AZ U:3:286 (ASM)	Occupation Surface 2	Beta-96315, Beta-96316	2210 ± 60, 2220 ± 40	$T' = 0.005 < \chi^2_{0.05} = 3.841$	390–200 cal BC
Finch Camp	AZ U:11:7 (ASM)	Feature 1105	WK-21401, WK-21403, WK-21404	1754 ± 37, 1775 ± 37, 1773 ± 37	$T' = 0.211 < \chi^2_{0.05} = 5.991$	cal AD 220–340

[a] These contexts have multiple archaeomagnetic samples as well.

made on the same structural element (Beta-178607 and 178608) were pooled according to Ward and Wilson's Type I procedure, and the pooled data for the element were then combined with a third determination (Beta-178609) from the structure following the Type II procedure. When two or more determinations from the same context were found to be statistically different, other archaeological information from the context or site was consulted in order to identify the anomalous date(s). If it was unclear which dates were anomalous, the context was excluded from the study. Overall, pooled radiocarbon dates were calculated for nine contexts, including three that also produced mean archaeomagnetic data.

2.3 Final dataset summary

The final dataset compiled for this study consisted of 104 independently dated VGPs, including nine mean context VGPs, that span the period between 2580 BC and AD 675 (Supplementary Material). Despite the fairly large precision cut-off, the α_{95} values for all but one sample ranged from 0.44° to 7.29°, with a median value of 2.83°. The mean context VGP from Hay Hollow Valley (Dubois 1106 and 1109) had a larger α_{95} value of 14.64° due, primarily, to the relative distance between the two sample VGPs, each of which, individually, had values of 3.1° and 2.4°, respectively. Similarly, the size of the age estimates ranged from a low of 20 years to the cut-off value of 300 years, with a median age range of 205 years.

Although the dataset spans nearly 3300 years, the data are not distributed uniformly within that period (Fig. 1). Instead, they are spread over three discrete periods of fairly continuous coverage. Roughly 93% of the VGPs date to the period of 375 BC–AD 675, although the majority (60%) is clustered between roughly AD 400 and 675. Furthermore, there is a noticeable drop in the number of VGPs dating to the period between roughly 100 BC and AD 150, resulting in sparse coverage for this period. The remaining 7% of the dataset is divided between the periods of 1120–800 BC (4%) and 2580–2200 BC (3%), with no coverage for the intervening time spans.

3. Extending the U.S. Southwest curve

A variety of methods are available for smoothing archaeomagnetic datasets into regional dating curves, including several

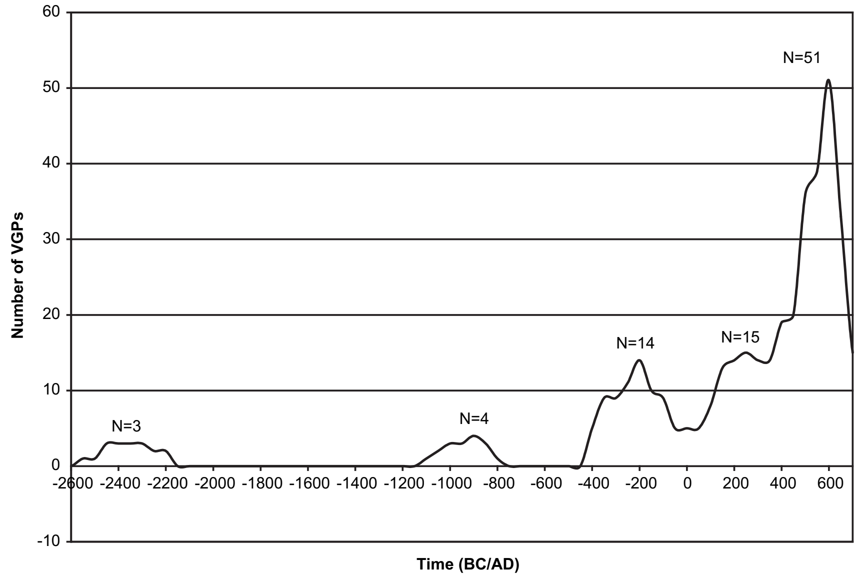

Fig. 1. This cumulative curve depicts the temporal distribution of the study dataset within the covered period of 2580 BC–AD 675. The curve was calculated by treating each VGP age estimate as a flat probability, and then summing the number of VGP age estimates that encompass a particular year. Thus, each point on the curve reflects the number of VGPs that might date to that year.

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that employ running averages (Sternberg, 1982, 1989; Le Goff et al., 2002; e.g., Batt, 1997; Lengyel and Eighmy, 2002) and a more recent approach that uses Bayesian modeling to fit a spherical spline to the data (Lanos et al., 2005; e.g., Schnepp and Lanos, 2005, 2006; Zananiri et al., 2007). In keeping with previous studies in the U.S. Southwest (e.g., Eighmy, 1991; LaBelle and Eighmy, 1997; Lengyel and Eighmy, 2002; Sternberg and McGuire, 1990b), this study used the moving window method developed by Sternberg (1982, 1989; Sternberg and McGuire, 1990a) to fit a smooth temporal curve to the dataset. This approach uses a running average to smooth the archaeomagnetic dataset into a sequential series of mean VGPs that define the regional reference curve. These mean VGPs are calculated by averaging individual data points within set time intervals, or windows, that are shifted by a fixed increment over the time period covered by the dataset. Each individual data point is weighted by its precision parameter, *k*, and by the extent to which its age estimate overlaps the averaging window, thereby taking into account the uncertainty in both the archaeomagnetic data and the associated date ranges. This method defines the shape of the curve by averaging the independently dated VGPs over incremental windows of time. Typically, an optimal window length is selected for these calculations that reduces the noise in the dataset without smoothing over important details in secular variation (Eighmy, 1991). In most cases, the length of the averaging window corresponds to the size of the age ranges of the included data (Eighmy, 1991:207; Sternberg and McGuire, 1990a:118), and it is moved in increments of half the window length. This fixed window approach works well for smoothing evenly distributed data, but it requires a compromise window size to smooth variably distributed data such as in this study dataset (Hagstrum and Blinman, 2010). Furthermore, when data are distributed unevenly within an averaging window, not all portions of that interval will be represented by archaeomagnetic results, and in some cases these gaps can be quite large (e.g., Lengyel, 2004). Likewise, the mean VGP calculated for that window can be pulled towards one end of the window range, skewing the shape of the dating curve towards time periods with higher data densities and leading to potentially inaccurate dating results for samples that happen to fall within underrepresented time periods (Lengyel and Eighmy, 2002). To avoid these problems, the study dataset was averaged over variably sized windows, with the size of each window determined by the density of the data.

3.1 Variable windows

Recently, Le Goff and others (Lanos et al., 2005; Le Goff et al., 2002) have suggested utilizing variable window sizes in order to accommodate the temporal variability in data density that is present in many archaeomagnetic datasets. To do this, a minimum data density (*Nj*) per averaging window is established for the dataset, and the data are then averaged within windows that meet the threshold value. Although recent studies have advocated using minimum threshold values of roughly 3.0 (Hagstrum and Blinman, 2010; Le Goff et al., 2002), this study employs a more conservative threshold value of 5.0. This larger value reflects findings by Sternberg and McGuire (1990a:120–121) that suggests a threshold value of 7.0 would maximize the precision of the calculated curve. A threshold value of 5.0 serves as a compromise between the various studies and facilitates smoothing of the earlier portion of the study dataset, for which the overall data density is relatively low. In addition to the minimum data density threshold, the averaging windows used in this study have a minimum length of 50 years, which is in-line with values used by previous studies (e.g., Hagstrum and Blinman, 2010; LaBelle and Eighmy, 1997; Lengyel, 2004).

The averaging windows used in this study were identified by first subdividing the dataset into segments of internally continuous temporal coverage (2580–2200 BC, 1120–800 BC, 410 BC–AD 675), and then working from the youngest to oldest data in each subset. For each segment, the youngest window was established by determining the smallest time range that would encompass the youngest VGPs in that segment and meet the window size and data density thresholds established for the study dataset. Once the youngest window was set, the subsequent window was established by shifting the youngest window's mean age back by an increment of half its window length to find the next youngest window's mean age, and then determining the smallest window size centered on that mean age that met the study's threshold parameters. For instance, the youngest window in the study was centered on AD 650 with a span of AD 625–675; this was shifted 25 years (half the window length) to find the mean age of the next window at AD 625. It was determined that the smallest window centered on AD 625 that met the threshold parameters was AD 600–650, and the data within this window were averaged to calculate the mean VGP for the interval. This process continued until averaging windows were determined for the entire span of the dataset. For convenience, window lengths were set in increments of 25 years (e.g., 50, 75, 100 year lengths), with a median window length of 100 years. It should be noted that the two earliest windows did not meet the data density threshold parameter for the study due to the scarcity of data for these periods.

3.2 Outliers

Once the averaging windows were identified, the distribution of the data within each window was evaluated in order to identify potential outliers from the group or data that otherwise skewed the location of the mean VGP calculated for the window. The three standard deviation test described by Sternberg (1982:27) was used. This test involves removing a potential outlier from the dataset, and calculating a new mean and angular standard deviation for the window. If the potential outlying VGP is more than three standard deviations from the new mean, it is identified as an outlier. None of the study VGPs failed this test.

Although no statistical outliers were identified for the study dataset, the mean context VGP calculated for Feature 1 from Ocho Metates in Colorado (Dubois-815 and Dubois-816) was identified as problematic because it significantly skewed the locations of the mean VGPs for the averaging windows it intersected. The precision parameter (*k*) associated with the Feature 1 mean VGP was so large that it essentially pulled the mean VGP calculated for each window towards it. This resulted in skewed mean window VGP locations because the Feature 1 VGP was located at the edge of each window's data distribution, although it was not, technically, an outlier from the group (Fig. 2). To circumvent this problem, the two individual sample VGPs from the feature were utilized in the curve calculations rather than the mean context VGP, resulting in more centralized locations for the affected mean window VGPs.

4. The expanded archaeomagnetic reference curve for the U.S. Southwest

The resulting reference curve calculated for this study (Table 3) is depicted in Fig. 3 as a change in pole location during the period between 2390 BC and AD 650. For all but the two earliest averaging windows, the precision in estimating the mean curve location was very good, with A_{95} values for the mean VGPs ranging from 0.63° to 2.56° and a median value of 1.95°. These results suggest that the calculated curve segment has captured the general shape of secular variation in the Southwest for the period of 375 BC–AD 650,

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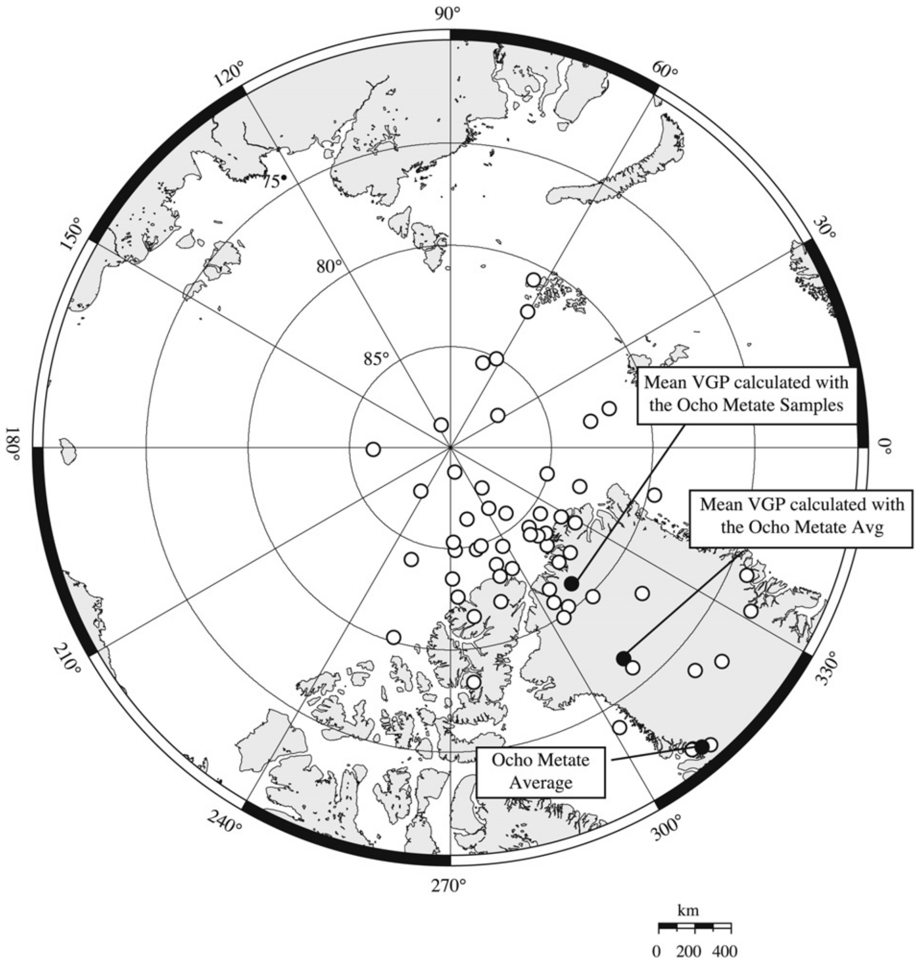

Fig. 2. The distribution of all sample VGPs that intersect the period between AD 400 and 600 is plotted along with the two mean VGPs calculated for the window AD 475–525. The location of the mean VGP calculated for Feature 1 at Ocho Metate is highlighted to illustrate the affect it had on the weighted mean window VGPs for this period.

Table 3
SWCV2010 mean VGPs.

Window	Range	Plat	Plong	*K*	A95	*N*	*Nj*	*R*	Arc distance	Decadal rate of *SV*
650	AD 625–675	84.44	309.23	590.87	0.88	45	13.76	44.77	***	
625	AD 600–650	84.13	314.39	917.73	0.63	55	18.92	54.67	0.60	0.24
600	AD 575–625	83.65	315.31	624.36	0.76	56	17.43	55.61	0.49	0.20
575	AD 550–600	82.17	311.47	202.46	1.43	49	12.81	48.66	1.55	0.62
550	AD 525–575	80.67	309.45	138.64	1.83	44	10.69	43.66	1.53	0.61
525	AD 500–550	80.33	308.46	146.73	1.90	39	9.82	38.69	0.38	0.15
500	AD 475–525	80.37	306.40	159.16	1.90	36	7.14	35.74	0.35	0.14
475	AD 438–513	80.51	305.22	156.00	1.92	36	8.07	35.74	0.24	0.10
438	AD 400–475	79.97	304.51	138.28	2.28	29	6.18	28.79	0.56	0.15
400	AD 350–450	80.61	303.64	136.27	2.39	27	6.53	26.81	0.66	0.18
350	AD 300–400	86.52	307.08	380.17	1.68	20	5.53	19.92	5.92	1.18
300	AD 250–350	87.12	320.74	350.35	1.85	18	6.03	17.93	0.96	0.19
250	AD 200–300	87.28	325.10	306.07	1.92	19	6.24	18.90	0.27	0.05
200	AD 150–250	87.92	327.74	299.58	2.06	17	5.95	16.91	0.65	0.13
150	AD 88–213	88.18	329.94	299.46	2.14	16	6.33	15.91	0.26	0.05
88	AD 1–175	88.48	327.42	328.96	1.97	17	6.16	16.89	0.31	0.05
0	113 BC–AD 113	88.29	243.77	223.30	2.32	18	5.79	17.92	2.16	0.25
−113	188–38 BC	86.22	269.61	288.16	2.35	14	5.63	13.95	2.36	0.21
−188	238–138 BC	85.87	267.92	318.54	2.15	15	5.32	14.94	0.37	0.05
−238	300–175 BC	85.66	264.89	324.59	2.21	14	6.11	13.95	0.31	0.06
−300	375–225 BC	85.52	259.65	322.34	2.42	12	5.99	11.97	0.43	0.07
−375	500–250 BC	85.41	257.20	318.97	2.56	11	5.48	10.97	0.22	0.03
−960	1120–800 BC	81.34	28.42	670.60	3.55	4	4.00	3.99	***	***
−2390	2580–2200 BC	81.35	62.09	589.94	5.08	3	3.00	3.00	***	***

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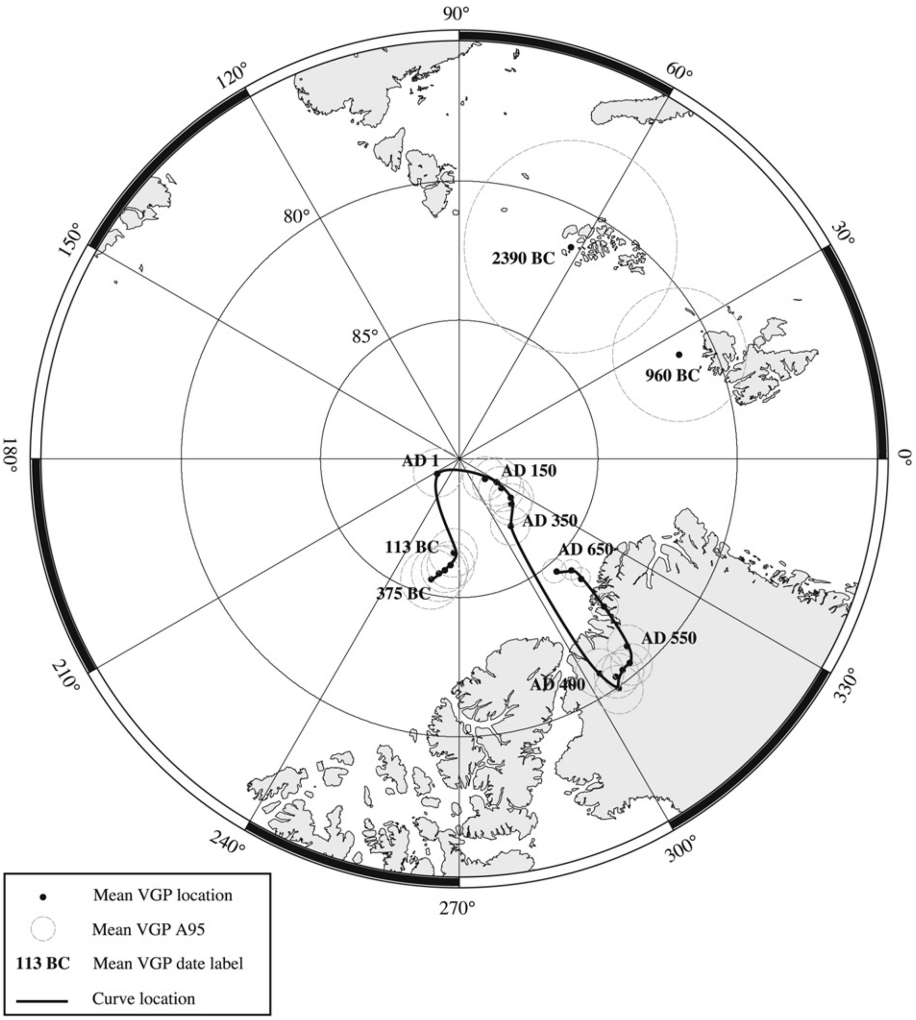

Fig. 3. The newly constructed dating curve for the period 2580 BC–AD 675. The dashed circle around each VGP represents the 95% confidence limit (A_{95}) associated with that VGP.

although it is likely that at least some of the finer details have been smoothed out by the larger date ranges and averaging windows used to create the curve. Not unexpectedly, the averaging windows were smallest for the periods with highest data density, particularly between AD 500 and 650, and largest for periods with the lowest data density. It should be noted that the averaging window centered on AD 1 is relatively large due to the paucity of data that date to the period between roughly 100 BC and AD 150. In fact, this window draws heavily on data from the adjacent averaging windows, and only three of the 18 sample VGPs that intersect it have date ranges that overlap it by 50% or more. This increases the likelihood that data from other time periods would have been included in the AD 1 mean VGP, potentially skewing its location. This problem is compounded by the fact that the time period coincides with a change in the direction of secular variation, enhancing the effect that earlier and later sample VGPs would have on the location of the mean VGP (see Lengyel and Eighmy, 2002: Fig. 3). Given this, it seems prudent to treat this particular portion of the reference curve cautiously until additional data from this period can be procured.

Although the reference curve segment calculated for this study was developed as a stand-alone curve, it can be appended to the early end of the existing regional reference curves to create a 2350-year long continuous curve. To facilitate this step, the study dataset included all of the SWCV595/2000 sample VGPs that predated AD 675 ($n = 14$) and augmented these data with an additional 49 sample VGPs that intersected the period between AD 575 and 675. Comparison of the resulting mean VGPs calculated for the AD 600, 625 and 650 windows with their SWCV595 counterparts revealed no statistical difference between the locations of the paired VGPs, although the study mean VGPs were somewhat more precise (Table 4). Therefore, the two curves were combined to create a single reference curve, SWCV2010 (Fig. 4), such that the AD 650 and earlier mean VGPs are those calculated in the study reported here and the AD 700 and later mean VGPs are those calculated previously for SWCV595 (LaBelle and Eighmy, 1997).

It should be noted that the new curve incorporates the mean VGPs calculated for SWCV595 rather than those from SWCV2000 because the latter curve is not strictly a statistically calculated curve and cannot be used for statistical dating. As discussed briefly above, SWCV2000 was developed to compensate for specific shortcomings in the calculations used to construct SWCV595, namely the tendency for the averaging statistics to dampen the true amplitude of the path of secular variation (Cox and Blinman, 1999; Lengyel and Eighmy, 2002), and, for the most part, these problems have been circumvented in the current study by using variably-sized averaging windows that are tied to data density. A future study is planned to recalculate the SWCV595 mean VGPs using the variable windowing scheme employed here with an augmented dataset, but

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Table 4
Side by side comparison of three VGPs from SWCV2010 and SWCV595.

SWCV2010						SWCV595						Arc distance
Range	Plat	Plong	A_{95}	*N*	*Nj*	Range	Plat	Plong	A_{95}	*N*	*Nj*	
AD 625–675	84.44	309.23	0.88	45	13.76	AD 635–665	84.92	308.95	2.78	9	5.86	0.48
AD 600–650	84.13	314.39	0.63	55	18.92	AD 610–640	84.24	317.46	1.18	12	4.99	0.33
AD 575–625	83.65	315.31	0.76	56	17.43	AD 585–615	84.02	318.46	0.70	5	2.86	0.50

for now the existing mean VGPs adequately document secular variation back to AD 650.

For comparison, the average rate of secular variation documented by SWCV2010 for the period between 375 BC and AD 650 is 0.22°/decade, with a maximum rate of 1.18°/decade, while the average rate of secular variation for nearly the same length of time between AD 650 and 1975 is 0.63°/decade, with a maximum rate of 2.81°/decade. Additionally, the density of data used to construct the 375 BC–AD 650 segment is roughly 1 VGP/decade on average, whereas the overall data density incorporated into the AD 650–1975 segment is roughly 2 VGPs/decade. It is possible that the overall rate of secular variation was significantly slower during the 375 BC–AD 650 period as compared to the more recent period. However, it is more likely that the reference curve calculated for this period has significantly compressed the true amplitude of secular variation into a much shorter and tighter path than was actually followed. It also is likely that the significant details of secular variation, such as kinks and loops in the curve, have been overly smoothed during curve calculations, particularly for the pre-AD 150 period.

These findings are supported by comparison with the equivalent portion of a newly constructed curve for the western U.S. (Hagstrum and Blinman, 2010), which suggest that while SWCV2010 has captured the overall trend of secular variation for the period between 375 BC and AD 650, there has been significant compression and loss of detail for the portion that predates AD 350 (Fig. 5). The two curves share only 18 samples – the 14 that were included in the SWCV595/2000 dataset and four that were generated by DuBois's lab (Dubois, 2008) – and all of these samples postdate AD 400. The portion of the western U.S. curve that predates AD 400 is based entirely on radiocarbon-dated paleomagnetic samples recovered from lava flows located in the northwestern U.S., as well as a few samples from flows in New Mexico. Originally, these data were considered for inclusion in the study dataset as well, but most of them do not meet the study's temporal precision criterion, and those that do are from flows located outside the study area. It may

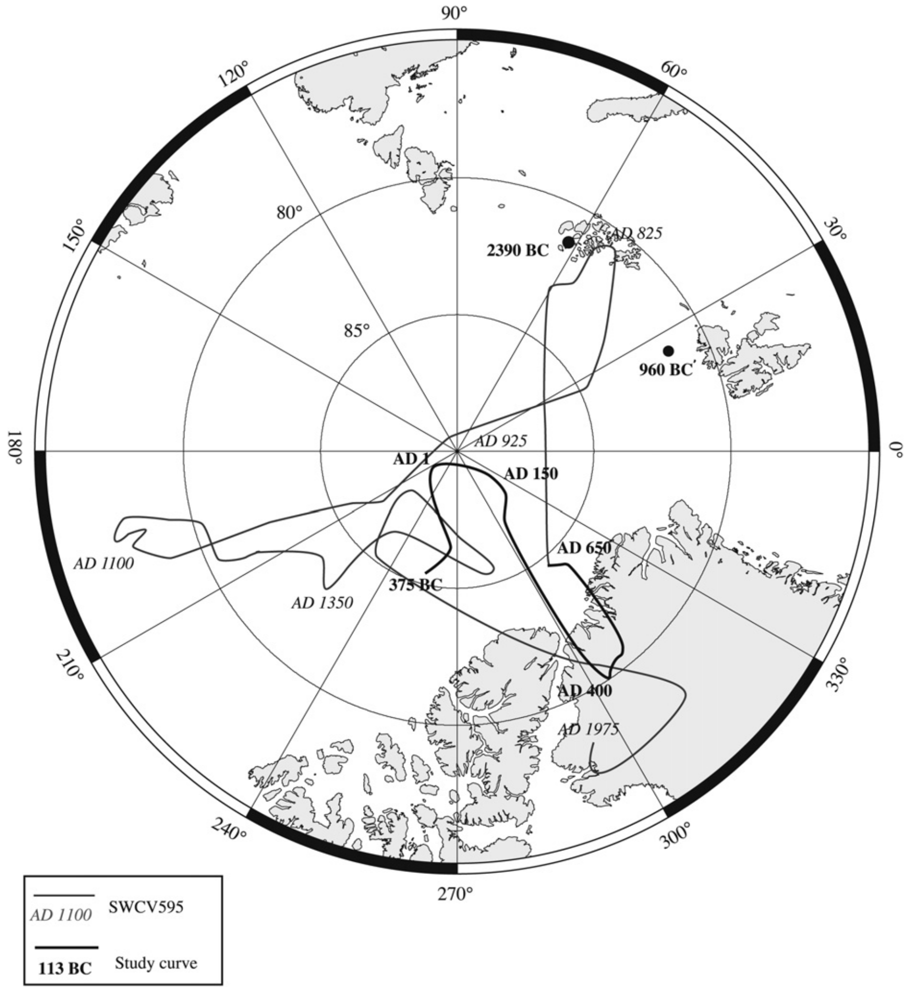

Fig. 4. Depiction of the full dating curve SWCV2010, formed by appending the early curve calculated through this study to the end of the existing curve SWCV595.

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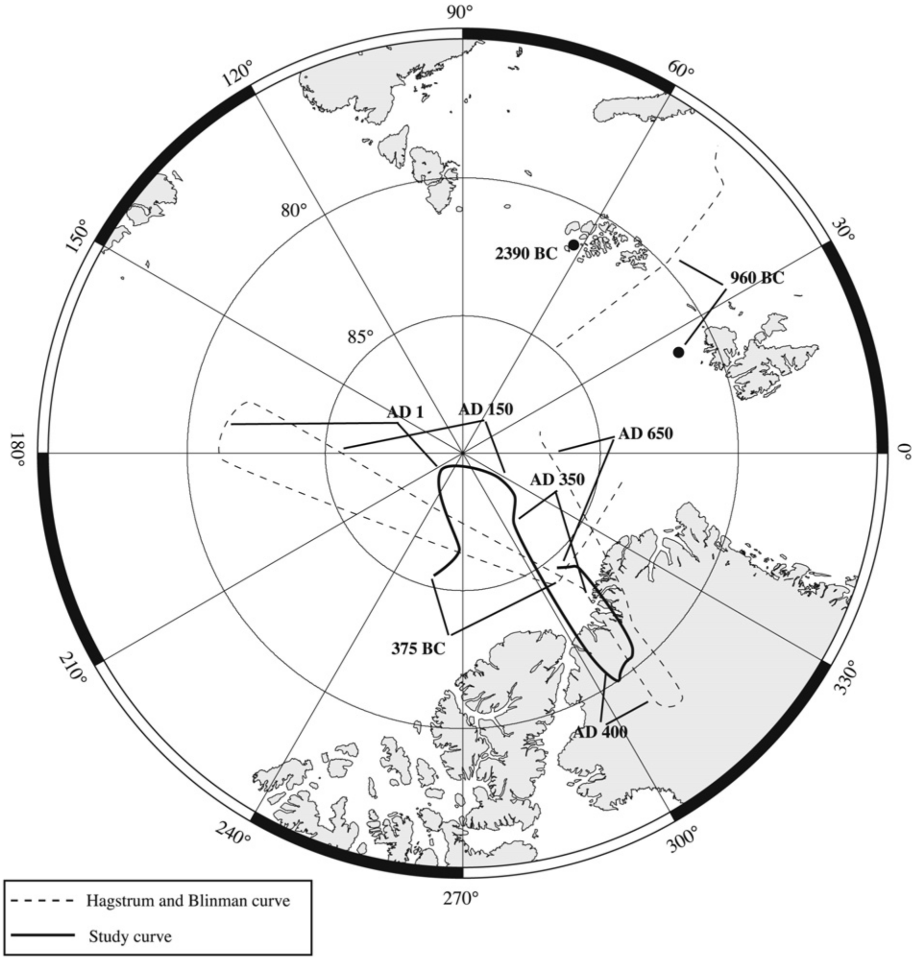

Fig. 5. Comparison of the early portions of SWCV2010 and the curve recently developed by Hagstrum and Blinman (2010).

be that Hagstrum and Blinman's (2010) curve for the western U.S. provides a more accurate depiction of secular variation for the period between roughly 400 BC and AD 400, but this cannot be assessed until additional well-dated archaeomagnetic data from this period are recovered from contexts within the Southwest.

5. Conclusions

The compilation of 104 independently dated archaeomagnetic samples from the U.S. Southwest has made it possible to extend the regional secular variation record back to 375 BC, with isolated mean VGPs centered on 960 BC and 2390 BC. This new record has been combined with the existing curve, SWCV595, to form the continuous regional curve SWCV2010. Overall, the precision in estimating the location of the new curve segment is quite good, indicating that it has captured the general shape of regional secular variation for the period of 375 BC–AD 650. Closer analysis of the resulting curve, however, suggests that some of the finer details of secular variation may be missing and that the overall amplitude may be highly constrained. It is likely that these problems are due in part to the larger date ranges of the underlying data, which would result in greater smoothing of the dataset and increased constriction of the resulting curve, as well as the variability in data density for the period prior to AD 400, which could mask some of the details in the path of regional secular variation. This assessment agrees with the recent findings of Lanos et al. (2005:469), who demonstrated that curve precision is controlled by the density of data in each averaging window and by the temporal precision of those data. It is likely that these issues have been compounded by this study's reliance on radiocarbon dates for calibrating most of the magnetic data, since the vagaries of the radiocarbon calibration curve could essentially dictate the temporal precision possible for different time periods, and for some periods could even limit the amount of data that meets the temporal precision criterion, thereby impacting the density of data available for curve construction.

Clearly more data are needed to bolster the weaker portions of the new curve and to fill in the temporal gaps in the regional record. To the extent possible, new data should be procured from contexts that date between 400 BC and AD 400, with a particular emphasis on contexts that pre-date AD 150, in an effort to increase the uniformity of the distribution of data across this period. An increase in data during this period should help to improve the accuracy and precision of the reference curve and reveal the finer details of secular variation that may have been missed by the more sparsely populated dataset of the current study. Finally, it is hoped that eventually enough data will be secured from the period prior to 400 BC to allow the floating mean VGP centered on 960 BC to be linked with the rest of the curve.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jas.2010.07.008.

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