Archaeomagnetic intensity results from California and Ecuador: evaluation of regional data

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Abstract

We present new archaeointensity data for southeastern California (33°N, 115°W, 50–1500 yr BP) and northwestern South America (Ecuador, 2.4°S, 80.7°W, 4000–5000 yr BP). These results represent the only data from California, as well as the oldest archaeointensity data now available in northwestern South America. In comparing our results to previously published data for the southwestern United States and northwestern South America, we note that significant scatter in the existing data makes comparisons and interpretations difficult. We undertake an analysis of the sources of data scatter (including age uncertainty, experimental errors, cooling rate differences, magnetic anisotropy, and field distortion) and evaluate the effects of scatter and error on the smoothed archaeointensity record. By making corrections where possible and eliminating questionable data, scatter is significantly reduced, especially in South America, but is far from eliminated. However, we believe the long-period fluctuations in intensity can be resolved, and differences between the Southwestern and South American records can be identified. The Southwest data are distinguished from the South American data by much higher virtual axial dipole moment values from 0–600 yr BP and by a broad low between 1000–1500 yr BP. Comparisons to global paleofield models reveal disagreements between the models and the archaeointensity data in these two regions, underscoring the need for additional intensity data to constrain the models in much of the world.

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1. Introduction

Archaeological materials have long been recognized as a possible means of recovering a closely spaced record of paleointensity variations over the last 5000–10 000 yr (see [1], and references there-in). They can potentially provide greater temporal and spatial resolution than volcanic materials. While extensive archaeointensity data now exist, coverage is far from uniform. In particular, large parts of the western and southern hemispheres lack intensity data. Furthermore, much of the existing data are several decades old, of questionable reliability by today’s standards, and exhibit significant scatter.

This dearth of intensity data in particular re-
gions can have important consequences in the development of any global geomagnetic model. Because the virtual axial dipole moment (VADM) at a given time varies dramatically with location, good spatial coverage is essential in these global models. For example, in approximating the average global dipole moment, as in McElhinny and Senanayake [1] or Yang et al. [2], the resulting value will be biased towards regions with large quantities of data.

In this paper, we examine archaeointensity data from the southwestern United States and northwestern South America, two regions that could benefit from additional intensity data. Studies from both regions show that significant differences exist between the European paleointensity curve and the Western Hemisphere data. However, considerable scatter among the data sets has made comparisons and conclusions difficult.

We first examine the possible sources of scatter in archaeomagnetic data. We make corrections where possible and apply minimum reliability criteria to extract a more reliable data set. We then compare this data set, along with our new data from southwestern California and southern Ecuador, to global paleointensity models.

2. Examination of existing data

We have assembled all published archaeointensity data from the southwestern United States and northwestern South America, plus the volcanic paleointensities of Champion [3] (Table 1; see also Background Data Set1). The materials used for the archaeointensity studies are mostly ceramics, with some baked clays (Table 1). The existing southwestern United States data span a region approximately 1000 km across, covering parts of Arizona, New Mexico, Colorado and Utah (Fig. 1). The first archaeomagnetic study in this region was undertaken by Bucha et al. [4], and significant amounts of data were added by Lee [5], Hsue [6], and Sternberg [7]. The South American data span a region roughly 2000 km across, covering parts of Ecuador, Peru and Bolivia (Fig. 1). Data are contributed by Nagata et al. [8], Kitazawa and Kobayashi [9], Gunn and Murray [10], Kono et al. [11], and Yang et al. [12].

Data from the southwestern United States are concentrated in the last 2000 yr (Fig. 2), because earlier materials are rare in this region. The lone point at 4800 yr BP is a volcanic sample. The majority of the South American data are also concentrated in the last 2000 yr, but a significant amount of data covers the period from 2000 to 4000 yr BP.

Both sets of data exhibit substantial scatter (Fig. 2) that may obscure any real trends. Potential sources of scatter and uncertainty in the data include dating errors, experimental inaccuracy, cooling rate differences, magnetic anisotropy, and distortion of the ancient field during firing. We examine these age and experimental uncertainties below, using data from the southwestern United States and northwestern South America to illustrate the magnitude of the errors.

2.1. Sources of scatter

2.1.1. Age uncertainty

Age uncertainty is perhaps the biggest concern in archaeointensity data sets and the most difficult to eliminate. Dates are assigned to archaeological materials through a variety of methods, including stratigraphic association, dendrochronology, pottery style, archaeomagnetic dating, association with radiocarbon dates, and thermoluminescence dating. Each of these methods has its drawbacks, and the best dates are usually derived from some combination of methods.

With the exception of thermoluminescence – and occasionally radiocarbon – dating the age of archaeomagnetic materials invariably involves association with other independently dated materials. The most common method of association relies on the stratigraphy of excavations. Stratigraphic association can provide accurate dates if the stratigraphy is properly identified, including non-horizontal layering, cultural deposits, intrusions and erosional channels that cut through stratigraphy [13]. Unfortunately, in instances

1 http://www.elsevier.com/locate/epsl.
where soil layering and stratigraphy are not visible (and even in some cases where they are), excavation by metric level is used instead. This introduces an ‘artificial stratigraphy’ by arbitrarily assigning a common age to all artifacts at a given depth [13].

Pottery style and archaeomagnetic dating provide indirect age constraints through comparison with existing records of temporal changes in pottery style or the regional magnetic field. Association of a unique pottery style with a particular cultural period may yield excellent dates (within tens of years) if the cultural period is short and its age is well-constrained by other methods.

In some instances, artifacts can be sorted into proper age order, but the details of the absolute cultural chronology may be in dispute. For example, many of the southwestern samples excavated near Snaketown, Arizona, were produced by the Hohokam culture. Until recently, conflicting chronologies for this culture resulted in age differences of up to 700 yr. In 1989, Sternberg [7] acknowledged this problem and discussed both the ‘long-count’ chronology of Haury [15], as well as the ‘short-count’ chronology of Schiffer [16], which is much compressed and results in consistently younger dates. Further work suggests that a short-count chronology is more likely [17−19]. We therefore use a recent chronology [18] to adjust all Hohokam data in our final compilation (Fig. 3). It should be pointed out, however, that details of the Hohokam chronology before approximately 1300 yr BP remain in dispute.

As with dating by pottery style, the accuracy of archaeomagnetic dating depends directly on the quality of existing records used for comparison. Two early studies which provide a significant amount of data for the Southwest [5,6] cite archaeomagnetic dating for some samples. In the case of oriented samples, archaeomagnetic dating involves comparing the remanence with a reference curve of directional secular variation. However, all of the samples from Hsue [6] and many of the samples from Lee [5] are unoriented, meaning the sherds must be compared to a reference paleointensity curve. Because these were the first two extensive paleointensity studies in the Southwest, it is difficult to accept that even an approximate date could be assigned in this manner.

In addition to possible uncertainties from the indirect associations outlined above, the absolute ages of datable material may also have significant errors. For example, radiocarbon dating has numerous pitfalls that are important to recognize [20]. Laboratory errors, resulting primarily from errors in counting the radioactive disintegrations,

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Previous paleomagnetic studies of the southwestern United States and northwestern South America</th>
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</thead>
<tbody>
<tr>
<td>Author</td>
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<td>Champion [3]</td>
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<td>Kitazawa and Kobayashi [9]</td>
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<tr>
<td>Gunn and Murray [10]</td>
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<tr>
<td>Kono et al. [11]</td>
<td>Peru</td>
</tr>
<tr>
<td>Yang et al. [12]</td>
<td>Peru</td>
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</table>

C = 14C, S = stratigraphy, PS = ceramic (pottery) style evolution, T = thermoluminescence, M = modern, AM = archaeomagnetic, D = dendrochronology, HD = historic documents and material culture, A = other archaeological and historical methods.
can become greatly amplified in the calibration from radiocarbon years before present to calendar dates. Even if the laboratory’s reported standard deviation is small (20 yr) and the data fall on a ‘steep’ part of the calibration curve, the estimated calendar age range can be as great as 100 yr (68.3% confidence level) [20]. Calibration across a relatively flat portion of the curve can lead to estimated calendar date ranges of 250 yr or more. Unfortunately, many of the $^{14}$C dates used in our compilation studies have much larger laboratory standard deviations, leading to much larger calendar date ranges (500 or even 700 yr at the 68.3% confidence level). Finally, because the calibration curve is not monotonic, it is possible for a single radiocarbon date to have more than one possible calendar date.

Where original references were provided, we have calibrated or recalibrated $^{14}$C dates with the most recent CALIB v4.3 program of Stuiver and Reimer [21] and associated data sets [22,23]. Except in a few instances, this recalibration had very little effect on placement of age mid-points, although it generally increased the age uncertainty.

Thermoluminescence (TL) dating, used in two studies in our compilation, was developed in the 1960s specifically as a means to directly date pottery (see e.g. [24]). Since then, it has come to be accepted as a reliable method of dating baked archaeological materials. The technique is based on the accumulation of trapped electrons, primarily in quartz and feldspar, from natural radioactive decay. These trapped electrons are released when the pot is fired, resetting the luminescence ‘clock’ [24]. While TL dating will never approach the precision of radiocarbon dating, it does have certain advantages over that method. Because potsherds can be directly dated, errors related to artifact association are avoided. Calibration errors also do not come into play. Uncertainties in TL dating are usually about ±5–10% of the estimated age and result from errors in properly estimating the natural level of radiation to which the sample was exposed [24].

Perhaps the most accurate ages may be obtained from the stratigraphic association of wooden artifacts and ceramics. Dendrochronology may
yield dates accurate to a calendar year [14]. While a time lag between the death of the tree and its association with other cultural deposits must be considered, this method has the potential to provide very tight age constraints.

This brief review of dating methods highlights the uncertainties inherent in the techniques. An ideal date might come from a recently measured $^{14}$C date (last 20 yr), combined with one or two other methods, reducing uncertainty to less than $\pm$ 50 yr. However, this kind of information is generally not available, and the fact remains that age
control on most of the data in our compilation is poor. The average age uncertainty in the compilation is nearly $\pm 140$ yr (1σ for radiocarbon and thermoluminescence, or the length of the assigned ceramic phase or other archaeological context). Thus, short-period ($< 200$ yr) fluctuations in geomagnetic intensity are unlikely to be reliably determined.

Fig. 3. Data selected from the literature based on the selection criteria described in the text. New data from this study are shown as squares. The light solid line is a cubic spline fit to the binned and averaged data. For comparison, the Hongre et al. [47] model (dotted line) and the gufm1 model of Jackson et al. [48] (bold line) have been evaluated for these two regions. The inset in (b) is a close-up of the last 700 years showing the discrepancy between gufm1 and the archaeomagnetic data.
2.1.2. Experimental uncertainties

Two main techniques are currently in use for determination of paleointensity: Thellier–Thellier [25] and Shaw [26]. The stepwise double-heating method of Thellier and Thellier [25], modified by Coe [27], is commonly believed to be the most reliable method of determining paleointensity, and most of the studies in the compilation use a variation of this method. The method involves heating samples twice at each temperature step – once in zero field to remove a portion of the natural remanent magnetization (NRM) and once in a controlled field to determine the partial thermoremanence (pTRM) gained. The ratio of NRM lost to pTRM gained is proportional to the ancient field. Errors associated with the Thellier method include uncertainty in oven temperature and lab field, errors in the measurement of sample intensity, and sample thermal alteration. Measurement errors should average out if multiple specimens are taken from each sherd. It is important that temperature between in-field and zero-field steps is accurately reproduced. Thermal alteration of the sample can also lead to significant error. The so-called ‘pTRM checks’ are designed to reveal such alteration by back-tracking to repeat a lower-temperature in-field step. Most of the early studies in the compilation do not use these checks.

The Shaw method [26], modified by Kono [28] and Rolph and Shaw [29], has been used in one study in the compilation. Designed to avoid or correct for thermal alteration, the Shaw method uses AF demagnetization, but still requires heating the sample above the Curie temperature to impart a total TRM. In theory, some thermal alteration from this heating can be corrected for [29,30]. In practice, results generally tend to agree with those of the Thellier method, but in several cases have been reported to show more scatter [31,32].

2.1.3. Anisotropy of TRM

Rogers et al. [33] report strong magnetic anisotropy in pottery samples that could lead to errors of 30–40% (up to 60% for wheel thrown pottery) if left uncorrected. They suggest that this anisotropy stems from preferential alignment of magnetic grains during shaping of the pot which results in an easy plane of magnetization in the plane of the pot. Scatter from remanence anisotropy can be corrected by measuring the TRM anisotropy tensor [36].

2.1.4. Cooling rate

Another potential source of data scatter is introduced through differences between cooling rates in antiquity and in the lab [34,35]. A slower cooling rate produces a larger TRM, as magnetic moments have more time to come into equilibrium with the field. In general, lab cooling rates are faster than original cooling rates, leading to an overestimation of the ancient field, the degree of which depends on the actual cooling rate difference, as well as the blocking temperature. Lab cooling times reported in the compilation studies ranged from 10 min to 2 h.

For ceramics and bricks fired in brick kilns, original cooling can take over 24 h, leading to an overestimation of the field by approximately 10% (based on a lab cooling time of 25 min) [36]. Most of the ceramic samples from the compilation studies were likely fired instead in the open or in small pit kilns, with cooling times on the order of 1–12 h, based on observations of Native American potters [37,38]. Pots may be removed from the fire while still at high temperature [37], or they may be left over the fire until cool [38]. How long it takes pots left over the fire to cool depends on the kind and amount of fuel used, as well as to what degree the fuel surrounds the pots and how well they are insulated [38]. Actual lab overestimation of ancient field could therefore range from ~2 to 8%.

Given the variation among modern potters, it is difficult to comment on precise techniques in a given location thousands of years ago. It is likely that the maximum cooling rate error is 10%, and in many cases it is probably less than 5%. If no correction is made, paleointensity will always be overestimated, leading to an upward bias of the entire averaged curve. For this reason, we choose to make a 5% correction to all the data. While some of the resulting paleointensity estimates will now be too low and others still too high, this blanket correction should have the ef-
fect of centering the scatter closer about the true value.

2.1.5. Field distortion during firing

A possibility exists that the field seen by the pots during firing was not equivalent to the ancient ambient field. Field distortion from a self-demagnetizing field and/or proximity to other pots, sherds or metal during firing can also increase scatter in paleointensity data. A self-demagnetizing field will always act to subtract from the main field, but little can be done to reproduce or correct for this, although Aitken et al. [39] attempted to measure the possible degree of self-demagnetization. Distortion from external sources is a distinct possibility, as open pit kiln construction can include placing broken sherds both under and over the pots to be fired [37]. After introduction of iron by Europeans roughly 500 years ago, there is also the possibility that iron objects were used to support or shield pots during firing [39], although this is probably more common only in modern times [38,40]. Aitken et al. [39] suggest that one way to partially mitigate field distortion effects is simply to take multiple specimens from different parts of the pot and multiple pots from each time period.

2.1.6. Temporal and spatial field variation

Two final sources of scatter in the data may be geomagnetic in origin. Temporal variations in intensity may appear as scatter if samples cannot be well dated or if sampling density is insufficient. Spatial variation in the field may also introduce apparent scatter. Based on the present field, regions the size of our study areas (∼1500 km) may have intensities that differ by as much as 15%. As more data become available worldwide, it will be possible to average over smaller regions, eliminating some of this spatial scatter.

2.2. Data selection

While some of the potential sources of scatter mentioned above cannot be eliminated, many can be compensated for or minimized. By selecting only the most reliable data, we should produce a much less scattered record that more accurately represents the true paleofield behavior. We can use updated ceramic chronologies, calibrate or re-calibrate 14C dates, and make cooling-rate corrections to existing data. Corrections for other factors cannot be made in retrospect, however, and some data must be excluded. Because data reproducibility is essential, we eliminate over 40% of the data from the compilation because only one specimen per sample was tested. We further exclude any samples that show excessive intra-sample scatter as measured by the standard deviation of the paleointensity estimates divided by the mean ($\sigma_B/B_{avg}$).

Ideal data points would have at least two subsamples, $\sigma_B/B_{avg} \leq 0.10$, use the method of Thellier and Thellier with pTRM checks, have an anisotropy correction, and an age uncertainty of less than ±100 yr (1σ). Sadly, this would leave only one study from each region. Instead, we apply somewhat less stringent acceptance criteria: samples must have at least two specimens; the Thellier technique should be utilized; and $\sigma_B/B_{avg}$ should be less than 0.20 for each sample to ensure at least a reasonable degree of within-sample scatter. The Lee [5] and Hsue [6] studies are excluded because of extreme uncertainty in dating. They state that they use radiocarbon dating, historical, or archaeomagnetic dating. As discussed above, archaeomagnetic dating in this context is highly questionable. They also provide no information on their radiocarbon dates so the calibration status is uncertain. Because neither study specifies on a sherd by sherd basis the method of dating, we reject all of these samples from the compilation. We have also not included a study on Peruvian ceramics [41] because site locations and individual results were not presented.

After applying these selection criteria, the scatter is indeed reduced (Fig. 3), especially in South America. However, very few points remain to define changes in the geomagnetic field through time, and we must recognize that even these points are not ideal. Many of these points are from studies which did not use pTRM checks or made no anisotropy correction. It is clear that new data adhering to strict reliability standards will go far in resolving a more dependable paleointensity record.
3. New results

In an attempt to increase the amount of high-quality data available for the southwestern United States and northwestern South America, we carried out paleointensity experiments on six potsherds from the southern California desert (\(\sim 33.3^\circ\text{N}, \sim 115.5^\circ\text{W}\)) and 14 from Ecuador (Table 2). The surface-collected California sherds are ceramics of the Lowland Patayan tradition [42] and were obtained from the San Diego Museum of Man where they were typed by Michael Waters. These sherds have been classified into three time periods spanning the past 1500 years based on pottery style. Unfortunately, more precise dating in southern California is not possible due to very plain ceramic styles and the lack of dendrochronology data. The South American sherds were excavated from the Real Alto (Valdivia) site at 2.37\(^\circ\text{S}, 80.72\(^\circ\text{W}\)) and span the period of roughly 4000–5000 yr BP. These sherds have also been classified based on style, and the dates of these styles are based on extensive radiocarbon assays as well as some TL dating [43]. Several individual sherds have also been directly associated with radiocarbon-dated material. The Real Alto sherds were obtained from the University of Illinois Laboratory of Anthropology collections and were typed by James Zeidler.

We trimmed four specimens from each sherd and pressed them into salt pellets for ease of handling and to ensure consistent orientation throughout the experiments. We used the stepwise double-heating method of Thellier and Thellier [25], modified by Coe [27], to recover an estimate of the ancient field. Thermal alteration of the sample was monitored by pTRM checks after approximately every third temperature step. Two salt pellet ‘blanks’ were also included in the Thellier experiments and showed no remanence acquisition.

The reliability of the ancient field determinations was assessed using the criteria of Selkin and Tauxe [44], which are much more stringent than the selection criteria applied above. These criteria are: (1) The temperature interval selected for paleointensity interpretation should correspond to the final remanence component of magnetization – what we hope is the sample’s original thermoremanence. This is illustrated by the decay of the zero-field steps in the selected interval to the origin of a vector endpoint diagram (e.g. Fig. 4); the angle (\(\alpha\)) between the principal component of the selected interval and the vector average of the data should be less than 15\(^\circ\). (2) The maximum angular deviation of this principal component must also be less than 15\(^\circ\). (3) The slope calculated from the NRM–pTRM pairs (e.g. Fig. 4) must have the ratio (\(\beta\)) of the standard error of the slope to the absolute value of the
slope less than 0.1. (4) To ensure sufficient reproducibility between two in-field measurements at a given temperature, the difference between repeat in-field steps normalized by the length of the selected NRM–pTRM segment must be less than 0.10. (5) \( q \), the quality factor as defined by Coe et al. [46], must be greater than 1. (6) For each sample, the standard deviation of the field estimates divided by the mean \((\sigma_B/B_{\text{avg}})\) must be < 0.20. Application of these criteria produced acceptable paleointensity interpretations for 39 specimens representing 10 different sherds. Representative data are shown in Fig. 4, and data from all interpreted specimens are presented in Table 3, along with sample averages.

The California sherds all showed either unidirectional demagnetization behavior (for the zero-field steps) or the presence of a small, secondary, low-temperature component that was removed by 250°C (Fig. 4a). Paleointensity interpretations were made for all of the California specimens, but one sample (sic182) was rejected because of excessive intra-sherd scatter. The Ecuadorian samples yielded fewer successful ancient field estimates. Many sub-samples exhibited vector endpoint plots that did not decay to the origin, did not pass pTRM checks or showed other non-ideal behavior. We believe this is caused by incomplete oxidation during ancient firing or firing under reducing conditions. As observed by others (e.g. [4,7]) the well-oxidized sherds that display a red to orange color in cross-section typically provide better results than sherds that are gray to black in color. Of the Ecuadorian samples that produced interpretable results, most showed two or more components, but the characteristic component was usually isolated by 350°C (Fig. 4b). We speculate that the lower-temperature components result from a second firing at a lower temperature, removal of the pots from the fire mid-way through cooling [37], or use of the pots as cooking vessels. Of the four Valdivia sherds that gave good results, one is rejected because of excessive intra-sherd scatter (sio014).

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Fig. 4. Typical results from Thellier–Thellier experiments. (a) Vector endpoint plot of zero-field NRM steps (left) and NRM–pTRM (right) plots for California sample sic188-1a. (b) Same for Ecuador sample sio1-1a. \( x^{\prime}y^{\prime} \) projection on the vector endpoint plot is in circles; \( x-z \) projection is in squares. Closed circles on the NRM–pTRM plot indicate temperature steps chosen for paleointensity determination; open triangles are pTRM checks. Numbers on both plots refer to temperature steps.
Finally, we made a correction to the paleointensity values for TRM anisotropy and cooling rate as described by Selkin et al. [36]. The anisotropy tensor for each specimen was determined by heating above $T_c$ and cooling in lab field in six different positions ($\pm x$, $\pm y$, $\pm z$). The degree of anisotropy as measured by the ratio of the maximum to minimum eigenvalues [45] ranges from 1.09 to 1.35. Thirty out of 39 specimens show weakly to moderately developed oblate anisotropy ellipses.

Table 3
Results of Thellier–Thellier experiments on Californian and Ecuadorian ceramic pot sherds

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<th>Specimen</th>
<th>$\sigma$</th>
<th>$B$</th>
<th>$B^*$</th>
<th>$B^*_{\text{avg}}$</th>
<th>$\sigma_B$</th>
<th>$\sigma_B/B^*_{\text{avg}}$</th>
<th>$f$</th>
<th>$g$</th>
<th>$q$</th>
<th>VADM ($\times 10^{22}$ A m$^2$)</th>
<th>VADM$^1$ ($\times 10^{22}$ A m$^2$)</th>
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<td>92</td>
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<td>15.6</td>
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Specimens beginning with ‘sic’ represent sherds from Ecuador, while ‘sic’ denotes Californian sherds. $\sigma$, standard error of slope; $B$, ancient field ($\mu$T); $B^*$, ancient field ($\mu$T) corrected for magnetic anisotropy of sample; $B^*_{\text{avg}}$, site mean; $\sigma_B$, standard deviation of site values; $f$ (NRM fraction), $g$ (gap factor), and $q$ (quality index) as defined by Coe et al. [46]; VADM, virtual axial dipole moment ($\times 10^{22}$ A m$^2$); VADM$^1$, cooling rate-adjusted VADM (5%). Note that samples sic182 and sio014 were rejected based on excessive intra-sample scatter.
consistent with an easy plane of magnetization within the plane of the sherd, as predicted by Rogers et al. [33]. This resulted in corrections to the preliminary ancient field values of up to 30%. A further 5% reduction to intensity values was applied to correct for cooling rate.

4. Discussion

Our new data from California generally agree with earlier data from the southwestern United States that meet the minimum reliability criteria outlined above (Fig. 3). While the dates of the Californian sherds examined in this study remain too poorly constrained to provide clear distinctions between new and existing data, the lower of the two points at 750 yr BP suggests that the decrease in field intensity between 500 and 1000 yr BP was possibly lower than previous data imply. In general, the combined southwestern compilation and new data show significant differences from both South American and global data. In Fig. 5 we show the new and compilation data averaged into 500 yr bins to compare with the global archaeointensity curve of Yang et al. [2]. The southwestern data show a distinct low between ~1000 and 1500 yr BP that is not present in either the South American or the global curves.

Our new paleointensity results from Ecuador are significant in that they extend the reliable South American chronology back over 1500 yr (Fig. 3b). The well-dated point at approximately 4000 yr BP is especially useful in providing an accurate paleointensity estimate for a well-constrained time. These data roughly agree with what is expected on a global basis, falling on either side of the global curve (Fig. 5). Like the southwestern compilation data, the South American data show a much narrower peak than the broad, 2000–3000 yr high of the global curve, which is dominated by European data. However, after removing the European data from the curve, we see that the remaining world data (bold, dashed line in Fig. 5) provide a closer match to the long-period variations in South American data.

To examine shorter-period trends represented by the southwestern and South American data sets, we bin and average the selected compilation data along with our new data in 200 yr bins over the last 2500 yr (Fig. 3). The arithmetic mean VADM of each bin is given an age equal to the arithmetic mean of the sample ages within the bin. We connect the averaged data points (represented by asterisks in Fig. 3) with a cubic spline, merely to guide the eye rather than to suggest a ‘true’ paleointensity curve. We must recognize that the data scatter (especially age uncertainty) and the method of averaging degrade any higher-frequency signal that may be present in the data. Certainly earlier than 2000 yr BP, both curves are poorly defined and we cannot expect that the true curve is adequately represented by connecting the few dots.

Nonetheless, results of this averaging process highlight potentially significant differences between the two regions, including a higher VADM in the southwestern United States from ~0 to 600 yr BP and the broad low from ~1000–1500 yr BP mentioned above. These differences illustrate the importance of having spatially well-distributed data sets for any kind of global geomagnetic model. It is equally important, however, not to use data of questionable

![Fig. 5. Global archaeointensity curve of Yang et al. [2] (bold solid line), and the global curve minus European data (bold dashed line). The southwestern United States (thin solid line and circles) and South American (thin dotted line and triangles) data of Fig. 3 are shown here averaged in 500 yr bins to match the bins used by Yang et al. Symbols shown with no connecting line represent single data points rather than binned averages.](image-url)
quality merely because they exist where little else does.

The lack of sufficient quality data in certain areas of the world can place limitations on global models of field behavior. This becomes evident in the global archaeointensity model of Hongre et al. [47]. In South America, where the Hongre et al. model uses much of the same data as we show in Fig. 3, an evaluation of their model does provide a rough fit to the data, at least back to about 1700 yr BP. However, in the southwestern United States, where Hongre et al. provide no intensity control, the model only roughly approximates the data and overestimates intensity (Fig. 3a). This illustrates the danger of drawing any conclusions from evaluations of such models in poorly constrained areas.

Models based on direct observations provide a closer match to the archaeointensity data, although even these models show some discrepancies with the data. Since 1832, when Gauss developed a method to measure absolute intensity, one might expect the field to be quite well-defined. But evaluation of the gufm1 model of Jackson et al. [48], which is based on historical observations, shows a discrepancy of ~10% in South America (Fig. 3b, inset). Whether this discrepancy is due to a bias in the archaeointensity data or to the inadequate constraints on the gufm1 model in this region, it is important to recognize the potential limitations of such models.

5. Conclusions

Existing archaeointensity data covering the past 5000 years in the southwestern United States and northwestern South America exhibit significant scatter and contain more uncertainty than is generally recognized. Experimental inaccuracies, cooling rate differences, magnetic anisotropy, field distortion during firing, and especially dating uncertainty serve to create scatter in the record and obscure short-period variations in field intensity. While we can approximate corrections for some of the sources of scatter, only a fraction of the existing data can be used with any confidence. Much work remains to increase the quantity of high-quality paleointensity data available and provide more uniform spatial coverage for the past 5000 years. While our new data start to fill in the gaps, there is still a long way to go. Complete uniform global coverage may never be achieved, but significant improvements on present data will result in global models that are much better constrained.

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