MagIC as a FAIR repository for America's archaeomagnetic legacy data

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Key Points:

- We digitized 6 decades of legacy archaeomagnetic measurements from 3 archives (over 51k specimens), adding them to a FAIR repository, MagIC
- The site-level results (reanalyzed using modern statistical conventions) are consistent between the archives
- The majority of the data have site provenience in North America and are dated to less than 2000 years old

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Abstract

Beginning in 1964, an academic lineage of Robert DuBois and his students, Daniel Wolfman and Jeffrey Eighmy, developed dedicated United States-based archaeomagnetic research programs. Collectively, they analyzed over 5377 archaeomagnetic sites, primarily from North America, dated to less than 2000 years old. Yet despite their decades of effort, few journal publications resulted. Most of their published results are embedded in archaeological reports, often without technical data, which limits the data's accessibility. Furthermore, when published, the results are generally averaged at the site-level using statistical conventions different from today's standards, limiting the data's comparability and (re)usability.

In 2015, we undertook a salvage archival study to digitize the surviving data and metadata from the scientists' individual estates and emeritus collections. We digitized measurement data from more than 51,000 specimens, reinterpreted them using modern conventions, and uploaded them to the FAIR-adhering magnetic data repository – MagIC. The reinterpreted site-level results from the three laboratories are mutually consistent, permitting the individual datasets to be combined and analyzed as single regional entities.

Through incorporation into the MagIC repository, these legacy data are now accessible for incorporation into archaeomagnetic and global magnetic field modeling efforts, critical to understanding Earth's magnetic field variation through time. In the Four Corners region of the United States Southwest, this digitized archive advances the development of a new regional paleosecular variation curve used in archaeomagnetic dating. This project highlights both the value and complexities of managing legacy data; the many lessons learned set a precedent for future paleomagnetic data recovery efforts.

Plain Language Summary

Archaeomagnetism is the study of Earth's past magnetic field through researching the magnetic signatures retained in well-dated archaeological materials. The most commonly studied materials are those that have experienced high temperatures due to human-made fires. Due to humans' global occupation, there is a potential for globally distributed archaeomagnetic sampling, which is essential for high resolution global magnetic field models. However, there is considerable variation in the documentation and accessibility of data from certain regions, including North America.

In 2015, a salvage archival project was initiated to recover the life's work of three North American archaeomagnetists. The effort resulted in the digitization and formatting of the data within DuBois' and Wolfman's estates, and Eighmy's archive. In total, measurement data from more than 51,000 specimens, from 5377 archaeological features, were processed and uploaded to a centralized online data repository – MagIC. This repository ensures that the data, representing 130 person-years of work, are now findable and accessible, permitting the data to be utilized in future modeling projects. One such reuse of these data is the development of a new regional model for the Four Corners region of the United States Southwest that traces the location of the magnetic north pole through time.

1 Introduction

Archaeomagnetism applies many of the techniques of paleomagnetism to samples of anthropogenic origin. The materials most often studied are those heated by past peoples (hearths, burned floors, pottery, etc.) because the heating and subsequent cooling of the material generally preserves a stable and measurable magnetization. These heated anthropogenic materials hold tremendous potential for contributing to the understanding of variations in Earth's magnetic field over the last several thousand years because anthropogenic materials often have more precise chronologies than natural rocks or sediments and are spatially and temporally diverse. This is especially true as past humans had a nearly global distribution (excluding oceans) and their dependence on fire for warmth and cooking has resulted in an abundance of sites for investigation. Additionally, past cultures moved about the landscape a moderately slow rate, which means most regions have the potential to preserve a nearly continuous record of absolute field variations.

Unfortunately, there is considerable variation in the documentation and accessibility of archaeomagnetic records across the world. Published archaeomagnetic records are primarily clustered in the Northern Hemisphere, specifically Europe. While other areas have been studied, and are being studied, their current contribution to the global databases is more limited (Figure 1). This lack of uniform coverage limits the resolution of global field models.

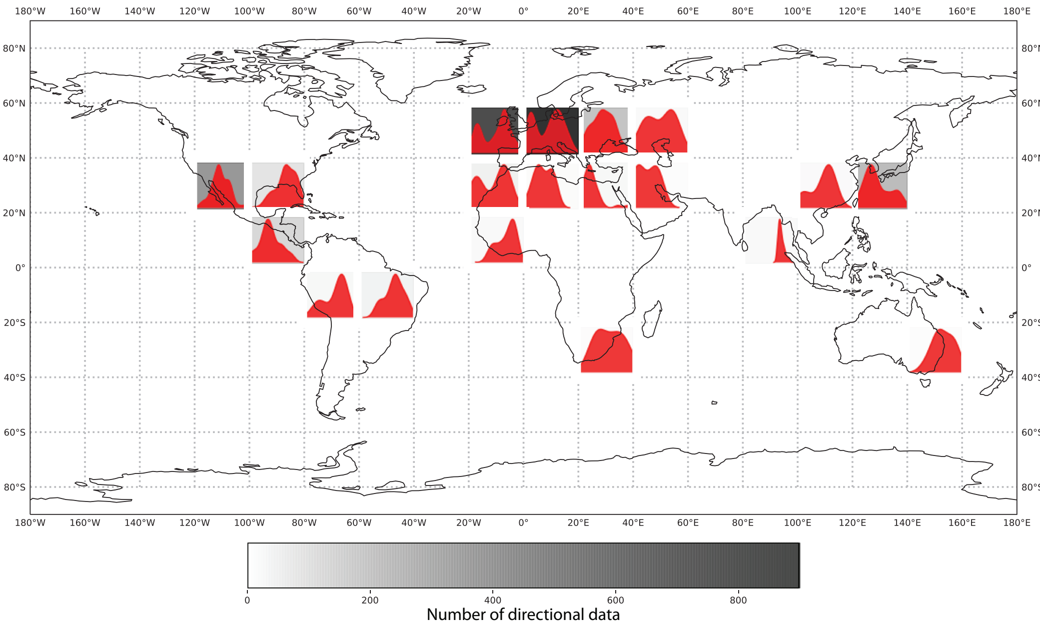

Figure 1. Spatial and temporal distribution of archaeomagnetic directional data from the last 2000 years, by provenience (defined in section 3): The shading of each latitude-longitude defined grid depict the number of archaeomagnetic directional results available in the gridded region (volcanic data excluded). The overlaid red histograms represent the temporal distribution of the results, with 2000 years before present on the left and the year 2000 CE on the right. GeoMAGIA data downloaded on 19 Jan 2021 (Brown et al., 2015).

One such under-published area in the global databases is the United States Southwest. Fortunately, this is not for lack of archaeomagnetic study (Figure 2). Over nearly six decades, starting in the early 1960s, an academic lineage of scientists and archaeologists dedicated their careers to the development of a highly robust archaeomagnetic record covering the greater Four Corners region of the United States Southwest (defined here as the four states of New Mexico, Arizona, Utah, and Colorado) and beyond. But in comparison to other global regions, these laboratories' data have seen limited peer-reviewed publication. Only about 10 percent of the site-level data, are available in open source paleomagnetic archives, such as GeoMAGIA (Brown et al., 2015) and MagIC (Tauxe et al., 2016). The remaining 90 percent of the data are generally either unpublished or sparsely published in hard-to-access archaeological reports. Moreover, when the data were published, the averaged site-level results were typically not reported with specimen or measurement data, limiting their potential for reproducibility and reinterpretation.

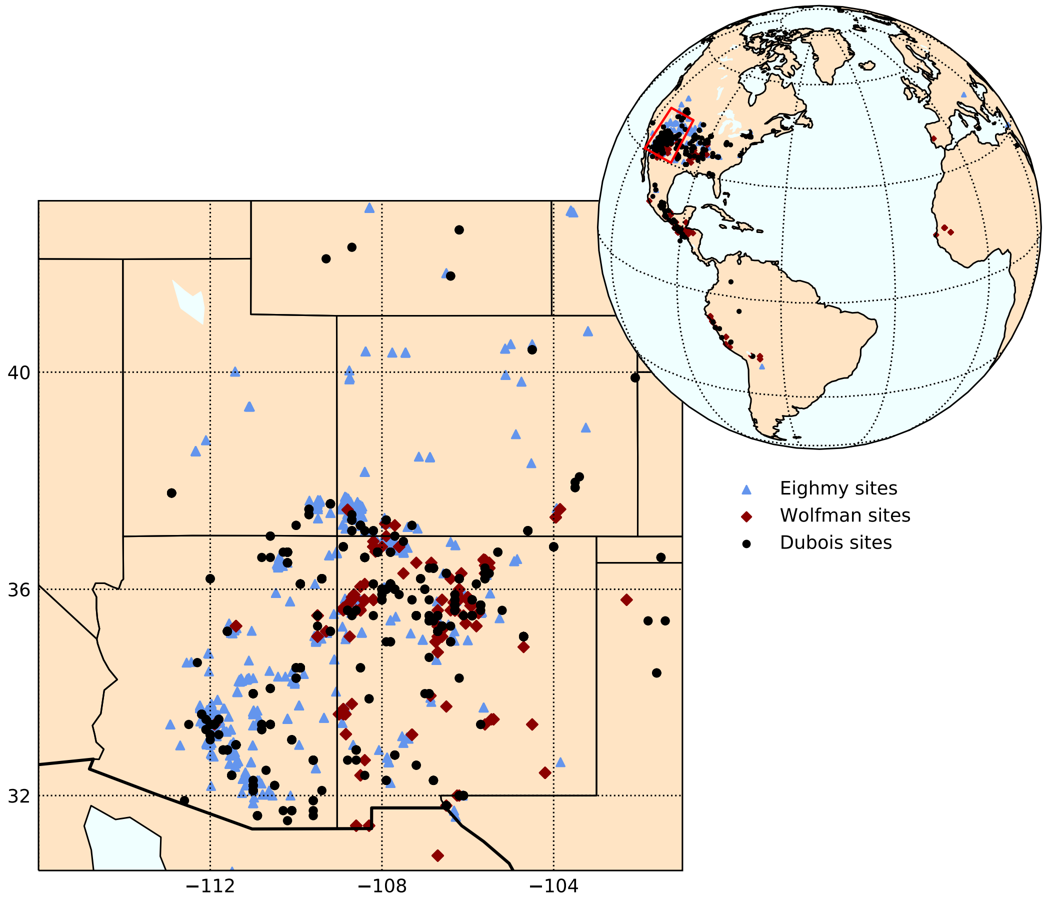

Figure 2. Provenience location map of sites sampled for archaeomagnetic direction, by contributor: The red quadrangle on the globe represents the bounds of the inset. The inset map depicts the sampling locations within the four United States states (from the bottom right corner clockwise) New Mexico, Arizona, Utah, and Colorado. This region has the highest sampling density in our dataset and comprises the Four Corners region of the United States Southwest. From the intersection of the four states, in the center of the map, to their farthest corner is about 750 km.

Fortunately, the original directional measurement data for over 5000 archaeomagnetic sites (defined here as a single heated feature in an archaeological site, such as a single hearth) are still available in personal collections. In this study, we digitized and reanalyzed the measurement data (magnetic declination and inclination data, in the form of Cartesian coordinates measured by a magnetometer) from the previously under-published sites within the Robert DuBois, Daniel Wolfman, and Jeffrey Eighmy-Stacey Lengyel collections. In the process we submitted the measurement data, along with our new interpretations, and, where possible, independent chronology estimates to the MagIC database. This is the first step towards the long-term goal of making these invaluable data FAIR principles compliant – Findable, Accessible, Reusable, and Interoperable (Wilkinson et al., 2016).

Bringing these datasets into FAIR compliance is productive for geomagnetism and also for archaeology. One of the original motivations for collecting the data was in order to develop regional virtual geomagnetic pole (VGP) reference curves of paleosecular variation, in order to allow application of directional archaeomagnetic dating. These three principle investigators operated under the assumption that Earth's magnetic field varies through time and the result of this variation is a traceable magnetic north pole path through time (defined as a VGP curve) that can be used as a relative, and in some cases as an absolute, dating technique. With this goal in mind, over decades these investigators collected independently-dated archaeodirectional specimens, then used those data to develop their own VGP curves using a subset of the complete dataset and a variety of curve construction techniques (e.g. Kawai et al., 1965, DuBois, 1989, LaBelle & Eighmy, 1995, Lengyel & Eighmy, 2002, and Hagstrum & Blinman, 2010). This resulted in development of VGP curves with significant discrepancies and has led to incongruent archaeomagnetically-derived age ranges (Blinman & Cox, in press). The most striking differences between developed VGP curves is seen in the curves developed for the Four Corners region of the United States Southwest (Figure 3).

Recognizing these discrepancies, two of the longest-term goals of this data recovery project are:

1. Develop a new VGP reference curve for the Four Corners region using modern statistical techniques and data from all contributors, and
2. To support a web-based platform that is accessible to archaeologists desiring to update previously published archaeomagnetically-derived chronologies.

But these goals require data to be FAIR principle compliant, making this project critical to the success of these aims.

2 A brief history of archaeomagnetism in the United States

As early as the 1950s, scientists from Europe and Japan began developing archaeomagnetic theory, methods, and applications (e.g. Thellier & Thellier, 1951, Cook & Belshé, 1958, Watanabe, 1959, Aitken, 1961, and Burlatskaya & Petrova, 1961) but they were not embraced by North American scientists until the early 1960s. In 1964, geophysicist Robert DuBois began his life-long pursuit of sampling and measuring archaeomagnetic materials. Within a few years, he had amassed a large enough dataset of archaeomagnetic data with associated dates, that he began publishing the first VGP models of paleosecular variation for the Four Corners region (e.g. DuBois & Watanabe, 1965, Watanabe & DuBois, 1965, Weaver, 1967, DuBois, 1989, and DuBois, 2008) and using those regional VGP models to date archaeological sites in the region. Most noteworthy was DuBois' partnership with Emil Haury, who used DuBois' archaeomagnetically-derived dates to confirm his hypothesis about the early irrigation development at the Snaketown site (a pre-Spanish, Mogollon culture site 30 miles or 48 km southeast of Phoenix, Arizona) (Haury, 1976:331-333, and J. L. Eighmy, 2000:107). This partnership led to the development of the foundational cultural chronology that is still used in the southern Arizona region (Schiffer, 1982:327-329, and Deaver, 1998:464-490).

By the early 1970s, as a professor at University of Oklahoma, DuBois supported many students, most notably Daniel Wolfman and Jeffrey Eighmy, who later became trailblazers in archaeomagnetism in the United States. Wolfman, an archaeologist by training, helped expand DuBois' range to include Central America (most notably Mexico), and the Andean region of South America (specifically Peru). Post-graduation in 1973, Wolfman went on to develop his own archaeomagnetic research program in Arkansas, where he held positions until 1988. With the support of the National Science Foundation, Wolfman partnered with Dodson at the Rock Magnetism Laboratory at UC Santa Barbara (UCSB) in 1982-83. This collaboration resulted in the publishing of their ref-

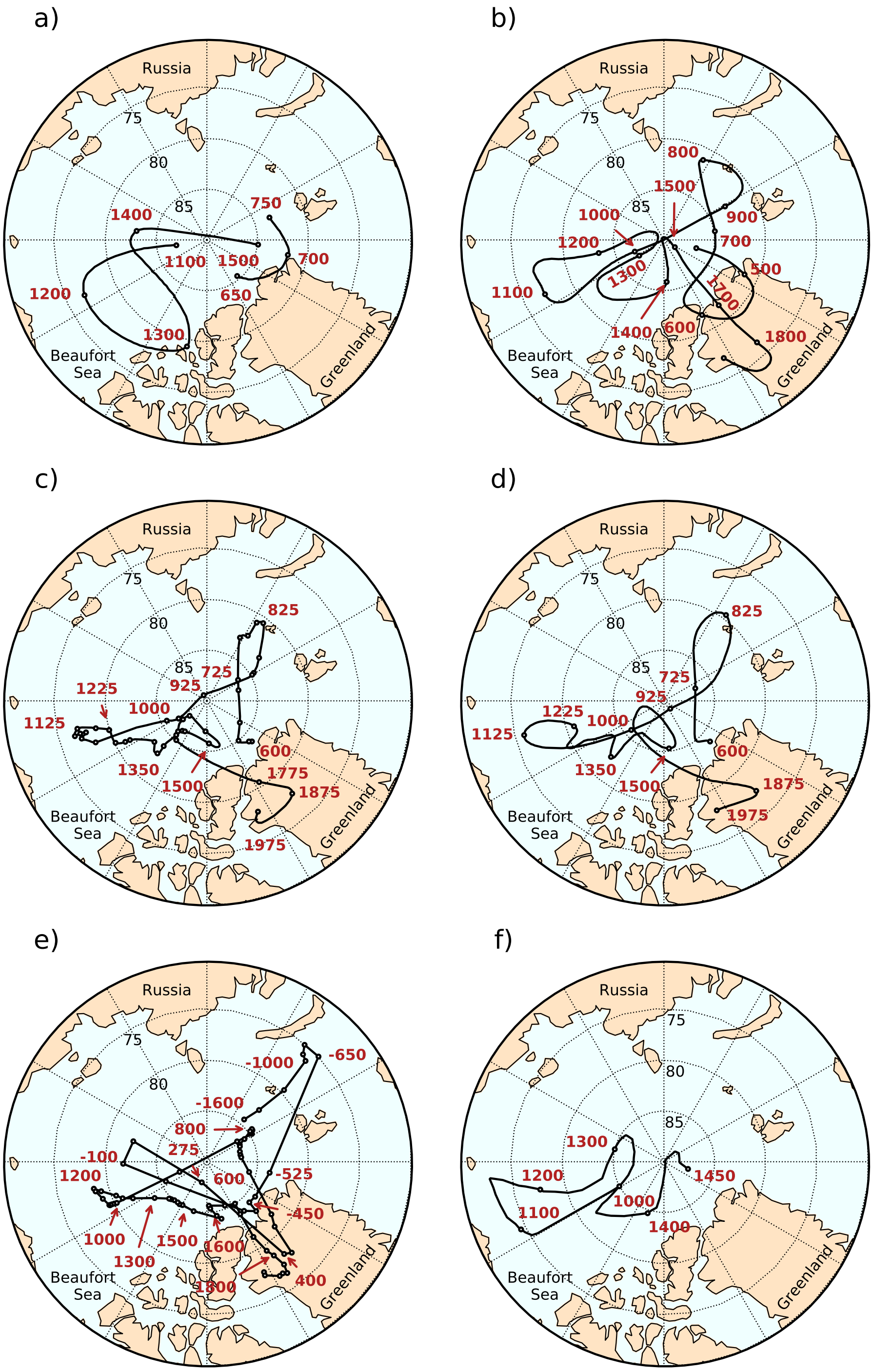

Figure 3. Past VGP reference curves from the Four Corners region: Over the decades, several VGP reference curves have been developed for the Four Corners region of the United States Southwest (not all presented here). a) (Kawai et al., 1965), the first published VGP curve for the region, was never used for archaeomagnetic dating. b) (DuBois, 1989), the first VGP reference curve used for archaeomagnetic dating in the region is hand drawn. c) SWCV 595 (LaBelle & Eighmy, 1995) and d) SWCV2000 (Lengyel & Eighmy, 2002) are computer-calculated moving-windows average derived reference curves. Both have been used by the Eighmy laboratory for archaeomagnetic dating, SWCV2000 replaced SWCV 595 and continues to be applied to dating applications. e) The VGP curve based on the declination-inclination curves published in Hagstrum & Blinman, 2010, computer-calculated using a moving-windows averaging technique, never used for archaeomagnetic dating. f) The unpublished, hand-drawn curve, employed by Wolfman for archaeomagnetic dating. All ages are CE.

erence work on Peruvian archaeomagnetism (Wolfman & Dodson, 1998). It was during this partnership that contacts were developed between Wolfman and Jeffrey Royce Cox, who later became Wolfman's primary laboratory technician.

In 1988, Wolfman moved from Arkansas to the Office of Archaeological Studies (OAS) in New Mexico where he founded the Archaeomagnetic Dating Laboratory. While Wolfman set up the OAS laboratory, Cox continued to make measurements at UCSB until 1993 when he joined Wolfman in New Mexico. Following Wolfman's sudden death in late 1994, Cox continued Wolfman's legacy under the supervision of Eric Blinman (then deputy director of OAS). Since then, Cox and Blinman have continued to collect and measure additional archaeomagnetic samples primarily from New Mexico for the purpose of enterprise archaeomagnetic dating. They also worked to increase the precision of field sampling methods and refine their archaeomagnetic dating procedures. For a more detailed description of Wolfman's work and legacy, see for example Schaafsma & Schaafsma, 1996; Sternberg, 1996, and J. L. Eighmy, 2000:105-123).

The other notable student of DuBois is Jeffrey Eighmy, also an archaeologist. Eighmy worked as an undergraduate field technician for DuBois in the early 1970s, collecting samples from archaeological sites across the United States Midwest and the Southwest (J. L. Eighmy, 2000:107). Following the completion of his dissertation in 1977, he formed a collaboration with Robert Butler and Robert Sternberg at the University of Arizona. This multi-decade collaboration with Sternberg led to the development of several VGP models of paleosecular variation used primarily for enterprise archaeomagnetic dating aims, the later models are derived from a moving-windows statistical program (e.g. J. Eighmy et al., 1980, Sternberg, 1982, Hathaway et al., 1983, Sternberg, 1989, J. L. Eighmy & Sternberg, 1990, J. L. Eighmy, 1991, LaBelle & Eighmy, 1997, Lengyel & Eighmy, 2002, and Lengyel, 2010). These models confirm the large-scale field movements depicted in DuBois' original VGP models (DuBois & Watanabe, 1965, Watanabe & DuBois, 1965, and DuBois, 1989) but also show small-scale variability that has still not been reconciled. That is one of the aims of this data recovery project.

In his professorial role, Jeffrey Eighmy trained and worked extensively with Stacey Lengyel, now a faculty member at East Tennessee State University (ETSU). Together they expanded the datasets from Arizona and brought new paleomagnetic perspectives to the conventional archaeomagnetic approach founded by DuBois. After Eighmy's retirement, Lengyel continued to work in the discipline and founded an archaeomagnetism laboratory at the Illinois State Museum, before moving to ETSU. Of all the dedicated archaeomagnetists in the United States, Lengyel and Eighmy are best known for publishing their data in accessible journals. The majority of the archaeomagnetic data in GeoMAGIA (Brown et al., 2015) from the United States is a result of their efforts, often in partnership with Sternberg.

3 Brief description of terminology used in this paper

The final destination for the data recovered here is the MagIC database, as such this paper's data files are formatted to be consistent with the nomenclature used in the MagIC database (adopted from the paleomagnetism community). This nomenclature is slightly different from the definitions traditionally used by archaeologists (Table 1). The MagIC database understands a site as a heated feature with uniform magnetic properties and a single age (Tauxe et al., 2016). An example of a paleomagnetic site would be a single lava flow. Applied to archaeology, this nomenclature most closely aligns with the archaeological definition of a feature (e.g. hearths). The use of the MagIC definition of site eliminates the potential age ambiguity associated with the archaeological definition of a site, due to generational reuse and reoccupation.

Table 1. MagIC Terminology use in this paper

Column name	MagIC definition	Geologic example	Archaeodirectional application (this archive)
Location	Geographical location with several different aged sites	Stratigraphic section	Archaeological site
Site	Feature whose magnetic properties and age are expected to be uniform	A single lava flow	Archaeological feature (e.g. hearth)
Sample	Piece of material collected from a single site	Multi-centimeter drilled cylinder of lava	Plaster cube encasing burned material
Specimen	Piece that was measured	Standard 1-inch paleomagnetic core	Subdivisions of the material[a]
Region (optional)	Larger geographic area encompassing multiple locations	Maui Island, Hawaii	Mesa Verde National Park

[a] In this study, no original plaster cubes (samples) were subdivided into specimens; as such, the MagIC sample and specimen names are equivalent. For simplicity, in this study, the MagIC sample table reports the interpreted vector direction in geographic coordinates, transformed using the field azimuth and dip. The MagIC specimen table reports the interpreted vector direction in the same coordinate system as the measurements.

Applying the MagIC definition of site to an archaeological context (e.g., a hearth), promotes an archaeological 'site' to MagIC's definition of a location. In this study, the archaeological site names (MagIC locations) are frequently recorded with alternative names, because United States' archaeological sites are designated by an official alpha-numeric identifier and a common name. For example, the archaeological site in New Mexico known as Lower Arroyo Hondo is also known as LA12. If both names are identified within the metadata of the recovered legacy data, then both are recorded in the MagIC compatible files. If only one archaeological site name was found within the metadata, it was used as the MagIC location and no alternative name was added by these authors.

The MagIC definition of a sample is material collected from a MagIC site. As an analogy with a lava flow, a sample is the multi-centimeter long drilled cylinder. Back in the laboratory, that sample can be subdivided into MagIC specimens, which are measured. Specimens may or may not be the same object as a sample. The sampling custom used in archaeomagnetism in the United States is to collect multiple cubes of material from a single heated feature (i.e. the MagIC site). In this case, each individual cube is synonymous with the MagIC definition of a sample. Any subdivisions of these sample cubes would be defined as multiple MagIC specimens from the sample. However, it is not the practice of United States-based archaeomagnetists to subdivide the material encased in the plaster sample cubes, as such the collected sample is equivalent to the measured specimen. The legacy data recovered in this project and compiled into MagIC compatible data files use a cube's identification number for both the MagIC sample name and the MagIC specimen name.

At a larger level, if an archaeological site (MagIC location) is identified in the metadata as being from a specific well-known archaeological location, this was noted in the MagIC compatible column "region" (e.g. Chaco Canyon National Historical Park or Mesa Verde National Park). The use of the "region" column is optional and incompletely used in the project.

All archaeological sites (MagIC locations) are recorded in the MagIC compatible table with a country identifier and, where possible, state/province information. Some of this information was clearly defined within the recovered dataset's metadata, but not always. Where the political boundary information was not defined by the original contributors, it was identified and included by the authors of this paper. This was completed using the latitudinal and longitudinal data provided and/or the official alpha-numerical archaeological site names, which encode the US state information within the identifier. These political boundary identifiers are critically important to the sorting and analysis of these data by geographic region. The authors of this paper advocate for the inclusion of these information in future archaeomagnetic contributions to MagIC.

All the geographical metadata included in this dataset are with respect to the sample's provenience (the point of recovery in the archaeological record) (Blinman, 1988: 97). In this project, the site provenance (the geographic point of origin) (Blinman, 1988: 97) and the provenience of a sample are equivalent, since the thermal remanent magnetization (TRM) vector under investigation was imparted in the same location and orientation that it was recovered (a requirement of directional paleomagnetic studies). This equivalence may not hold true for pottery-based archaeointensity studies, since some pottery can be transported great distances from the location of magnetic acquisition (provenance) and the point of archaeological recovery (provenience).

4 State of the datasets and methods

Over the course of six years, with the help of a few dedicated undergraduates, the accessible data from the DuBois, Wolfman, and Eighmy-Lengyel datasets were converted into a format compatible with upload into the MagIC database. For the DuBois and half the Wolfman datasets, this involved extensive hand digitization of the measurement data and locational metadata. For the second half of the Wolfman dataset and the Eighmy-Lengyel dataset, this involved detailed reformatting of non-conforming digital formats (early 1990's formatting and a single 2000-page Word document, respectively).

Collectively there were twelve different formats of measurement data, representing nearly 60 years of sampling, measurement, and technology advancements. The locational and chronological metadata were all uniquely formatted, ranging from tables, to hand written notes in margins, to field notes, to personal correspondence, to tagged pages in books and manuscripts. In most cases, citable archaeological reports are not associated with the archaeomagnetic data, but where present those citations were noted.

The DuBois and Wolfman archives are housed at the Office of Archaeological Studies (OAS) in New Mexico, USA. These archives are nearly complete repositories of their respective life-work with nearly all samples, field notes, measurement data, metadata, and equipment safely stored within the working facility. This project represents the first comprehensive attempt to digitize these datasets and was conducted in two parts. First, if the records did not have a digital copy, a scan of the original paper records was taken. This permitted the second step of the digitization process (typing/ reformatting the data into a MagIC compatible format) to occur off-site, as well as ensures that a back-up of the primary records exists. An ongoing follow up aim is to create a searchable digital database for these primary scanned records.

In the process of organizing the paper records for scanning, it was noted that a not insignificant portion of the DuBois estate documents were stored in sub-par conditions prior to their rescue by OAS staff and volunteers in 2013. These less than ideal conditions resulted in damage from mold and rodents. Fortunately, in general the data destroyed by mold and rodents were usually also duplicated on other printouts, permitting the successful preservation and digitization those data.

Generally, the Wolfman dataset was in superior condition to the DuBois dataset. The biggest limitation to digitization of the paper records was the fading ink on some of the printouts. This led to some difficulties in completely digitizing the accessible dataset. But thankfully, this did not affect the large majority of the dataset. Further work is needed to read and digitize the few sites that are currently too faded to read.

The Eighmy dataset was entrusted to Stacey Lengyel. Those datafiles were curated under Lengyel at her archaeomagnetism laboratory associated with the Museum of Illinois, until her relocation to ETSU in 2017. The digital files associated with Eighmy's dataset were provided by Lengyel for this project, those files are complete to 2004.

5 Context and chronology

The locational and chronological metadata for the DuBois dataset were derived from DuBois, 2008, a catalog compiled by DuBois but published after his death. The data were included "as is" and were not verified for accuracy. In the decade since its publication, a few inaccuracies have been noted. For the sake of consistency, any edits were not included unless the inaccuracy was an egregious error in the latitude and longitude reported. These few locational errors were generally longitudinal hemisphere errors, since the convention used in DuBois, 2008 was -180°W to 180°E. Occasionally, a similar hemispherical error was discovered in the latitudinal data and corrected. In a few cases, typos in the longitudinal value resulted in sites from the continental United States plotting in the wrong location (i.e. in the ocean or in an incorrect state), these were also corrected. All corrections were easily made because in most cases multiple sets of specimen cubes were collected from the same archaeological sites (i.e. multiple fire pits from one larger archaeological site), so the correct latitude and longitude were borrowed from those data.

A note on the chronological metadata of the DuBois dataset presented here and in DuBois, 2008: For the most part, the ages reported are age estimations recorded by DuBois at the time of sample collection. These dates were rarely updated when the official archaeological reports were published, or as additional information was acquired during subsequent excavation. The exception to this norm, is the chronology data compiled by archaeologist Tom Windes for the specimens collected from the Chaco Canyon National Historical Park (U.S. National Park Service). Windes compiled detailed chronologies and reviewed the metadata for each heated feature that DuBois sampled for archaeomagnetism. These detailed and cited information are included in the description column of the MagIC formatted file.

Due to DuBois' convention of asking for an age estimate at the time of collection and recording that age on his field records, nearly all the data from the DuBois estate are associated with an age estimate. In general, these age estimates are usually quite accurate because the chronology of the United States Southwest is well understood. The quantity and quality of archaeology conducted over the last century in this region, paired with the large amount of datable materials and features (organic material preserved by the dry climate, pottery variation, and architecture variation) allow for accurate in-field age estimations to within a few dozen years. This is a unique attribute of United States' Southwest archaeology. A detailed reassessment of the chronology is planned as part of the long-term aims of this project, but that reassessment is likely to improve the precision of the original estimates, rather than significantly change the age.

In constrast to DuBois' nearly complete age record, Wolfman and Eighmy have a significantly lower percentage of archaeomagnetic samples with associated ages. But in general, their reported chronologies are more precise than DuBois' and are usually associated with citable archaeological reports.

The Wolfman metadata were compiled into a Microsoft Access database with referencing to project names, archaeological site names, archaeologists, and cited reports.

Each archaeological feature sampled for archaeomagnetism had varying levels of completeness in their metadata, ranging from very detailed to almost no information.

The chronological data for the Eighmy dataset was accessed from the Colorado State University Archaeometric Lab Technical Series (CSU Technical Series) (J. L. Eighmy et al., 1987; J. L. Eighmy & McGuire, 1989; J. L. Eighmy & Klein, 1988, 1990; LaBelle & Eighmy, 1995; Premo & Eighmy, 1997). These volumes include the age for each sampled archaeological feature that Eighmy, Lengyel, Sternberg and associates used in their regional paleosecular VGP models (e.g. J. L. Eighmy, 1991, LaBelle & Eighmy, 1997, Lengyel & Eighmy, 2002, and Lengyel, 2010), but do not always cite the archaeological report that qualifies those chronologies.

6 Formatting challenges, creating master file, merging the datasets

Following the digitization, the three datasets were independently reformatted into MagIC compatible files to ensure that the idiosyncrasies of each dataset could be addressed completely. Since the DuBois dataset was completely hand-digitized, the formatting idiosyncrasies were limited but still numerous because the DuBois datasets had several unique data formats, nine of the twelve formats worked with in this project. In many cases, there was ambiguity in the units of the measured moments as well as the order of magnitude of the measured moment. As such, all the DuBois moments have been classified as "uncalibrated moments", which is consistent with the MagIC column conventions. Future, very detailed and time-consuming work, may be able to reconcile the unit ambiguity for a few of the nine formats, but it is unlikely that a complete reconciliation will be possible.

The Wolfman database was stored in two formats. About half the accessible data were stored in a 1990s era digital format with two files for each archaeomagnetic site: a file with the basic locational metadata and a second file with the measured magnetizations. The other half of the data were stored in printouts; these were hand-digitized. Similar to the DuBois dataset, there was ambiguity in the units of the measured moments and order of magnitude; as such the moments in the MagIC compatible format are also classified as "uncalibrated moments". Future work will be required to address this challenge. Additionally, there were significant difficulties with referencing the magnetic data to the chronological and locational metadata. These metadata were stored within a Microsoft Access database in a format that was not easily exportable into a single column delimited file (like a Microsoft Excel file). The result was multiple exported files that were inconsistently referenceable, limiting the ability to easily merge the metadata together and then merge it with the magnetic data.

The Eighmy database had far more idiosyncrasies than the DuBois and Wolfman datasets. This has been attributed to the file format that the data were preserved in: a Microsoft Word document. The file had all the magnetic data and basic locational information but had many typos and was inconsistently delimitated. Transferring the data from the Word document to a delimited format that could be converted into a MagIC compatible file required the development of a short python script to search line-by-line for specific string patterns and characters. This python script worked remarkably well but not completely. Accuracy verification was done visually and was corrected by hand. The most common challenges were typos related to the demagnetization step. The original program that stored the data had a maximum number of characters permitted in the specimen name and demagnetization step columns. This resulted in demagnetization steps 50 Oe, 100 Oe, 150 Oe, 175 Oe, etc. being recorded as 50, 10, 15, and 17 respectively. It also led to demagnetization step 100 Oe and 1000 Oe both being recorded as 10. These corrections were easily edited by hand because the data were organized by increasing demagnetization level and the set of demagnetization steps used was regular. All demagnetization steps have been converted to tesla, for compatibility with the MagIC database. Another common challenge was typos in the specimen or site name that made referencing for principle component analysis and fisher mean site-level averaging difficult. These typos were also corrected by hand. Where appropriate, all edits were noted in the description column of MagIC compatible file. For consistency with Dubois and Wolfman datasets, the reported magnetic moments are labeled as "uncalibrated moments". It is likely that the units for these moments can be verified with moderate ease in the future.

The biggest challenge with the Eighmy dataset was merging the chronology data from the CSU Technical Series publications with the magnetic data. The chronological data presented in the CSU Technical Series publications are associated with an archaeomagnetic sample's DVPG number rather than the archaeomagnetism laboratory specimen number. In most cases, an association between the two numbers was possible to determine, but not always. Where the association was possible, the DVGP number is recorded in the "alternative sample name" column of the MagIC compatible file.

7 Data Processing

After the three datasets were compiled into their respective MagIC compatible files, the datasets were filtered for quality (Table 2) and visualized independently using the plotting scripts within the PmagPy software package (Tauxe et al., 2016). After plotting the sample data that passed the acceptance criteria (Figure 4), it was noted that each dataset had idiosyncrasies resulting in sample vector locations that were improbable, as every site sampled is less than a few thousand years old (i.e., during the current normal polarity field state). For example, the Dubois and Wolfman datasets (Figure 4a and c) showed clusters of data, not only in the direction of the expected field (green dots) but also to the east (blue), south (magenta) and west (yellow). As no excursions have been reported for the last few thousand years, the unexpected directions are likely the result of misunderstandings in the orientations of the sample cubes.

Table 2. Acceptance criteria: All the data digitized as a result of this project were reinterpreted using modern statistical conventions and subject to a set of acceptance criteria threshold to determine the highest quality sample vectors and site averages. Criteria described in (Paterson et al., 2014).

Criteria Group	Statistic	Threshold
Specimen/sample criteria	$N_{measurements}$	≥ 3
	DANG	≤ 5
	MAD	≤ 5
Site criteria	$N_{samples}$	≥ 3
	κ	≥ 100
	α_{95}	≤ 5

To adjust for the evident idiosyncrasies within the datasets, the data from each collector's datasets were analyzed independently and by region. The regions were very broadly defined as data from the United States, from Mesoamerica (Panama north to the US-Mexican border), and from South America. These divisions were required to limit the latitudinal dependence of inclination within the datasets that would add ambiguity to the cluster analyses used in classifying the data that required adjustment. Any data from regions not defined above, were not evaluated for adjustment, due to the low number of records. Mathematical clustering using functions within the KMeans function in the sklearn.cluster python module were used to identify the data that required systematic adjustment. These functions helped eliminate the subjectivity of human bias, while allowing for the expected variability in magnetic direction due to the paleosecular variation over the last several thousand years.

The DuBois and Wolfman datasets required very similar adjustments of 90°, 180°, or 270° in the measured field azimuth. The prevalence of this inaccuracy is likely the result of the collection protocol used by both these contributors. Their convention was to collect heated anthropogenic material encased in plaster cubes, level the top surface of the cube (i.e. a dip of zero degrees), and then measure the azimuth with respect to a reference corner marked on the top of the cube. The clustering analysis indicates that there are a non-negligible number of sample cubes with azimuth directions measured along an incorrect side of the cube, resulting in the prevalence of magnetic vector directions that are 90°, 180°, of 270° off the expected northerly direction for this recent time period (Figure 4a and c).

The cluster analysis was used to classify each of the sample directions into five clusters (expected northernly direction, 90 degrees east of north, 180 degrees from north, 90 west of north, and unable to cluster). For the Dubois and Wolfman USA data, this clustering was completed in two steps, due to the overwhelming prevalence of northernly directions. The first clustering code isolated out the northernly directions, while the second code clustered the remaining non-north data into their respective clusters. Then the data were merged back together and the required 90, 180, or 270 degree azimuth adjustment was applied (Figure 4b and d).

The Eighmy dataset required a different adjustment, the dataset does not exhibit the same prevalence of 90, 180, and 270-degree clusters. It is unclear if this distinct lack of 90-degree inaccuracies is a result of corrections applied prior to the dataset's submission to this project or if the collection procedure used by the Eighmy laboratory contributed to this notable decrease. Eighmy also collected archaeomagnetic material using the plaster cube convention, but instead of measuring the field azimuth with respect to a reference corner like DuBois and Wolfman, his convention was to measure the azimuth with respect to an arrow parallel to a chosen side of the cube.

The pre-adjustment Eighmy sample data exhibit a southern hemisphere spread of positive directions, with shallower inclinations than predicted by the geocentric axial dipole (GAD) equation (Figure 4e). This behavior is not consistent with an inaccuracy in the field azimuth reading, as was seen in the Wolfman and DuBois datasets. But the shallowed inclination is consistent with an inaccuracy in the dip reading (recording 0 instead of 90, or visa versa) in addition to an non-90-degree inaccuracy in the field azimuth.

Visual interpretation of the specimen data (i.e. the vector data in specimen coordinates – not transformed into geographic coordinates) yielded a cluster of data with the expected inclination and northerly declination. Comparing the sample vectors within the shallow positive inclination spread in the southern hemisphere with the specimen vectors that cluster in the expected direction northern direction, it was noted that the cube identification numbers were the same. This suggests that the measurement data received for these cubes were provided in geographic coordinates rather than the expected specimen coordinates. To correct for this inconsistency, mathematical clustering was used identify and isolate the cubes that required adjustment (those in the southern spread). In the MagIC compatible specimen table, those cubes were identified to be geographic coordinates, and the vector direction was copied into the MagIC compatible sample table (Figure 4f).

8 Site-Level Results

After the required sample-level adjustments, Fisher means (Fisher, 1953) were calculated for each site using the pmag.fisher_mean function within the PmagPy package.

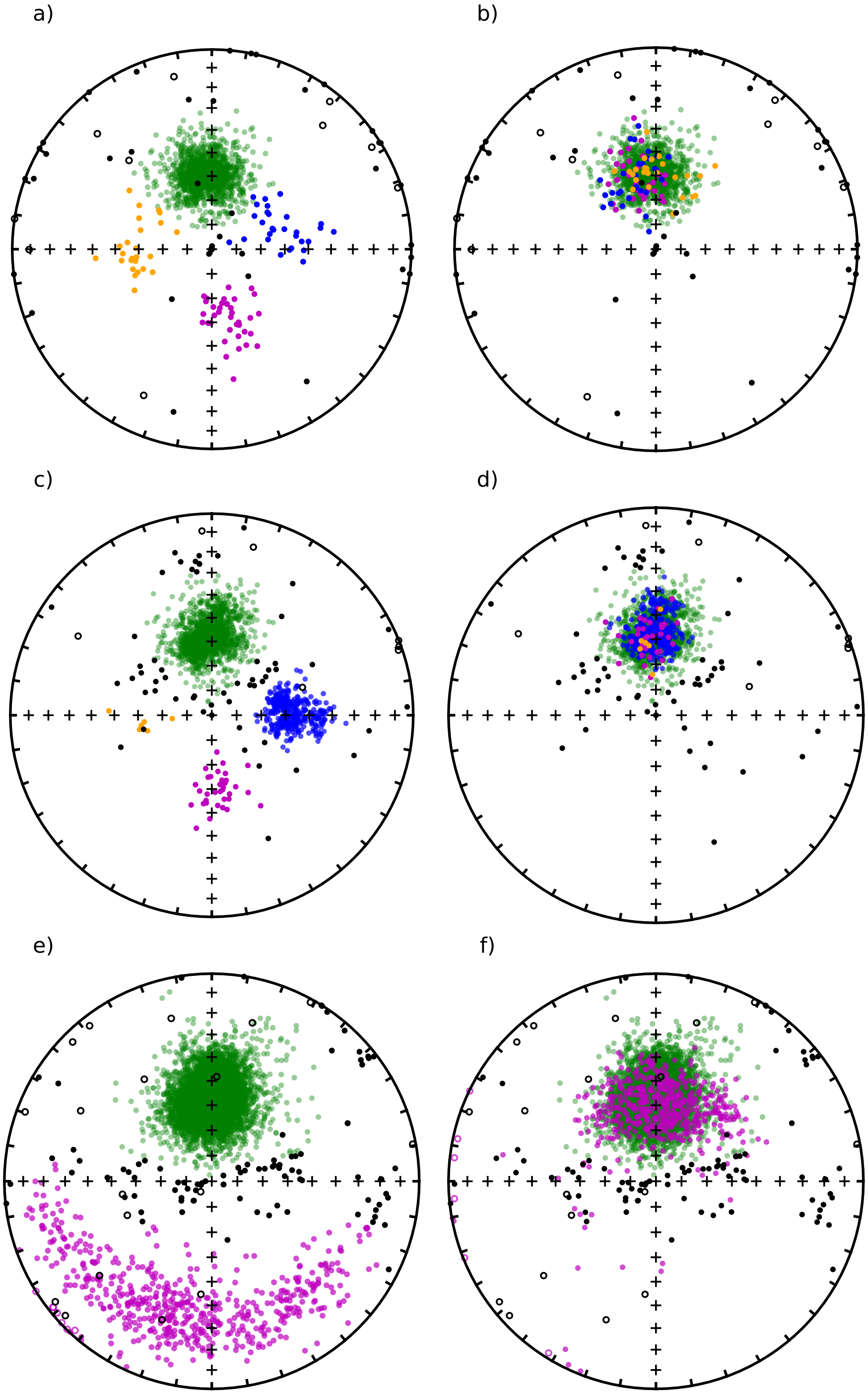

Figure 4. Stereonets of accepted samples, by contributor, pre- and post- adjustment: Inconsistencies in data collection and management through time resulted in idiosyncrasies within each of the three archives (shown here the US-based data). a) DuBois directions original. b) Dubois after adjustment. c) Wolfman original. d) Wolfman after adjustment. e) Eighmy original. f) Eighmy after adjustment. The clusters of data oriented East, South, and West in the DuBois and Wolfman datasets (a,c) are attributed to reading the field azimuth along the incorrect side of the sample cube. Applying an adjustment of either 90°, 180°, or 270° to the originally noted field azimuth yields adjusted directions for Dubois and Wolfman (b,d). The swath of south and down directions in the Eighmy dataset (e) is attributed to that subset of data already transformed into geographic coordinates, when provided to these authors. Ensuring those data are not doubly transformed into geographic coordinates, results the adjusted Eighmy data set (f).

Only samples that satisfied the acceptance criteria were included in the site-level average (Table 2). These site-level averages were filtered for quality using the acceptance criteria in Table 2 then by regional location.

The application of the selection criteria filtered the data significantly (Table 3), especially the number of acceptable sites from the DuBois' dataset. The percentage of DuBois' sites that passed this study's selection criteria is extremely low (3.3%). This low percentage is attributed to the laboratory methodologies used by DuBois through the decades, which were customary at the time. DuBois' convention was to measure a "pilot group" of specimen cubes from a site through a multi-step demagnetization protocol, this pilot group usually consisted of only one to three cubes. The remaining cubes collected from the site were usually only measured at NRM and the "optimum" demagnetization step, identified from the pilot group study, typically 150 Oe (15 mT). A side effect of this laboratory convention is that the vast majority of DuBois' specimen cubes have only two demagnetization steps, which results in a significant number of them failing the specimen acceptance criteria. Additionally, due to the low number of cubes measured as part of the pilot group, many sites failed to meet the site-level criteria which require at least three samples. Later in life, DuBois changed his laboratory conventions slightly to increase the number of cubes within his pilot group, this change results in a higher percentage of DuBois' later studies to successfully pass our acceptance criteria. Fortunately, nearly all of DuBois' original specimen cubes still exist in storage at OAS, so additional steps could be measured and the percentage of sites that pass this paper's acceptance criteria has to potential to increase.

Table 3. **Number of samples, sites, and locations - by contributor**

Category	**Contributor**	**Number**
Samples	DuBois	15,312 (1,903 accepted)
Total = 51,166 (16,079 accepted)	Wolfman	29,662 (10,673 accepted)
	Eighmy	6,192 (3,503 accepted)
Sites (e.g. archaeological features)	DuBois	1,991 (67 accepted)
Total = 5,377 (1,183 accepted)	Wolfman	778 (331 accepted)
	Eighmy	2,608 (785 accepted)
Locations (e.g. archaeological sites)	DuBois	497
Total = 1,185	Wolfman	157
	Eighmy	531

9 Results from the Four Corners region

One of the motivations for initiating this project, in addition to archiving these valuable datasets into FAIR compliant database, was to use the composite dataset to develop a model that reconciles the differences between the commonly used models of the Four Corners region of the United States Southwest. Historically, the different scientists used primarily their own laboratory's data in the production of their VGP curves, separate from the data of the other contributors. Because the data, up to now, were not publicly available, it has not been possible to develop a regional model of paleosecular variation, using the composite datasets of DuBois, Wolfman, and Eighmy.

The aim of producing a composite regional model requires the chronology information to be reported with the magnetic vector information collected by the contributors. Filtering for sites that have reported chronology eliminates a significant number of sites from all three contributor's datasets. The quality of the age reported was not used as a filter, and the chronology reported was not updated (as described in Section 5).

In the Four Corner region, a combined 3920 archaeological features were sampled for archaeomagnetism. Of these, 422 have reported ages and 223 passed the selection criteria (Table 4). Plotted against age, these data show a clear trend in declination and inclination over the last 1500 years (Figure 5a and b). The data are plotted by contributor, with the accepted archaeomagnetic sites noted as solid symbols and all the data with ages noted as open symbols. Superimposed on these data is a degree-10 polynomial fit calculated using functions within the python Seaborn module. The uncertainty bounds are defined through a Monte Carlo style resampling with 1000 iterations.

Table 4. Summary of the number of archaeomagnetic sites within the datasets by contributor and region

Region	Contributor	Sites	Sites with ages	Accepted Sites with ages
Four Corners	DuBois	1050	71	22
	Wolfman	486	229	114
	Eighmy	2384	122	87
Lower Mississippi River	DuBois	287	17	3
	Wolfman	33	5	4
	Eighmy	63	0	0
Mesoamerica (southern region)	DuBois	251	18	10
	Wolfman	117	29	14
	Eighmy	8	0	0
Mesoamerica (northern region)	DuBois	3	1	0
	Wolfman	14	7	7
	Eighmy	7	0	0
South America	DuBois	56	9	4
	Wolfman	37	5	2
	Eighmy	0	0	0

The declination and inclination data modeled by the polynomial fit and its respective uncertainty bounds, is based on the sub-portion of the dataset that satisfies the filter of $\alpha_{95} \leq 4$, paired with eleven predictions from the GUFM paleosecular variation model equally spaced between 1700 CE and 1950 CE (Jackson et al., 2000). The latter are denoted as black plus-signs. The addition of the GUFM predictions constrain the polynomial fit model in the historic time period, during which there is a low density of archaeomagnetic records. We chose 1700 CE as the minimum extent of the GUFM predictions used in these models because in the land-locked Four Corners region of the United States few historical records prior to 1700 CE were included in the development of GUFM, limiting the precision of the predictions for the region during the 17^{th} century.

In addition to modeling the data with a polynomial fit based on the subset of data that satisfy $\alpha_{95} \leq 4$, three other fits were explored (all the data with age constraints, the data that passed this paper's acceptance criteria, and $\alpha_{95} \leq 3$). Analysis of the four polynomial fit models resulted in the decision to select the curve derived from the subset of data that meet the $\alpha_{95} \leq 4$. A discussion is included in the supplemental information.

Using the python function get_children, one hundred declination and inclination pairs of data were retrieved from the polynomial fit derived from the subset of data with

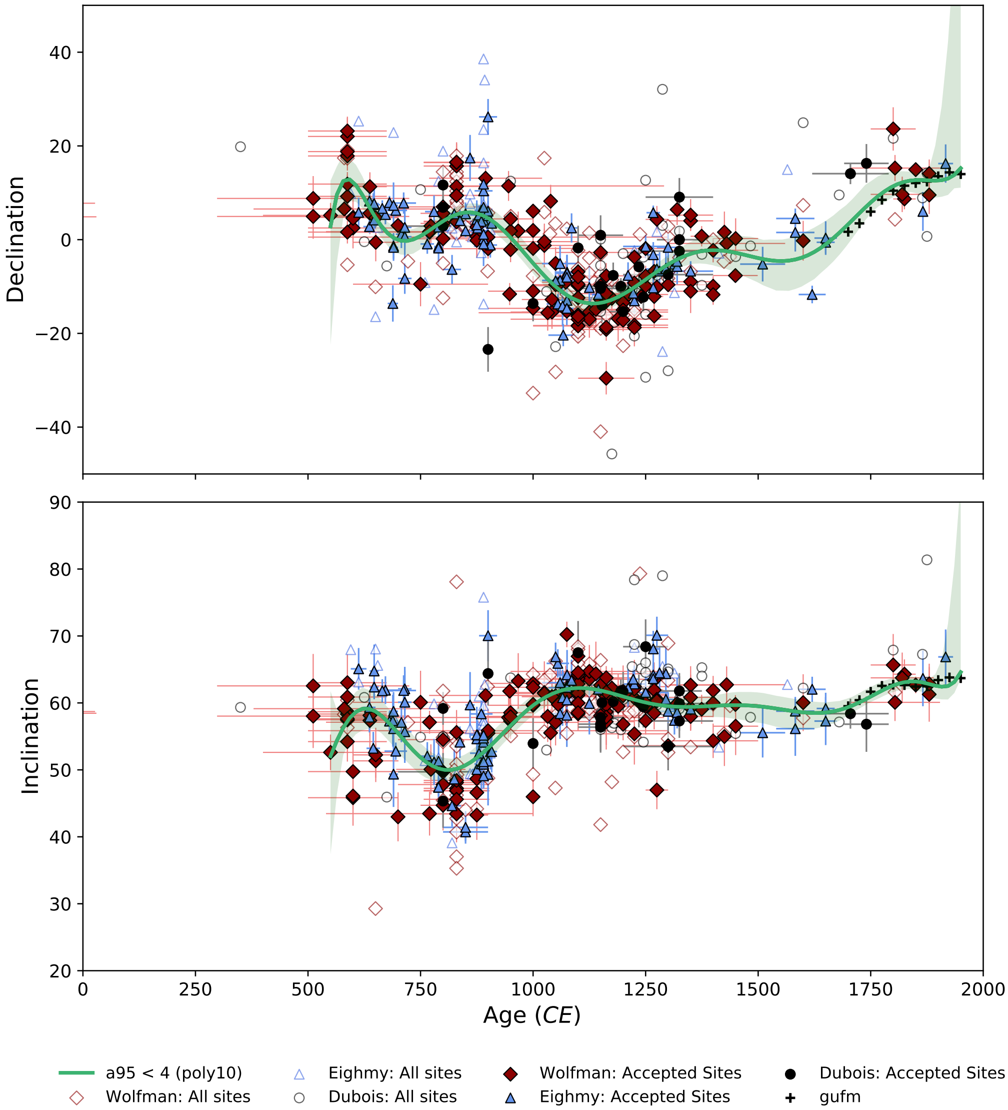

Figure 5. Magnetic declination and inclination of sites from the Four Corners region with respect to time: The data are plotted by contributor. Sites that do not meet our acceptance criteria but have ages are represented as open symbols. The accepted archaeomagnetic sites are denoted as solid symbols. Superimposed on the data is a degree-10 polynomial model fit based on the subset of data that satisfy a filter of $\alpha_{95} \leq 4$. The uncertainty bounds of the fit are defined by a Monte Carlo style bootstrapping of 1000 iterations. The black plus-signs are field values predicted by GUFM (Jackson et al., 2000) to constrain the polynomial fit during the most recent centuries that have limited data density.

$\alpha_{95} \leq 4$. These data pairs were evenly distributed between the ages 550 CE and 1950 CE. A central latitude and longitude defined as 36°N, 108°W was used in the conversion of the modeled fit to VGP coordinates (Figure 6). Prior to plotting, the modeled curve was truncated to between 600 CE and 1840 CE to limit the any potential inaccuracies at the margins of the polynomial fit model caused by a lack of data.

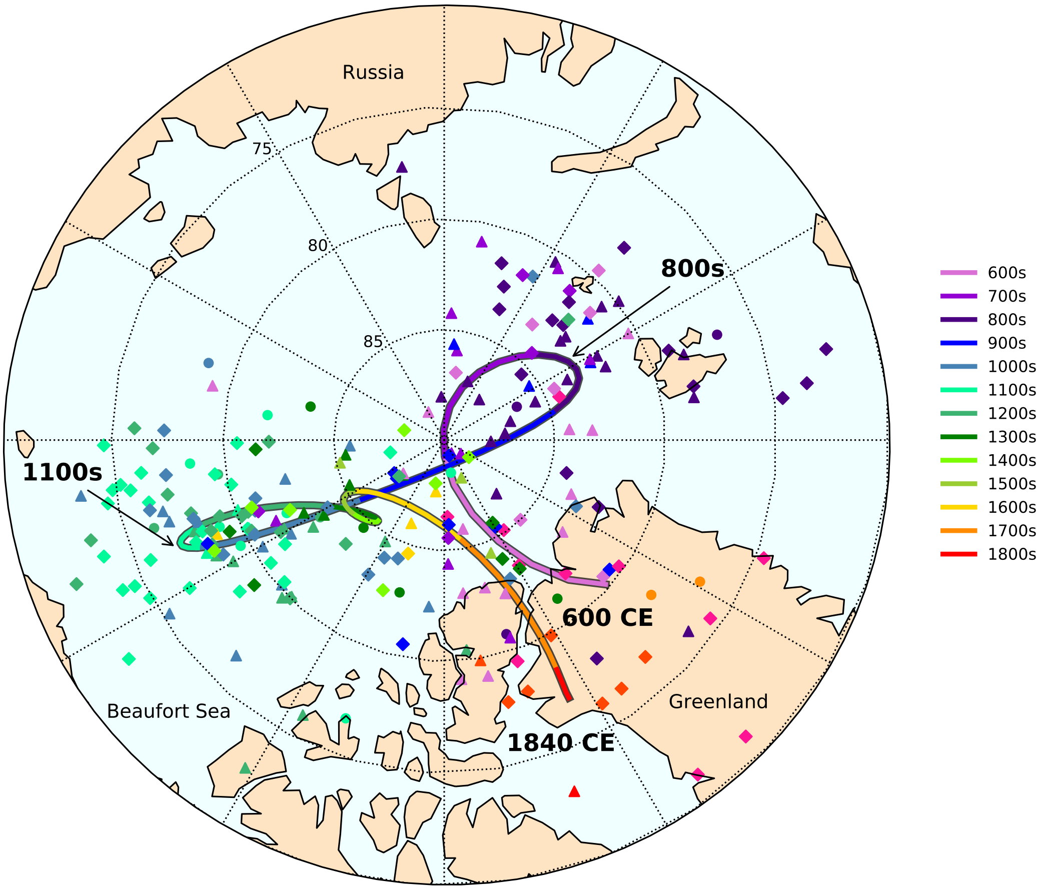

Figure 6. Newly interpreted Four Corners regional VGP curve, superimposed on the accepted sites by contributor and colored by age: The overlaid VGP curve is based on the accepted sites from the composite dataset that have age chronology recorded in the metadata. The curve is transformed from a degree-10 polynomial fit model of regional declination and inclination. The data and curve are are colored by century between 600-1900 CE. Circle symbols represent data derived from the DuBois estate. Diamond symbols represent Wolfman data and triangle symbols represent Eighmy data.

The model shown in Figure 6 is the first VGP curve developed from a composite dataset with significant contributions from DuBois, Wolfman, and Eighmy. On first order, this new polynomial-derived curve corroborates the pattern of VGP motion depicted in the regional curves presented by the three individual datasets (Figure 3b-d and f). The characteristic clockwise loop at roughly 800 CE, followed by a rapid movement towards Alaska and the Pacific Ocean between 900 and 1100 CE, is seen in all curves, including ours. Additionally, the clockwise loop at roughly 1200 CE is consistent with the previously presented curves, as is the trend towards Greenland post 1600 CE.

There are stark differences between this new polynomial-derived VGP curve and the previous curves, however. Most notably, the amplitude of the loops is significantly decreased in this new model compared to past curves. Additionally, the paleosecular variation seen between 1200 CE and 1600 CE is inconsistent among all curves. We attribute these differences to variations in the methods used in curve construction. This is an important issue to reconcile, as the various curves have been and continue to be used as reference VGP curves for enterprise archaeomagnetic dating. A statistically more robust model with uncertainty bounds is required to further this aim; this work is ongoing.

10 Results from the regions of Mesoamerica, South America, and the Lower Mississippi River

In addition to the significant volume of work conducted in the Four Corners region of the United States Southwest, a large amount of work was also conducted by DuBois and Wolfman in other regions of the Western Hemisphere. Specifically, their work targeted Mesoamerica, and, to a slightly lesser degree, the Lower Mississippi River region of the United States. There are also data from the greater Peruvian region of South America in the archives.

The Lower Mississippi River region, formally replacing Wolfman's use "Southeast" or "Arkansas and the border areas", is defined by the roughly 650-km radius between Memphis, Tennessee and New Orleans, Louisiana. This newly defined Lower Mississippi River region includes the states of Louisiana, Mississippi, Alabama, Tennessee, Kentucky, Missouri, and Arkansas, and portions of southern Indiana, southern Illinois, and eastern Texas (to roughly the city of Dallas). Within this region, DuBois sampled material from 287 burned features, Wolfman sampled 33 features, and Eighmy sampled 63. Of these only twenty-two have independent age chronology, and seven passed this paper's acceptance criteria (Table 4).

Analysis of the data from Mesoamerica required an additional division between northern Mesoamerica and southern Mesoamerica. A latitude of 25°N was chosen as a threshold. This division is important for analysis because of the latitudinal dependence of inclination. Additionally, a division of northern and southern Mesoamerica is consistent with the climatic variation that influenced the cultural trends of the indigenous populations. The few archaeomagnetic sites sampled in the northern region (24 sites) are culturally similar to the indigenous populations of southern New Mexico and Arizona and may be in close enough proximity they could be included in the Four Corners regional dataset for future modeling purposes. In total, samples were collected from 400 archaeomagnetic sites in Mesoamerica; of those only 55 have reported ages, of which 31 satisfied the acceptance criteria (Table 4).

The fewest number of sites were collected from South America, with a total of 96 archaeomagnetic sites. Of these, DuBois collected the majority of the data (56 sites), and Wolfman in partnership with Dodson sampled 37 archaeomagnetic sites. Only 14 sites have independently dated age constraints and of those only six passed the acceptance criteria (Table 4).

The low quantities of accepted archaeomagnetic sites from these regions, complete with independent chronology, limit our ability to corroborate the previously developed models from these areas (Lower Mississippi River region - Wolfman, 1982, reproduced in Wolfman, 2000a:250-251; Mesoamerica - Wolfman, 1973:179,238,244,247 and Wolfman, 2000b:287; Peruvian - Dodson & Wolfman, 1983, Wolfman & Dodson, 1986, and Wolfman & Dodson, 1998). Reproductions of these previously published curves are available upon request. The recovered magnetic vector data for each region are plotted against age are available in the supplemental information.

11 Conclusions and Future Goals

The datasets compiled as a result of this multi-year recovery and digitization project contribute previously unpublished measurement data for 51,166 archaeomagnetic specimens from 5377 heated archaeological features. Of these, 1183 reinterpreted archaeomagnetic sites have been accepted by our selection criteria. At present, only 283 archaeomagnetic sites are recorded with independent age constraints, and 239 of the dated sites come from the Four Corners region of the United States Southwest.

Future work on these datasets aims increase the proportion of data that satisfy this paper's selection criteria, while also improving the accuracy and precision of the independent chronologies. These improvements are possible through continued demagnetization of the archived specimens, further analysis of existing demagnetization data, and recovering additional metadata for the archaeological features that currently have limited archaeological details.

The value of verification and refinement of the archaeological chronologies is highlighted in Figure 6, where occasional VGP pole positions are incongruent with the expected positions based on its assigned ages. Although the vast majority of independent ages appear to accurate, ages were assigned beginning in the early 1960s. Archaeological dating tools and models have improved over the decades, and reassessment can correct errors and improve the accuracy and precision of the age assignments, while maintaining the independence and integrity of the geomagnetic data. Verifying and refining the chronology of these archaeological features that have incongruent VGP pole position and a history of site reoccupation is an ongoing project.

Additionally, just over 2000 archaeological features (MagIC sites) from the dataset have been targeted for continued research (Table 5). These archaeological features have been targeted because they either passed this paper's acceptance criteria but were not paired with an independent age date (878 features), or they have an independent age date and at least eight cubes were collected from the feature but did not pass this paper's selection criteria (1138 features). The majority of the later group are features within the DuBois archive, nearly 890, and the result of DuBois' use of a "pilot group" protocol for demagnetization. Fortunately, the sample cubes for these archaeological features are accessible for further demagnetization and measurement. With effort, the inclusion of these additional data will greatly enhance the spatial diversity of accepted data and has the potential to aid in the development of additional regional VGP reference curves (Figure 7).

Table 5. Number of sites targeted for further study - by contributor

Category	Contributor	Number
Have independent chronology	DuBois	890
and at least eight sample cubes	Wolfman	169
Total = 1138	Eighmy	79
Accepted quality of magnetism but	DuBois	22
requires an independent chronology	Wolfman	159
Total = 878	Eighmy	697

And finally, over the years, there have been a number of additional scientists, primarily archaeologists, that have contributed to and are contributing to the archaeomagnetic record of the United States. Identifying all the collaborators and finding their data has proved to be a challenge. Their contributions are not presented in this paper, as that work is ongoing.

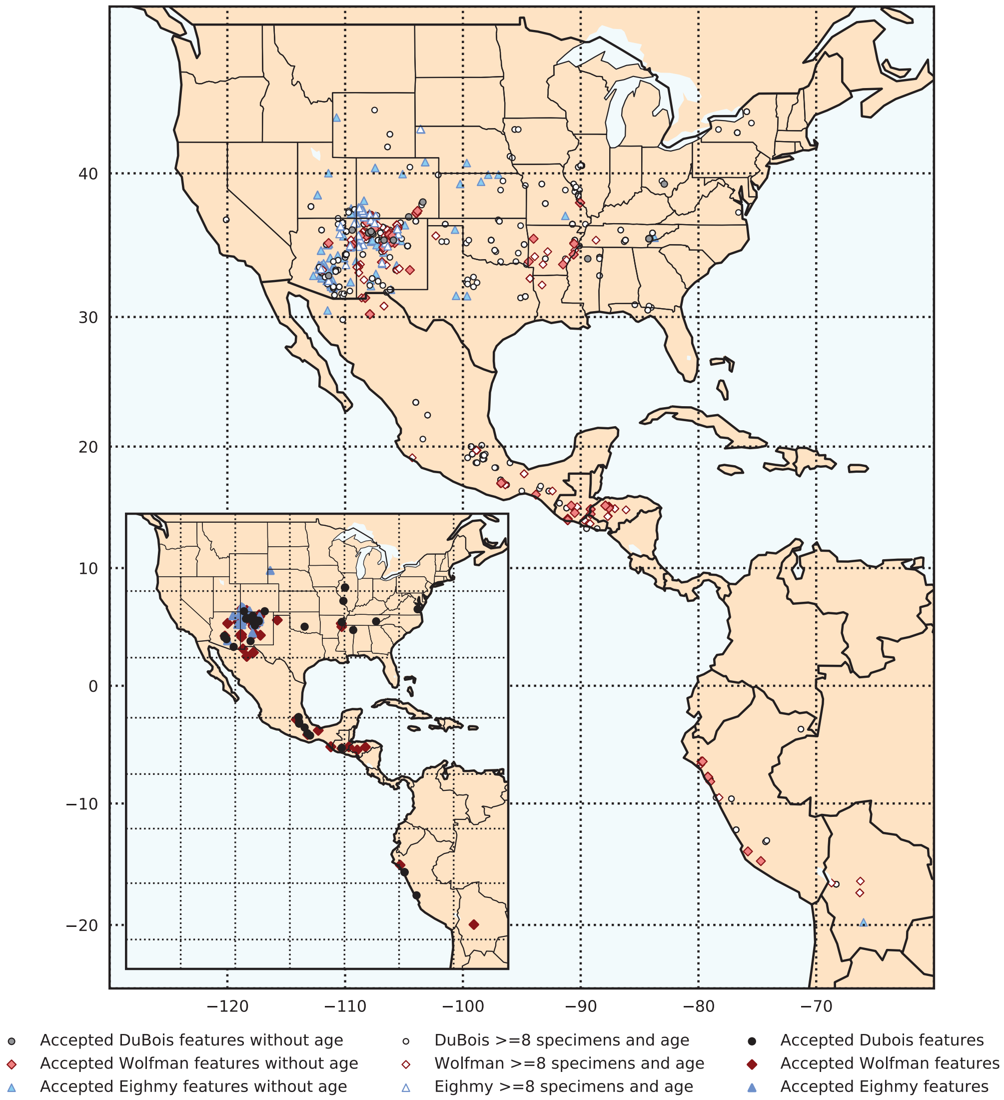

Figure 7. Provenience location map for sites targeted for future study, by contributor: The solid symbols on the inset map depicts the 283 site locations that do satisfy this paper's criteria (Table 4). The 878 faded-solid symbols do not satisfy this paper's criteria because an independent chronology is not paired with the accepted magnetic data (Table 5). The 1138 white-filled symbols do not currently meet this paper's acceptance criteria but have at least eight sample cubes available for reanalysis or continued measurement (Table 5). The circle symbols represent data derived from the DuBois estate. Diamond symbols represent Wolfman data and the triangle symbols represent Eighmy data.

The effort directed at documenting these existing records is critically important because one of the unique aspects of this archive is that nearly all of the samples were collected from archaeological features that either no longer exist or are no longer accessible. Most archaeology today occurs when features are set to be destroyed by construction development projects and archaeology tends to be inherently destructive. In either case, the physical specimens within these archives are often the only surviving components of the archaeological and archaeomagnetic record.

These data represent the legacy of nearly 130 person-years of collective archaeomagnetic sampling and measurement, by DuBois, Wolfman, and Eighmy. This archive will serve as the foundation for continued archaeomagnetic research in North America and will enhance global magnetic field modeling efforts for decades to come. The data span a temporal and spatial completeness that is unprecedented in North America. Such high quality, temporally diverse, and globally distributed data are required for accurate time-varying global magnetic field models.

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Author contributions: SAJ initially compiled the physical datasets and digital archives, carried out the analyses, produced the figures, wrote the manuscript. EB provided access to the Wolfman and DuBois estates, provided archaeological context, and assisted in writing the manuscript. LT obtained funding for and helped design the project, assisted in the digital reformatting and figure production, and assisted in writing the manuscript. JRC manages the Wolfman scientific estate and helped collect and measure samples within the Wolfman archive. SL provided access to the Eighmy dataset, helped collect and measure samples within the Eighmy archive. RS instrumental in discussions by providing historical context, and helped collect and measure samples within the Eighmy archive. JE provided access to his unpublished data and edited the manuscript. DW collected and measured samples within his archive, proposing several initial VGP curves. RD collected and measured samples within his archive, proposing several initial VGP curves.

The data presented in this paper will be available at https://earthref.org/Magic/17115 upon publication of this article. For the purposes of review the data are available here: https://earthref.org/MagIC/17115/194b1e5c-27bc-41e4-bf53-c5f8bae5dd5f

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