frontiers in Earth Science

MINI REVIEW
published: 14 November 2017
doi: 10.3389/feart.2017.00092

Recent Advances in Chinese Archeomagnetism

Shuhui Cai[1, 2, 3]*, **Lisa Tauxe**[1], **Greig A. Paterson**[3, 4], **Chenglong Deng**[2, 3, 5], **Yongxin Pan**[3, 4, 5], **Huafeng Qin**[2, 3] **and Rixiang Zhu**[2, 3, 5]

[1] Scripps Institution of Oceanography, University of California, San Diego, San Diego, CA, United States, [2] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [3] Institutions of Earth Science, Chinese Academy of Sciences, Beijing, China, [4] Key Laboratory of the Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [5] University of Chinese Academy of Sciences, Beijing, China

The geomagnetic field is one of Earth's fundamental properties with a history of ∼3.5 Gyr. The field, generated in Earth's core is a window to the deep interior of Earth and may have played a key role in evolution of life on our planet. Materials on Earth's surface that contain magnetic minerals can record information about the geomagnetic field in which they formed. Fired archeological materials (e.g., pottery, brick, and burnt clay) are favorable recorders of the field, and have been widely employed to recover geomagnetic variations over periods of hundreds to thousands of years. The longevity of Chinese civilization and the abundant nature of archeological artifacts make Chinese archeomagnetism a promising source of data. The main work of Chinese archeomagnetism was carried out in the 1980s and 90s, followed by a break of more than a decade; in the 2010s activity resumed. In this paper, we review the development of Chinese archeomagnetism, including a summary of previous work, recent progress, remaining issues and future studies with the aim of promoting an understanding of archeomagnetic work in China and to guide the way for future studies. Here, we compile published data, including some data discovered in old publications that have not yet been included in paleomagnetic databases. We also establish the first, albeit preliminary, archeomagnetic reference curves (with 42 declination / inclination pairs and 76 / 192 archeointensities) for the geomagnetic field in China (ArchInt_China.1a / ArchInt_China.1b, ArchDec_China.1, ArchInc_China.1), which can be used for global comparison of the field and regional archeomagnetic dating.

Keywords: archeomagnetism, China, geomagnetic reference curves, the Holocene, archeomagnetic dating

INTRODUCTION

Fired archeological artifacts, such as pottery, brick, burnt clay, furnace fragments and metallurgical slags, are favorable materials for recording the evolution of the geomagnetic field, owing to their suitable magnetic characteristics as well as their abundance and relative temporal continuity. Archeomagnetism contributes greatly to recovering the secular variation of the geomagnetic field during the Holocene, which has applications for exploring the geodynamo in Earth's interior (Tarduno et al., 2015; Terra-Nova et al., 2016; Davies and Constable, 2017) and establishing various global models [e.g., the CALS series (Korte and Constable, 2011; Korte et al., 2011; Constable et al., 2016), ARCH3k.1 (Korte et al., 2009), ARCH10k.1 (Constable et al., 2016), pfm9k (Nilsson et al., 2014), and SHA.DIF.14k (Pavón-Carrasco et al., 2014)]. Archeomagnetic studies can also be used

OPEN ACCESS

Edited by:
*Joshua M. Feinberg,
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***Correspondence:**
*Shuhui Cai
shc252@ucsd.edu*

Specialty section:
*This article was submitted to
Geomagnetism and Paleomagnetism,
a section of the journal
Frontiers in Earth Science*

Received: *01 September 2017*
Accepted: *30 October 2017*
Published: *14 November 2017*

Citation:
*Cai S, Tauxe L, Paterson GA, Deng C, Pan Y, Qin H and Zhu R (2017) Recent Advances in Chinese Archeomagnetism.
Front. Earth Sci. 5:92.
doi: 10.3389/feart.2017.00092*

to solve archeological issues, such as dating an artifact by comparing its recorded geomagnetic intensity and/or direction to a local geomagnetic reference curve (Aitken, 1990; Pavón-Carrasco et al., 2011; Carrancho et al., 2017; Peters et al., 2017), or testing the synchronicity of archeological units by comparing the geomagnetic information extracted from them (Carrancho et al., 2016). Archeomagnetic studies even have potential applications for exploring the relationship between positions of virtual geomagnetic poles and historical records of aurorae (Liritzis, 1988).

Archeomagnetic studies originated in France (Folgerhaiter, 1899; Chevallier, 1925; Thellier, 1938; Thellier and Thellier, 1959), followed by studies from other countries, including Japan (Hirooka, 1971; Sakai and Hirooka, 1986), the U.K. (Aitken et al., 1981) and Bulgaria (Kovacheva, 1980). Recent archeomagnetic studies are mostly concentrated in Europe (Gallet et al., 2002; Gómez-Paccard et al., 2012; Tema et al., 2012; Genevey et al., 2013; Hervé et al., 2013a,b; Kovacheva et al., 2014) and the Middle East (Ertepinar et al., 2012, 2016; Gallet et al., 2015; Shaar et al., 2016; Ben-Yosef et al., 2017), with a few publications from other areas such as Mexico (Guerrero et al., 2016), Africa (Mitra et al., 2013; Tarduno et al., 2015; Kapper et al., 2017) and Asia (Yu et al., 2010; Hong et al., 2013; Venkatachalapathy et al., 2013). China constitutes a huge part of Eastern Asia and has a civilization that spans thousands of years leaving abundant archeological artifacts. Archeomagnetic studies in this region are essential and feasible. In this paper, to promote an understanding of current archeomagnetic studies in China and to help guide future work, we summarize the development of Chinese archeomagnetism and establish the first archeomagnetic reference curves of geomagnetic field variations in China.

ADVANCES OF CHINESE ARCHEOMAGNETISM

Archeomagnetic studies in China were first carried out in the 1960s by Deng and Li (1965), who retrieved a few paleointensity and inclination data points from the Beijing area. This was followed by a paper, with the by-line of Paleomagnetism Laboratory of the Institute of Geology, Chinese Academy of Sciences (named the author "IGCAS" hereafter), which reported a number of paleointensity results from the Jokhang Temple in Lhasa, Tibet (IGCAS, 1977). A great quantity of Chinese archeomagnetic studies were carried out in the 1980s by Wei et al. (1980, 1981, 1982, 1983, 1984, 1986, 1987) from the Institute of Geophysics, Chinese Academy of Sciences, which constitute the majority of archeomagnetic data in China. A few results were then published in the 1990s (Tang et al., 1991; Yang et al., 1993a,b; Shaw et al., 1995, 1999; Batt et al., 1998; Huang et al., 1998). After that, archeomagnetic studies in China ceased for ∼15 years before revival in the current decade (Cai et al., 2014, 2015, 2016, 2017).

The quality of the twentieth century Chinese archeomagnetic data, especially paleointensity data, is uneven and sometimes hard to assess, which is due to lack of modern experimental techniques and/or relaxed selection criteria. The descriptions of experimental techniques for the paleointensity publications are summarized in Table S1, including a range of Thellier-type thermal methods (Thellier and Thellier, 1959; Coe, 1967; Yu et al., 2004), the Shaw method (Shaw, 1974) as well as microwave based methods (Walton et al., 1993). We also summarize if the studies reported basic statistical descriptions (σ_B, the paleointensity standard deviation as a measure of the consistency of sister specimens); if authors conducted partial thermal remanent magnetization (pTRM) checks to monitor alteration during experimental heating (Coe et al., 1978); if they considered the effect of TRM anisotropy (Aitken et al., 1981, 1988), by either applying an anisotropy correction (Veitch et al., 1984) or aligning the laboratory field to the direction of natural remanent magnetization (NRM); if they considered the possible bias caused by cooling rate effects (Dodson and McClelland-Brown, 1980; Halgedahl et al., 1980) and carried out a cooling rate correction (Genevey and Gallet, 2002). The data published in the twentieth century either have no or only partial quality controls, making unambiguous estimation of their reliability difficult. In contrast, the data published in the current decade are obtained from more rigorous modern experimental techniques with stringent data selection and openly available measurement data; these should therefore be more robust.

Most of the published data from China are archived in the GEOMAGIA50.v3 database (http://geomagia.gfz-potsdam.de) (Brown et al., 2015) with the exception of data published by Deng and Li (1965); IGCAS (1977); Wei et al. (1980), and Yang et al. (1993a,b) and the recent work of Cai et al. (2014, 2015, 2016, 2017). The former three are absent from the database probably because they were originally published in Chinese. Yang et al. (1993a) did not include their data list in the paper. However, results from Shaw et al. (1999) were obtained from the same batch of samples as in Yang et al. (1993a), but with different experimental techniques. Data from Yang et al. (1993b) were left out for some unknown reason. The last four papers were published in or after 2014 and data therein have not been included in the GEOMAGIA50.v3 database yet, but are already in the MagIC database (https://www2.earthref.org/MagIC). In this paper, we collated the data from the publications not included in any database and listed them in Table S2 for the convenience of future work; these have also been uploaded into the MagIC database (https://earthref.org/MagIC/16283). The geographic locations of all published archeomagnetic data (both direction and intensity) are plotted in **Figure 1**.

COMPILATION OF PUBLISHED ARCHEOMAGNETIC DATA FROM CHINA

The archeointensity data published in recent years by Cai et al. (2014, 2015, 2017) were selected with different criteria, making the data quality inconsistent. In this paper, we combined all the measurement data from each paper and reanalyzed the data with the "Thellier Auto Interpreter" function incorporated in the Thellier GUI software (Shaar and Tauxe, 2013) included in the PmagPy software package (Tauxe et al., 2016). The strict selection criteria suggested by Cromwell et al. (2015) and named "CCRIT"

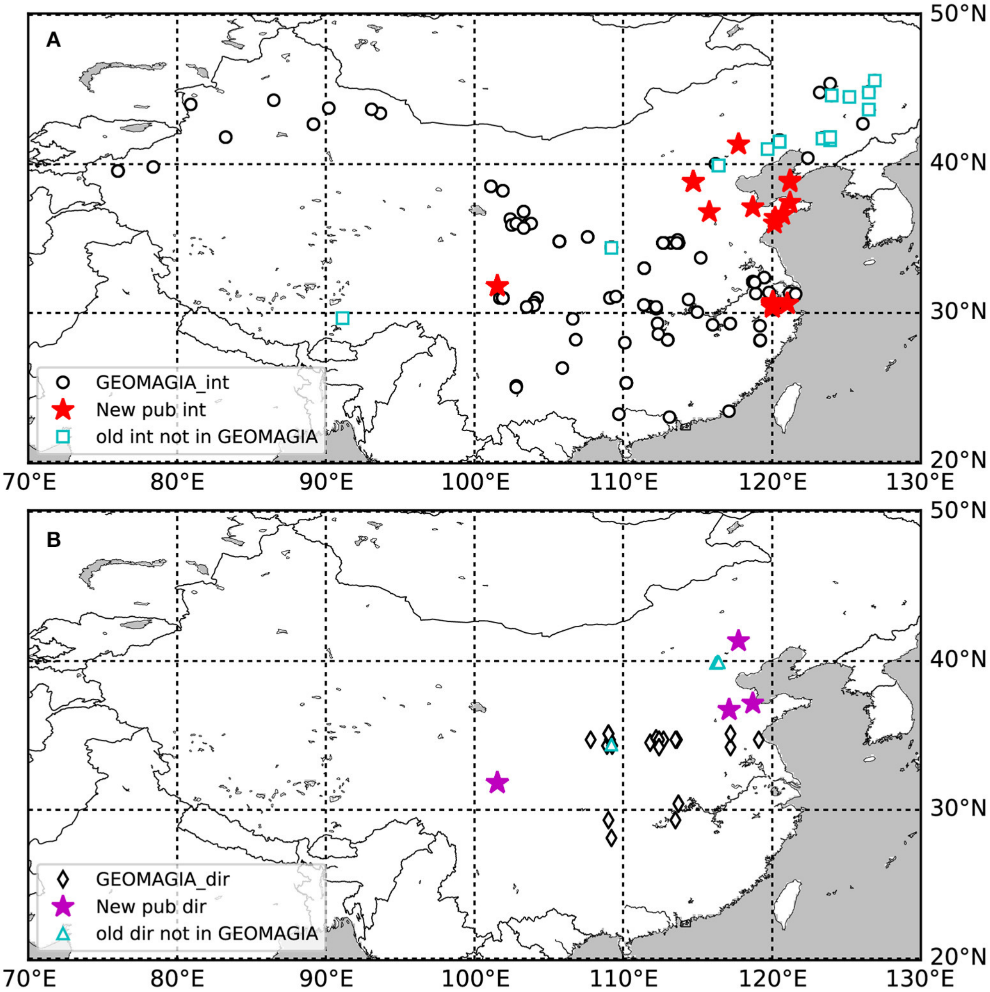

FIGURE 1 | Sitemap of all the published archeointensity **(A)** and archeodirection **(B)** data in China. "GEOMAGIA_int" and "GEOMAGIA_dir" represent locations of published archeointensity and archeodirection data from the GEOMAGIA50.v3 database. "New_pub int" and "New_pub dir" represent locations of archeointensity and archeodirection data published in the recent years (Cai et al., 2014, 2015, 2016, 2017). "old int not in GEOMAGIA" and "old dir not in GEOMAGIA" represent locations of archeointensity and archeodirection data published in the twentieth century but not included in the GEOMAGIA database (Deng and Li, 1965; IGCAS, 1977; Wei et al., 1980; Yang et al., 1993b).

by Tauxe et al. (2016) were adopted. These criteria are established based on paleointensity study on modern lava flows in Hawaii where the historical field can be reproduced with reasonable accuracy (Cromwell et al., 2015). The parameters of CCRIT are listed in Table S3. The definition of each parameter is described in Cromwell et al. (2015) while the detailed explanation can be found in Shaar and Tauxe (2013) and Paterson et al. (2014) and references therein. We only provide a brief reminder of each statistics here: β is the normalized standard deviation of the slope of selected data points; *DANG* is the angle of the best-fit line deviated from the origin; MAD_{free} is the unanchored maximum angular deviation of selected NRM data points; *FRAC* is the fraction of remanence used for calculating the paleointensity; *SCAT* is a Boolean that defines the allowed degree of scatter of the selected data points (including pTRM checks); $|\overrightarrow{k'}|$ is the absolute value of curvature of the data points used for determining the best-fit line (Paterson, 2011; Paterson et al., 2015); *Gap Max* is the maximum length of the normalized vector differences between consecutive NRM steps along the chosen segment; N_{min} is the minimum number of accepted specimens; σ is the one-sigma standard deviation of site-mean intensity. The new results reanalyzed with CCRIT are listed in Table S4 (sample means) and Table S5 (specimen results with statistic values). The reanalyzed paleointensity data (Int_new pub) as well as the data published in the twentieth century are plotted in **Figure 2A**. We calculated two Chinese archeointensity reference curves of the geomagnetic field: one (ArchInt_China.1a) with only the reanalyzed data published in the 2010s (76 in total), assuring equal quality of data used for calculating the reference curve; the other (ArchInt_China.1b) with both the reanalyzed data and selected old data published in the twentieth century (192 in total). Since limited statistic parameters were reported

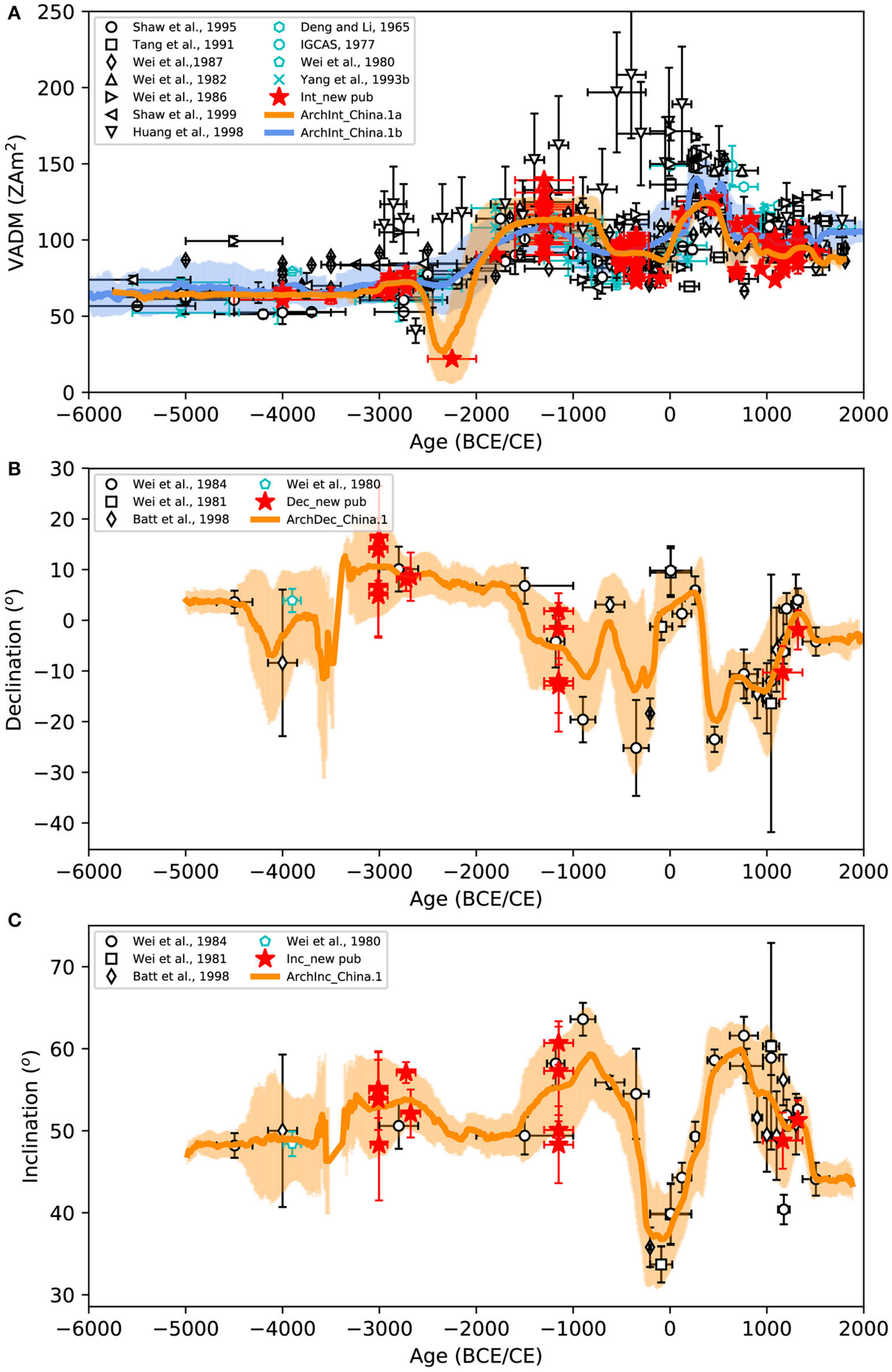

FIGURE 2 | Compilations of Chinese archeomagnetic data: **(A)** Virtual Axial Dipole Moment (VADM), **(B)** declination and **(C)** inclination. "Int_new pub" represents reanalyzed archeointensity data published by Cai et al. (2014, 2015, 2017). "Dec_new pub" and "Inc_new pub" represent directional data published by Cai et al. (2016). The shaded area of each curve represents the one standard deviation coverage interval. All the directional data were relocated to the center of China (35°N, 105°lE).

in the old publications (Table S1), we can only use the most general selection criteria when selecting the old data. Only those data with age sigma less than 500 yr and standard deviation of the intensity less than 4 μT or 10% (the same requirement for sample mean as in CCRIT) were included. The reference curve was calculated with a parametric bootstrap and running average technique, following Cai et al. (2017) and Gallet et al. (2015). The procedure is: resample 1,000 times at each data point considering uncertainties of both age and virtual axial dipole moment (VADM) and then calculate the running average of the new dataset with a time window of 200 y shifted by 10 y (only time intervals including more than three data points were calculated). The one-sigma standard deviation (orange / light blue shadow in **Figure 2A**) is calculated as well. ArchInt_China.1b is generally similar to ArchInt_China.1a except for two obvious differences: 1) ArchInt_China.1b smooths out the field low at ∼2200 BCE in ArchInt_China.1a; and 2) ArchInt_China.1b is higher than ArchInt_China.1a between ∼100–600 CE because of high intensity data published by Wei et al. (1982, 1986). Special attention should be paid to these two time periods in the future work to resolve the source of these differences.

The published directional data in China are plotted in **Figures 2B,C**. Only data with both declination and inclination are included. In order to reduce the difference caused by locations, we relocated all the directional data to the center of China (35°N, 105°E) using the VGP relocation method (Noel and Batt, 1990): first, calculate the VGP with declination, inclination, site latitude and longitude; and then calculate the declination and inclination at the relocated location from the VGP assuming a dipolar field. All the new and old published data and the relocated data are presented in Cai et al. (2016). The directional data are scarce because *in-situ* materials are less likely to be preserved. The experimental techniques and influence factors of determining geomagnetic directions are less complicated than those of paleointensities, meaning that directional data are less prone to suffer from large biases away from the correct value. Actually, all the 95% confidence intervals (α_{95}s) of the old published data are less than 10°, except one is 12.6°. Therefore, we calculated the preliminary Chinese archeodirection reference curves of the geomagnetic field (ArchDec_China.1 and ArchInc_China.1) with all the published data (42 declination / inclination pairs in total). The reference curves were calculated using the same technique as used for calculating the archeointensity reference curve. The running average data for all four reference curves are attached in Table S6.

We also calculated reference curves for adjacent areas of Japan and Korea using the same technique above (Figure S1). The Japanese reference curves were calculated with data from GEOMAGIA50.v3. The intensity data were selected with the same criteria as for the old published intensity data in China while for directional data only those with α_{95} less than 10° were included. Since there are only two directional data points between 6000 BC and 400 CE after selection, the Japanese directional reference curves start from 400 CE. The Korean intensity / directional curves were calculated with data from Hong et al. (2013) and Yu et al. (2010). The Korean intensity curve and predictions at the center of China (35°N, 105°E) of global models [pfm9k.1a (Nilsson et al., 2014) and ARCH10k.1 (Constable et al., 2016)] are generally consistent with our new archeointensity curves except certain time periods, for example, the extremely low intensity at ∼2,200 BCE (Figure S1). The Japanese intensity curve agrees well with our new curve before ∼2,800 BCE and after ∼100 CE but deviates from our curve between them. The directional data are too sparse to discuss the consistency among different models before ∼1,100 BCE. After then the global models are consistent well with our new reference curves because they all mainly rely on the present published data (Figure S1A). Both the Japanese declination and inclination curves agree well with our new curves and the global models. However, the Korean declination curve fits our curve between ∼1,100 BCE and ∼500 CE but departs from our curve after then while the inclination curve deviates far away from the Chinese curve most of the time except after ∼1,200 CE (Figures S1B,C). The difference between 500 and 1,000 CE is probably caused by the absence of Korean data during that period. Discrepancies during other time periods can either due to geomagnetic local field anomalies or lack of robust data from both areas.

Our new archeomagnetic reference curves are preliminary due to the lack of a large number of robust data, for example, the paucity of paleointensity data at certain times (i.e., before ∼1,300 BCE, ∼1,000 BCE-500 BCE, 1 CE-500 CE) and the overall scarcity of directional data. More high-quality data are required in the future to enhance the precision and resolution of the reference curves and to promote global comparison.

CURRENT ISSUES AND THE FUTURE OF CHINESE ARCHEOMAGNETISM

The Chinese archeointensity data published during the twentieth century are scattered because of a lack of modern experimental techniques and/or relaxed selection criteria—their reliability is difficult to assess. The data published in recent years have a higher precision, but are insufficient in both space and time to define a robust reference curve. Most of the data are from Eastern China and data from other regions are lacking (**Figure 1A**). Similarly, data from certain time periods (e.g., before ∼1,300 BCE, ∼1,000 BCE-500 BCE, 1 CE-500 CE) are sparse (**Figure 2A**). The directional data from China, especially those with full directions (both declination and inclination) are quite rare (**Figures 2B,C**) because of the difficulty of preserving *in-situ* materials since they were fired. Data with full vector information (both direction and paleointensity) of the field are certainly more deficient. Furthermore, dating of the published data mainly relies on archeological context and the age resolution of some data is a limiting factor (e.g., data around 1,300 ± 300 BCE in **Figure 2A**).

Filling these spatial and temporal data gaps is a frontier for Chinese archeomagnetism. Future workers should carefully focus on obtaining more high-quality data. Considering the sparseness of directional data, special attention should be paid to collecting more oriented *in-situ* materials. Fortunately, relics as kilns or hearths are not rare and a number of them have not been moved since they were fired last. All we need to do is cooperating with the archeologists and collecting oriented samples from these sites before they were destroyed. The enhancement of data quality must include two aspects: (1) increasing the data precision by adopting modern experimental techniques and stringent selection criteria and (2) reinforcing age constraints by combining multiple dating techniques (e.g., archeological context, radiocarbon dating and stratigraphic information)—for example, dating techniques adopted in Cai et al. (2016). We also strongly encourage the deposition of original measurement data (both inside and outside China) in an accessible database such as MagIC. This can allow older datasets to be carefully reassessed and avoids the blanket rejection of older data.

With the accumulation of new reliable data, the Chinese archeomagnetic reference curves can be updated and become a more precise tool for archeological and Earth scientists. To achieve these ambitious goals, more attention should be paid to enhancing the cooperation between paleomagnetists and archeologists. For example, archeologists can assist paleomagnetists in collecting abundant excellent samples while paleomagnetists can lend their expertise in archeological applications (e.g., estimating firing temperature of artifacts, testing the synchronicity of various archeological units, determining if artifacts from an archeological unit are *in-situ*, among others).

SUMMARY

Archeomagnetic research is one of the most efficient methods to explore the detailed secular variation of the geomagnetic field during the Holocene and has applications to geodynamics, global modeling, establishing regional reference curves, archeomagnetic dating and other archeological and Earth science issues. In this paper, we have outlined the current state of archeomagnetic studies in China and the future challenges that this discipline faces—namely a scarcity of high quality data measured with modern standard of reliability. Nevertheless, by reanalyzing the most recently acquired datasets, we provide a number of consistent high-precision archeointensity data from China. We have established the first, albeit preliminary, Chinese archeomagnetic reference curves (ArchInt_China.1a / ArchInt_China.1b, ArchDec_China.1, ArchInc_China.1). These can be used for regional geomagnetic comparison and archeomagnetic dating and form a basis on which future studies can expand by targeting time periods and regions that are currently underrepresented. Future work that focuses on filling these spatial and temporal gaps should make great efforts to obtain more high-quality (both high data precision and well age constraints) data, which can be achieved by enhancing the cooperation between paleomagnetists and archeologists to the benefit of both communities.

AUTHOR CONTRIBUTIONS

SC, LT, and GP wrote the paper; RZ, CD, YP, and HQ helped designing research and sampling as well as revising the paper.

FUNDING

This work was supported by the NSFC grants 41504052, 41621004, 41374072 and L1524016, the CAS priority project XDB18010203. LT acknowledges support from NSF Grants No. EAR1520674 and EAR1547263.

ACKNOWLEDGMENTS

We thank all the archeologists we have worked with (Guiyun Jin, Jianming Zheng, Xuexiang Chen, Fei Xie, Wei Chen) for providing the samples.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2017.00092/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.