INITIAL REFERENCE CURVE OF THE GEOMAGNETIC FIELD INTENSITY IN WEST AFRICA COVERING THE AGE INTERVAL BETWEEN 0-2000 AD

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ABSTRACT

We present first absolute geomagnetic field intensities from iron smelting furnaces located at the metallurgical sites of Doumbala and Siola (Ivory Coast), together with new archeointensities results from Korsimoro (Burkina Faso). In order to obtain intensities, we applied the classic Thellier-Coe double-heating and the calibrated Pseudothellier method that has never before been applied to archeological artifacts. Radiocarbon ages confine samples to a time range between 700-1900 AD. In order to obtain a preliminary reference curve for West Africa, these new intensities were combined with data from the Geomagia50.v3 archeomagnetic database for the past 2000 years and other data not included in this database. The data cover a circular area with a radius of 2500 km around a central relocation point (19.15º N, 4.26º E). In an initial attempt, a cubic smoothing spline fit was obtained. An intensity maximum at around 750 AD coincides with a maximum in a West European reference curve. Furthermore, we observe a general decrease of intensity during the past 2000 years.

Keywords: West Africa, paleosecular variation curve, archeointensity, geomagnetic field.

RESUMEN

Presentamos las primeros datos de las intensidades geomagnéticas absolutas a partir de hornos de fundición de hierro situados en los sitios metalúrgicos de Doumbala y Siola (Costa de Marfil), junto con nuevos resultados de sitio Korsimoro (Burkina Faso). Para obtener intensidades se aplicaron el método clásico de doble calentamiento de Thellier-Coe y el método calibrado de Pseudothellier que nunca antes se había aplicado a los artefactos arqueológicos. Las edades de radiocarbono confinan las muestras a cubrir un intervalo de tiempo de 700-1900 DC. Con el fin de obtener una curva de referencia preliminar para África Occidental, estas nuevas intensidades se combinaron con datos de la base de datos arqueológica Geomagia50.v3 de los últimos 2000 años y otros datos no incluidos en esta base de datos. Los datos cubren un área circular con un radio de 2500 km alrededor de un punto central de reubicación (19.15º N, 4.26º E). En un intento inicial, se obtuvo un ajuste de splines cúbicos suavizado. Una intensidad máxima de alrededor de 750 DC coincide con un máximo en una curva de referencia de Europa Occidental. Además, observamos una disminución general de intensidad durante los últimos 2000 años.

Palabras Clave: África del Oeste, curva de variación secular, arqueointensidad, campo geomagnético.

1. Introduction

Archeological artifacts, (*e.g.*, ceramics, bricks, ovens, or furnaces) are reliable recorders of the geomagnetic intensity and direction at the time of the last cooling from temperatures exceeding about 580º C. Obtaining archeointensities is, compared to archeodirections, a rather difficult task due to complex mineralogy in the samples, non-ideal carrier of the magnetic signal and measurement protocols that often include multiple heating steps. The most accepted and reliable method to determine archeointensities is the Thellier-Thellier family of experiments, in which samples are heated stepwisely up to about 600º C (Thellier, Thellier, 1959). The advantage of these types of experiments is that they include several quality checks for chemical alteration during the experiment and detection of non-ideal magnetic carriers. The disadvantage is that the multiple heating steps, sometimes up to 50, can lead to chemical alteration of the mineralogy and hence, the original magnetic signal is lost. Therefore, several non-heating methods have been introduced. One of these methods, the Pseudothellier method, has never been applied before to archeological artifacts, but to volcanic rocks (*e.g.*, de Groot *et al.*, 2013). In this method, an anhysteretic remanent magnetization (ARM) is applied to the the samples. The stepwise demagnetization behavior of the ARM is compared to the natural remnant magnetization (NRM) in order to obtain the ancient intensity.

To obtain regional paleosecular variation curves (PSVCs) of the geomagnetic field variation, samples need to be dated. These curves cover an area not larger than 1000 km in radius, in general, and help understanding regional geomagnetic field variation. One of the most important application of these curves is archeomagnetic dating, which is an alternative dating method where radiocarbon or thermoluminescence dating is not possible or or does not lead to satisfying results.

Global or regional geomagnetic field models are mainly based on intensity and directional data from lacustrine and marine sediments, followed by archeological artifacts and data from lavas (*e.g.*, Donadini *et al*., 2009). Although abundant, and yielding continuous records of the geomagnetic field, sediments provide only relative intensities due to the type of remanent magnetization they obtain. Furthermore, they lead to rather smooth models and reference curves because their magnetic signal is smoothed. Hence, archeological artifacts that can provide absolute intensities are a valuable alternative. However, the majority of all available data is located in the Northern hemisphere and mainly in Europe (*e.g.*, Brown *et al.*, 2015). Recently, several local features of the geomagnetic field, *e.g.*, intensity spikes at around 1000 BC and 700 BC in the Levantine (*e.g.*, Shaar *et al.*, 2016), or a strong geomagnetic field intensity in Western Europe at around 800 AD (*e.g.*, Gómez-Paccard *et al.*, 2016), have been observed. Due to the lack of data it is not clear if these features are of local or global nature.

2. Motivation

Africa is a large continent with very little data available. In the largest database for archeological artifacts and volcanic data from the past 50 000 years, the Geomagia50.v3 database (Brown *et al.*, 2015), are currently only 46 intensity data available for Africa and for the past 2000 years. Africa is of great interest for investigating the geomagnetic field in the past because an important geomagnetic field feature, the South Atlantic Anomaly (SAA), has probably been located over Africa about 1000 years ago, and subsequently moved westward to South America, into its current position (*e.g.*, Pávon-Carrasco, de Santis, 2016). The SAA, an area of very low field intensity, has been brought into connection with an upcoming reversal of the geomagnetic field. However, geomagnetic field models reconstructing this anomaly rely mainly on data from Europe, which makes the need for reliable data from Africa clear. A recent investigation of archeomagnetic data from South Africa suggests an onset of the SAA at around 1250 AD (Tarduno *et al.*, 2015).

In this study, we present new archeointensity data from West Africa obtained with the absolute Thellier-Coe (Thellier, Thellier, 1959; Coe *et al.*, 1978) and the relative Pseudothellier method (*e.g.*, de Groot *et al.*, 2013). By combining these new promising data with the existing database we aim to construct the first intensity reference curve for West Africa. Furthermore, we intend to incorporate the new data in global geomagnetic field models in order to investigate their impact on these models, and finally, to obtain clues about the SAA between 0 – 2000 AD.

3. Sites, samples and methods

Samples of iron furnaces were taken from three sites that are located in two West African countries: in Burkina Faso (BF), and Ivory Coast (IC) (Fig. 1). Korsimoro (12.79ºN, 1.09º W, BF) covers a time range of 700-1700 AD, Siola (9.86ºN, 7.45ºW, IC) covers 1020-1900 AD, and Doumbala (9.88º N, 7.41º W, IC) 1350-1900 AD. All samples are related to radiocarbon ages, or their age is determined from the archeological context by determining the characteristics of the furnaces. Preceding rock magnetic measurements were performed to determine the ferromagnetic (*s.l.*) carriers of the magnetic signal, their grain sizes and the stability of the remanent magnetization. These measurements include determination of thermomagnetic curves, hysteresis loops, and backfield and isothermal remanent magnetization curves. Directional pilot measurements were performed on at least one specimen per furnace.

To determine the archeointensities, the Thellier-Coe experiment was applied on 54 specimens. Specimens were heated in 15 steps to 620ºC. After each second new temperature step a pTRM-check and a tail-check

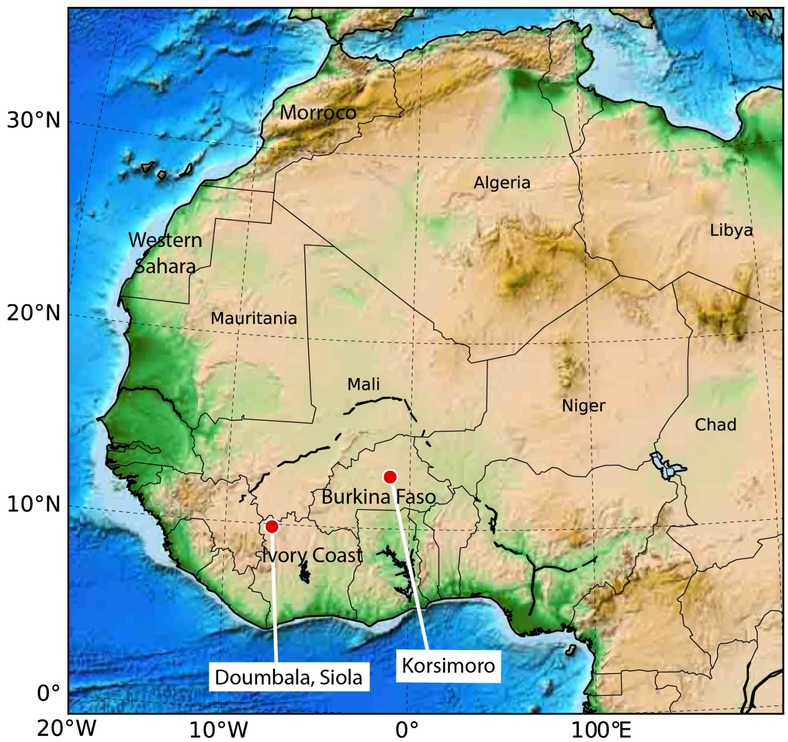

Figura 1. Map of West Africa that shows the sampling locations Doumbala, Siola and Korsimoro.

were performed. Cooling rate experiments were performed at 480º C and 550º C. The anisotropy correction was performed implicitly by obtaining six specimens that are oriented along the axes +x, -x, +y, -y, +z, -z. This way, possible influence of anisotropy is averaged out. However, from a previous study on iron furnace samples from Korsimoro, the anisotropy correction was found to be on average 1.6 ± 1.5 %, in general, and was therefore considered negligible (Kapper *et al.*, 2017). Then, archeointensities were determined with the Pseudothellier protocol on 31 specimens. In this method the NRM first gets demagnetized with alternating fields (AF) in up to fields of 300 mT. Then an ARM was applied with the same steps. And finally, the ARM was AF demagnetized with the same steps. The relative archeointensity is determined from the slope between NRM lost and ARM gained at each temperature step. The calibration relation is obtained from the GUFM1 (Jackson *et al.*, 2000) and IGRF (Thebault *et al.*, 2015) models for the recent time and archeointensity data for older time periods.

4. Results

Rock magnetic results show magnetite as main carrier of the magnetic signal, with some hematite in some specimens. Many specimens have reversible or nearly reversible thermomagnetic curves indicating a stable magnetization and optimum prerequisite for Thellier-Thellier experiments. TH and AF demagnetization of Doumbala and Korsimoro specimens show in most cases a characteristic remanent magnetization and a small viscous component.

To obtain the most reliable archeointensities in the Thellier-Coe experiment the following selection criteria were applied, adapted from Shaar, Tauxe (2013): the ratio of the standard error of the slope to the absolute value of the slope, $\beta \leq 0.08$; the fraction of remanence, FRAC ≥ 0.6; scatter parameter, SCAT = TRUE; the maximum angular deviation, MAD ≤ 5º; the deviation of the angle, as to ensure that the characteristic component was chosen, DANG ≤ 5º; the gap factor, GAP_MAX ≤ 0.6 on specimen level; and the standard deviation $\sigma_{Ba} \leq 5$ µT and 10 % on sample level. For the Pseudothellier experiment we selected only specimens that fall within the grain size parameter range of $23 < B_{1/2} < 63$ mT (de Groot *et al.*, 2013). Out of 88 measured specimens 23 were accepted.

In order to establish a first reference curve for West Africa data were chosen from the Geomagia50.v3 database from within a radius of about 2500 km around a central relocation point at 19.15ºN and 4.26ºE. Data were selected based on the following selection criteria: $\sigma_{Ba} \leq 10$ µT and $\sigma_{Age} \leq 80$ years. Data that is not in the database have been taken into account as well, e.g., data from the Canary Islands (*e.g.*, de Groot *et al.*, 2015). Data from this study obtained from the Pseudothellier method have only been accepted if the standard deviation of the two methods of a specific furnace satisfy $\sigma_{Ba} \leq 10$ µT. The relocation error for all data from the radius is < 2.5 µT and was added to σ_{Ba} in order to weight data that is further away less and *vice versa*. Several methods to obtain the PSVC were tested. As a preliminary test a cubic smoothing spline fit was applied to the data in order to identify the major field features (Fig. 2).

5. Discussion

Rock magnetic results indicate that the iron furnace samples are a suitable material for archeointensity determinations. This is supported by the linear demagnetization vector diagrams. The data selection is rather strict compared to other publications and reveals two major time periods: (1) the period between 100-

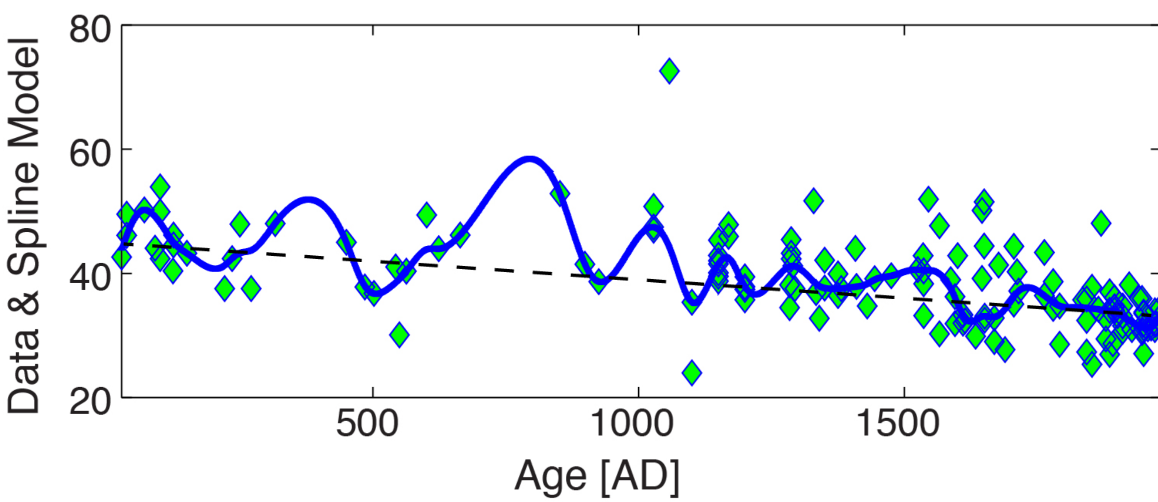

Figura 2. Preliminary smoothing spline fit (blue) of the data (green diamonds). The black dashed line indicates the general intensity decay.

1100 AD with sparse data and peaks in the spline fit that are weakly defined, *e.g.*, at around 400 AD and 800 AD; and (2) the period between 1200-2000 AD with abundant data. However, data from the second period have a rather large spread that leads to a very smooth curve. The curve reveals the most pronounced intensity maximum at around 750 AD and a subsequent field intensity decay until 900 AD, agreeing with an intensity high at around 800 AD in Western Europe (Gómez-Paccard *et al.*, 2016). The general trend of the geomagnetic field intensity within the past 2000 years is decreasing, which coincides with the growing trend of the SAA area extent during the past 200 years (Pavón-Carrasco, De Santis, 2016; Fig. 2).

6. Conclusion and ongoing work

We first explored the smoothing spline fit in order to obtain an interpolation curve between the data points. The penalized smoothing spline fit involves minimization of the L_2 misfit to the data and a smoothness measure taken to be the quadratic norm of the second time derivative. The smoothing parameter that controls the trade off between the smoothness and the data fit is chosen objectively using a cross validation method. The smoothing time, obtained as an output result from the spline fit analysis, shows that the time scale we can resolve with this dataset (*i.e.*, the time resolution) is 40 years. However, this smoothing spline fit does not take into account the uncertainties in age and intensity. Therefore, we are considering other methods to construct the PSVC, *e.g.*, a smoothing spline fit that weights the data according to their errors in age and intensity, as well as combination of errors including the relocation error. Another method that we plan to investigate for obtaining the PSVC is the stochastic modeling approach (Hellio *et al.*, 2014). At the end, the most stable and reliable curve will be selected to represent the geomagnetic secular variation in West Africa for the past two millennia.

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