A first regional model of the past Earth's magnetic field from Africa for the last 4,000 years

Di Chiara, Anita[1,2]; Pavón- Carrasco, F. Javier[3]

[1]Istituto Nazionale di Geofisica e Vulcanologia, INGV, via di Vigna Murata 605, 00143, Roma (Italy)
[2]Scripps Institution of Oceanography, La Jolla, (CA, USA)
[3]Department of Earth Physics and Astrophysics. U. Complutense de Madrid, 28040 – Madrid (Spain)

Key Points:

- Using a set of FAIR principles, a robust dataset is selected with paleomagnetic data from archaeologic and volcanic sites from Africa
- We present a first regional geomagnetic model for Africa for the last 4000 years
- The new model shows the evolution of the South Atlantic Anomaly and serves as an archaeomagnetic dating tool

Corresponding author: Anita Di Chiara, dichiaraanita@gmail.com

Abstract

The understanding of the Earth's magnetic field variations over time on the African continent is fundamental for several reasons. For instance, the most important feature of the present geomagnetic field, the South Atlantic Anomaly (SAA) characterized by weaker geomagnetic strength values than those expected for their latitudes, may have emerged in South Africa at the beginning of the second millennium AD. Here, we first selected the available volcanic and archaeomagnetic data following a set of three criteria inspired by the FAIR principles. We then built a first regional geomagnetic model for Africa covering the last 4000 years, using a revised version of the spherical cap harmonic (SCH) analysis in 2 dimensions. The new regional model shows, at the Earth's surface, the westward migration of the SAA from the Indian Ocean over Africa since 1100 AD. In addition, the regional model is tested as a paleomagnetic dating tool

by re-dating previous archaeomagnetic data from Africa and thus can be used to date other African archeological sites and the numerous active and dormant volcanoes of the East African System.

Plain Language Summary

The spatial and temporal evolution of the Earth's magnetic (geomagnetic) field is based on direct historical or instrumental data and the indirect information extracted from rocks and archeological artifacts (palaeo- and archaeomagnetic data). While the present field is well sampled at both spatial and temporal domains, this is not the case for the past evolution of the geomagnetic field, where the paleomagnetic data are not globally distributed. There are large areas in the Southern Hemisphere yet to be investigated. However, recent data from Africa enables us the building of the first regional geomagnetic model for the last 4000 years. The new regional model sheds light on the past evolution of the most remarkable feature of the present geomagnetic field, the South Atlantic Anomaly (SAA), showing details of the westward migration of the SAA from the Indian Ocean over Africa since 1100 AD. Moreover, the new model refines the use of paleomagnetism as a dating tool for volcanic units from East African Rift System and for the abundant African archeological sites improving the knowledge of the history of human civilizations.

1. Introduction

Direct measurements of the Earth's magnetic (geomagnetic) field are mostly limited to the last 400 years (Jackson et al., 2000; Jonkers et al., 2003; Figure 1a), and before that, only indirect measurements are available through paleomagnetic studies carried out on volcanic or sediment rocks and archaeological artifacts. Although the models of the present geomagnetic field take advantage of the good spatial and temporal global distribution of the instrumental data (for instance from ground observatories or satellite missions) this is not the case for the past indirect measurements. So far, data collections (e.g., GEOMAGIA50) covering the Holocene from the Southern latitudes are limited; they make up only 6% of the dataset derived from sediment cores (Brown et al., 2015a), and 4% of the entire dataset based on volcanic and archaeomagnetic data (Brown et al., 2015b, 2021).

Despite this bias, global paleomagnetic reconstructions (e.g., Panovska et al., 2019, and references therein) have provided a general view of the past field changes in this region. However, due to the limited dataset covering the Southern hemisphere, questions about general and local characterizations of the paleofield remain open. This is the case for the most remarkable feature of the modern geomagnetic field, the so-called South Atlantic Anomaly (SAA): a region where the field strength is about 35% lower than expected from a dipole field at those latitudes. The SAA, well constrained after the first direct intensity measurements around 1833 (Gauss, 1837), is characterized by a westward drift for the last two centuries moving from Africa to South America (Hartmann & Pacca, 2009; Pavón-Carrasco & De Santis, 2016). At present, the SAA covers almost a major part of South America, Southeast Pacific, and South Atlantic oceans. In order to understand the past evolution of the SAA, paleomagnetic data from the Southern hemisphere are crucial. Based on those indirect measurements, the SAA has been located in central-southern Africa during the first half of the second millennium AD (Tarduno et al., 2015; Hare et al., 2018; Campuzano et al., 2019). Other works (Shah et al., 2016; Trindade et al., 2018; Engbers et al., 2020) suggested the persistency of the SAA at geological timescales in the South Atlantic region.

In this context, data from the African continent play an important role to understand the past evolution of the SAA. Thanks to recent paleomagnetic studies, Africa s.l. (sensu latu, including near surrounding oceans and archipelagos; hereby referred as Africa) can now be characterized by a greater database for the last 4 kyrs (Di Chiara, 2019; Kapper et al., 2020), while it remains sparse for older ages. In this study, taking advantage of the present database, we reconstruct a first regional geomagnetic field model for the last 4000 yrs for Africa. The aim is to refine our understanding of paleomagnetic field behavior and features (such as the SAA) in this continent. Moreover, the African regional model can be used as a tool for dating, for the several active large volcanoes of East African Rift System, a 3000-km long rift system from the Afar depression in the North to Lake Malawi in the South (Chorowicz, 2005). In this regard, the regional model will also help to untangle the history of human civilization and migrations in Africa during the Holocene by dating archaeological sites (Haber et al., 2016).

2. Methods

2.1 African paleomagnetic dataset

The Holocene African dataset is made up by 48 studies (see Figure S1 and Table S1 of the Supporting Information, SI), 44 of which are discussed in a recent review by Di Chiara (2019), with four studies published more recently (Kapper et al., 2020; Nami et al., 2020; Lund et al., 2020; Madingou et al., 2020). 62.5% of the data are from northern Africa (from 35°N to 12°N), 23% from central Africa (12°N to 10°S) and 14.5% from southern Africa (10°S to 34°S). In terms of the type of data, the dataset contains (see Table S1):

- Data from volcanic units. They represent 23% of the available studies, among which nine from lava flows emplaced in the Canary Islands (Table S1), one in Kenya (Skinner et al., 1975) and at the Mt. Cameroon (Herrero-Bervera et al., 2004).
- Data from archaeological materials. Twenty-five studies are available for entire Africa (Table S1). 64% of the data (from 16 studies) are from Northern Africa, 16% (from 4 studies) are from Central Africa and 20% from Southern Africa (from 5 studies).
- Data from lacustrine and marine sediments. Twelve studies present 13 PSV curves, one from the off-shore of Morocco, two from South Africa and the remaining 10 from Central Africa.

In this study, we rank the available African paleomagnetic data following the FAIR data principles (Wilkinson et al., 2016), i.e., Findability, Accessibility, Interoperability and Reusability. Thereby, we identify three criteria to select a robust dataset: AGE (A): the data used for age determination need to be reported and made available for recalibration. DATA (D): original data need to be available into an accessible online dataset (e.g., MagIC, https://www2.earthref.org/MagIC, or GEOMAGIA databases) or made available upon request, ensuring the possibility to select and/or reinterpret the original data (which can only be performed when the measurement data are uploaded into MagIC database or made available upon request) using a consistent approach. The DATA criterion is defined here for the first time but implicitly used in Di Chiara et al. (2021a; 2021b). In Di Chiara et al. (2021a) all data available in MagIC from the

Cretaceous Normal Superchron period were re-analysed using the same consistent set of criteria (CCRIT; Cromwell et al., 2015), obtaining lower and less dispersed values. In Di Chiara et al. (2021b) all the GEOMAGIA data for the Levant region were filtered out using the same set of D, A, and M, criteria and about 21% of the initial dataset was not deemed reliable. Unfortunately, due to the very limited amount of data available in their measurement-level original format, we could not apply the reinterpretation of the data in this study. METHOD (M): this criterion is mainly based on both the laboratory protocol which needs to be referred to and statistical approaches involved in the archaeointensity measurement, which also need to be discussed. Here, we chose the laboratory protocols based on the Thellier methods (Thellier and Thellier 1959; and subsequent variations) since they are the most widely adopted, to favor the consistency of the data. Since very few datasets are available on the MagIC database to allow for the data reinterpretation, we ranked the data for the M criterion according to a standard deviation σ_F <10 μT to estimate site mean intensities, together with the requirement of a reported anisotropy and cooling rate corrections for archaeomagnetic data; for ranking the mean directions, we imposed the confidence angle α_{95} <15°. Following previous studies (e.g., Osete et al., 2020; Di Chiara et al., 2021b), we establish a minimum threshold in the number of (independently oriented) samples equal to 3 both for paleointensity and directional data (Table S1).

After comparing all African sedimentary data with archaeomagnetic and volcanic data combined, we found little or no agreement between records probably due to a smoothed trend and large age inaccuracy. Therefore, we opted not to include the sedimentary data in our regional model at this stage. In addition, some data from outside Africa and within our targeted area were included in the model (i.e., data from Spain, Italy, Greece, and Israel) to better constrain the past geomagnetic field in the north edge of the selected spherical cap region. All these European data are extracted from the Supporting Information of Pavón-Carrasco et al. (2021) where a complete European database (based on GEOMAGIA 50) is provided. The European data were also classified according to the previous description about the data selection and weighting scheme. After ranking the archaeomagnetic and volcanic database, we follow the procedure detailed in Campuzano et al. (2019) and Pavón-Carrasco et al. (2021) for field modelling. That is, to weight the data that satisfy the previous criteria 10 times more than the rest of the data (where a weight equal to 1 is assumed).

Considering all the volcanic and archaeomagnetic sites together within the selected spherical cap region (see Figure 1 for their spatial and temporal distributions), we have 553 declinations (527 of them satisfy the previous criteria), 581 inclinations (545), and 982 archaeointensities (329). As expected, the selection criteria strongly affect the archeointensity data, reducing the initial number of these data by two-thirds. From the complete database, 25% and 35% correspond to directional and intensity data, respectively, coming from Africa (we obtain similar percentages when considering the African data that satisfy the selection criteria). It is worth noting that the number of data coming from Africa is low in contrast with the number of the selected South European data (see Figure 1). The chosen European data are located in a small region in the north-boundary of the spherical target region and the role of those data will be to constrain the longest spatial wavelength of our model (i.e., the dipole field). The relatively small number of African data will allow to have a more spatial variability within the spherical cap related to the low degree non-dipole features.

Finally, geomagnetic historical data recovered mainly from shipboard navigation routes from Europe to Asia are also considered to constrain the regional model during the last centuries. These data are extracted from the HISTMAG database of Arneitz et al. (2017). The total number of historical data used for the new regional model was 2000 declinations, 1110 inclinations and 675 intensities (see Figure 1). The number of declinations was considerably higher than the other two geomagnetic elements, with historical values measured since the XV century. Historical data do not provide information about measure uncertainties, however we have considered 0.2º as α_{95} and 0.2μT as σ_F, for the directional and intensity data, respectively, estimated through comparison with the gufm1 model. Finally, a weight of 10 is applied for the historical data.

2.2 Modeling approach and parametrization

To develop the African regional model, we apply the revised version of the spherical cap harmonic analysis in 2 dimensions (RSCHA2D, Thébault, 2008) in space and penalized cubic splines in time. This technique has been successfully used to reconstruct the past geomagnetic field during the last millennia in Europe (Pavón-Carrasco et al., 2021 and references therein).

One of the most important benefits of this regional approach is that it provides geomagnetic regional models with a similar resolution (in terms of spatial wavelengths) of the global spherical harmonic models, but with a lower number of parameters (Thébault, 2008). This issue is clearly a key-point in our study due to a low number of archaeomagnetic data available for Africa.

In R-SCHA2D the geomagnetic field is defined within a spherical cap by the scalar potential expression (Thébault, 2008):

$$V(\theta,\lambda) = a\sum_{k=0}^{K_{int}}\sum_{m=0}^{k} P_{n_k}^{m}(cos\theta)\left(g_{n_k}^{m,i}\cos m\lambda + h_{n_k}^{m,i}\sin m\lambda\right) +$$
$$+\, a\sum_{k=0}^{K_{ext}}\sum_{m=0}^{k} P_{n_k}^{m}(cos\theta)\left(g_{n_k}^{m,e}\cos m\lambda + h_{n_k}^{m,e}\sin m\lambda\right) + \qquad [1]$$
$$+\, a\sum_{m=0}^{M} P_{-1/2}^{m}(cos\theta)\left(G_{-1/2}^{m}\cos m\lambda + H_{-1/2}^{m}\sin m\lambda\right),$$

where the spatial parameters are represented by the geographic colatitude θ and longitude λ (both referred to the cap reference frame) and a is the mean Earth's radius. $P_{nk}^{m}(cos\theta)$ is the associated Legendre function that depends on the colatitude and is indexed by the real degree n_k (ordered by the integer degree k) and the integer order m. For the revised SCH version, Thébault et al. (2008) also introduced the $P_{-1/2}^{m}(cos\theta)$ function as a special case of the Mehler functions. $g_{nk}^{m,i-e}$ and $h_{nk}^{m,i-e}$ are the SCH coefficients (Haines, 1985), with the subindex i indicating the internal potential and e the external potential; and $G_{-1/2}^{m}$ and $H_{-1/2}^{m}$ are the new coefficients introduced by Thébault (2008). Finally, it is worth noting that these coefficients do not have the same meaning as in the Spherical Harmonic Analysis (see Haines, 1985).

Using Eq.1, we can express the three geomagnetic field elements, declination, inclination and intensity, as a function of the SCH coefficients by means of the Fréchet derivative matrix as follows (here, we show the case of the declination D, but similar procedure can be applied for inclination and intensity, see Pavón-Carrasco et al., 2021):

$$D(\vec{m}) = D(\vec{m}_0) + \left.\frac{\partial D(\vec{m})}{\partial m}\right|_{m_0} \cdot \delta\vec{m} = D(\vec{m}_0) + \widehat{A_D}(\vec{m}_0)\cdot\delta\vec{m} \qquad [2]$$

where $D(\vec{m}_0)$ is an initial value of the declination, $\left.\frac{\partial D(\vec{m})}{\partial m}\right|_{m_0} = \widehat{A_D}(\vec{m}_0)$ is the Fréchet derivative matrix of the declination expression, and $\delta\vec{m}$ is the vector of the SCH coefficients.

To get the final set of SCH coefficients $\delta\vec{m}$, we apply the following regularized weighted least square inversion:

$$\delta\vec{m} = \left(\hat{A}' \cdot \widehat{W} \cdot \hat{A} + \alpha \cdot \widehat{\Psi} + \tau \cdot \widehat{\Phi}\right)^{-1} \hat{A}' \cdot \widehat{W} \cdot \vec{\gamma} \qquad [3]$$

were $\widehat{W}$ is the weight matrix, $\widehat{\Psi}$ and $\widehat{\Phi}$ are matrices representing the spatial and temporal regularization, respectively, within the spherical cap (Talarn et al., 2017); and $\vec{\gamma}$ is the vector of input data (i.e., declinations, inclinations and intensities). The best compromise between data residual and model complexity helps to fix the spatial and temporal damping parameters, i.e., α and τ respectively.

In paleomagnetic reconstructions, both measure and age uncertainties of the paleomagnetic data play an important role (Panovska et al., 2019 and references therein). In order to quantify how these uncertainties affect the modelling approach, we carried out 5000 inversions using the Eq. 3, providing an ensemble of 5000 sets of SCH coefficients. For each set of coefficients, the directional and archeointensity data are resampled by two random distributions: one considers the uncertainty of the input data as the standard deviation of normal distributions, and the other takes into account the dating uncertainties following homogeneous distributions. The mean and standard deviation of the 5000 ensembles of SCH coefficients provide the final set of SCH coefficients.

Our regional model is obtained using this parameterization: the spherical cap is centered at 12.5ºN of latitude and 2.5ºE of longitude with semi-amplitude of 40º. For the potential expansion, we set $K_{int} = 2$ for the internal functions (6 SCH coefficients), $K_{ext} = 2$ for the external functions (5 SCH coefficients), and M = 2 for the Mehler functions (5 SCH coefficients). Taking into account the size of the spherical cap (40º) and the maximum value K_{int}, the spatial resolution of the regional model, in terms of spatial wavelengths, is about 8000 km (Thébault et al., 2008). In a global spherical harmonic expansion, this spatial resolution corresponds to a harmonic degree n = 5. To include the temporal domain in the SCH coefficients, we use penalized cubic b-splines with knot points every 50 years from 2000 BC to 1900 AD. In addition, we perform several tests to estimate the optimal values of the damping parameters α and τ, fixing them as $3{\cdot}10^{-4}$ nT^{-2} and $2{\cdot}10^{-3}$ $nT^{-2}yr^{4}$, respectively. Finally, as shown in Eq. 2, an initial model $\vec{m}_0$ is needed to run the inversion approach. This initial model was set by an inclined dipole global field (spherical global model up to harmonic degree 1) that is generated using all the data within the spherical cap. Figure S2 shows the Gauss coefficients of the initial dipole field that we use to generate initial values for declinations, inclinations and intensities of Eq. 2.

3. Geomagnetic field evolution in Africa for the last 4 kyrs

3.1. A first regional archaeomagnetic model for Africa

We have named the regional paleo-reconstruction as SCHAFRICA.DIF.4k, referring to the applied technique (SCHA), the continent (AFRICA), the geomagnetic field elements (DIF) and the time window (4k). To analyze how the new regional model fits the input data, we have calculated and plotted in Figure 2 the data residuals for both archaeomagnetic and historical data. All residuals present a Gaussian behavior (blue lines in Figure 2) with mean values close to zero and histograms look quite symmetric, except for the intensity, where a slight asymmetry (balanced to negative residuals) is shown for both Thermal Remanent Magnetization (TRM) and historical data. Figure 2 also provides the mean and the root mean square (rms) errors for each element and type of data. As expected, the higher rms errors are associated to the TRM data, since these data are associated with a higher dispersion than the historical data.

To show the past evolution on the Earth's magnetic field in Africa, Figure 3 contains snapshot maps of each geomagnetic element every 500 years from 2000 BC to 1500 AD (plus the maps at 1900 AD). In the SI there is an animation with a continuous time evolution of the paleofield within the spherical cap available. The maps indicate a high variability of the geomagnetic elements during the last 4 millennia in Africa in both spatial and temporal domains. In the declination maps, we have highlighted in white the isogonic line equal to 0° (i.e., the agonic line) where the geographic and magnetic norths directions coincide. The agonic line is present over Africa during the major part of the last 4 kyrs and is moving continuously within the spherical cap (see animation of the SI). Located half in the north hemisphere and half in the south hemisphere, Africa is the ideal region to analyze the past evolution of the magnetic equator (isocline line of zero inclinations). This virtual line (plotted in the inclination maps as a white line) wobbles around the true geographic equator during the last millennium.

Finally, the intensity maps show the evolution of the isodynamic lines (lines of equal intensity), characterized by higher intensities in polar regions and lower intensities around the equator (Figure 3). Lower intensities characterize central-southern Africa during the entire 4 kyrs time window. After 1000 AD, these low values decrease even more reaching values of 20 – 25 μT in large areas of Africa preluding the presence of the SAA (delimited by white lines in Figure 3). It is important to note that the intensity element also shows low values for epochs prior to 1000 AD in the Atlantic region (e.g., map at 0AD in Figure 3 or the intensity map animation of the SI), however, for this case, the intensity element is not well constrained by the currently available data and new data are needed to confirm these low values.

In order to study the past evolution of the geomagnetic field in Africa in further detail, we choose three different locations (see Figure 4): location A (16°N, 5°W) in north-western Africa, location B (12°N, 30°E) in northeastern Africa, and location C (10°S, 35°E) in the central-southern Africa. At these locations, we have synthesized different PSV curves using the African model (black lines in Figure 4 with error bands given by dashed black lines). To compare the PSV curves with the input data (red dots in Figure 4), we plot all the African archaeomagnetic data within a circular area of 20° (or 2200 km radius) from the reference locations (all data are relocated to the reference point by the virtual dipole field method, Noel & Batt, 1990). In addition, PSV curves from previous published global paleomagnetic reconstructions are shown in Figure 4 (blue and yellow lines for the CALS10k.2 and ARCH10k.1, respectively, global models of Constable et al., 2016; and green lines for the SHAWQ family models of Campuzano et al., 2019 and Osete et al., 2020).

In location A, declinations from input data and the different PSV curves compare remarkably well. For inclinations, the African data and the regional model present higher values during the first millennium BC than the global estimations. This is not the case for the inclination minimum around 1250 AD, where the regional model shows higher inclination values than some of the input data and global models. As expected, the intensity data appear more scattered than the directional data but show a good agreement with all the PSV curves. The regional model better defines the high maxima around 500 BC and 700 AD. The first maximum is comparable to the high maximum observed in Western Europe during the first millennium BC (Hervé et al., 2017; Osete et al., 2020) while the second around 700 AD also agrees with the intensity maximum present in all European datasets (e.g., Kovacheva et al., 2014; Gómez-

Paccard et al., 2016). It is important to note that the Levantine spike, a high intensity maximum around 1000 – 700 BC located in Eastern Europe (Shaar et al., 2016) is not present in either intensity data or PSV curves. This observation is in agreement with recent works (Korte & Constable, 2018; Osete et al., 2020) that define the Levantine spike as a maximum intensity patch that grew and decayed in situ with a possible westward drift characterized by vanishing intensity values. The new model also compares well with the recent PSV from West Africa (Kapper et al., 2020) from 0 to 900 AD, while the relative peaks in intensity around 1050 and 1550 AD are not as pronounced (see Figure 3 in Kapper et al., 2020).

While inclination data from location B and C are scarce, they still display a good agreement with the regional model confirming a low in inclinations around 100 AD (location B) and an inclination maximum around 750 AD (location C). Unfortunately, no declination data is available in location B, but the low number of data from location C helps to constrain the regional model confirming the high east declination values around 1000 AD. Finally, intensities from location B and C reveal interesting features. At location B, the regional model presents a maximum around 800 AD, but with lower amplitude than the corresponding maximum at location A. Interestingly, a similar feature is also recognized in the European record (e.g., Gómez-Paccard et al., 2016), which include many additional data compared to those used to build our new model. Hence, the feature around 800 AD seems to be characterized by a significantly large spatial wavelength, being constrained not only by data located in all Europe and Northwest Africa, but also in Central-East Africa. In addition, the model predicts high intensities in location B around 1000–900 BC (mainly due to the Egyptian data) which are potentially related to the Levantine spike. Although the number of intensity data from the location C is low, they provide very useful information about the intensity behavior during the last millennium. The new regional model shows lower intensity values for the period 1000–1900 AD than the previous global model, revealing the emergence and persistence of the SAA during this period over this part of Africa. In this interval, it is interesting to remark the pronounced minimum around 1700 AD presented in the three intensity curves, due to the new data coming from the location A. More data around this epoch from locations B and C would be needed to corroborate this minimum in the whole African continent.

Finally, for the further comparison between the regional model and the previous global models, we have estimated the residuals of the TRM data using the global models. Mean and root mean square (rms) values of these residuals are given in the Table S2 of the SI. Since the whole database also includes data from Southern Europe and Near East, we have also performed this calculation using only the African TRM data (right columns of Table S2). Results show that the mean residuals from global models are not close to zero, especially for the intensity element in both CALS10k.1 and ARCH10k.1 models. These shifted means can be due to the African data from 12 studies published after the generation of those models. In terms of rms values, the SCHAFRICA.DIF.4k model provides the lowest values for the whole database and for the selected African data, indicating a lower misfit for the regional model than for the global models, and reinforcing the importance of the new regional paleoreconstruction for this continent.

3.2. South Atlantic Anomaly evolution

During the last decade, several paleomagnetic studies have focused on understanding the spatial and temporal evolution of the SAA at the Earth's surface. New archaeointensity data and recent global paleoreconstructions suggest the emergence of the SAA in the southern hemisphere from at least around 860 AD (Trindade et al., 2018) or 950 AD (Tarduno et al., 2015; Campuzano et al., 2019). However, other studies suggest earlier periods, around 400-800 AD, based on paleomagnetic data from South Africa (Neukirch et al., 2012; Tarduno et al., 2015; Hare et al., 2018), linking the SAA with a large low-shear velocity province (LLSVP) and its anomalous composition at the core-mantle boundary (Tarduno et al., 2015). In addition, new paleointensity data suggests a recurrence of a SAA. Shah et al. (2016) report on weak local intensities from Tristan da Cunha, South Atlantic Ocean, between 90 and 46 kyrs, and high PSV variability in directional data from Saint Helena island suggest that the SAA or a similar anomaly occurred around 8-11 Ma (Engbers et al., 2020).

For the last millennium (from 1000 AD to the present), the SAA at the Earth's surface is the response of a reversed flux patch (RFP) of the radial geomagnetic field located at the core-mantle boundary (CMB). From 1000 – 1500 AD, Campuzano et al. (2019) suggested that this RFP moved beneath Africa from east (Indian Ocean) to west (Africa). After 1500 AD, the RFP journeyed into the CMB regions beneath the South

Atlantic Ocean acquiring its current configuration. At the CMB, the present SAA is represented by two RFPs, one is vanishing beneath South America and the other is being reinforced under South Africa (e.g., Finlay et al., 2020). In this spatio-temporal context, archaeomagnetic data from Sub-Saharan Africa are crucial to better constrain the path and amplitude of the SAA beyond the last century, and especially to confirm if it originated in the Indian Ocean (Hellio & Gillet, 2018; Campuzano et al., 2019) or in Southern Africa (Tarduno et al., 2015).

The SCHAFRICA.DIF.4k regional model can help investigating the SAA. It is worth noting that the RSCHA2D approach does not allow a downward continuation of the radial geomagnetic field and thus information of the SAA at the CMB cannot be deciphered. Nonetheless, the regional model can provide new insights of the SAA at the Earth's surface. Here, we plot in Figure 5a the intensity maps from 1100 AD up to 1900 AD (every 100 yrs) with isodynamic lines lower than 32 μT. This threshold is the mean intensity value at the magnetic equator for the current strength field and therefore Earth's surface regions characterized by lower intensity values are considered as part of the SAA extension (see Amit et al., 2021 and references therein). An animation of these maps every 20 yrs can be found in the SI. To complement these maps, we also represent in Figure 5b and 5c two intensity profiles crossing the region where the SAA is located. An east-west profile at constant latitude of 10°S (Figure 5b) and a south-north profile at 12.5°E of longitude (Figure 5c). Along each profile, we generate intensity PSV curves and plot them into two Hovmöller diagrams (Figure 5b and c).

Results indicate that the SAA emerged (within the spherical cap) around 1100 AD migrating westward from North Madagascar until 1400 AD, when the SAA covered Central and Southern Africa (see maps of Figure 5a). After 1400 AD, the SAA moved eastward and seems to vanish for a century (around 1500 AD, see Hovmöller diagrams). The SAA forcefully reappeared around 1600 showing lower intensity values for a large geographical area around 1700 AD, and migrated westward, further into the South Atlantic Ocean. Modern geomagnetic models show the arrival of the SAA to South America at the beginning of the 20th century (Hartmann & Pacca, 2009; Pavón-Carrasco & De Santis, 2016). The lowest intensity values (around 20 μT) reached by the SAA in Africa are similar to the present lowest values in South America (Finlay et al., 2020), where the anomaly is currently located. The SAA behavior detailed above, should be analyzed using new data coming from South Africa (region C in Figure 3), since the current database only contains data from that region after 1000 AD, just 100 yrs before observing the SAA (see Figure 3c, right panel). Consequently, more ancient data are needed to better constrain the emergence of the SAA in this continent.

To analyze the evolution of SAA observed with the new regional model, we have also plotted in Figure S3 the SAA extension (using the same intensity contour lines) for the previous global models. The SHAWQ model (second column in Figure S3) generally shows a westward drift of the SAA but without motion and growing in situ during the time interval 1400 – 1700 AD. The CALS10k.2 does not show a westward drift, i.e. between 1100 and 1600 AD the intensity anomalies are growing but moving eastward (from the Atlantic to the center of Africa), then the SAA moves again towards the Atlantic Ocean reaching the lowest intensity values around 1800 – 1900 AD. The ARCH10k.1 model follows a similar pattern, but the SAA is not observed before 1500 AD. It is worth noting that around 1900 AD both CALS10k.2 and ARCH10k.1 agree with the new regional model. This agreement is due to the used constraint by historical information in the three paleoreconstructions. However, the SHAWQ model does not show the same pattern since this model did not use historical data.

Finally, we have also compared the SAA extension of the regional model with that of the historical GUFM1 (Jackson et al., 2000) and COV-OBS2x (Huder et al., 2020) models (see Figure S4). The regional model provides a larger extension of the SAA over Central Africa from 1840 to 1880 that is not shown by the historical models. This difference is due to the influence of the archeointensity data covering the last centuries in the regional model, that were not used in the historical models GUFM1 and COV-OBS2x. However, all of them present a good agreement at 1900 AD.

Finlay et al. (2020) finally reveal that the SAA is nowadays growing again in South Africa confirming that the behavior of the SAA is more complex than a simple westward motion and expansion of a single anomaly.

3.3. The regional model as a tool for dating

Paleomagnetism is widely used as tool for high precision dating and correlating volcanic deposits (e.g., Hagstrum & Champion, 1994; Böhnel & Schnepp, 1999; Di

Chiara et al., 2014, and others) and archeological artefacts (e.g., Clark et al., 1988; Gómez-Paccard et al., 2012; Casas et al., 2008; García-Redondo et al., 2020, and others). In summary, paleomagnetic dating is based on the statistical comparison between the geomagnetic elements of the archaeomagnetic or volcanic data with unknown age with a well-constrained PSV curve (Lanos, 2004). These reference curves can be derived from regional or global paleomagnetic models at the same location of the studied structure. In this study, we test the SCHAFRICA.DIF.4k model as a tool for archaeomagnetic dating (e.g., Clark et al., 1988; Gomez-Paccard et al., 2012; Casas et al., 2008; García-Redondo et al., 2020) by using previous archaeomagnetic studies from Africa (Table 1; Casas et al., 2016; Fouzai et al., 2012, 2013; Madingou et al., 2020; not included in the model). The studies of Casas et al. (2016) Fouzai et al. (2012, 2013) are included in the Table S1 because they present new archaeomagnetic data and use them to date additional undated sites. We did not include in the model the archaeomagnetically dated sites, but we used them for testing the new model. Thus, we include the regional model into the Matlab tool archaeo_dating (Pavón-Carrasco et al., 2011), already successfully tested in several studies (e.g., Di Chiara et al., 2014; Kissel et al., 2015a; Mahgoub et al., 2017). Archaeo_dating generates synthetic PSV curves at the study location and then it compares the curves with the given paleomagnetic information (following the methodology of Lanos, 2004). Finally, the most probable age is estimated by a combination of probability density functions (pdf) of the geomagnetic elements.

For Northern Africa, Casas et al. (2016) presented archaeomagnetic data from seven archeological sites from Tunisia, two of which have not been archeologically dated: El Haouaria and Zahruni (last use in Roman age 3-4th century AD). In the original publication, these data were dated using the European regional model SCHA.DIF.3k (Pavón-Carrasco et al., 2009) due to the proximity to Europe. Both archaeomagnetic records provide the full geomagnetic vector, i.e., declination, inclination and intensity. For Zahruni, SCHAFRICA.DIF.4k (evaluated from 0 AD to 1900 AD) points out two possible age intervals (149-307 AD; 1220-1423 AD) of which the first interval is in agreement with the archeological considerations (Table 1; Figure 6a). For El Haouaria, no previous age estimates were available and thus the model is evaluated for the last 4000 yrs, obtaining four age intervals (2000-1750 BC; 1700-1560 BC; 101-385 AD; 1299-1480 AD; Table 1). Considering that the site was probably first occupied by the

Punic (2nd century BC) and that the probable latest occupancy was by the Romans we may suggest that the most probable age interval is 101-392 AD, but an accurate answer will require additional archeological constraints from the area, which are not available yet.

In central Africa, Madingou et al. (2020) archaeomagnetically investigated 14 smelting furnaces: four (KAM1-4) from Kamuturi, an archaeological site in the Mbeere region, Central Kenya, and ten from three archaeological sites in Guéra Massif, Central Chad, Bankakotch (BANK1-3), Bogrom (BOG1-4) and Djogolo (DJO1-3), from the 'abasia' stage of steel industry, starting between 1611 and 1635 CE and ending around 1909 CE with the French colonization. Radiocarbon dates indicate an age interval between 1450 to 1650 AD for the Kamuturi site and 1650-1950 AD for the Chadian sites. Madingou et al. (2020) used archaeomagnetic data to constrain the age of six of the ten smelting furnaces from Chad (BANK1 and 3, BOG1,2 and 4, and DJO1 and 2) from 1829 to 2000 AD, while no age was provided for the other Chadian and Kenyan furnaces. We test the new regional model on the four Kamuturi sites (only directional data are available), obtaining similar but slightly older ages from about 1290 to 1360 AD, than previously suggested by the radiocarbon dates (1450-1650 AD). We also test the new regional model on the Chadian sites. We confirm the dates determined by Madingou et al. (2020) for BANK1 and 3, and we provide a new age for BANK2 of 1805-1871 AD, consistent with BANK1 and 3. We also confirm BOG1 and BOG2 ages and provide a slightly older age for BOG4 of 1845-1900 AD (previously dated as 1907-1996 AD), consistent with BOG1 and 2. The new archaeomagnetic dating of BOG3 suggests an older use of the furnace in the 2nd century AD but additional constrains are needed to confirm this data. We finally provide a slightly older age range for the remaining two sites DJO1 and 2, suggesting a minimum age for the furnaces use around 1850 AD (consistent with the rest of the Chadian sites) rather than 1907 AD, the date when the France colonized the country. The new dates suggest that all furnaces (except BOG3 and DJO3) could belong to a late stage of the abasia stage of steel industry in the Guéra Massif.

Finally, one data point from South Africa (Nami et al. 2020) from cave sediments has an accurate radiocarbon age (777-1016 AD, recalibrated here using the OxCal online tool and the Reimer et al., 2020 calibration curve; it was not included in our model). Despite the paucity of data to constrain the model from this region, the new dating using the directional information from 0 AD to 1900 AD provides three possible time intervals (Table 1; Figure 6d) where one of them, 990–1053 AD, is in agreement with the radiocarbon age.

4. Conclusions

In this study, we followed a set of three criteria inspired by the FAIR principles to rank the available volcanic and archaeomagnetic studies from the African continent and surroundings. We build SCHAFRICA.DIF.4k, a first regional geomagnetic model for Africa covering the last 4000 years, using the revised version of the spherical cap harmonic analysis. The SCHAFRICA.DIF.4k model is available in the following website http://earthref.org/ERDA/2470/. Using this link, the users can download a Matlab tool to get PSV curves for the declination, inclination, and intensity at any location in Africa and neighboring areas. The curves include the error bars at 68% or 95% of probability obtained from the ensemble of models detailed in the previous section.

The regional model shows the westward migration of the SAA at the Earth's surface from the Indian Ocean over Africa since 1100 AD, improving the temporal and spatial resolution and accuracy of the SAA evolution. We test the model as a paleomagnetic dating tool by re-dating previous archaeomagnetic data from northern, central, and southern Africa, both confirming previous ages for Central and South Africa and providing new age constrains for the rest of the sites. Concluding, while additional data will certainly improve the resolution of African regional models, SCHAFRICA.DIF.4k can be used to date other African archeological sites and the active and dormant volcanoes of the East African System in the last 4000 years.

Acknowledgments

We are grateful to Steve Lund and Torsten Haberzettl for sharing their original dataset. Erwan Thébault is also acknowledged for providing the code of the RSCHA2D functions. FJPC is grateful to the Spanish research project PGC2018-099103-A-I00 of the Spanish Ministry of Science, Innovation and Universities. ADC thanks the

Nextdata Grant for the support. The authors would like to dedicate the paper to the late Prof. Roberto Molina-Cardìn.

References

Amit, H., Terra-Nova, F., Lézin, M. et al. Non-monotonic growth and motion of the South Atlantic Anomaly. Earth Planets Space 73, 38 (2021). https://doi.org/10.1186/s40623-021-01356-w

Arneitz, P., Leonhardt, R., Schnepp, E., Heilig, B., Mayrhofer, F., Kovacs, P., . . . others (2017). The HISTMAG database: combining historical, archaeomagnetic and volcanic data. Geophysical Journal International, 210 (3), 1347– 1359.

Brown, M. C., Donadini, F., Korte, M., Nilsson, A., Korhonen, K., Lodge, A., . . Constable, C. G. (2015b). GEOMAGIA50. v3: 1. general structure and modifications to the archeological and volcanic database. Earth, Planets and Space, 67 (1), 83.

Brown, M. C., Donadini, F., Nilsson, A., Panovska, S., Frank, U., Korhonen, K.,. . . Constable, C. G. (2015a). GEOMAGIA50. v3: 2. a new paleomagnetic database for lake and marine sediments. Earth, Planets and Space, 67 (1), 70.

Brown, M.C., Hervé, G., Korte, M. and Genevey, A. (2021). Global archaeomagnetic data: The state of the art and future challenges. Physics of the Earth and Planetary Interiors, p.106766.

Campuzano, S. A., Gómez-Paccard, M., Pavón-Carrasco, F. J., & Osete, M. L. (2019). Emergence and evolution of the South Atlantic Anomaly revealed by the new paleomagnetic reconstruction SHAWQ2k. Earth and Planetary Science Letters, 512, 17–26.

Casas, L., Briansó, J. L., Alvarez, A., Benzzi, K., & Shaw, J. (2008). Archaeomagnetic intensity data from the Saadien Tombs (Marrakech, Morocco), late 16th century. Physics and Chemistry of the Earth, Parts A/B/C, 33 (6-7), 474–480.

Casas, L., Fouzai, B., Prevosti, M., Laridhi-Ouazaa, N., Járrega, R., & Baklouti, S. (2016). New archaeomagnetic data from Tunisia: Dating of two kilns and new archaeointensities from three ceramic artifacts. Geoarchaeology, 31 (6), 564–576.

Chorowicz, J. (2005). The east African rift system. Journal of African Earth Science, 43 (1), 379-410.

Clark, A., Tarling, D., & Noel, M. (1988). Developments in archaeomagnetic dating in Britain. Journal of Archaeological Science, 15 (6), 645–667.

Constable, C., Korte, M., & Panovska, S. (2016). Persistent high paleosecular variation activity in southern hemisphere for at least 10 000 years. Earth and Planetary Science Letters, 453, 78–86.

Cromwell, G., Tauxe, L., & Halldórsson, S. A. (2015). New paleointensity results from rapidly cooled Icelandic lavas: Implications for Arctic geomagnetic field strength. Journal of Geophysical Research: Solid Earth, 120(5), 2913–2934. https://doi.org/10.1002/2014jb011828

de Groot, L. V., Béguin, A., Kosters, M. E., van Rijsingen, E. M., Struijk, E. L., Biggin, A. J., . . . Dekkers, M. J. (2015). High paleointensities for the Canary Islands constrain the Levant geomagnetic high. Earth and Planetary Science Letters, 419, 154–167.

Di Chiara, A. (2019). Paleo-secular variations of the geomagnetic field in Africa during Holocene: a Review. Geological Society, London, Special Publication, 497.

Di Chiara, A., Speranza, F., Porreca, M., Pimentel, A., D’Ajello Caracciolo, F., & Pacheco, J. (2014). Constraining chronology and time-space evolution of Holocene volcanic activity on the Capelo Peninsula (Faial Island, Azores): The paleomagnetic contribution. Bulletin,126(9-10), 1164–1180.

Di Chiara, A., Tauxe, L., Staudigel, H., Florindo, F., Protti, M., Yu, Y., Wartho, J.A., van den Bogaard, P. and Hoernle, K. (2021a). Earth's magnetic field strength and the Cretaceous Normal Superchron: New data from Costa Rica. Geochemistry, Geophysics, Geosystems, 22(4), p.e2020GC009605.

Di Chiara, A., Tauxe, L., Levy, T.E., Najjar, M., Florindo, F. and Ben-Yosef, E. (2021b). The strength of the Earth’s magnetic field from Pre-Pottery to Pottery Neolithic, Jordan. Proceedings of the National Academy of Sciences, 118(34).

Engbers, Y. A., Biggin, A. J., & Bono, R. K. (2020). Elevated paleomagnetic dispersion at Saint Helena suggests long-lived anomalous behavior in the South Atlantic. Proceedings of the National Academy of Sciences, 117 (31), 18258–18263.

Finlay, C. C., Kloss, C., Olsen, N., Hammer, M. D., Tøffner-Clausen, L., Grayver, A., & Kuvshinov, A. (2020). The CHAOS-7 geomagnetic field model and observed changes in the South Atlantic Anomaly. Earth, Planets and Space, 72 (1), 1–31.

Fouzai, B., Casas, L., Ouazaa, N. L., & Alvarez, A. (2012). Archaeomagnetic data from four Roman sites in Tunisia. Journal of Archaeological Science, 39 (6), 1871–1882.

Fouzai, B., Casas, L., Ouazaa, N. L., Fantar, M., & Alvarez, A. (2013). Archaeomagnetic data from three Punic sites in Tunisia. Journal of Archaeological Science, 40 (4), 1703–1714.

García-Redondo, N., Carrancho, A., Goguitchaichvili, A., Morales, J., Calvo- Rathert, M., & Palomino, A. (2020). New constraints on the medieval repopulation process in the northern Iberian plateau from the full vector archaeomagnetic dating of two hearths at La Pudia site (Caleruega, Burgos, Spain). Archaeological and Anthropological Sciences, 12 (4), 1–14.

Gauss, K. F. (1837). Intensitas vis magneticae terrestris ad mensuram absolutam revocata. In Abstracts of the papers printed in the Philosophical Transactions of the Royal Society of London (pp. 166–174).

Gómez-Paccard, M., McIntosh, G., Chauvin, A., Beamud, E., Pavón-Carrasco, F. J., & Thiriot, J. (2012). Archaeomagnetic and rock magnetic study of six kilns from North Africa (Tunisia and Morocco). Geophysical Journal International, 189 (1), 169–186.

Gómez-Paccard, M., Osete, M. L., Chauvin, A., Pavón-Carrasco, F. J., Pérez- Asensio, M., Jiménez, P., & Lanos, P. (2016). New constraints on the most significant paleointensity change in Western Europe over the last two millennia. a non-dipolar origin? Earth and Planetary Science Letters, 454, 55–64.

Haber, M., Mezzavilla, M., Bergström, A., Prado-Martinez, J., Hallast, P., Saif-Ali, R., . . . others (2016). Chad genetic diversity reveals an African history marked by multiple Holocene Eurasian migrations. The American Journal of Human

Genetics, 99 (6), 1316–1324.

Hagstrum, J. T., & Champion, D. E. (1994). Paleomagnetic correlation of Late Quaternary lava flows in the lower east rift zone of Kilauea Volcano, Hawaii. Journal of Geophysical Research: Solid Earth, 99 (B11), 21679–21690.

Hare, V. J., Tarduno, J. A., Huffman, T., Watkeys, M., Thebe, P. C., Manyanga, M., . . . Cottrell, R. D. (2018). New archeomagnetic directional records from Iron Age southern Africa (ca. 425–1550 CE) and implications for the South Atlantic Anomaly. Geophysical Research Letters, 45 (3), 1361–1369.

Hartmann, G., & Pacca, I. (2009). Time evolution of the South Atlantic Magnetic Anomaly. Anais da Academia Brasileira de Ciências, 81, 243-255.

Hellio, G., & Gillet, N. (2018). Time-correlation-based regression of the geomagnetic field from archeological and sediment records. Geophysical Journal International, 214 (3), 1585–1607.

Herrero-Bervera, E., Ubangoh, R., Aka, F., & Valet, J.-P. (2004). Paleomagnetic and paleosecular variation study of the mt. Cameroon volcanics (0.0–0.25 ma), Cameroon, West Africa. Physics of the Earth and Planetary Interiors, 147 (2-3), 171–182.

Hervé, G., Faβbinder, J., Gilder, S. A., Metzner-Nebelsick, C., Gallet, Y., Genevey, A., . . . others (2017). Fast geomagnetic field intensity variations between 1400 and 400 BCE: New archaeointensity data from Germany. Physics of the Earth and planetary Interiors, 270, 143–156.

Huder, L., Gillet, N., Finlay, C. C., Hammer, M. D., & Tchoungui, H. (2020). Cov-obs. x2: 180 years of geomagnetic field evolution from ground-based and satellite observations. Earth, Planets and Space, 72(1), 1–18

Jackson, A., Jonkers, A. R., & Walker, M. R. (2000). Four centuries of geomagnetic secular variation from historical records. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 358 (1768), 957–990.

Jonkers, A. R., Jackson, A., & Murray, A. (2003). Four centuries of geomagnetic data from historical records. Reviews of Geophysics, 41 (2).

Kapper, L., Serneels, V., Panovska, S., Ruíz, R. G., Hellio, G., de Groot, L., ... & Ruíz, R. C. (2020). Novel insights on the geomagnetic field in West Africa from a new intensity reference curve (0-2000 AD). Scientific reports, 10(1), 1-15.

Kissel, C., Laj, C., Rodriguez-Gonzalez, A., Perez-Torrado, F., Carracedo, J. C., & Wandres, C. (2015b). Holocene geomagnetic field intensity variations: Contribution from the low latitude Canary Islands site. Earth and Planetary Science Letters, 430, 178–190.

Kissel, C., Rodriguez-Gonzalez, A., Laj, C., Perez-Torrado, F., Carracedo, J. C., Wandres, C., & Guillou, H. (2015a). Paleosecular variation of the earth magnetic field at the Canary Islands over the last 15 ka. Earth and Planetary Science Letters, 412, 52–60.

Korte, M., & Constable, C. G. (2018). Archeomagnetic intensity spikes: global or regional geomagnetic field features? Frontiers in Earth Science, 6, 17.

Kovacheva, M., Kostadinova-Avramova, M., Jordanova, N., Lanos, P., & Boyadzhiev, Y. (2014). Extended and revised archaeomagnetic database and secular variation curves from Bulgaria for the last eight millennia. Physics of the Earth and Planetary Interiors, 236, 79–94.

Lanos, P. (2004). Bayesian inference of calibration curves: application to archaeomagnetism. In Tools for constructing chronologies (pp. 43–82). Springer.

Lund, S., Platzman, E., & Johnson, T. C. (2020). Paleomagnetic secular variation records from Holocene sediments of Lake Victoria (0.5° S, 33.3° E). The Holocene, 0959683619901214.

Madingou, B. T., Hervé, G., Perrin, M., M'Mbogori, F., Guemona, D., Mathé, P.-E.,. . . Robion-Brunner, C. (2020). First archeomagnetic data from Kenya and Chad: Analysis of iron furnaces from Mount Kenya and Guéra Massif. Physics of the Earth and Planetary Interiors, 106588.

Mahgoub, A. N., Böhnel, H., Siebe, C., Salinas, S., & Guilbaud, M.-N. (2017). Paleomagnetically inferred ages of a cluster of Holocene monogenetic eruptions in the Tacámbaro-Puruarán area (Michoacán, México): implications for volcanic hazards. Journal of Volcanology and Geothermal Research,347, 360–370.

Nami, H. G., Vasquez, C. A., Wadley, L., & la Peña, P. d. (2020). Detailed palaeomagnetic record at Rose Cottage Cave, South Africa: Implications for the Holocene geomagnetic field behaviour and chronostratigraphy. South African Journal of Science, 116 (1-2), 1–9.

Neukirch, L. P., Tarduno, J. A., Huffman, T. N., Watkeys, M. K., Scribner, C. A., & Cottrell, R. D. (2012). An archeomagnetic analysis of burnt grain bin floors from ca. 1200 to 1250 AD Iron-Age South Africa. Physics of the Earth and Planetary Interiors, 190, 71–79.

Noel, M., & Batt, C. (1990). A method for correcting geographically separated remanence directions for the purpose of archaeomagnetic dating. Geophysical Journal International, 102 (3), 753–756.

Osete, M. L., Molina-Cardín, A., Campuzano, S., Aguilella-Arzo, G., Barrachina-Ibañez, A., Falomir-Granell, F., . . . Rivero-Montero, M. (2020). Two archaeomagnetic intensity maxima and rapid directional variation rates during the Early Iron Age observed at Iberian coordinates. implications on the evolution of the Levantine Iron Age Anomaly. Earth and Planetary Science Letters, 533, 116047.

Panovska, S., Korte, M., & Constable, C. (2019). One hundred thousand years of geomagnetic field evolution. Reviews of Geophysics, 57 (4), 1289–1337.

Pavón-Carrasco, F. J., & De Santis, A. (2016). The South Atlantic Anomaly: The key for a possible geomagnetic reversal. Frontiers in Earth Science, 4, 40.

Pavón-Carrasco, F. J., Osete, M. L., & Torta, J. M. (2010). Regional modeling of the geomagnetic field in Europe from 6000 to 1000 BC. Geochemistry, Geophysics, Geosystems, 11 (11).

Pavón-Carrasco, F. J., Osete, M. L., Torta, J. M., & Gaya-Piqué, L. R. (2009). A regional archeomagnetic model for Europe for the last 3000 years, SCHA.DIF.3K: applications to archeomagnetic dating. Geochemistry, Geophysics, Geosystems, 10 (3).

Pavón-Carrasco, F. J., Rodríguez-González, J., Osete, M. L., & Torta, J. M. (2011). A Matlab tool for archaeomagnetic dating. Journal of Archaeological Science, 38 (2), 408–419.

Pavón-Carrasco, F.J., S.A. Campuzano, M. Rivero-Montero, A. Molina-Cardín, M. Gómez-Paccard, M.L. Osete (2021), SCHA.DIF.4k: 4000 years of paleomagnetic reconstruction for Europe and its application for dating. Journal of Geophysical Research: Solid Earth, e2020JB021237.

Reimer, P. J., Austin, W. E., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B.,. . . others (2020). The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon, 62 (4), 725–757.

Böhnel, H., & Schnepp, E. (1999). Precision of the paleomagnetic method: An example from the Quaternary Eifel volcanics (Germany). Earth, Planets and Space, 51 (6), 403–412.

Shaar, R., Tauxe, L., Ron, H., Ebert, Y., Zuckerman, S., Finkelstein, I., & Agnon, A. (2016). Large geomagnetic field anomalies revealed in bronze to iron age archeomagnetic data from Tel Megiddo and Tel Hazor, Israel. Earth and Planetary Science Letters, 442, 173–185.

Shah, J., Koppers, A. A., Leitner, M., Leonhardt, R., Muxworthy, A. R., Heunemann, C., . . . Matzka, J. (2016). Palaeomagnetic evidence for the persistence or recurrence of geomagnetic main field anomalies in the South Atlantic. Earth and Planetary Science Letters, 441, 113–124.

Skinner, N., Iles, W., & Brock, A. (1975). The recent secular variation of declination and inclination in Kenya. Earth and Planetary Science Letters, 25 (3), 338–346.

Soler, V., Carracedo, J., & Heller, F. (1984). Geomagnetic secular variation in historical lavas from the Canary Islands. Geophysical Journal International, 78 (1), 313–318.

Talarn, Á., Pavón-Carrasco, F. J., Torta, J. M., & Catalán, M. (2017). Evaluation of using R-SCHA to simultaneously model main field and secular variation multilevel geomagnetic data for the north Atlantic. Physics of the Earth and Planetary Interiors, 263, 55–68.

Tarduno, J. A., Watkeys, M. K., Huffman, T. N., Cottrell, R. D., Blackman, E. G., Wendt, A., . . . Wagner, C. L. (2015). Antiquity of the South Atlantic Anomaly and evidence for top-down control on the geodynamo. Nature communications, 6 (1), 1–6.

Tema, E., Fantino, F., Ferrara, E., Giudice, A. L., Morales, J., Goguitchaichvili, A.,. . . Gulmini, M. (2013). Combined archaeomagnetic and thermoluminescence study of a brick kiln excavated at Fontanetto Po (Vercelli, northern Italy). Journal of Archaeological Science, 40 (4), 2025-2035.

Thébault, E. (2008). A proposal for regional modelling at the Earth's surface, R-SCHA2D. Geophysical Journal International, 174 (1), 118–134.

Thellier, E. & Thellier, O. 1959 Sur l'intensité du champ magnétique terrestre dans le passe historique et géologique. Ann. Geophys. 15, 285/378.

Trindade, R. I., Jaqueto, P., Terra-Nova, F., Brandt, D., Hartmann, G. A., Feinberg, J. M., et al. (2018). Speleothem record of geomagnetic South Atlantic Anomaly recurrence. Proceedings of the National Academy of Sciences, 115 (52), 13198–13203.

Tulloch, A. M. (1992). A study of recent secular variation of the geomagnetic field as recorded by lavas from Mount Vesuvius and the Canary Islands. (Unpublished doctoral dissertation). University of Liverpool.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. Scientific data, 3.

Figure Captions.

Figure 1: Spatial (maps) and temporal (histograms) distributions of the archaeomagnetic/volcanic data (circles in the maps) and historical data (small squares in the maps). For each geomagnetic element, the left (right) histograms correspond to the archaeomagnetic/volcanic (historical) data.

Figure 2: Residual data from the SCHAFRICA.DIF.4k model. Upper panel: a) declination, b) inclination and c) intensity residuals for the archaeomagnetic and volcanic data. Lower panel: d) declination, e) inclination and f) intensity residuals for the historical data. Blue lines represent theoretical normal distribution derived from the mean and standard deviation of each histogram. Values of mean and standard deviation are provided within each histogram.

Figure 3: Maps of the past geomagnetic field elements declination (left panel), inclination (central panel) and intensity (right panel) according to the regional model SCHAFRICA.DIF.4k. The white star indicates the center of the spherical cap and the white lines indicate the agonic line, the magnetic equator and the threshold of 32 μT that defines the SAA, in the declination, inclination and intensity maps, respectively (see text for more details).

Figure 4: Paleosecular variation curves at three different locations from the SCHAFRICA.DIF.4k regional model (black curves and their associated 1σ error as black dashed lines) and from global models (blue and yellow lines are the CALS10k.2 and ARCH10k.1 models of Constable et al., 2016; green lines refer to the SHAWQ family models of Campuzano et al., 2019; Osete et al., 2020). For comparison, all the available archeomagnetic and volcanic data (red dots) for the three African regions are also plotted. The inset map indicates the location of the three regions, A, B and C.

Figure 5: a) Intensity snapshot maps from the SCHAFRICA.DIF.4k model every 100 yrs from 1000 to 1900 AD. Hovmöller diagrams of East-West (b) and South-North (c) profiles of the intensity element for the last millennium. Only the isodynamic lines below 32 μT are shown in both maps and Hovmöllers to reveal the past evolution of the SAA over the last millennium.

Figure 6: a-d) Archaeomagnetic dating of different archaeomagnetic studies of Africa using the SCHAFRICA.DIF.4k model. For each subfigure a-d: Upper panel= paleosecular variation curves (red lines) and the undated archaeomagnetic data (blue line with associated uncertainties given by the green line); Middle= probability density function (PDF) of the used geomagnetic elements; Lower= Location map and the combined PDF providing the most probable age of the archeological structure at 95% of confidence level ('new dating') and the previous assigned age ('previous dating').

Table 1: Archaeomagnetic dating of previous archaeological sites from references (Ref.) (1) Casas et al. (2016), (2) Madingou et al (2020, and (3) Nami et al. (2020). Lat and Lon represent the geographical coordinates in degrees of Latitude (N; negative

Lat. corresponding to S) and Longitude (E). Arch.= archaeological. The type of archaeomagnetic data (Data) is reported as D=declination, I= inclination and i= paleointensity. The column Age range (Ref.) refers to the radiocarbon or archaeomagnetic age range reported in each study, while the preferred age in the reference is reported in the column 'Age (Ref.)'. The archaeomagnetic age calculated with the new model in this study is reported in the last column, Age (this study), and the chosen age is printed in bold.