ARCHEOINTENSITY AND ARCHEODIRECTIONAL DETERMINATIONS FROM ANCIENT IRON KILNS LOCATED IN WEST AFRICA

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ABSTRACT

In this work we present new determinations of geomagnetic field intensity and direction from iron smelting kilns discovered at the metallurgical site of Korsimoro in Burkina Faso, West Africa. A large number of kilns were found at this site, which extends over an area up to 50 km^2. Based on archeological investigations, the kilns are related to different types of smelting techniques that probably correspond to four distinct time periods. Radiocarbon ages were obtained from charcoal and confine the studied kilns to ages ranging from 700 to 1800 AD. Rock magnetic investigations on representative samples show that the main ferromagnetic mineral is magnetite. One kiln also shows a significant contribution of hematite and a high coercivity-low unblocking temperature magnetic phase (HCSLT). In general, directional results indicate a good agreement with results from neighboring kiln structures. Comparison of directions with models and European secular variation curves, as well as archeomagnetic and lake sediment data from Africa show that the long term trend of the geomagnetic field between 1000 and 1600 AD in West Africa was similar to that of Europe for the same time period. The comparison of intensity data with models and archeomagnetic data also indicates similarities between European and West African geomagnetic field trends.

Keywords: Archeomagnetic intensities, Archeomagnetic directions, Iron kilns, West Africa

RESUMEN

En este trabajo presentamos las nuevas determinaciones de la intensidad y de la dirección del campo geomagnético de los hornos de fundición de hierro descubiertos en el sitio metalúrgico de Korsimoro en Burkina Faso, África Occidental. Un gran número de hornos se encuentran en este sitio, que se extiende sobre un área de hasta 50 km^2. Basado en investigaciones arqueológicas, los hornos están relacionados con diferentes tipos de técnicas de fundición que probablemente corresponden a cuatro períodos de tiempo distintos. Las edades de radiocarbono se obtuvieron a partir de carbón y limitan los hornos estudiados a edades entre 700-1800 dC. Las investigaciones sobre el magnetismo de las rocas en muestras representativas muestran que el principal mineral ferromagnético es magnetita. Un horno también muestra una importante contribución de hematita y una fase de alta coercitividad y de baja temperatura de desbloqueo (HCSLT). Resultados direccionales indican, en general, un buen acuerdo con los resultados de estructuras de hornos vecinos. La comparación de direcciones con los modelos y las curvas de variación secular de Europa, así como los datos de sedimentos arqueomagnéticos y lacustres de África muestran que la tendencia a largo plazo del campo geomagnético entre 1000 y 1600 dC en el África occidental fue similar a la de Europa para el mismo período de tiempo. La comparación de los datos de intensidad con modelos y datos arqueomagneticos también indica similitudes entre las tendencias de campo geomagnético de Europa y de África Occidental.

Palabras Clave: Intensidades arqueomagneticas, Direcciones arqueomagneticas, Hornos de hierro, África Occidental

Background

Archeomagnetic investigations allow reconstructing the geomagnetic field changes during Holocene based on the remanent magnetization recorded by baked archeological artifacts. Incorporating these investigations in geomagnetic field models can help understanding the variations of the geomagnetic field. Furthermore, it is also widely used for dating purposes by comparing directions and/or intensities recorded by an archeological artifact with existing geomagnetic field variation reference curves. One of the limitations of these reconstructions is due to the fact that most data available up to now are limited to the past 2000 years, and to Europe. These geographic and temporal limitations hamper accurate dating outside of this time frame or geographic boundary. The efforts that have been made to investigate artifacts from outside Europe or from older periods are still scarce (*e.g.*, Carrancho *et al.*, 2013; Kapper *et al.*, 2014; Hartmann *et al.*, 2010; 2011; Goguitchaichvili *et al.*, 2011). In particular, studies covering the African continent and the Holocene are extremely rare. In West Africa, for example, only one recent archeointensity study (Mitra *et al.*, 2013) of ceramics from Mali and Senegal is available. This is one of the reasons why several features of the geomagnetic field revealed by observatory and satellite data are not visible in archeomagnetic data. Such features include for example, equatorial flux spots (Jackson, 2003), likely representing the tops and bottoms of the columnar flow of the liquid iron; or the South Atlantic Magnetic Anomaly, an intensity low located over the South Atlantic, which originates from a reversed flux patch bundle located under South Africa (*e.g.*, Hulot *et al.*, 2002).

Archeological Context

The history of metallurgy in Western Africa spans backs at least two millennia, according to Bocoum (2002). The large amount of slags found in certain regions gives evidence that they represented one of the main economical activities in the area. Nevertheless, the early appearance of iron metallurgy in West Africa is still a matter of dispute (Bocoum, 2002; Killick, 2004; Alpern, 2005). During the first millennium AD, iron became common in the material culture of most West African populations. Later on, at about 800 AD, the scale of the production rose to a very high level and the African societies entered a true Iron Age as testified by numerous archeological remains (slag heaps and ruined furnaces). The understanding of the development of massive iron production and its trading is undoubtedly a key-question for inferring the global history of the area. In this study, we focused on gathering new reliable directional and intensity data from smelting kilns excavated at the metallurgical site at Korsimoro (Burkina Faso, West Africa). The new archeomagnetic data from West Africa presented here utterly contribute to improve the understanding of the global geomagnetic field dynamics during Holocene, and set a basis for the establishment of a novel West African reference secular variation curve. The Korsimoro sampling site is located about 70 km north of the capital of Burkina Faso, Ouagadougou, at about 12.79°N latitude and 1.09°W longitude. The metallurgical activity occurred in various sectors, spreading over an area of about 10 km around Korsimoro (Fig. 1). Individual sectors can reach up to 1 km. Sectors 20 and 50 were studied in detail. The archeological excavation identified four different smelting techniques based on the grouping and typology of kilns, slags, and tuyeres (Serneels *et al.*, 2011). Kilns were dated by radiocarbon analysis using charcoals extracted from the basis of the slag deposits. The radiocarbon ages indicate that the four techniques belong to distinct phases covering a period ranging between 650 and 1800 AD.

Magnetic Experiments

In total, 32 structures were sampled (Fig. 1). Seven to nine blocks were collected from each structure; all of them oriented *in situ* using both a magnetic and a sun compass. The blocks were cut in cube specimens of 2 cm side at the facilities of the University of Fribourg (Switzerland). The correction for local magnetic declination was calculated using the MagIC software of Tauxe *et al.* (2010). Rock magnetic analyses

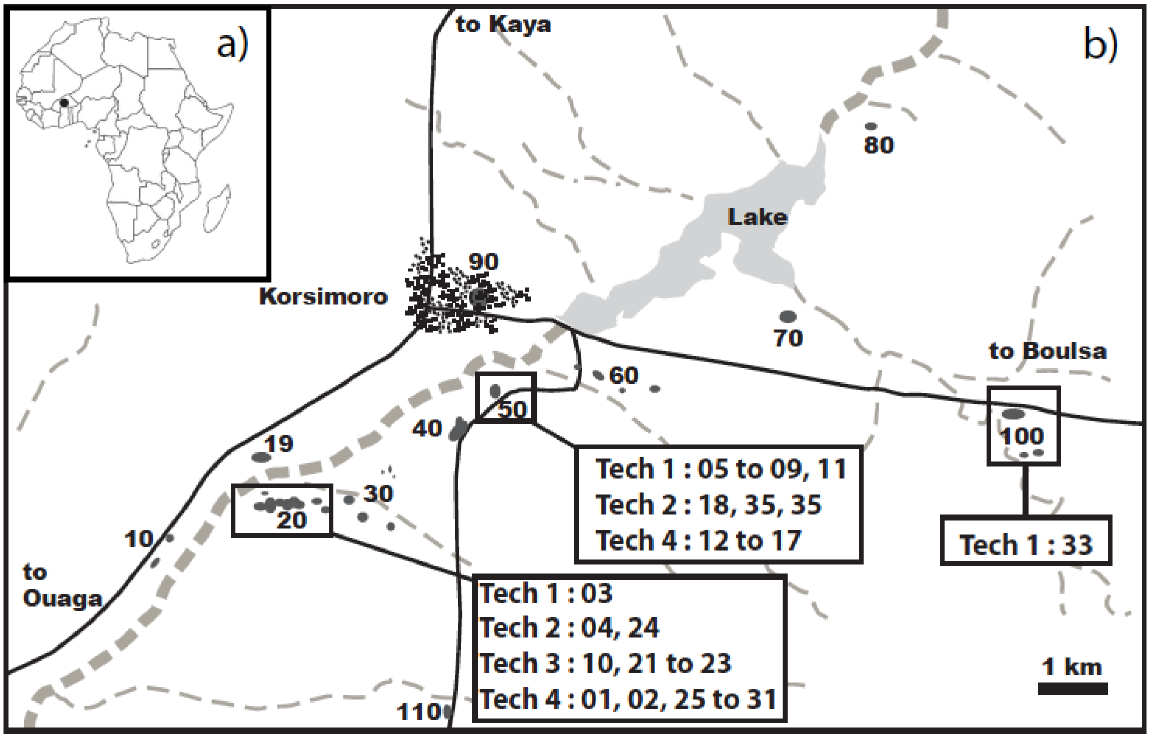

Figure 1. a) Map of Africa showing the location of Korsimoro (black circle). b) The metallurgical remains around the village of Korsimoro (Burkina Faso) spread over 10 km along the river. Twelve sectors (numbered 10 to 100) with abundant remains were excavated. The boxes indicate the structures sampled from a particular sector and the technique (tech) they belong to.

included thermomagnetic curves (magnetic susceptibility versus temperature up to 700°C), hysteresis and backfield measurements, and a 3-axes Isothermal Remanent Magnetization (3IRM) experiment. Both thermal and alternating field demagnetization treatments were used to isolate the Characteristic Remanent Magnetization (ChRM). Furthermore, we measured intensities of 78 specimens from 17 kilns using the IZZI protocol (*e.g.*, Tauxe and Staudigel, 2004). In order to select the intensity results with the highest quality we applied the following selection criteria: $\beta \leq 0.05$, $f_{VDS} \geq 0.7$, Drats ≤ 15%, Dang ≤ 8°, MAD ≤ 6° and number of specimens per kiln ≥ 2. The anisotropy of anhysteretic remanent magnetization (AARM) was also investigated in order to correct for possible magnetic anisotropy effects. Only specimens for which AARM measurements were performed have been taken into consideration for the final mean value calculations. In total we performed AARM measurements on 27 specimens.

In general, kilns belonging to techniques 1 and 4, characterized by brown to black colored materials, present magnetite as main magnetic carrier, with a typical Curie temperature of around 580°C and hysteresis loops saturating at about 0.2 T. Instead, kilns belonging to techniques 2 and 3 show colors ranging from red to brown. Most of the red specimens show wasp-waisted loops, characteristic of mixtures of high and low coercivity minerals. High temperature susceptibility curves and the three axes-IRM (3IRM) experiment reveal Curie temperatures of about 580 and 680°C, and indicate the presence of both magnetite and hematite. Additionally, the 3IRM experiment shows a Curie temperature of 200°C associated with the high-coercivity component. Due to the reversibility of most high temperature susceptibility curves of these specimens, we infer that a high coercivity-low unblocking temperature magnetic HCSLT-phase (McIntosh *et al.*, 2007) is also present in these structures. Generally, directional results show a well-defined ChRM with small viscous overprint, which is removed by a 5 mT alternating field or by a temperature of 100°C. Structures and samples yielding $\alpha_{95} \geq 6.5°$ were rejected. In total, 10 structures did not yield reliable results. Archeointensity results of accepted specimens show a success rate of 58 %, with 45 accepted specimens out of 78. The rejected specimens have not passed the quality criteria mainly because they show a pronounced concave Arai diagram, which is typical for grains with different blocking and unblocking temperatures. Specimens with anisotropy correction factor larger than 10% were also rejected. This was the case for two specimens. The remaining 11 accepted specimens from 6 kilns were averaged first at sample and then at kiln level. AARM correction factors range from 0.3% to 8.8%, with a relative low average of 3.4%. A summary of intensities at kiln level together with their corresponding ages is reported in Table 1. Results from two kilns (KRS05 and KRS23) have both a very large standard error (Tab. 1). For KRS05 intensities of specimens from the same sample are different, but sample averages agree very well. For KRS23 the agreement of specimens from one sample is very good, but averages on sample level are different. Due to this large spread of values for these two kilns we further performed a different type of experiment to obtain archeointensities, the Pseudothellier method (*e.g.*, Tauxe *et al.*, 1995; de Groot *et al.*, 2013). This method that does not involve heating of the material, avoids therefore mineralogical alterations caused by heating, which can occur during Thellier-Thellier type experiments.

Main Results and Concluding Remarks

In general, there is a good agreement between the results obtained from the kilns that belong to the same technique and are located closely to each other. For example, KRS04 (radiocarbon dated) and KRS24 (not radiocarbon dated) belong to the same group of kilns and lie about 5 m apart from each other. The similar archeomagnetic directions obtained indicate that the two structures are contemporaneous. In these cases we assume the same age for both structures. However, in some other cases discrepancies can be observed. For example, structures KRS18 (undated), KRS34 (dated) and KRS35 (dated) also belong to the same group of kilns, confined by a layer of slags within an area of about 4000 m^2. Based on the undistinguishable archeomagnetic directions, the three structures seem to be contemporaneous. Nevertheless, the radiocarbon date of KRS34 indicates an age about 200 years younger than KRS35. This discrepancy is probably caused by the different locations of charcoals sampled for radiocarbon analyses. The charcoal sample collected from the KRS34 kiln was taken from the filling of the furnace above the slag of the last smelt. It is thus assumed to be contemporaneous to the last kiln's firing and to represent the age of the registration of the archeomagnetic direction. On the contrary, the charcoal of KRS35 was collected at the very bottom of the furnace. Its date may be related to an iron production predating the last smelt, and so the radiocarbon age would be older than the time of the acquisition of the last registered archeomagnetic direction.

The Figure 2 shows the secular variation in terms of declination and inclination at Korsimoro. The mean directions of the studied structures are illustrated with black dots along with the CALS3K.4 global geomagnetic field model shown with the yellow line (Korte and Constable, 2011) and the Balkan secular variation curve relocated at Korsimoro in red (Tema and Kondopoulou, 2011). Although from a distant region, the Balkan curve is the most complete and detailed paleosecular variation curve. Additionally, the Spanish reference curve of Gomez-Paccard *et al.* (2006), located about 3000 km North of Burkina Faso, is presented as a green line. Available data from Northwestern Africa are also shown as white circles (Kovacheva, 1984; Thellier and Thellier, 1959; Najid, 1987; Casas *et al.*, 2008; Gomez-Paccard *et al.*, 2012). Marine sediment data from Cape Ghir (Bleil and Dillon, 2008), about 2300 km north of Korsimoro, are indicated as blue circles. Compared to our data, the CALS3k.4 model does not show a minimum in inclination around 1250 AD. Instead, it follows the trend of the neighbor marine sediment data relocated to Korsimoro. On the other hand, the Balkan curve and the Spanish data, relocated to Korsimoro, appear to agree well with our new results. This comparison suggests that the long-term trend of the geomagnetic field between 1000 and 1600 AD was similar in Europe and West Africa.

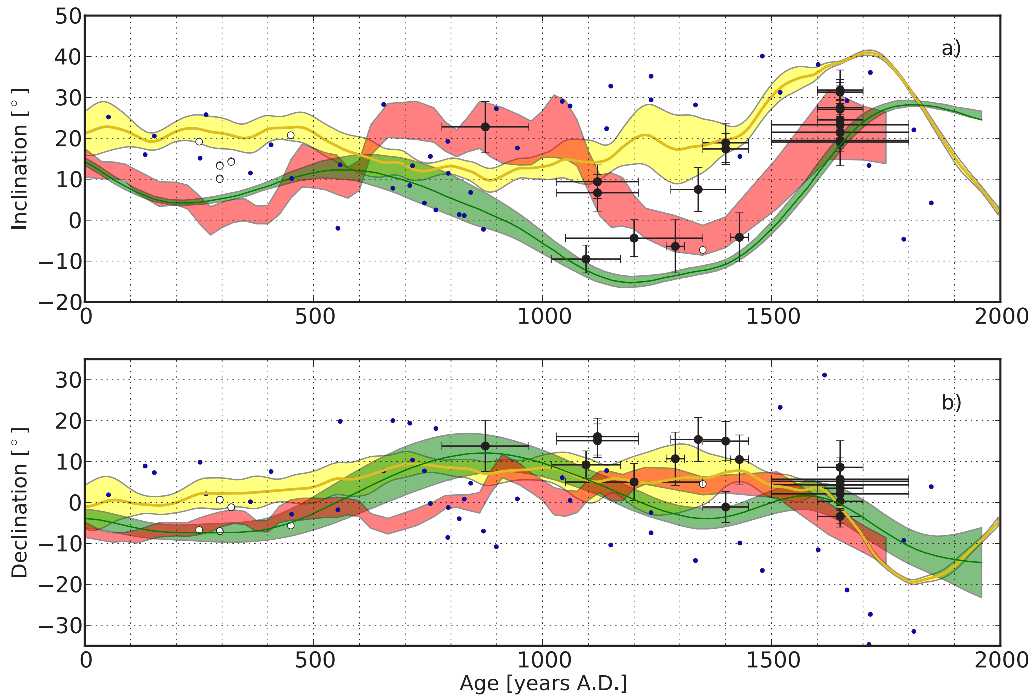

Figure 2. Secular variation at Korsimoro. The data from this study are shown as black circles, the CALS3K.4 model as yellow line (Korte and Constable, 2011), the Balkan curve in red (Tema and Kondopoulou, 2011), and the Spanish curve of Gomez-Paccard *et al.* (2006) as a green line. Available data from Northwestern Africa are also shown as white circles (Kovacheva, 1984; Thellier and Thellier, 1959; Najid, 1987; Casas *et al.*, 2008; Gomez-Paccard *et al.*, 2012). Marine sediment data from Cape Ghir (Bleil and Dillon, 2008) are indicated as blue circles. All data are relocated to Korsimoro.

This first paleointensity results from Burkina Faso are compared to the ARCH3K.1 global geomagnetic field model (Korte *et al.*, 2009), archeointensity data from Morocco from the Geomagia 50v2 database (Korhonen *et al.*, 2008; Donadini *et al.*, 2006) (Fig. 3). Our data agree very well with the model predictions and the Balkan curve. Especially the decreasing intensity trend of models and Balkan curve between 800 and 1400 AD is also observed in our data, while data from Tunisia complement this trend. Our preliminary results of the Pseudothellier method show that in the case of kiln KRS23, which is characterized by large differences at sample level, the Pseudothellier method also shows these different values at sample level. Such results indicate that the observed differences do not depend on the archeointensity technique applied but are most probably related to the material itself. Furthermore, in three out of five cases the Pseudothellier method agrees very well with the Thellier method and seems to be a good addition to the standard heating techniques.

The data obtained in this study set the basis for the construction of a secular variation curve in West Africa and show that smelting kilns used for iron production are suitable for archeomagnetic investigations. The comparison of directions between neighbor structures also helps clarifying their degree of contemporaneity. The comparison of the West African directional and intensity data with European studies suggests that the long-term trend of the field between 1000 and 1600 AD was very similar. Preliminary results of intensity determinations using the Pseudothellier method show good agreement with the Thellier-type method. Additionally, the intensity data together with the directional paleosecular variation curve can be used in future studies to constrain ages of archeological artifacts with little or no datable organic material for radiocarbon dating.

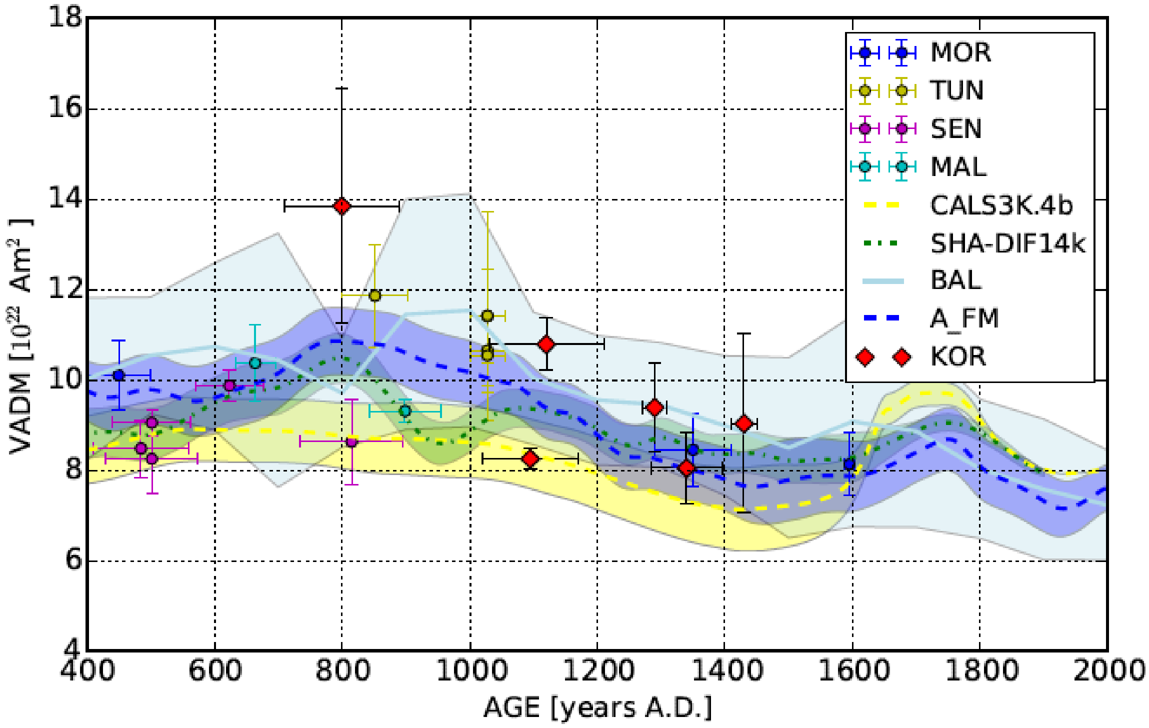

Figure 3. Virtual axial dipole moments (VADMs) of Korsimoro kilns (red diamonds) are compared to data from Morroco (MOR), Tunesia (TUN), Senegal (SEN), and Mali (MAL). Furthermore, we compare the new intensity data to the CALS3K.4b, SHA-DIF14k, and the A_FM model. In light blue we also plot the Balkan curve (BAL). The corresponding intensity values and kiln names are summarized in Table 1.

Table 1. Summary of final intensity results for the studied six kilns. Intensity is Ba, σ_Ba is the standard error of Ba, Age is the radiocarbon dated age or based on archeological evidence, and σ_Age is the 2-sigma standard error of the Age.

Kiln	**Ba (µT)**	σ_Ba (µT)	**Age (yrs AD)**	σ_Age (yrs)
KRS05	57.39	10.77	800	90
KRS35	34.22	0.97	1095	75
KRS24	44.73	2.35	1120	90
KRS34	39.92	4.12	1290	20
KRS10	33.37	3.33	1340	55
KRS23	37.45	8.2	1430	20

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