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VARIATIONS OF THE GEOMAGNETIC FIELD INTENSITY IN SOUTH AMERICA OVER THE PAST FIVE CENTURIES

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Abstract

Although South America has a great potential for archeomagnetic studies, there are presently a few archeointensity data available that are meeting reasonable quality criteria. This may have a strong consequence on the accuracy and the reliability of the global geomagnetic field models built using large archeomagnetic dataset. Acknowledging this weakness, we are involved in a project focused on the archeointensity variations on the eastern side of South America over the past few centuries. Here, we present archeointensity data from Northeast and Southeast Brazil (Hartmann et al., 2010; 2011) determined from architectural brick fragments dated between 1550 AD and 1920 AD. Ages were established from archeological studies and historical documents of the buildings, giving age uncertainties of less than 30 years. Archeointensity values were determined by two methods: (a) double-heating with measurements in room temperature, using the modified version of the Thellier protocol; (b) double-heating with measurements in high temperatures, using the Triaxe protocol. All data were screened using strict selection criteria resulting in 23 high-quality site-mean intensity values. Our datasets allow one to show mainly two aspects of the field: (1) We find evidence for a strong non-dipole field contribution in Brazil over the past few centuries likely due to the occurrence of the nearby South Atlantic Magnetic Anomaly, and (2) the different versions of the field models encompassing the past four centuries are not accurate enough to satisfactorily report the actual non-dipole field variations in Brazil. We will also discuss the contribution of the archeointensity results recently obtained from North Argentina.

Resumo

Embora a América do Sul apresente um enorme potencial para estudos arqueomagnéticos, atualmente há poucos dados que atendem a razoáveis critérios de qualidade. Isso pode influenciar fortemente na acurácia e confiabilidade dos modelos de campo geomagnético globais construídos a partir de grandes conjuntos de dados arqueomagnéticos. Reconhecendo essa escassez de dados, está sendo desenvolvido um projeto sobre as variações de arqueointensidade na parte oriental da América do Sul para os últimos cinco séculos. Neste trabalho, serão apresentados os dados de arqueointensidade das regiões Nordeste e Sudeste do Brasil (Hartmann et al., 2010; 2011) determinados em fragmentos de tijolos datados entre 1550 AD e 1920 AD. As idades foram estabelecidas através de estudos arqueológicos e documentos históricos das construções, que forneceram incertezas de menos de 30 anos. Os valores de arqueointensidade foram determinados através de dois métodos: (a) duplo aquecimento com medidas em temperaturas ambiente, utilizando a versão modificada do protocolo Thellier; (b) duplo aquecimento com medidas em altas temperaturas, utilizando o protocolo Triaxe. Todos os dados foram analisados através de rigorosos critérios de seleção resultando em 23 valores de intensidade de alta qualidade. Os dois conjuntos de dados permitem analisar dois aspectos principais do campo: (1) as evidências para uma forte contribuição do campo não-dipolar no Brasil para os últimos séculos, provavelmente devido a presença da Anomalia Magnética do Atlântico Sul, e (2) as diferentes versões dos modelos de campo para os últimos quatro séculos não são precisos o bastante para descrever satisfatoriamente as variações do campo não-dipolar no

Brasil. Serão discutidos também a contribuição dos resultados de arqueointensidade recentemente obtidos para o Norte da Argentina.

Introduction

The Earth's magnetic field (EMF) is generated by magneto-hydrodynamical processes acting in the outer core. Constraints on these processes can only be obtained from direct and indirect magnetic measurements made on or close to the Earth's surface. Direct measurements were made available from ships and from a few observatories since the XVIIth century, while magnetic satellites now provide a geographically complete description of the EMF at the Earth's surface. Indirect measurements of the geomagnetic field can be retrieved from the remanent magnetization recorded in archeological and geological materials, whose ages range from a few tens to several billions of years (e.g. Merrill et al., 1998; Hulot et al., 2010). The dataset covering the recent past, up to a few millennia, are dense enough for carrying out global field modelling using spherical harmonic analysis (e.g. Jackson et al., 2000; Korte et al., 2009). Such models offer a continuous view of the EMF variations both in time and space at centennial and millennial time scales. However, the accuracy and the reliability of that geomagnetic field models are strongly dependent on the quality and on the geographical distribution of the data. In this regard, the southern hemisphere remains very poorly documented, contributing to only ~5% of the intensity data available for the past few millennia (Genevey et al., 2008; Donadini et al., 2009).
The EMF evolution during the so-called *historical period* (i.e. over the past five centuries) is well known thanks to the vast collection of declination and inclination data measured by mariners who travelled around the world (*e.g.* Bloxham et al., 1989; Jackson et al., 2000). Based on these datasets, Jackson et al. (2000) constructed global geomagnetic field models for the 1590-1990 AD time interval. But, the lack of direct intensity measurements before 1840 AD forced these authors to extrapolate a linear decreasing trend for the axial dipole coefficient (g_1^0). Using the available archeointensity dataset, Gubbins et al. (2006) and Finlay (2008) proposed a more or less constant value for the g_1^0 between 1590 and 1840 AD. Recently, Korte et al. (2009) developed several new geomagnetic field models using archeomagnetic datasets involving different selection criteria (Donadini et al., 2009) and they argued in favour of a decreasing albeit rather "wavy" behavior for g_1^0 during the same period. In contrast, Genevey et al. (2009), using a selection of high-quality archeointensity data from France, proposed an oscillatory behavior for g_1^0 marked by a minimum at ~1750-1800 AD and a maximum ~1840 AD. At present, it is then possible to find out different conclusions for the evolution of the g_1^0, depending on whether all (scattered) data or a selection of them (with very stringent selection criteria) are considered. Deciphering this evolution requires the acquisition of new well-dated archeointensity data. In this respect, the South Atlantic Ocean and South America, mainly Brazil, constitute a very interesting region because this area is characterized by the world's lowest field intensities known during the XIXth and the XXth century. These very low intensity values are likely due to the occurrence of the so-called *South Atlantic Magnetic Anomaly* (SAMA), which is driven by strong non-dipole field components (e.g. Bloxham and Gubbins, 1985; Bloxham et al., 1989; Gubbins et al., 2006; Hartmann and Pacca, 2009).

We will present a summary of the archeointensity results, which are presently available from Northeast and Southeast Brazil (Hartmann et al., 2010; 2011). We will then compare them both with the intensity evolutions derived in the concerned regions from the different versions of the global geomagnetic field models and with the recent archeointensity results obtained from North Argentina (Goguitchaichvili et al., 2011).

Archeological sampling and archeointensity methods

The two archeological collections comprise architectural baked clay fragments sampled in seven different cities of Northeast and Southeast Brazil (Figure 1a). The selected cities were considered in this work because of their historical importance. For example, Salvador was settled in 1549 AD and housed the first capital of Brazil, and Rio de Janeiro was settled in 1565 AD and housed important governmental, religious and private buildings of colonial and imperial periods in Brazil. The archeological fragments (bricks and some tiles) were collected considering only well documented and well dated buildings. In all cases, the ages were ensured mainly by historical constraints from official and non-official reports of the buildings (e.g. Bahia, 1997; Salazar, 1998; Costa, 2005; Fausto, 2008). These studies allow us to determine precisely the ages of the buildings, like the well-known “Farol da Barra Fortress” (1696-1702 AD, Salvador, Figure 1b) and the house of the third President of Republic of Brazil (Mr. Prudente de Morais) “Museu Prudente de Morais” (1870 AD, Piracicaba, Figure 1c). It is worth to mention that the historical cities experienced an accelerated growth, which required local production of the materials and their rapid use in the buildings (e.g. Costa, 2005). In some cases, additional dating constraints were applied to guide the sampling strategy and ensure that the ages correspond to the initial phase of their constructions. Archeological constraints consist of architectural style of the buildings, stratigraphy of the excavations and typology of bricks from rough-textured made by the Jesuits between XVIth and XVIIth centuries to the refined made later. This typology was important to avoid any recent restorations of the buildings. In addition, our sampling was conducted in the basements of the buildings assuring that all fragments correspond to the initial phase of the construction (Hartmann et al., 2010; 2011).

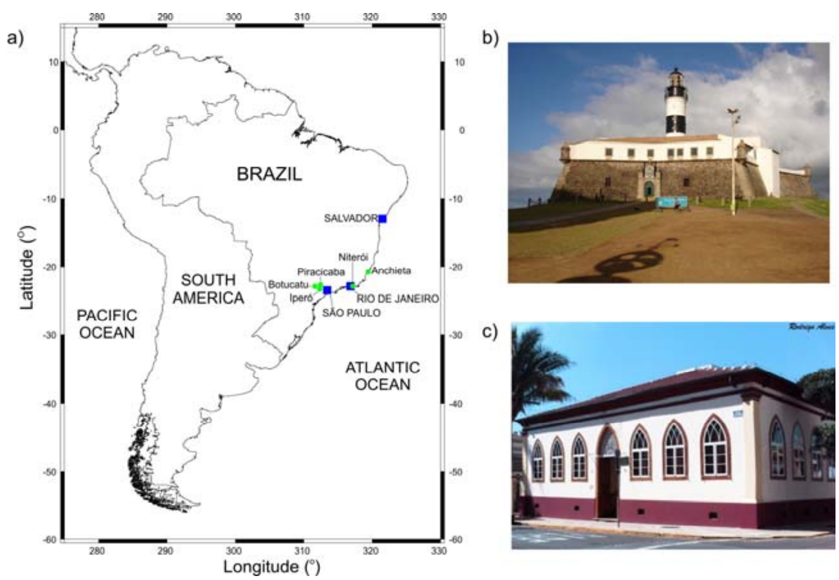

Figure 1: Location map of the different cities where the baked clay fragments were sampled in the Northeast and Southeast Brazil (a) and examples of well-dated sites: “Farol da Barra Fortress” (b; Salvador, Bahia State) and “Museu Prudente de Morais” (c; Piracicaba, São Paulo State) (after Hartmann et al., 2010; 2011).

Archeointensity experiments were performed using two different protocols, both based on the classical Thellier and Thellier (1959) double heating paleointensity method. The first protocol correspond to the Coe (1967) approach of Thellier and Thellier (1959) method. It consists of double heating-cooling steps the first in Zero field and the second In field (the so-called TT-ZI protocol). Experiments were carried out between 100 ºC and 600 ºC, with temperature intervals of 50 ºC from 100 ºC and 25 ºC afterward. The magnetization measurements were performed at room temperature and the laboratory field of 35 μT was applied parallel to *X*-axis of the specimen. The standard partial Thermo Remanent Magnetization (pTRM) checks were performed every two temperature steps and the pTRM-tail checks were performed at six different temperatures (200 ºC, 300 ºC, 350 ºC, 400 ºC, 500 ºC and 600 ºC). The second protocol uses high-temperature magnetization measurements performed with the Triaxe magnetometer (Le Goff and Gallet, 2004). The so-called Triaxe protocol relies on the comparison between a demagnetization of the Natural Remanent Magnetization (NRM) and a laboratory TRM. Both magnetizations are determined between T_1 and T_2 temperature interval, usually corresponding to 150 ºC for T_1 and a high temperature (e.g. 350 ºC to 500 ºC) for T_2. The laboratory field is applied close to the expected value and its direction is applied parallel to that of the NRM of the sample. An intensity value is computed from the ratio between the NRM and TRM fractions unblocked between T_1 and T_2 temperature interval, then multiplied by the laboratory field (Le Goff and Gallet, 2004). In both protocols, the TRM anisotropy and cooling rate effects were taken into account in order to correct the intensity value for each specimen.

Results and discussion

A total of 240 fragments from the Northeast (104 fragments) and Southeast (136 fragments) Brazil were submitted to heating-cooling cycles of magnetic susceptibility measurements up to 600 ºC. Among those fragments, 183 fragments showed a good stability of their magnetic mineralogy upon temperature, indicating a favorable behavior for archeointensity experiments. These cycles, together with the acquisition of hysteresis loops and of Isothermal Remanent Magnetization (IRM) indicate that Ti-poor magnetite and hematite are the main magnetic carriers of remanence with clear predominance in most samples of magnetite over hematite (Hartmann et al., 2010; 2011).

Archeointensity measurements using TT-ZI and/or Triaxe protocols were applied on 94 fragments (295 specimens) from 14 sites of the Northeast collection and 89 fragments (289 specimens) from 11 sites of the Southeast collection. Intensity values from the TT-ZI protocol were determined from the least square fitting of linear segments in the Arai diagrams, comprising at least 5 temperature steps and 40% of the total NRM. For the retained samples, the standard deviation of the linear slopes was in all cases of less than 5%. Moreover, they had to present less than 5% of variations on pTRM checks and less than 10% on pTRM tail checks. Intensity values from the Triaxe protocol were determined from averaging continuous intensity estimates over large temperature intervals of 200 ºC or more, comprising at least 50% of the total NRM. A slope was computed considering a cutoff of less than 10% of the linear trend fitting for the temperature interval used to compute an intensity value. At the fragment level, a mean intensity value was computed using a minimum of 2 individual values (specimens) determined using the TT-ZI and/or Triaxe protocols. That value was retained when the difference between the individual values, after TRM anisotropy and cooling rate corrections, was less than 5% of the mean. At the site level, a mean intensity value was computed using the intensities from a minimum of 3 different fragments (i.e. 6 specimens). The value was considered as satisfactory when its standard deviation was of less than 10% of the mean.

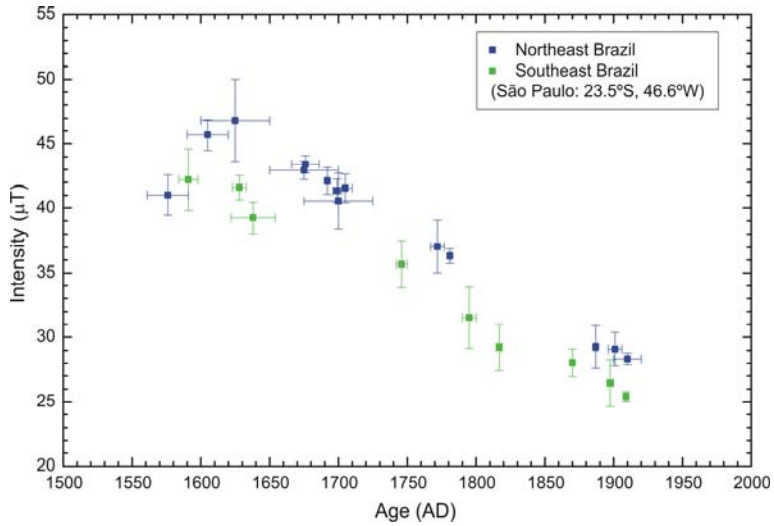

Figure 2: Archeointensity results from Northeast and Southeast Brazil reduced at the latitude of São Paulo.

Figure 2 shows the 23 high-quality archeointensity results hence obtained from 14 sites (57 fragments, 183 specimens) of the Northeast and 9 sites (43 fragments, 150 specimens) of the Southeast Brazil. It is worth noting that a good consistency is observed between sites of similar ages and from the same region. This is for example the case for sites from Northeast Brazil dated to ~1700 AD. All results were relocated to the latitude of São Paulo (23.5ºS, 46.6ºW) using the geocentric axial dipole (GAD) approximation. For both regions, the relocated values vary between ~25 μT (Southeast) and ~47 μT (Northeast). They describe a continuous decreasing trend of ~5 μT per century between the beginning of the XVIIth century and the XXth century. Figure 2 further shows that the intensity values from Northeast Brazil transferred to São Paulo are systematically higher than those obtained from Southeast Brazil, indicating that the GAD approximation between the two Brazilian regions is not valid.

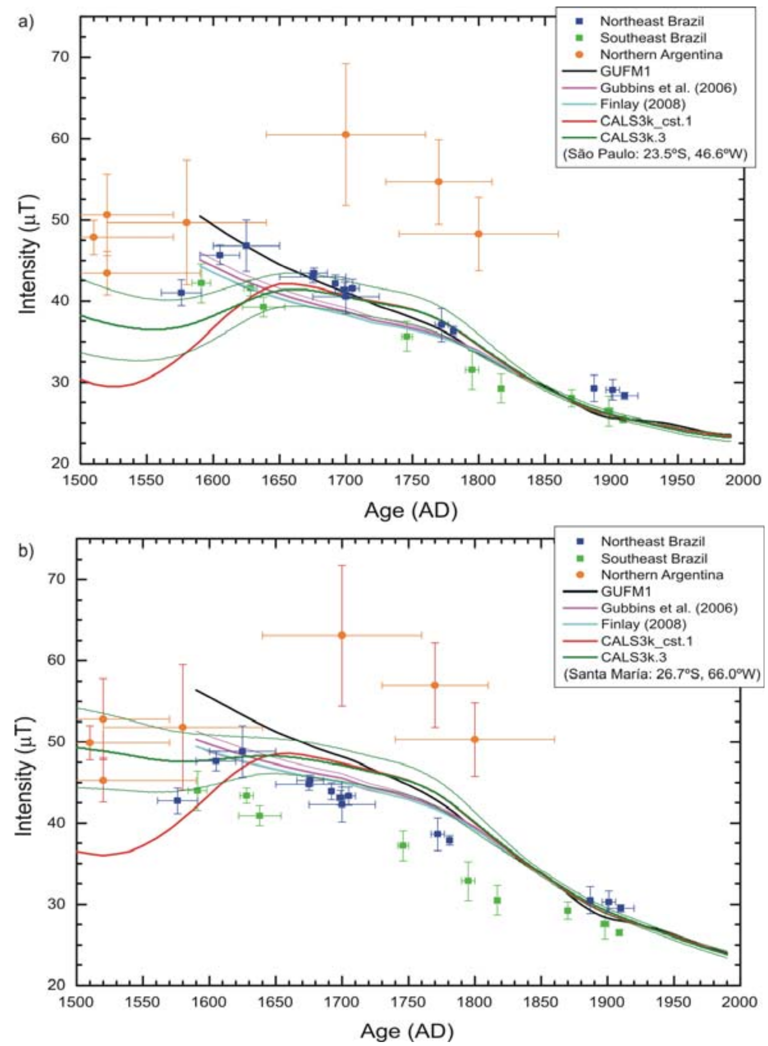

Figure 3: Three archeointensity datasets and geomagnetic field models computed at the two different latitudes: (a) Comparisons at the latitude of São Paulo (23.5ºS, 46.6ºW) and (b) at the latitude of the Argentinean sites (Santa María, 26.7ºS, 66.0ºW).

Figure 3 shows the geomagnetic field evolution provided by our archeointensity data and by the available geomagnetic field models spanning the past five centuries. The latter models are those of Jackson et al. (2000; GUFM1), Gubbins et al. (2006), Finlay (2008) and Korte et al. (2009; CALS3k.3 and CALS3k_cst.1). We also report the recent results obtained from pottery samples collected in North Argentina (Goguitchaichvili et al., 2011), for which both TRM anisotropy and cooling rate effects were taken into account. Figure 3a shows the respective evolution in geomagnetic field intensity expected at the latitude of São Paulo. As discussed by Hartmann et al. (2011), the differences between the Northeast (after having transferred the data to São Paulo) and the Southeast datasets can be ascribed to a significant non-dipole field contribution existing over Brazil, implying that one dataset cannot be transferred to another locality distant by ~1,000 km – or less – using the GAD approximation. Nevertheless, both datasets suggest a similar evolutionary trend. Of interest is the fact that the data obtained from Northeast Brazil appear in better agreement with the intensities derived from the GUFM1 models, whereas the data from Southeast Brazil are more in agreement with the models incorporating the g_1^0 evolution proposed by Gubbins et al. (2006) and Finlay et al. (2008). This clearly suggests that the accuracy of the geomagnetic field models is presently not good enough to correctly describe the non-dipole effect occurring between Northeast and Southeast Brazil.

While the differences discussed above are limited, those introduced by the new Argentinean data are surprisingly large, at least for the ~1650-1800 AD time interval. If these data are indeed correct, this would indicate that all versions of geomagnetic field models give erroneous intensity values by ~10 μT in North Argentina (see Figure 3b where all data are transferred to the latitude of the city of Santa María). A better, but still limited agreement is however observed for the XVI th century with the intensity evolution derived from the CALS3k.3 models. Nevertheless, the large differences observed with the Argentinean data for the XVII th-XVIII th centuries are puzzling and clearly demand further confirmation by continuing acquisition of new archeointensity data from this region.

In conclusion, South America is a vast field of research in archeomagnetism and the existence of the SAMA generating strong non-dipole field effects makes this region particularly exciting for this research. Our studies show that archeointensities may help in refining the time evolution of SAMA.

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