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# New constraints on the most significant paleointensity change in Western Europe over the last two millennia. A non-dipolar origin?

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ABSTRACT

Over the last years new evidences of several short-lived regional maxima of the geomagnetic field intensity at various times and locations have been defined. These features have important implications both for geomagnetic field modeling and for Earth's dynamo simulations. However, the nature, extent and underlying causes of these variations are still poorly understood. The major constraint for an adequate description of these important features is the absence of continuous detailed records and the current limited availability of precisely dated geomagnetic field recorders. In this context, archeological materials from superimposed strata covering long sequences of occupation provide a powerful tool to investigate the temporal variability of geomagnetic field strength at decadal and centennial time scales. In this work we report the archeomagnetic study of 79 potteries from Southeastern Spain collected in 14 different stratigraphic units. The chronological framework of the studied collection, ranging from the 9th to the 12th centuries, is based on historical/archeological data such as written sources and well-established typological and archeometric documentation on ceramics found on reference contexts in the area. Additionally, two radiocarbon dates obtained from two different stratigraphic units confirm the proposed chronological intervals. From classical Thellier and Thellier experiments including partial thermoremanent magnetization (pTRM) checks and TRM anisotropy and cooling rate corrections, height new high-quality mean intensities were derived. The new data provide an improved description of the sharp abrupt intensity decay that took place in Western Europe after the 800 AD intensity maximum, the most significant geomagnetic field intensity feature observed in Europe over the last two millennia. The new results confirm that several rapid intensity changes (with rates higher than 10 μT/century) took place in Western Europe during the recent history of the Earth. The comparison between the regional curve of Western Europe and the SHA.DIF.14k global field model predictions suggests that the 800 AD event observed in Europe is probably controlled by non-dipolar geomagnetic sources.


## 1. Introduction

Recent studies (e.g. Ben-Yosef et al., 2009; de Groot et al., 2013; Ertepinar et al., 2012; Genevey and Gallet, 2002; Gallet et al., 2003; Hervé et al., 2013; Hong et al., 2013; Schnepp et al., 2009; Shaar et al., 2011; Genevey et al., 2009, 2013; Gómez-Paccard et al., 2008, 2012a; Mitra et al., 2013; Cai et al., 2014) corroborate the occurrence of short-lived regional maxima of the geomagnetic field intensity during the last few millennia. A better understanding of the nature and causes of these intriguing phenomena is not only important to understand the processes that govern the Earth's dynamo but also to place into a long-term temporal perspective the current decay of the low field intensity anomaly currently centered around Southern Brazil and Paraguay (the so-called South Atlantic Anomaly, SAA) and the historically observed rapid decay of the dipole moment (of about 5% per century for the last

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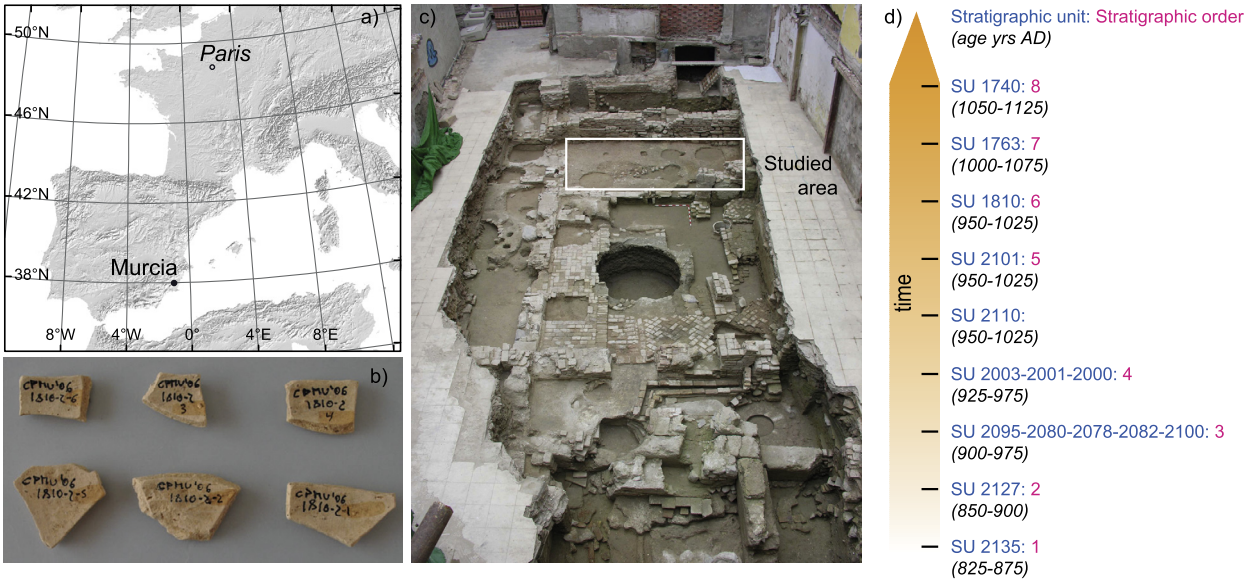


**Fig. 1.** (a) Location of the archeological site where the archeomagnetic material was recovered (Murcia). The reference location (Paris) where the archeointensity data have been relocated is also shown; (b) picture of the six pottery fragments studied corresponding to the stratigraphic unit SU 1810; (c) photograph of the excavated area (white rectangle); (d) schematic picture showing the temporal sequence of the different stratigraphic units studied. Red numbers correspond to the red circles plotted in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

80 yr). In addition, reconstructions of past solar modulations are crucially dependent on magnetic field strength (Muscheler et al., 2005). This factor and its uncertainties need to be carefully included in the reconstruction of solar activity. In this context, one of the biggest challenges currently facing the paleomagnetic community is to characterize these rapid geomagnetic field intensity events in order to investigate their spatial and temporal variability. Due to the limited number of high-quality intensity data a proper description of geomagnetic field strength during the last millennia is still lacking even for Western Europe, the best-covered region in terms of high-quality archeointensity data. One of the main difficulties in obtaining geomagnetic field reconstructions with a decadal and centennial time scale resolution is the scarcity of precisely dated heated archeological materials. Age uncertainty is perhaps the biggest concern and the most difficult to avoid. Pottery fragments from superimposed strata covering long sequences of occupation provide a powerful tool to recover a clear temporal sequence of the geomagnetic field intensity trend in the past.

In this paper, we report the archeomagnetic study of 79 ceramic fragments collected in the city of Murcia (Southeastern Spain) and that were found in 14 stratigraphic units grouped in 9 consecutive stratigraphic levels (Fig. 1). The present study uses the new data obtained for 8 of the 9 studied levels together with selected high-quality data to investigate the maximum rate of variation of the geomagnetic field strength observed in Western Europe during the last two millennia. Additionally, the spatial and temporal variability and the dipolar/non-dipolar origin of the most significant rapid event (here and after called the 800 AD event) are also investigated by comparing the obtained regional geomagnetic intensity trend with other regional reconstructions and global geomagnetic field models predictions.

## 2. Archeological context, dating and magnetic characterization

The ceramics studied here were collected in 14 stratigraphic units (SU) identified in a surface no bigger than $3 \times 7$ m$^2$ (white square in Fig. 1c) located in the hearth of the ancient medieval *madîna* of Murcia and corresponding to the long-lasting *andalusí* period. Between four and eight pottery shards per SU were selected for analysis. These SU's are grouped in six consecutive archaeological phases, from phase I (the older phase) to phase VI (the younger phase), and with ages ranging between the 9th and the 12th centuries AD (Fig. 1d). The different phases are defined by different historic moments and can include several SUs. For example, they can be defined by the building of a room and include several SU such as the digging of the foundation ditches, their filling up, the soil that supports pavements, etc. (see Supplementary Material for further details). Several fragments per stratigraphic unit were subjected to rock magnetic analysis in order to gain information about the main magnetic carriers contained in the studied samples. Together (Fig. 2, Supplementary Material), the results indicate that the magnetic mineralogy is dominated by low coercivity phases corresponding to Curie temperatures in the range of 350–590 °C. This suggests that the main magnetic careers are minerals of the titanomagnetite family with very variable Ti contents. In some samples, the presence of a magnetic phase characterized by higher coercivity, Curie and blocking temperatures above 590 °C has also been detected but its remanence contribution is negligible in comparison to the magnetic phase described previously.

## 3. Paleointensity determination: laboratory protocol

We applied one of the most reliable and widely used approaches for paleointensity determination: the classical Thellier and Thellier method (Thellier and Thellier, 1959) including regular partial thermoremanent magnetization (pTRM) checks and TRM anisotropy and cooling rate corrections. Several pottery fragments per SU and between two and four specimens per fragment were studied. In order to obtain standard paleomagnetic samples, 1 cm $\times$ 1 cm specimens were cut and packed into salt pellets or into quartz cylinders. The archeointensity experiments were conducted at the Paleomagnetic Laboratories of the Institute of Earth Sciences Jaume Almera ICTJA CSIC-CCiTUB (Barcelona, Spain) and Géosciences-Rennes (Rennes, France). Remanent magnetizations were measured using a SRM755R (2G Enterprises) three-axes cryogenic superconducting and Agico JR6 magnetometers. Experiments were made in air and laboratory fields of 50 or 60 μT were applied. Nine to fifteen temperature steps during Thellier experiments were performed between 100 °C and 600 °C. At each