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Fast geomagnetic field intensity variations between 1400 and 400 BCE: New archaeointensity data from Germany

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ABSTRACT

Thirty-five mean archaeointensity data were obtained on ceramic sherds dated between 1400 and 400 BCE from sites located near Munich, Germany. The 453 sherds were collected from 52 graves, pits and wells dated by archaeological correlation, radiocarbon and/or dendrochronology. Rock magnetic analyses indicate that the remanent magnetization was mainly carried by magnetite. Data from Thellier-Thellier experiments were corrected for anisotropy and cooling rate effects. Triaxe and multispecimen (MSP-DSC) protocols were also measured on a subset of specimens. Around 60% of the samples provide reliable results when using stringent criteria selection. The 35 average archaeointensity values based on 154 pots are consistent with previous data and triple the Western Europe database between 1400 and 400 BCE. A secular variation curve for central-western Europe, built using a Bayesian approach, shows a double oscillation in geomagnetic field strength with intensity maxima of ~70 μT around 1000-900 BCE and another up to ~90 μT around 600-500 BCE. The maximum rate of variation was ~0.25 μT/yr circa 700 BCE. The secular variation trend in Western Europe is similar to that observed in the Middle East and the Caucasus except that we find no evidence for hyper-rapid field variations (i.e. geomagnetic spikes). Virtual Axial Dipole Moments from Western Europe, the Middle East and central Asia differ by more than $2 \cdot 10^{22}$ A·m^2 prior to 600 BCE, which signifies a departure from an axial dipole field especially between 1000 and 600 BCE. Our observations suggest that the regional Levantine Iron Age anomaly has been accompanied by an increase of the axial dipole moment together with a tilt of the dipole.

1. Introduction

Knowing how geomagnetic field intensity has changed through time represents an important challenge in palaeomagnetic research. Such information is crucial, for example, to understand how the geodynamo functions (e.g. Aubert et al., 2013). Defining the geomagnetic dipole moment over centennial timescales is also essential to reconstruct the past solar activity through the production rate of cosmogenic nuclides (e.g. Usoskin et al., 2016). Finally, once a time-dependent palaeointensity curve is established for a region, one can use it to date archaeological sites.

An absolute estimate of field strength relies on the study of the thermoremanent magnetization of ferrimagnets hosted within a material that cooled through their Curie temperatures. The growth of the worldwide reference database in the past ten years (e.g. Brown et al., 2015; Donadini et al., 2006; Genevey et al., 2008) has facilitated the construction of increasingly sophisticated global geomagnetic models over the last three to fourteen thousand years

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(e.g., Constable et al., 2016; Licht et al., 2013; Nilsson et al., 2014; Pavón-Carrasco et al., 2014a for the most recent examples). Despite these progresses, the models are still limited by an inhomogeneously-distributed data in space and time and by an unequal data quality, especially for the BCE period (e.g., Pavón-Carrasco et al., 2014b).

The period between 1000 and 500 BCE contains the highest virtual axial dipole moments in the Holocene, with a peak around 40% higher than at present (Genevey et al., 2008; Usoskin et al., 2016). This is a key period where experimental constraints are needed to improve our understanding of the geodynamo. Moreover, in the Levantine area, Shaar et al. (2011, 2016) found that the fastest secular variation rates occurred at that time. They found two geomagnetic spikes at the beginning of the tenth and eighth century BCE. However, these sharp increases in field intensity at the sub-centennial scale are debated because they would require variation rates of several μT/yr, inconsistent with our present understanding of core flow patterns at the surface of the Earth's outer core (Livermore et al., 2014). The spikes could be associated with a regional geomagnetic anomaly centred on the Middle East between ~1050 and ~700 BCE (Shaar et al., 2016, 2017). These authors called it the "Levantine Iron Age Anomaly" (LIAA), which is characterized by a high average geomagnetic field with VADM values close to $14{\cdot}10^{22}$ A·m^2 and by a ~20° deviation from the Geocentric Axial Dipole (GAD) direction. The LIAA extended to Caucasus and Central Asia but maybe not to Europe (Shaar et al., 2017).

In Western Europe, the direction of the geomagnetic field during the LIAA period deviated ~12–14° from the GAD direction (Hervé et al., 2013a), but intensity secular variation remains poorly constrained between the 15th and the 4th century BCE, as only twenty high-quality archaeointensity values are available (e.g., Hervé et al., 2013b; Kapper et al., 2015). These data hint toward fast secular variation with possibly two successive intensity maxima, yet no evidence for the occurrence of geomagnetic spikes (Hervé et al., 2016). Better temporal resolution and better knowledge of the amplitude and the rate of secular variation are clearly needed. For these reasons, we collected samples from Late Bronze Age and Early Iron Age archaeological sites in Bavaria. After presenting the archaeological context and sampling, we describe the laboratory procedures using three complementary protocols. The results shed new light on secular variation in central-western Europe from 1400 BCE to the beginning of the CE period. We discuss the speed and amplitude of secular variation from Europe to Central Asia and their geomagnetic implications.

2. Archaeological context

The archaeological sites were located close to Munich in Bavaria (Germany) (Fig. 1a), with each set of ceramics coming from a distinct feature (grave, pit or well). The 52 sampled features were dated between ~1400 and ~400 BCE within the end of the Middle Bronze Age, the Late Bronze Age (also called the Urnfield period in South Germany), the Early Iron Age and the beginning of the Late Iron Age (Fig. 1b). Dating methods include radiocarbon, dendrochronology and, in most cases, archaeological constraints, stratigraphy and typochronology. Typochronology of central-western Europe is divided in stages defined by a characteristic assemblage of ceramics and metallic objects (e.g. Müller-Karpe, 1959; Sommer, 2006). The three main phases are called Bronze (Bz), Hallstatt (Ha) and La Tène (Lt), themselves being divided in four subphases (A to D) (Fig. 1b). Each sampled feature was dated by comparing its artefacts against the archaeological chronology. Because the style of the artefacts did not change rapidly, the resolution of the reference chronology is generally not better than 150–200 years.

All the graves that we sampled were dated using typochronology. They were excavated in the cemeteries of Ingolstadt – Mailing Schindergrubäcker (Malcher and Weinig, 1995), München – Obermenzing (Winghart, 1984), Aschheim – Ostumgehung (Pütz, 2008) and, in the Lech valley, of Kleinaitingen – Gewerbegebiet Nord, Kleinaitingen – Kiesgrube Weigl, Königsbrunn – Firma Ampack, Oberottmarshausen – Kiesgrube Lauter and Oberottmarshausen – Leberbichl (Büttner et al., 2006).

In the Grünwald – Gymnasium settlement (Metzner-Nebelsick et al., 2016), we sampled an Early Iron Age grave and two Late Bronze Age pits, called grgy661 (Fig. 1c) and grgy665. The stratigraphy in the grgy661 pit clearly differentiated ritual deposits in the bottom layers and filling of the pit in the upper layers. The ceramics we sampled were distinguished in time according to this stratigraphy. Two AMS radiocarbon dates on animal bones associated with the sampled ceramics dated pit grgy661 (Poz-80712, 2955 ± 35 uncal. years BP and Poz-80713, 2950 ± 35 uncal. years BP). The synthesis of these dates using Bayesian Chronomodel software (Lanos and Philippe, 2017) constrained the interval [1270; 1045] BCE at 95% of confidence. We assumed the same date interval for pit grgy665 regarding the stratigraphical context.

Besides the graves, we sampled two wells with wooden walls in Aschheim (Zach et al., 2010). Dendrochronological dates on the wood are 762 ± 10 BCE for well 692 of Aschheim – Ostumgehung (asou692) (Fig. 1d) and 700 ± 10 BCE for well 390 of Aschheim – XXXLutz (asxx390) (Herzig 2008a,b). However, we do not think that the ceramics filling the wells are dated so precisely. The date of the ceramic assemblage must take in consideration that older and younger ceramics may have been dumped into the well during and after its use. According to the position of the sampled ceramics in the filling layers and to the assumed lifetime inferred from the dendrochronological study, we respectively assigned [780; 720] BCE and [760; 600] BCE for the ceramic sets of asou692 and asxx390 (Table 1).

The youngest of the studied sites, Haffstraβe in München – Trudering, was a settlement dated at the end of the Early Iron Age and at the beginning of the Late Iron Age (Bagley et al., 2010). There, we sampled ceramics from two wells and three pits.

3. Sampling and magnetic characterization

In total, 453 ceramic sherds from 271 different pots were collected. In Oberottmarshausen – Kiesgrube Lauter, we also sampled ten fragments of burnt daub (obla246e to obla246n). The pots were generally common wares that, for the period, were not produced farther than a few tens of kilometres from the sampled sites.

Sampling preferentially focused on red-coloured sherds because they were less sensitive to mineralogical alteration during the archaeointensity protocol than the grey-black sherds (e.g. Osete et al., 2016). Thermomagnetic curves measured with a Petersen Instruments variable field translation balance (VFTB) using a ~200 mT field on chips from 109 pots confirmed this observation (Fig. 2a). Almost all heating-cooling cycles of red sherds were reversible up to 600 °C. Some black sherds also showed a high degree of reversibility, but most did not, even at lower temperatures (~400 °C), so they were rejected from further experimentation. Most sherds from our collection were red only within a few millimeters from the surface, whereas their cores were greyish (Fig. 1e). This two-colour appearance is related to variations in oxygen conditions in the kiln during baking. In order to increase the success of the archaeointensity experiments, ~100 mg specimens were cut from the red-coloured part of the sherds. They were fixed in 8 mm diameter quartz holders filled with quartz wool.

In all 109 samples, the thermomagnetic curves highlighted a dominant ferromagnetic phase with Curie temperatures between