Geomagnetic field variations in the past: an introduction

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Abstract: In the last decades, palaeomagnetic research has provided us with a picture of the temporal and spatial behaviour of the Earth's magnetic field (EMF) from its origin up to the present day. Well-dated palaeomagnetic data offer important sources of information about the past variation of the geomagnetic field and have shown that it is characterized by temporal fluctuations such as reversals, excursions and spikes. Despite the advances in our understanding of EMF behaviour, the current dataset is biased towards high and northern latitudes and, therefore, several questions remain open to debate, such as the origin and evolution of the EMF and the frequency and spatial distribution of its variations. This Special Publication focuses on the study of the temporal and spatial evolution of the EMF in the past through new data from palaeomagnetic and rock magnetic studies of archaeological materials, sediments and lavas from Europe, Africa, Australia, New Zealand, India and Baltic Sea, and their applications in archaeology, stratigraphy and climate. This paper summarizes our current knowledge on geomagnetic field variations in the past, open questions and future challenges and gives an overview of the volume's context, which aims to disclose fundamental properties of the Earth's magnetic field evolution.

In recent decades, geo- and palaeo-magnetic research has shown that a combination of direct and indirect observations using both experimental and computational approaches can provide a picture of the temporal and spatial behaviour of the Earth's magnetic field (EMF) from its origin up to today. The importance of understanding the EMF's origin and evolution spans many Earth sciences disciplines and beyond. It is fundamental for constraining core–mantle dynamics, cosmogenic isotope production and solar activity and, in turn, is relevant to climate change, human history and life on Earth (Doglioni *et al.* 2016). Indeed, geomagnetic field variations can be correlated with climate change (e.g. Courtillot *et al.* 2007) in terms of total solar irradiance and cosmogenic isotope (^{10}Be and ^{36}Cl) production, where ^{10}Be/^{9}Be ratios in sediments or ^{36}Cl and ^{10}Be flux in ice cores are correlated with (and are indications of) past minima of the intensity of the geomagnetic field (e.g. Muscheler *et al.* 2005; Simon *et al.* 2016). Beyond this, they can also be applied as an independent and robust relative and/or absolute dating tool in stratigraphy (e.g. magnetostratigraphy), volcanology (e.g. Di Chiara *et al.* 2014), archaeology (e.g. Casas & Tema 2019), human history and art (Chiari & Lanza 1997). Palaeomagnetism (the discipline that studies the EMF recorded by rocks in the geological past) and archaeomagnetism (the study of the EMF recorded by archaeological baked clays) are fundamental for deciphering the EMF's variations in the past, and help to reveal its evolution.

EMF variation in the past: state of the art and open questions

Reference data and mathematical models have shown that the EMF is characterized by continuous spatial

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and temporal fluctuations over a million to thousands of years (reversals and excursions), centuries (secular variation) and decades (the so-called archaeomagnetic spikes). For the reconstruction of EMF variations over the last decades and centuries, direct measurements from geomagnetic observatories and satellites are now available. Prior to the instrumental data, geomagnetic field variations can only be recovered from the study of well-dated volcanic rocks, archaeological artefacts and sediments (Gallet *et al.* 2020). Altogether, instrumental measurements and palaeomagnetic data, compiled in online databases such as Magnetic Information Consortium (MagIC, http://www.earthref.org) or GEOMAGIA50 (https://geomagia.gfz-potsdam.de), are the fundamental starting points for computing geomagnetic field models at regional and global levels (e.g. CALS, from Korte & Constable (2005), and ARC (Korte *et al.* 2009) or SHA.DIF families (Pavón-Carrasco *et al.* 2014)).

Despite their importance and the great effort made during the last few decades, the distribution of the currently available palaeo- and archaeomagnetic reference data is still uneven both geographically and temporally. Overall, 95% of the data (combining both volcanic and archaeomagnetic records in the GEOMAGIA database for the last 50 ka) are concentrated within the Northern Hemisphere whereas only 5% come from southern latitudes. Moreover, most of these are from the Cenozoic and mostly from only the last 20 000 years. This significant bias in both time and space is due to the limited availability of suitable materials for palaeomagnetic analyses in certain areas or time periods, the low age-resolution of geochronological dating methods (the error estimates may be from a few hundred to a million years) and the logistical difficulties of reaching remote parts of the Earth (such as oceans and deserts) or war and conflict zones.

The most reliable materials for retrieving geomagnetic field directions (declination and inclination) and strength (palaeointensity) are volcanic rocks and archaeological structures and artefacts (fired during their use or manufacture, such as ovens or pottery) that can reliably record episodic snapshots of the geomagnetic field. The former can be dated with geochronological methods (radiocarbon, Ar/Ar, K/Ar), potentially covering the entire history of the Earth, but the latter have a much shorter potential age range (mostly limited at the last 10 000 years).

In contrast, sedimentary sequences may give a continuous record of the geomagnetic field, but they are often difficult to date (e.g. too little material for radiocarbon dating etc.) and they only allow the determination of the direction of the magnetic field and its relative palaeointensity. Additionally, the fidelity of the magnetic signal can be disturbed by several effects such as bioturbation, alteration, locking-depth, smoothing and inclination shallowing (Tauxe 2005). Finally, a continuous and reliable record of the geomagnetic field's secular variation and excursions can also be retrieved from other natural archives such as speleothems and flowstones (e.g. Lascu & Feinberg 2011; Zanella *et al.* 2018). These are potentially high-temporal-resolution recorders (Trindade *et al.* 2018) and can be accurately dated with U–Th techniques, although their magnetic signal is often extremely weak.

Because of a biased dataset, the origin and evolution of the EMF, along with the frequency and spatial distribution of its variations, remain a matter of debate. In particular, many questions are still open, such as:

(1) When did the Earth's geomagnetic field originate (e.g. Mittal *et al.* 2020)? The strength of the EMF is intrinsically correlated and fundamental for understanding the thermal evolution of the early Earth. Indeed, the formation of the inner core (Aubert *et al.* 2009; Ziegler & Stegman 2013; Driscoll 2016; Landeau *et al.* 2017) should be manifested in a clearly low magnetic field intensity, followed by a recovery of the strength. Because of the paucity of data, estimates of inner-core nucleation are still unclear, varying from 1.3 Ga (Mesoproterozoic, Biggin *et al.* 2015) to 0.5 Ga (Ediacaran, Smirnov *et al.* 2016; Bono *et al.* 2019).

(2) What is the average strength of the Earth's geomagnetic field (McFadden & McElhinny 1982; Juarez *et al.* 1998; Tauxe *et al.* 2013; Wang *et al.* 2015)? And how did it evolve over time? Knowing the average geomagnetic field strength is fundamental to, for instance, estimate the solar standoff distance (Tarduno *et al.* 2014) or model the geodynamo. No clear answer to this question has been reached so far, with average values spanning from 80 ZA m^2 (McFadden & McElhinny 1982) to 42 ZA m^2 (Juarez *et al.* 1998). Long-term variations may be a result of external forcing mechanisms, reflecting the hydrodynamic processes occurring in the Earth's mantle and outer core (McFadden & Merrill 1984), but due to the scarcity of data, numerical simulations have failed to describe these features of the EMF so far (Sprain *et al.* 2019).

(3) Why do reversals of the Earth's geomagnetic field occur and what is their frequency (e.g. Lowrie & Kent 2004)? Is there a correlation between intensity and reversal frequency? When is the EMF going to reverse again? Cox (1968) suggested that when the field is weaker it is also unstable and therefore the frequency of reversals is higher. For verifying a possible correlation, a robust record of

reversals and excursions is needed along with a reliable and well-distributed palaeointensity dataset both temporally and spatially. Identification of the existence and nature of such a relationship would provide important constraints on the heat flux across the Earth's core–mantle boundary, the energy states of the geodynamo and, accordingly, their modelling (Biggin *et al.* 2012). Recently, Channell *et al.* (2020) reviewed what is known and unknown of geomagnetic excursions and reversals during the Quaternary, as a starting point for future studies.

(4) On a shorter time interval (years to millennia), questions regarding the history and significance of large anomalous areas such as the South Atlantic Anomaly (SAA) arise (Hartmann & Pacca 2009; Campuzano *et al.* 2019). The SAA, characterized by very low magnetic intensities, high non-dipolar components and westerly inclinations, has been observed for the last 200 years, migrating eastward from Africa to South America. The SAA may be a much older and recurrent feature (e.g. Tarduno *et al.* 2014; Trindade *et al.* 2018) and a manifestation of an imminent reversal (Laj & Kissel 2015; Pavón-Carrasco & De Santis 2016), but the debate is still open (Constable & Korte 2006; Brown *et al.* 2018). The lack of data from the Southern Hemisphere dramatically limits the understanding of this anomaly and of the behaviour of the geomagnetic field in the past.

(5) What is the frequency, duration and geographical occurrence of the palaeointensity spikes in the EMF? Short-lived (years to decades) maxima in palaeointensity have been observed on archaeological artefacts (e.g. Gallet *et al.* 2003, 2006; Shaar *et al.* 2016) and sediments (Béguin *et al.* 2019) at several localities and time periods in the Northern Hemisphere (Cromwell *et al.* 2013). The best known is the Levantine Iron Age anomaly that was first reported by Ben-Yosef *et al.* (2009) and Shaar *et al.* (2011), who reported high field intensity fluctuations in the Middle East during the tenth and the ninth centuries BC. Such extreme variations are still not completely understood, and they may not be compatible with the commonly accepted structure of core–surface flow (Livermore *et al.* 2014). Korte & Constable (2018), using spherical harmonic modelling, suggested that these features may originate from intense flux patches growing and decaying mostly *in situ* and may be explained by normal axial dipole variations. Using numerical experiments, Troyano *et al.* (2020) suggested that, while geomagnetic spikes are not compatible with the magnetic flux expulsion model, periods of secular duration and smaller variations may be compatible.

Undoubtedly all of these questions are as much of fundamental importance as they are difficult to answer. However, obtaining new high-quality data will help to provide some of the answers.

Overview of papers in the volume

The papers included in this Special Publication aim to improve the data distribution from under-represented regions of the Earth, both temporally and geographically, and to present new advances in geomagnetic field variation studies and their applications. The volume is divided into two sections 'Archaeomagnetism and absolute palaeointensity' and 'Palaeosecular variation, sediments and climate'.

Archaeomagnetism and absolute archaeointensity

Thanks to the great advances that have taken place during recent decades, archaeomagnetism can now be considered a well-established technique and a promising dating tool for archaeology. Well-dated archaeological artefacts can offer precise and high-quality reference records for reconstructing variations of the EMF in the past within a given geographical area. Further more, once enough reference data are available, detailed secular variation curves and regional models can be computed, which, in turn, can be used to date archaeological structures and volcanic eruptions. Instrumental techniques and laboratory protocols are nowadays well established, and continuously updated approaches aim to guarantee the quality and reliability of the directional and intensity data acquired. However, the available data worldwide are still unevenly distributed in both time and space. Moreover, even though the directional records are generally well determined, open issues still exist regarding the quality of archaeointensity determinations that generally show high dispersion, probably due to complicated experimental procedures. The first section of this Special Publication presents new archaeomagnetic contributions that aim to enrich the reference data from underrepresented regions of the Earth such as India, Australia and New Zealand; strengthen the current European dataset with new high quality archaeointensity records from Italy and Bulgaria; and investigate the potential of archaeomagnetic data for understanding rapid EMF oscillations in the past at a regional scale.

In this context, **Deenadayalan *et al.* (2020)** present new archaeomagnetic data from baked clay artefacts from four archaeological sites (Ter, Junnar, Nalasopara and Kanheri) in India. The materials studied are pottery sherds and the new data aim to enrich the Indian archaeointensity dataset available for the last 3000 years. **Lisé-Pronovost *et al.* (2020)** present new archaeointensity data for nineteenth-century firebricks from a foundry in Melbourne, Australia. These new data are in agreement with historical absolute intensity measurements available for recent centuries and represent the most precisely dated archaeomagnetic data produced so far for Australia. **Turner *et al.* (2020)** use Hangi stones (volcanic stones used to retain heat in traditional Maori earth ovens) to recover the intensity of EMF at the time they were last used. They present 12 new archaeointensity records from New Zealand that, together with published data, give evidence for a possible fifteenth-century AD archaeomagnetic spike in the SW Pacific Region. In Europe, **Genevey *et al.* (2019)** present 14 new archaeointensity data from baked-brick fragments collected from civil and religious buildings in Pisa and surroundings (central Italy). The bricks studied are dated between the twelfth century and the end of the seventeenth century AD and they importantly enrich the Italian archaeointensity dataset. The new Tuscan results, together with previously published data from Italy and France, allow better recognition of three intensity peaks during the last millennium in Western Europe. **Kostadinova-Avramova *et al.* (2019)** also present new archaeomagnetic data for Europe but from a much older time period, the Neolithic. They studied archaeological baked clay structures from several archaeological sites in Bulgaria, offering new directional and absolute intensity records, enriching our knowledge about the secular variation path in Bulgaria during this period that is still poorly covered even in Europe, the geographical area with the greatest density of archaeomagnetic records. Finally, **Le Goff & Gallet (2019)** investigate the resolution of archaeomagnetism at a regional scale by analysing the French directional archaeomagnetic database between AD 1000 and 1500. Their analysis highlights the importance of the dating precision of reference data for constructing a detailed secular variation curve. They also show that, given the nature of the archaeomagnetic data used to calculate a reference curve at regional scale, it is very difficult to precisely detect rapid directional fluctuations that may have occurred over a timescale of one or two centuries.

Palaeosecular variation, sediments and climate

Apart from the archaeomagnetic data, palaeomagnetic records from sedimentary sequences can also offer precious information about the path of the geomagnetic field in the past. In contrast to archaeological artefacts, which can only give spot records, sediments offer continuous and often high-resolution data that can span time periods much older than the archaeological and historical record. The palaeomagnetic data from sedimentary sequences play a fundamental role in the detection and better understanding of geomagnetic field reversals and in extrapolating regional and global geomagnetic field models to much older periods than the last few millennia. Moreover, sediment cores can be drilled in parts of the Earth, such as oceans or isolated areas, offering data from areas that otherwise would be impossible to explore from a palaeomagnetic point of view. In spite of these great advantages, the recovery of palaeomagnetic declinations (orientations with the magnetic north of the EMF) from sedimentary records can be limited by problems related to the difficulty of retrieving long azimuthally oriented cores. They can only give paleoinclinations (orientation with the horizontal) and relative palaeointensity determinations and may be affected by deflections of the acquired detrital remanent magnetization owing to compaction, bioturbation, alteration, etc. Many of these limits can nowadays be overcome (e.g. automatic magnetic declination realignment; Lurcock & Florindo 2019) and new studies can constitute important contributions to the acquisition of new, high quality palaeomagnetic data from sedimentary cores.

In this section of the Special Publication, **Di Chiara (2020)** presents a review of all of the available literature data from the African continent, including palaeomagnetic data from lake and marine sediments, volcanic and archaeological materials spanning from 25 ka to the present day. Such a compilation clearly shows that Africa is still an undercovered area, despite its geographic importance for understanding the recurrence of the SAA and improving the reliability of global models. **Lakshmi *et al.* (2020)** present relative palaeointensity data for the past 2 ka from sediments of the Tirna Basin in India obtained using the pseudo-Thellier method. Good agreement is observed between the Tirna Basin relative palaeointensity proxies and global geomagnetic field curves with an age shift, suggesting that these Indian sediments successfully recorded the global-scale geomagnetic field pattern. **Lurcock *et al.* (2020)** present the palaeomagnetic secular variation and relative palaeointensity records from a 7 m-long sedimentary core drilled in the Tyrrhenian Sea. The new data offer a high-resolution dataset spanning the past 4500 years. An independent age model available based on tephro- and biostratigraphic information makes these magnetic records useful for the construction of future Italian and Western European master curves, and for the improvement of Holocene geomagnetic models. **Herrero-Bervera & Snowball (2020)** study the rock and palaeomagnetic properties of a *c.* 205 m core from the Baltic Sea (Kattegat, International Oceanic Drilling Project Expedition 347), presenting new inclination relative palaeointensity records from the western Baltic. Such records, accompanied by an age model based on calibrated radiocarbon dates, are used for comparison with the Fennoscandia palaeomagnetic master curve of the last 14 ka, and reveal several inclination oscillations due to a dominant north geomagnetic pole longitudinal band in Europe.

For longer time periods, the interest is mainly on polarity reversals and excursions. In this context, **Caminha-Maciel & Ernesto (2020)** examine 20 magnetostratigraphic profiles from International Oceanic Drilling Project sediment cores distributed on the Earth's surface in order to investigate some characteristics of Virtual Geomagnetic Pole displacements during Brunhes-–Matuyama times. They analyse the kinematics of Virtual Geomagnetic Poles, including directional and velocity changes, and show that, despite the uncertainties in the magnetization of the sediments, the use of several sedimentary records is valid for obtaining kinematic parameters of the geomagnetic field when analysed on a statistical basis.

Finally, in this section, a discussion on the possible relationship between geomagnetic field intensity and climate is included. **Kilifarska *et al.* (2020)** analyse several climatic variables during the twentieth century in order to offer evidence of a possible geomagnetic 'signal' imprinted on climate. Their analyses show that the geomagnetic field–climate relationship is not rigid, but is rather a flexible one, because it is mediated by the near-tropopause ionization, ozone and humidity, each of which is subject to other influences.

Summary

In this Special Publication, we have collected new palaeomagnetic and rock magnetic studies from regions where data were geographically and temporally limited. The new data from archaeological materials refine the current dataset from Europe and, importantly, provide new constraints of the evolution of the EMF from areas where data were lacking, such as Australia, New Zealand and India. These studies confirm the great potential of archaeological artefacts to retrieve fine characteristics of the EMF path in the past but they also underline the importance of precise dating of the reference data and the quality of experimental determinations. New data from sedimentary sequences also fundamentally contribute to constraining the EMF, offering almost continuous geomagnetic field records from India, the Baltic Sea and the Tyrrhenian Sea. These studies also show that sedimentary records can reveal important features in EMF secular variation, often overcoming the limitations of azimuthally unoriented cores. Using previously published datasets, new studies highlight the importance of enhanced resolution of the reference palaeomagnetic records for better understanding of EMF short- and long-term features and their link to climate.

The geographical and temporal coverage of the data presented in this Special Publication makes it an important contribution to the palaeomagnetic community's ongoing effort to further investigate the behaviour of the EMF in time. Even though it is still difficult to answer to many open questions, the new studies enhance our knowledge and offer a fundamental new basis for mathematical interpretation and geomagnetic field modelling. We hope that this Special Publication can put another brick in the wall of geomagnetic field variation studies and can serve to inspire future investigations, enhancing their quantity and quality.

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