Journal of Archaeological Science 85 (2017) 66–82

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Advances in archaeomagnetic dating in Britain: New data, new approaches and a new calibration curve

Catherine M. Batt [a, *], Maxwell C. Brown [b, c], Sarah-Jane Clelland [a, d], Monika Korte [c], Paul Linford [e], Zoe Outram [a, f]

[a] School of Archaeological Sciences, University of Bradford, Bradford, BD7 1DP, UK
[b] Institute of Earth Sciences, University of Iceland, Sturlugata 7, 107, Reykjavík, Iceland
[c] GFZ German Research Centre for Geosciences, Telegrafenberg, 14473, Potsdam, Germany
[d] School of Materials, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[e] Historic England, Fort Cumberland, Eastney, Portsmouth, PO4 9LD, UK
[f] Historic England, 24 Brooklands Avenue, Cambridge, CB2 8BU, UK

ARTICLE INFO

Article history:
Received 28 March 2017
Received in revised form
6 July 2017
Accepted 7 July 2017
Available online 20 July 2017

Keywords:
Archaeomagnetic dating
Secular variation
Britain
Geomagnetic field
Magnetic direction

ABSTRACT

Archaeomagnetic dating offers a valuable chronological tool for archaeological investigations, particularly for dating fired material. The method depends on the establishment of a dated record of secular variation of the Earth's magnetic field and this paper presents new and updated archaeomagnetic directional data from the UK and geomagnetic secular variation curves arising from them. The data are taken from publications from the 1950's to the present day; 422 dated entries derived from existing archaeo and geomagnetic databases are re-evaluated and 487 new directions added, resulting in 909 entries with corresponding dates, the largest collection of dated archaeomagnetic directions from a single country. An approach to improving the largest source of uncertainty, the independent dating, is proposed and applied to the British Iron Age, resulting in 145 directions from currently available databases being updated with revised ages and/or uncertainties, and a large scale reassessment of age assignments prior to inclusion into the Magnetic Moments of the Past and GEOMAGIA50 databases. From the significantly improved dataset a new archaeomagnetic dating curve for the UK is derived through the development of a temporally continuous geomagnetic field model, and is compared with previous UK archaeomagnetic dating curves and global field models. The new model, ARCH-UK.1 allows model predictions for any location in the UK with associated uncertainties. It is shown to improve precision and accuracy in archaeomagnetic dating, and to provide new insight into past geomagnetic field changes.

1. Introduction

The development of precise, robust site chronologies is a central concern in all archaeological work and there are a range of scientific dating methods available to address this issue. Archaeomagnetic dating is a valuable addition to the suite of chronological tools available to archaeologists working on both commercial and research excavations. Its particular strengths are the applicability to baked clays, fired stone and ceramic materials, which survive well in the archaeological record, and the clear relationship between the event dated, typically the last cooling of the material, and human activity. The method can be more precise than other techniques for certain periods of time and for specific situations (e.g. Outram and Batt, 2010); for example, it potentially has good precision in periods where radiocarbon dating has large errors, such as the British Iron Age and the Early Medieval period (Linford, 2006).

The method was first established in British archaeology by Aitken and colleagues (Aitken, 1958, 1960; Aitken and Weaver, 1962), building on an initial investigation by Cook and Belshé (1958). Following a period of development, the basis for its routine use was set out by Clark et al. (1988). Since then there have been significant developments to the method, both in the UK and

---

* Corresponding author.
E-mail addresses: c.m.batt@bradford.ac.uk (C.M. Batt), maxwell@hi.is (M.C. Brown), sarah-jane.clelland@manchester.ac.uk (S.-J. Clelland), monika@gfz-potsdam.de (M. Korte), Paul.Linford@HistoricEngland.org.uk (P. Linford), Zoe.Outram@HistoricEngland.org.uk (Z. Outram).

http://dx.doi.org/10.1016/j.jas.2017.07.002

internationally (Sternberg, 2008). The aim of this paper is to present new and re-evaluated UK archaeomagnetic data and the geomagnetic secular variation curves arising from them. Such discussions are uniquely important in archaeomagnetic dating as the precision and accuracy of dates provided by the method improve as more data are used in the construction of dating curves. Archaeomagnetic studies also have a wider significance as they provide the most detailed record of how the geomagnetic field has changed over recent millennia; crucial to understanding deep Earth processes, the space environment, palaeoclimate and volcanism (Brown et al., 2015a; Constable and Korte, 2015).

2. Context of investigation

In common with many dating methods, the development of archaeomagnetic dating requires expertise from both natural sciences and archaeology. However, in archaeomagnetic dating, archaeological input is particularly crucial. The principles of the method are well-established (Linford, 2006; Clark et al., 1988). The Earth's magnetic field in the past can be recorded by fired archaeological materials or sediments and a date is obtained for this geomagnetic record by comparison with a dated record of changes in the geomagnetic field over time, known as the secular variation (SV) record. Scientists have directly recorded changes in the Earth's field in the UK since the 16th century CE (Malin and Bullard, 1981; Jonkers et al., 2003); prior to this the SV record is obtained from magnetic measurements on materials with an independent date established using other scientific techniques (such as radiocarbon or luminescence), documentary sources or the archaeological information (Clark et al., 1988). The SV record is only as good as the independent dating evidence on which it is based. Hence, key to the method's development, is a good understanding of the challenges of archaeological chronologies and the interpretation of cultural remains, requiring excellent communication with archaeologists in the assessment of supporting dating evidence. The initial development of the method is slow and laborious, as it requires large numbers of measurements on materials of known date. It is also important that the independent dates are re-evaluated regularly, as more evidence becomes available and archaeological understanding develops. Lanos et al. (1999) describe SV records as ‘living organisms’ which evolve with the addition of new data; this development also extends to new archaeological approaches, new typological sequences and new theoretical paradigms that affect the independent dates. SV is specific to a region (c. 1000 km in diameter) as the geomagnetic field changes spatially as well as with time (Jackson and Finlay, 2015) and so the data need to be considered on a regional basis.

The mechanism by which fired materials acquire a thermoremanent magnetisation (TRM) which reflects the field at the time of last high temperature heating (over c. 580 °C) are well-understood (e.g., Tauxe, 2002) and such materials form the majority of archaeomagnetic studies. The acquisition of remanent magnetisation by sediments is still a subject of debate and different mechanisms have been proposed (see reviews by Tauxe and Yamazaki, 2007; Roberts et al., 2013). In essence, magnetic grains align with the geomagnetic field either during or after deposition. In some instances, remanence acquisition can be delayed and may not represent the time of deposition. Hence, there may be difficulty in associating depositional remanences with a specific archaeological event (Batt, 1999). Sediments are also more prone to bioturbation and disturbance after deposition, and such changes are harder to detect than they would be with fired structures. For these reasons, and because of their availability on archaeological sites, archaeomagnetic studies are dominated by the investigation of fired materials. However, sediments can provide a continuous record of SV, rather than the single magnetic direction typically available from a fired structure and studies have shown that fine grained, undisturbed sediments in archaeological environments can provide reliable archaeomagnetic directions (Batt, 1999; Ellis and Brown, 1998).

Archaeomagnetic dating can be based on variations in the direction (that is declination and inclination) or the intensity of the past geomagnetic field or, ideally, both. Estimates of intensity have the advantage that they can be obtained from fired materials that are not *in situ* and require very small samples, vastly increasing the range of materials investigated. However, intensity experiments on fired materials are challenging, with alteration and magnetic domain state effects potentially biasing estimates of past intensity (Thomas, 1983; Aitken et al., 1988; Valet, 2003; Tauxe and Yamazaki, 2007; Genevey et al., 2008; Brown et al., 2015a). In contrast, directions are experimentally straightforward to obtain, but require *in situ* material, with precise orientation during excavation (Clark et al., 1988). In many regions of Europe all three components of the magnetic field are routinely analysed and many countries have their own SV curves (e.g. Gómez-Paccard et al., 2006; Schnepp and Lanos, 2005; Lanos et al., 1999; Kovacheva et al., 2009, 2014; Tema and Kondopoulou, 2011). In addition Kostadinova-Avramova et al. (2014) have demonstrated the value of using stratigraphic constraints alongside all three components. Although ceramics are commonly available, intensity analyses have yet to be widely adopted in the UK, mainly because of the experimentally challenging nature of intensity determination. This leads to limited precision available in dating using intensity, as there are fewer data with which to build calibration curves and the data often have large uncertainties. There have been significant developments in the methods used to obtain estimates of intensity, which have now been applied to archaeological materials. These include the microwave method (e.g., Shaw et al., 1999; Hill and Shaw, 1999; Stark et al., 2010); the Triaxe method (Le Goff and Gallet, 2004; Gallet et al., 2015); the multi-specimen method (e.g., Ertepinar et al., 2016; Schnepp et al., 2016); modifications to the Thellier-Thellier method, e.g., the IZZI protocol (Shaar et al., 2011) and extended versions of the Shaw technique (e.g. Yamamoto et al., 2015). However, so far there are only a limited number of studies of intensities on UK samples (e.g. Casas et al., 2005; Suttie, 2010). None of the previous UK SV curves considered intensities, so updating these data was beyond the scope of the present work. Common practice in many other regions argues strongly for the routine measurement of the full magnetic vector in future UK studies, or at least the retention of suitable samples from directional investigations to allow intensity studies in future.

3. UK archaeomagnetic data

3.1. Databases

As discussed above, the biggest limitations to archaeomagnetic dating are the precision and accuracy of the SV curves. This can be addressed by increasing the amount of reliable data used to construct them, as well as improving the precision of the independent age estimates associated with each magnetic measurement. It is therefore vital to collate and evaluate all existing archaeomagnetic data in the UK. Such a compilation also allows regular review and can easily provide data for construction of SV curves.

3.1.1. The Magnetic Moments in the Past database

The ‘Magnetic Moments in the Past’ project (University of Bradford/English Heritage now Historic England) was initiated to develop archaeomagnetic dating in the UK, partly through producing a flexible database of archaeomagnetic information. Whilst several databases of archaeomagnetic and palaeomagnetic data currently exist, such as GEOMAGIA50 (discussed below), the IAGA archaeomagnetic directional database (http://www.ngdc.noaa.gov/geomag/paleo.shtml), and the databases hosted by the Magnetics Information Consortium (http://earthref.org/MAGIC/), these are designed specifically for archaeomagnetists, palaeomagnetists, and modellers of the geomagnetic field. The 'Magnetic Moments in the Past' database differs as it also contains information relevant to the archaeological community and was developed in consultation with archaeologists, heritage groups and archaeomagnetists to ensure that it contains the data required by each group. This was seen as essential in promoting the value of the technique and therefore increasing the number of archaeomagnetic determinations produced.

The database was constructed using Microsoft Access, utilising a series of relational tables that contain information about the site, sampled deposits, the archaeomagnetic data, independent age estimate for a feature and the publication details. The archaeological query form allows users to interrogate the database by location, type and age of feature sampled. The information presented for each study includes details of the site, sampled features and calibrated age ranges. The magnetic measurements include the number of samples, mean declination, inclination and α_{95} (measure of the uncertainty associated with the mean direction) for each feature after removal of unstable components (Tarling, 1983: 89), but not the individual sample magnetic measurements as it was concluded that this level of detail was too complex to include and rarely available or used. An image of the sampled feature is also provided where possible, informing sampling strategies on future sites. The archaeomagnetic query form allows the information required to construct a SV curve to be obtained from the database, including site information, archaeomagnetic data and evidence used to assign an independent age estimate to the sampled feature. The data can be filtered based on the mode of remanence acquisition, the precision of the archaeomagnetic data (defined by the α_{95} and/or the precision parameter, k), and the age of the sampled feature. The data from a specific geographic area can also be extracted based on the minimum and maximum latitude and longitude values. Where possible the precision associated with the independent age estimate is given using '68%' and '95% confidence' check boxes. A third option is available for estimates based on archaeological/historical evidence where the precision cannot be statistically defined.

The database is available from the Magnetic Moments in the Past website (http://www.bradford.ac.uk/archaeomagnetism) as a Microsoft Access database or as Microsoft Excel files. In addition, a simplified version of the query form designed for archaeologists is available as a web-searchable database on the Archaeological Data Service website (http://archaeologydataservice.ac.uk/archives/view/magmoments_ahrc_2010/).

The database also allows archaeomagnetists to identify where further work is required and to initiate sampling programmes accordingly. For example, sites dating to a particular period of time or from a specific region of the country can be targeted to address the uneven temporal and spatial distribution of archaeomagnetic studies. The database contains 939 directional pairs from 440 locations; however, a small number do not have ages, as discussed in Section 3.4.

3.1.2. GEOMAGIA50

In addition to being made available in the Magnetic Moments in the Past database, updated and new UK directional data have been added to the GEOMAGIA50 database (Korhonen et al., 2008; Brown et al., 2015a). GEOMAGIA50 is an online database (http://geomagia.gfz-potsdam.de/) of palaeomagnetic and chronological data from archaeological materials, volcanic rocks and sediments spanning the past 50 ka.

The most recent version of the database (GEOMAGIA50.v3) was published in May 2015 and contained 448 directional entries (pairs of declination and inclination) from the UK. As part of this study we reassessed all UK entries in GEOMAGIA50.v3. This involved cross-checking every entry with the Magnetic Moments of the Past database and updating any revised ages (see section 3.3). Inclination, declination, α_{95}, k, dating methods, age, age uncertainties, site coordinates, site names, site horizons, sample identifiers and material types were all checked and amended if necessary. Updates or corrections were made to 145 ages and/or their uncertainties, 207 latitudes and/or longitudes, 29 declinations, 60 inclinations and 18 values of α_{95}. Of the age revisions 65% resulted in a difference in the mean age of 100 years or less; however, nearly 10% of assigned ages were revised by 500–3000 years. Eleven directions from Gentles (1989), which had been uploaded as relocated to Meriden, were corrected by recalculating site mean directions using the specimen level data given in Gentles (1989). New site and context information was added for the majority of entries.

Twenty six entries were removed from GEOMAGIA50.v3 (leaving 422 remaining entries). They were duplicates, had an origin that could not be confirmed by the Magnetic Moments of the Past database, or were relocated to Meriden (and lacked specimen data in the original publication to confidently allow site mean directions to be recalculated, as discussed in Section 4.1).

In addition, 487 directions from the Magnetic Moments in the Past database, not previously included in GEOMAGIA50.v3, have now been uploaded. This totals 909 UK directional entries from 432 locations (presented below). This differs from the 939 entries in the Magnetic Moments in the Past database, as all GEOMAGIA50 entries require age and not all entries in the Magnetic Moments in the Past database have been assigned an age, for the reasons discussed in Section 3.4.

3.2. Data sources

The archaeomagnetic data collated includes the early UK publications (e.g. Cook and Belshé, 1958; Aitken, 1958, 1960; Aitken and Weaver, 1962), summarised in the first major compilation made by Clark et al. (1988). It also includes the data collated within the Plymouth archaeomagnetic directional database established by Tarling (http://www.ngdc.noaa.gov/geomag/paleo.shtml) as well as the work of Zananiri et al. (2007). A number of additional studies were located during the course of the 'Magnetic Moments in the Past' project and by Clelland (2011), including archaeomagnetic dating reports, theses, site monographs, grey literature and personal communications with UK archaeomagnetic laboratories.

3.3. New approaches to interpreting independent archaeological dates

As discussed in section 2, construction of the SV curve requires independent dates for measured magnetic directions. These may be provided by another scientific dating technique, documentary sources or archaeological information. By the 1970's a substantial body of archaeomagnetic data had been collected worldwide and it was becoming apparent that the dating errors were limiting attempts to estimate past secular variation, regardless of the type of archive utilised, whether archaeological, marine, volcanic or sedimentary records (e.g. Cong and Wei, 1989). This problem has been acknowledged by all workers since the 1980's (for example Barton, 1982; Bucur, 1994; Donadini et al., 2009; Márton, 2003) but it is often underestimated. There are two key issues that require consideration; whether the independent date reflects current archaeological knowledge, and whether it dates the archaeomagnetic event.

As early as 1960, Aitken recognised that the age estimates provided by archaeologists during archaeomagnetic sampling were often preliminary and required revision after post-excavation analysis, when the archaeological and scientific chronological evidence are synthesised into a holistic and objective model. The information recorded within archaeomagnetic databases usually relies on the data available at the time of sampling and therefore may not represent the best data available. Even the final archaeological site report represents the theories and interpretations prevalent when the report was produced. Approximately 20% of the studies included in the UK database were conducted in the 1950s and 1960s, before scientific dating was routinely used on archaeological sites. The discipline of archaeology has changed dramatically since this time, including methodological developments, improvements to scientific dating such as radiocarbon calibration, changes to theoretical paradigms, more cautious approaches to the relationship between artefacts and features of interest, developments in artefact typologies, and a greater awareness of archaeological formation processes (Trigger, 2007; Hodder, 1992; Renfrew, 1973; Schiffer, 1987). It is not acceptable for a SV curve to be based on out-dated ideas or theories and so the data must be regularly reassessed (Lanos et al., 1999:378).

Ensuring that the independent information dates the archaeomagnetic event is also complex, as it requires an understanding of how independent dates have been obtained, how archaeologists use this information and how this is related to the event recording the geomagnetic field. For example, the archaeomagnetic direction obtained from a hearth relates to last use of the feature, which may be interpreted as the abandonment of that structure, or at least the end of a particular phase of activity. Of UK archaeomagnetic studies approximately 85% rely on archaeological and/or historical evidence to assign this age estimate, usually because scientific dates were too expensive or there was a lack of suitable material. Dating strategies employed on most archaeological excavations focus on developing a narrative for the entire site, but archaeomagnetic studies require an estimation of the point in time an individual feature went out of use. A re-evaluation of this requires an understanding of the relationship between the physical processes being exploited for dating purposes and archaeological formation processes, to improve the accuracy of the age estimates applied to archaeomagnetic data. There has been no systematic review of the independent dating evidence for archaeomagnetic directions in Britain since their initial publications, so an investigation is timely.

In order to demonstrate the impact that reviewing the age estimates can have on the SV curve, the first millennium BCE section of the UK database was targeted (Clelland, 2011), specifically the Iron Age period of British prehistory. There is evidence from across Europe that the Earth's magnetic field experienced rapid changes in direction during this time (Frank et al., 2002; Gallet et al., 2002; Hervé et al., 2013; Nourgaliev et al., 2005; Ojala and Saarinen, 2002; Ojala and Tiljander, 2003; Snowball and Sandgren, 2002; Snowball et al., 2007; Stockhausen, 1998), suggesting that archaeomagnetism could potentially enable high-resolution dating of British Iron Age archaeology. Furthermore, many of the magnetic directions from prehistoric sites in the previously published British databases (Clark et al., 1988; Zananiri et al., 2007) had been given the generic date range 700BCE- 43CE as they had been defined as “pre-Roman Iron Age”. Therefore it was likely that a review of the dates would give increased precision and accuracy.

Over 230 directions from 98 prehistoric sites were evaluated using an adapted version of the approach suggested by Armit (1991), where the potential dating methods were placed into a hierarchy reflecting the reliability of each of the methods (Clelland, 2011). As with all dating methods, the challenge was associating the event dated by each method to the actual archaeological event of interest (Taylor, 1987: 15). For example, radiocarbon determinations were only considered if they could be closely related to the event that caused the geomagnetic field to be recorded (e.g. from a charred grain within a hearth rather than unidentified charcoal which might be old at the point of deposition) or when there was a stratigraphic relationship between the radiocarbon determination and the context sampled for archaeomagnetic studies, in which case Bayesian methods of analysis using Oxcal (Bronk Ramsey, 2009) were employed (Fig. 1a). Throughout this process the main concern was to ensure that the date range allocated to each of the magnetic directions provided the most accurate reflection of the associated archaeology based on the available information from the archaeologist, even if this reduced the precision of the independent date. The stratigraphic record was used to combine all the available chronological indicators to answer a single question: when did the feature sampled acquire its magnetisation?

In most instances, it was found that small adjustments could be made by considering the site chronology and understanding how the event dated by archaeomagnetism fits the overall site narrative (Clelland, 2011). In some cases major reinterpretation was possible. For example, at the site of Little Bay on the Isles of Scilly, first exposed during storms in 1891 and excavated in 1952–53, 1974 and 1980 (Neal, 1983), excavations revealed four buildings and archaeomagnetic samples were taken from a burnt feature in Building 2, a stone built roundhouse. This magnetic direction is included in the first British archaeomagnetic dataset (Clark et al., 1988) with an independent date of ‘probably Iron Age’, which became 700BCE-43CE in subsequent databases (Zananiri et al., 2007). However, three stratigraphically related radiocarbon determinations were subsequently obtained (Jordan et al., 1994). Bayesian analysis of this sequence (Fig. 1b) demonstrates that the dating evidence matches their stratigraphic positions, and indicates that the context sampled for archaeomagnetism actually dates to *1695BCE-1265calBCE*. The wide age range arises because of the imprecision of radiocarbon dating at the time and the nature of the samples, but it is clear that the feature is much earlier than the previous accepted age range, which has implications for the models obtained. This is supported by more recent interpretations of the archaeological evidence of the structures and ceramic assemblage as being Late Bronze Age (Neal, 1983; Clelland, 2011). More precise results would be obtained if modern radiocarbon dates on short lived samples were available.

This approach has led to significant improvements to the British archaeomagnetic dataset as the age estimates examined now represent a more accurate indication of the associated archaeology and over a third are more precise. In some cases the age ranges have increased as discussed in section 3.4.

3.4. Data evaluation

The exhaustive data collection has resulted in a significant increase in the total number of archaeomagnetic determinations from 92 determinations (Clark et al., 1988) and 620 in Zananiri et al. (2007) to 939 collected from 440 locations in this compilation (Fig. 2). Of the 620 entries in Zananiri et al. (2007), 571 entries had an associated age or site coordinates. Of the 939 in our new compilation 909 have been assigned an age. Some data are included in the Magnetic Moments in the Past database with no associated age estimate, usually because excavation or post-excavation work are still going on and this information needs adding at a later stage. This is the largest collection of independently dated

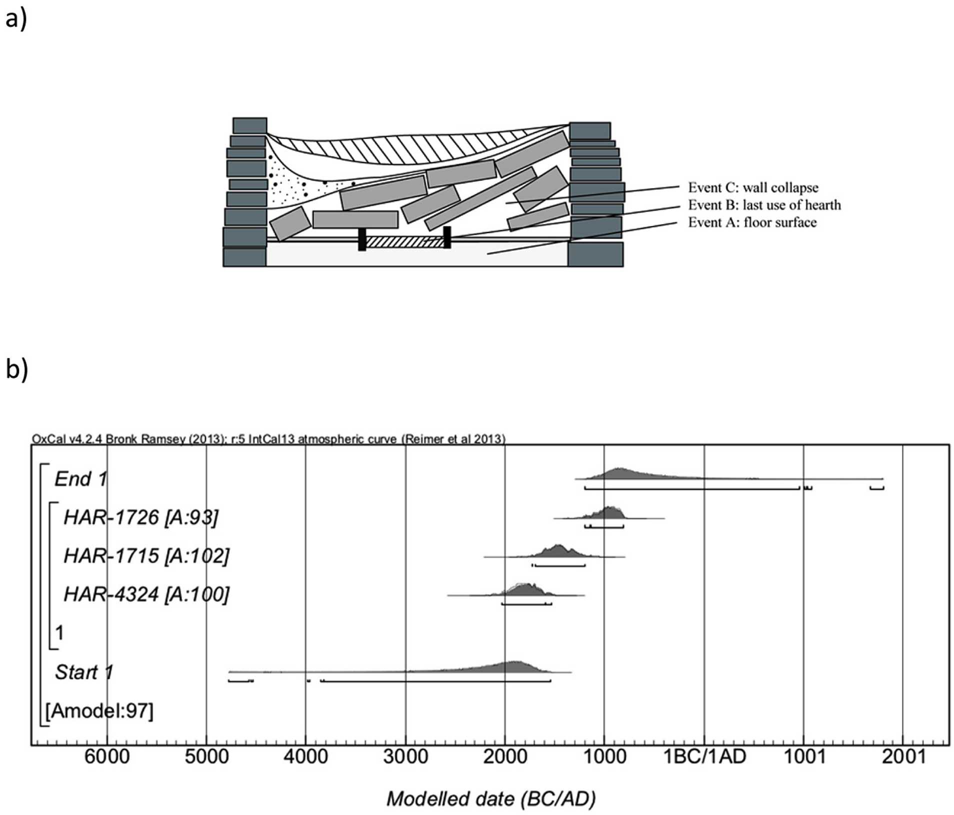


Fig. 1. Example of use of archaeological and Bayesian re-evaluation to improve independent dating. a) A sequence of archaeological events, A B and C, constrained within a structural unit. The archaeological evidence indicates that event A (floor surface) is earlier than B (last use of the hearth) and both A and B happened before event C (collapse of structure). If a date can be estimated for events A and C, for example via radiocarbon dating, then it is possible to calculate the most probable age range for event B, the event of archaeomagnetic interest. b) Radiocarbon dates on charcoal from Little Bay within a stratified sequence (HAR-1726 overlies HAR-1715 which overlies HAR-4324). HAR-1715 was obtained from the same context as the archaeomagnetic study. Bayesian analysis of the sequence allows a constrained date to be obtained for the context of interest (Clelland, 2011; Bronk Ramsey, 2009).

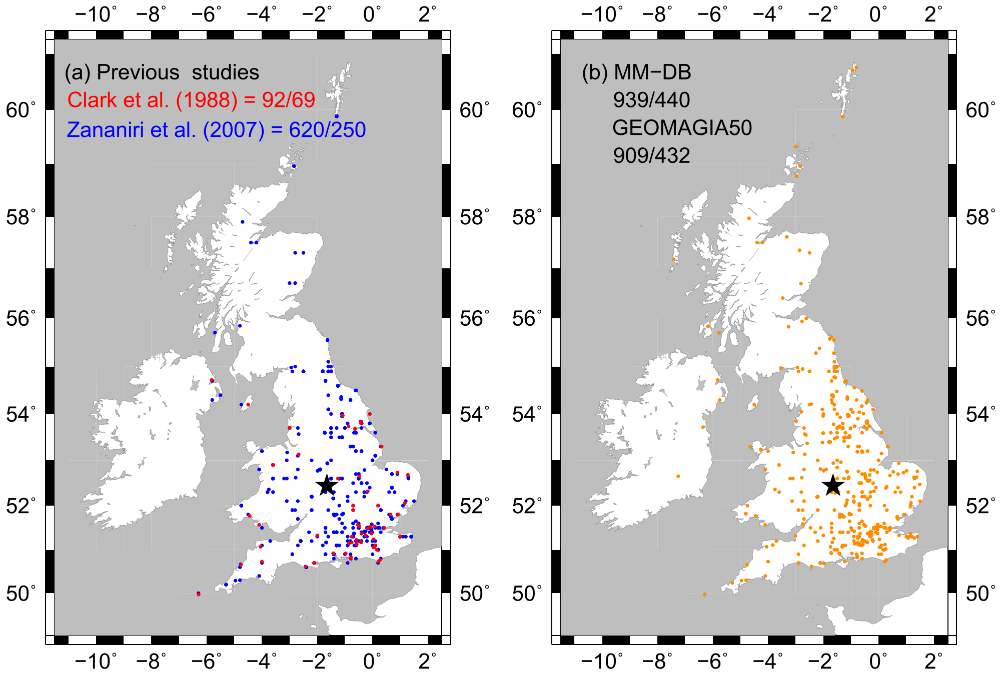


Fig. 2. Spatial distribution of archaeological locations within (a) the compilations of (red) Clark et al. (1988) and (blue) Zananiri et al. (2007) and (b) the Magnetic Moments in the Past (MM-DB) database (orange; this study). n/N is the number of entries and the number of locations. Differences between latitudes and longitudes of some archaeological sites in (a) and (b) arise from corrections made in the compilation of the Magnetic Moments in the Past database. Black star is the location of Meriden, traditionally used as the central location for UK data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

archaeomagnetic directions reported from a single country. The number of data in the Magnetic Moments in the Past database and GEOMAGIA50 differ as not all directions in Magnetic Moments in the Past have an associated age, some entries from that database have been combined into single entries in GEOMAGIA50 and some entries in GEOMAGIA50 do not appear in Magnetic Moments in the Past as they lack the necessary contextual metadata.

The geographical distribution of the sites sampled for archaeomagnetic dating is skewed, with the majority of studies being located in southern England: only 10% of the sampled sites are above 55° latitude (Fig. 2). This distribution may affect the accurate development of SV curves due to the way in which the Earth's magnetic field varies both temporally and spatially, as a result of the behaviour of the non-dipole field. It is generally accepted that ideally data for the SV curve should be gathered from approximately 1000 km around the site under investigation (Shuey et al., 1970; Tarling, 1989; Noel and Batt, 1990); but it is clear that some of the northern and western areas of the UK have little data in close proximity. Further studies are required to investigate the significance and impact that this may have on the application of archaeomagnetic dating in these areas.

The data are also unevenly distributed through time (Fig. 3a). The database is dominated by features sampled from Medieval (1066CE-1540CE), Roman (43CE-410CE) and Iron Age (800BCE-43CE) sites, which reflects activity in the past, the nature of recent archaeological investigations and preservation of features (definitions of dates used throughout are taken from Forum on Information Standards in Heritage, 2016). This distribution is also influenced by whether excavators consider archaeomagnetic studies worthwhile, and therefore whether they make features available for sampling; a factor that is particularly influential in early periods (for example only ~2% of directions have assigned ages before 1000BCE). Although the temporal distribution of data has improved, the early Iron Age (c. 800BCE-300BCE) is still poorly represented, probably a true reflection of the British archaeological record. Many Iron Age sites show continuity of use from the late Bronze Age through to the late Iron Age or early Roman period (Sørensen and Thomas, 1989), meaning that later occupation in the same location has destroyed earlier remains. Therefore, as archaeomagnetism provides a date for the last use of a feature, the early Iron Age will be poorly represented. This situation is further compounded by the difficulty of identifying late Bronze Age/early Iron Age transition sites and the under-use of archaeomagnetism on prehistoric sites. Concerted efforts are needed to collect more data from these periods.

The age uncertainty of the data (Fig. 3b) has largely improved following re-evaluation. Although for the majority (65%) of data in GEOMAGIA50 the modifications are smaller than 100 years, they range between 100 and 500 years for 26% of the revised data and are larger than that in about 9% of the cases. However, some of the independent dates derived from older studies were based on an over-reliance of the precision of typological dates for pottery and the age ranges have had to be revised upwards. Whilst 43% of the date ranges span less than 200 years, other periods would benefit from similar re-evaluation to the Iron Age focus described above. 76% of directions have α_{95} values of less than 5° (Fig. 3c), commonly considered to be the maximum appropriate for dating (Linford, 2006), but less precise data have been included as sometimes they are the only data available for a period or region. Sixteen directions were published without α_{95} values (Fig. 3c).

Analysis of the types of features investigated (Fig. 3d) shows that the vast majority (~70%) are ovens, hearths and kilns which reflects their use in the past, survival and ease of identification on archaeological sites. The range of materials amenable to archaeomagnetic studies is demonstrated by 'Other' which includes hypocausts, burnt pits and iron-smelting furnaces.

Site inclinations range from 30° to 86°, with a Fisher mean inclination of 65° (Fig. 3e). At two standard deviations, site inclinations lie between 52° and 78°. Although site declinations have a large range (Fig. 3g), between 289° and 82°, at two standard deviations the range is reduced, with site declinations between 338° and 30° and Fisher mean declination of 3.9°. It is common practice in UK archaeomagnetic studies to relocate magnetic directions to Meriden (52.43°N; 1.62° W), taken to be the centre of England, using the tilted dipole reduction method in order to reduce errors arising from spatial magnetic field variation (Noel and Batt, 1990; Tarling and Dobson, 1995). This correction results in only a small change to the Fisher mean directions and the shape of the inclination and declination distributions (Fig. 3f, h). This is unsurprising as the majority of data are from southern England and the Midlands, resulting in only minor changes in direction on relocation. The relocated Fisher mean inclination of 64.5° for all samples is slightly shallower than the geocentric axial dipole (GAD) value of 68.9° expected for Meriden.

Although Clark's hand-drawn SV curves (Clark et al., 1988) were informed by the SV recorded in British lakes (Turner and Thompson, 1981, 1982), the lake sediment values are not included in this British dataset due to the lack of precision of the associated radiocarbon dates, issues arising generally with dating sediment sequences from unvarved sediments (Nourgaliev et al., 2005), and obscuring of the signal through the sampling procedure (Katari and Bloxham, 2001; Tauxe et al., 2006). The directions obtained from lake sediments are available in GEOMAGIA50 (Brown et al., 2015b). However there are 18 examples of magnetic directions that originate from depositional recording process within the UK database (2%), largely from short sediment sequences or single event deposits.

4. Secular variation curves and models

4.1. Previous UK secular variation curves

As discussed in the introduction, in order to use the data collected for dating it is necessary to infer from them patterns of geomagnetic change in the past. Early studies (Aitken, 1958, 1960; Aitken and Weaver, 1962) initially presented the data as declination vs time and inclination vs time, as the data were sparse and widely distributed over time. Where sufficient data were available secular variation was interpolated. The first comprehensive SV curve for the UK was produced by Clark et al. (1988); constructed using 238 direct observations of the geomagnetic field and archaeomagnetic directional data from 92 features, covering 1000BCE to the present day. It was presented as a Bauer plot (declination vs inclination, Bauer, 1896), with magnetic directions corrected to Meriden. The Clark et al. (1988) SV curve remained the principal method of calibrating archaeomagnetic dates in the UK for 20 years, although a number of shortcomings were identified (Batt, 1997, 1998; Tarling and Dobson, 1995). The main limitations were that the curve was drawn by hand through the data points, errors in the magnetic measurements and the independent dates were not represented or assessed, and some periods (particularly the 1st millennium BCE) were based on limited archaeomagnetic measurements and relied heavily on data from British lake sediment sequences.

The SV curve developed by Zananiri et al. (2007) increased the number of available archaeomagnetic data points to 620 and extended the curve back to 2000BCE. The SV curve was derived statistically utilising a Bayesian approach through the use of the RenCurve software developed by Lanos (Lanos, 2004; Lanos et al., 2005), which resulted in a robust and more objective SV curve.

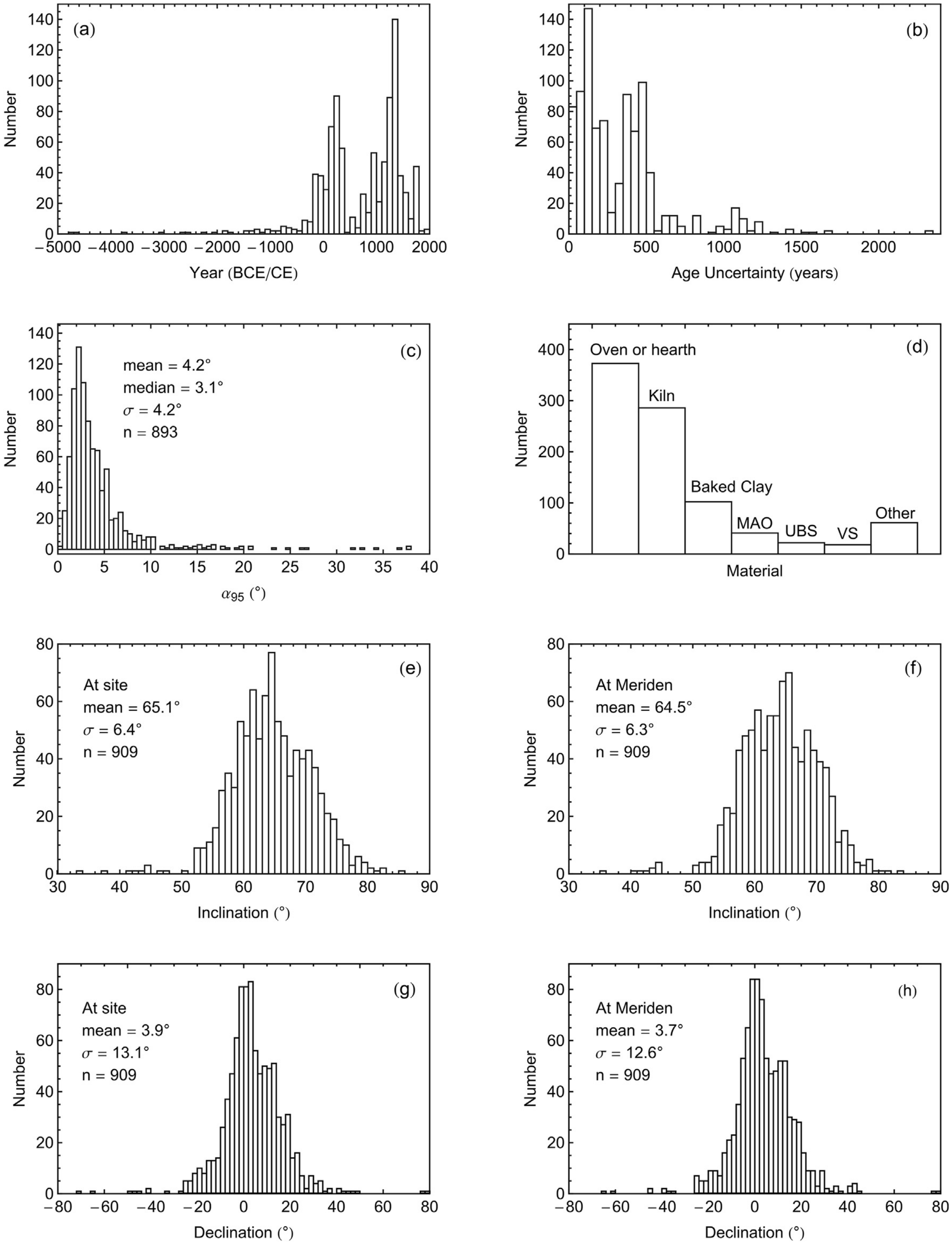


Fig. 3. Number of data by (a) age; (b) total age uncertainty (difference between youngest and oldest age); (c) α_{95} (Fisher, 1953; 16 entries lacked α_{95}); (d) material (MAO = mixed archaeological objects e.g. tiles and bricks combined; UBS = unbaked sediments; VS = vitrified stone; Other = ash, baked rock, brick, burnt earth/floor/pit/structure, hypocaust, not specified, pit structure, slag, soil); (e) inclination at site; (f) inclination relocated to Meriden; (g) declination at site; (h) declination relocated to Meriden; σ = one standard deviation, n = number of data.

This approach created a Bayesian hierarchical model of the experimental errors (Lanos, 2004), allowed the presence of any systematic errors due to sampling or measurement protocols to be identified, and made concessions to the quality of the magnetic data by weighting the analysis towards the more reliable magnetic data (Donadini et al., 2009; Lanos, 2004; Lanos et al., 1999), removing the need to reject data from an already limited dataset. RenCurve computes the directional curve using declination and inclination together but the record of SV was presented as two individual curves, inclination and declination vs. time, as there were now too many data to be clearly presented on a Bauer plot. An assessment of the error assigned to data included in the curve was presented as a 95% confidence envelope around each curve. Despite the improvements made, some periods of time were still not well defined, due to either a lack of data points, or a lack of precision associated with the independent age estimates assigned to each archaeomagnetic date, prompting the current study.

4.2. New UK geomagnetic field model and dating curve

The archaeomagnetic mean declination and inclinations of the updated and new data are presented in Fig. 4. In order to consider the data for future archaeomagnetic dating purposes, we derived a temporally continuous geomagnetic field and SV model for the UK. Such a model can provide curves of geomagnetic field variation for any location, in particular, new reference curves of declination, inclination and intensity for Meriden.

This UK model is based on a global model following the method used for the CALSxk and ARCHxk series of models, which are described in detail by, e.g. Korte et al. (2009), and similar to the method used by Lodge and Holme (2009). The model is obtained by an inversion using spherical harmonic functions in space and cubic B-splines in time. Spatial and temporal regularization constraints trade-off fit to the data against smoothness of the model, aiming at the simplest model that explains the observations within their uncertainties and avoiding spurious variations caused by too closely fitting erroneous data. Choosing the strength of these regularizations based on comparisons with the geomagnetic main field and secular variation power spectra provides models with the highest physically reasonable amounts of variability that can be inferred from the available data (Lodge and Holme, 2009; Korte et al., 2009).

We aim to obtain the best possible description of the surface geomagnetic field in a limited region by a model that is physically compatible with sources of secular variation deep in Earth's core, in order to avoid unrealistically fast or small-scale variations that might otherwise result from fitting some of the data too closely. Lodge and Holme (2009) used an existing global model as background with new European data with this same goal. In contrast, we use a global dataset and derived a new global model, while aiming for highest accuracy in the UK region. The global dataset is the same as used for ARCH10k.1 (Constable et al., 2016), i.e. all archaeomagnetic and volcanic data available from GEOMAGIA50.v3 (Brown et al., 2015a) up to 30th April, 2015. However, we removed all UK directional data from this data set and replaced them by the updated and new data described above. Our aim is the highest possible accuracy for the UK. Therefore we have down-weighted data from other regions by weighting all UK data four times more strongly than non-UK data; the factor of four was determined empirically through an assessment of misfit of model to data for different weighting factors. Each datum is weighted by its magnetic uncertainty estimate. Values of $\alpha_{95} = 3.4°$ and 5 μT, respectively, were used if no uncertainties were given. We do not have a good method to take age uncertainties into account directly. Therefore we discarded data with age uncertainties >750 yrs. In general the solution of our inverse problem is non-unique, therefore we

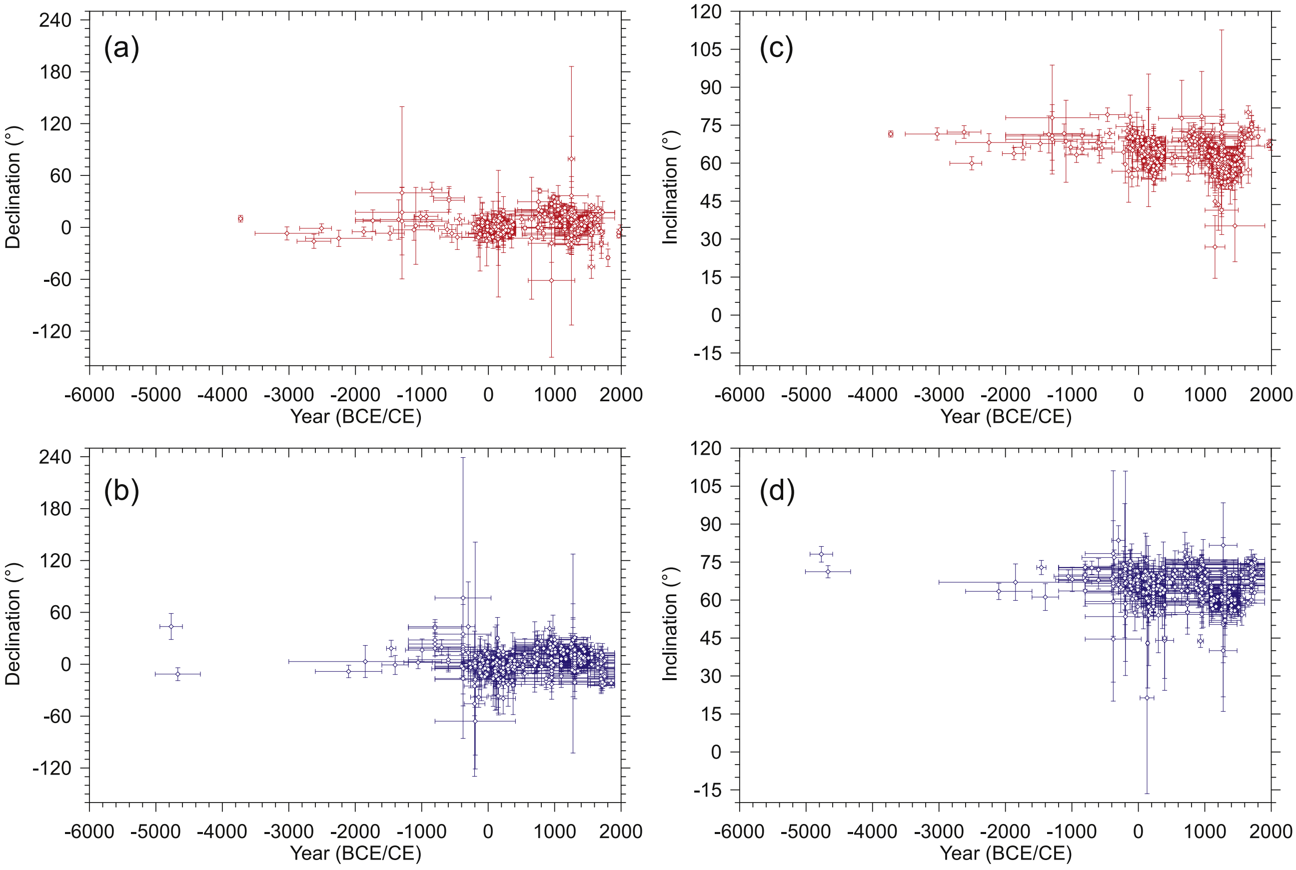
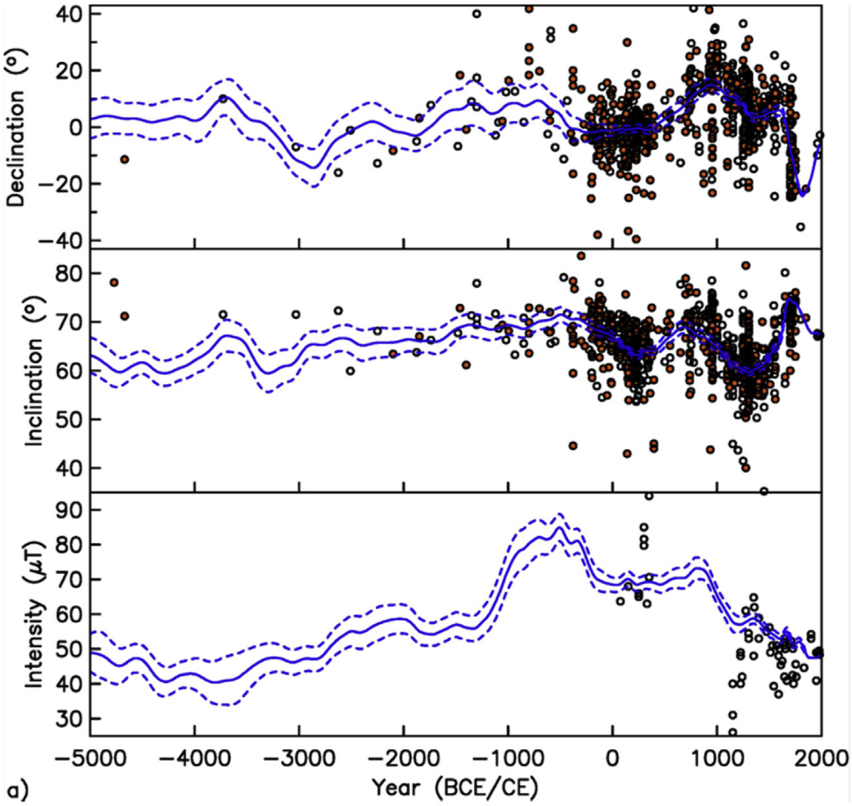


Fig. 4. The archaeomagnetic mean declinations and inclinations relocated to Meriden for updated data (red, a and c) and new data (blue, b and d), with their uncertainty estimates (declination uncertainty = α_{95}/cos(inc); inclination uncertainty = α_{95} (Tarling, 1983: 127)). The data without uncertainties is shown in Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



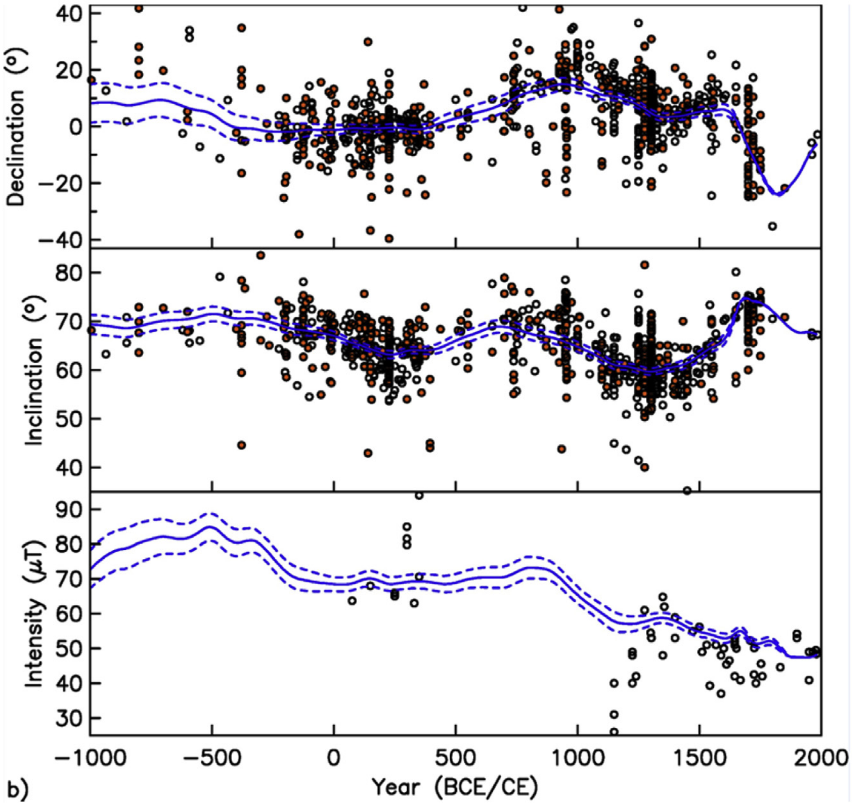


Fig. 5. Updated (open black circles) and new (orange dots) data reduced to Meriden compared with the output of the ARCH-UK.1 model (solid blue line) with its uncertainty estimates (dashed blue lines) for the same location. Data uncertainties have been omitted for clarity. (a) Full time interval and (b) zoomed in on 1000BCE to 1990CE with denser data coverage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

obtained an ensemble of 2000 models. Each model is based on a different data set where the archaeomagnetic data and their ages were varied randomly within their uncertainty estimates. The influence of the inhomogeneous data distribution was evaluated by bootstrap selections from the full data set (see Korte et al., 2009 for details). As with ARCH10k.1, our global models span the time interval 10 000BCE to 1990CE. Based upon the higher weighting of the UK data and their temporal coverage, we limited the validity of the model to the spatial range of 49° N to 61° N and 11° W to 2° E, and the time to 5000BCE to 1990CE. The recent part of the model is constrained to fit the *gufm1* model (Jackson et al., 2000) as described by Korte et al. (2009). *gufm1* describes the global field based on historical and recent direct magnetic field observations for 1590CE to 1990CE and provides the most accurate description of the geomagnetic field currently available for this time interval.

Our new ensemble average model is named ARCH-UK.1. Uncertainty estimates for component predictions can be obtained in two ways: from the standard deviation in the spherical harmonic coefficients of the ensemble or as the standard deviation of the individual components as predicted from all models. The first method gives somewhat larger and more uniform estimates, often more realistic in cases of sparse data coverage, but likely to be too pessimistic for times and areas with good data coverage. In general both methods might underestimate the uncertainties in large areas with insufficient data coverage (Korte et al., 2009).

We used the data's original site coordinates for the modelling, but for an easier comparison with the model, and as frequently done in previous archaeomagnetic studies (e.g. Clark et al., 1988; Zananiri et al., 2007), we show all data and model curves reduced to the location of Meriden (Fig. 5).

The model uncertainty estimates have been calculated as the standard deviation of all ensemble model predictions. Uncertainty estimates in declination and inclination are clearly small when data coverage is dense and larger for earlier periods where data are sparse. For intensity, where data coverage is extremely sparse, the uncertainty estimates are likely to be too optimistic. Several data fall outside the uncertainty estimates of the model in all components. Although in some cases this may result from the limited temporal variability of the model, which is not fully accounted for by its uncertainty estimates, for most periods there is no systematic under- or overestimation by the model predictions. Exceptions are intensity values younger than 1000CE, many of which are lower than the model predictions; a future study is need to evaluate these data in detail. The small number of UK intensity data (Fig. 5) clearly does not have a strong effect on the model, which is dominated by the much larger numbers of intensity values from France and other parts of Europe.

Part of the scatter of data around the model prediction for Meriden may result from variations in the non-dipole field that are not taken into account in the reduction to Meriden. The UK model allows the influence of the non-dipole field to be evaluated. Fig. 6 displays the geomagnetic field morphology over the UK and Ireland for two epochs, 500BCE and 1000CE, and Fig. 7a shows model predictions for the four outer corners of the same area. In Fig. 7b these curves have all been reduced to Meriden by the tilted dipole field assumption. Regional differences over this area are in the range of 10° in declination and inclination and 7 μT in intensity. In inclination and intensity most of the latitudinal differences result from a dipole field geometry. Changes in the contour line patterns between 500BCE (Fig. 6a) and 1000CE (Fig. 6b) illustrate variations in the non-dipole field over time. This is most clearly seen in declination, where the pattern of larger angles of declination in the west and smaller angles in the east in 500BCE is reversed in 1000CE. In inclination and intensity the latitudinal difference of the dipole field dominates. There is a nearly constant difference between northern and southern curves in Fig. 7a. Weaker non-dipole variations are indicated by slight differences in contour density between Fig. 6a and b, and by small variations in the predictions from the model area's four corners after reduction to Meriden (Fig. 7b). However, most of the time all four Meriden curves fall well within either of the bootstrap uncertainty estimates of the ARCH-UK.1 prediction for Meriden.

An important application of our new UK model is that individual dating curves, i.e. model predictions, can be generated for any location within the UK and Ireland. The reduction of archaeomagnetic data to a central location for dating is no longer necessary. However, for an area the size of the UK, a central dating curve can be used as reasonable approximation, if the data are corrected for the effect of dipole field geometry.

4.3. *Comparison to previously published global geomagnetic field models and reference curves*

We now investigate the improvements of ARCH-UK.1 in describing the geomagnetic field evolution over the UK and Ireland and its performance as a dating tool through comparisons with previously published archaeomagnetic field models and reference curves.

Recently published global models have been constructed from similar archaeomagnetic and volcanic datasets to those used in our UK model; however, these models include the old UK data and different strategies were used in the modelling. We compare our UK model with A_FM (Licht et al., 2013) spanning the past 3000 years; SHA_DIF.14k (Pavón-Carrasco et al., 2014) covering the past 14 000 years; and ARCH10k.1 (Constable et al., 2016) covering the past 10 000 years (Fig. 8a). All models at Meriden in general agree well, but the updated and new UK data revise the amplitudes of declination and inclination maxima around 1000CE and 800CE respectively, as a consequence of the scatter in the data set. Clear discrepancies existed among previous models between 1200BCE and 500BCE. Several new and updated directional data from these periods (see Fig. 5) lend credibility to our new model for this time interval. Prior to 1200BCE only slight differences are seen between ARCH-UK.1 and ARCH10k.1. These models are constructed in a similar way and there are only sparse data for this time (Fig. 5). ARCH-UK.1 is in slightly better agreement with the few existing and updated data from this time. The higher temporal variability of SHA.DIF.14k, particularly for times BCE, is not supported by our updated UK dataset. For most epochs the intensity variations predicted by all models agree within their uncertainty estimates (not shown in the figure). This is not surprising as data for the UK are scarce and were not reassessed as part of this study.

In Fig. 8b the two UK reference curves designed for archaeomagnetic dating by Clark et al. (1988) and Zananiri et al. (2007) are shown with ARCH-UK.1 predictions at Meriden. Also included are predictions from the GMADE2K.1 model (Lodge and Holme, 2009), which covers 1CE to 1900CE. GMADE2K.1is a global model, but was derived for Europe. It was constructed using European reference curves, including Zananiri et al. (2007), rather than individual data. Whilst there are broad similarities, differences among these curves underline the importance of plentiful data to obtain reliable reference curves. As discussed above Clark et al. (1988), nearly 30 years ago, had significantly less data to construct their curve. All more recent results suggest that some of the very strong variations seen in Clark's curve are spurious, due to too closely fitting uncertain data. However, it should be noted that any method that infers a smooth curve not constrained to pass through every data point will smooth out extrema, damping large variations even if genuine (Lengyel and Eighmy, 2002). We note that the scatter in our data set is relatively large, and the French secular variation curve (Gallet

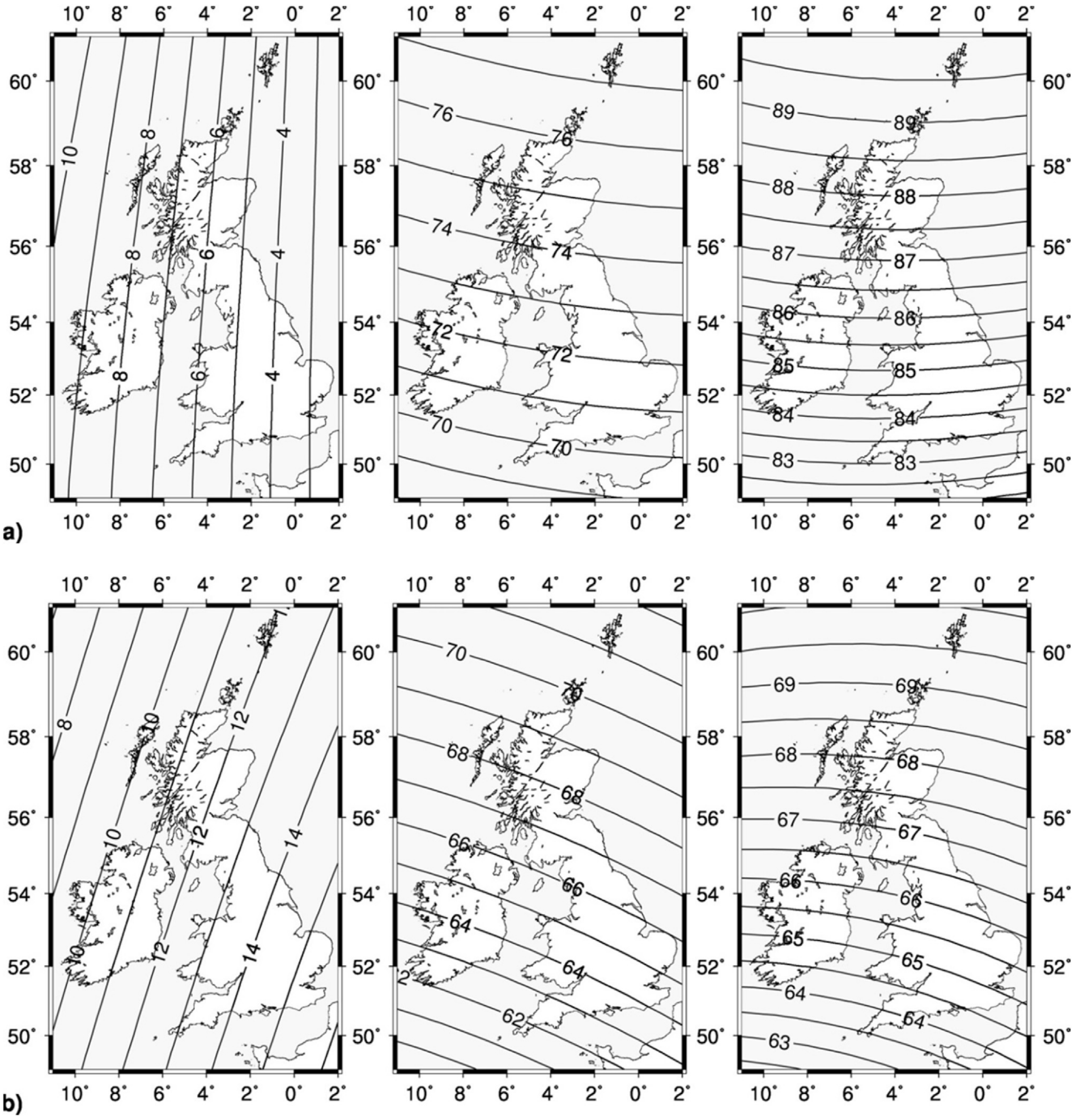


Fig. 6. Declination (left), inclination (middle) and field intensity (right) distribution over the UK and Ireland in (a) 500BCE and (b) 1000CE. Directions are in degrees, intensity in μT.

et al., 2002; Hervé et al., 2013) from further south shows a declination maximum of similar amplitude as the Clark et al. (1988) curve. The prominent declination swing to ~40°E in the Clark et al. (1988) curve arises from its reliance on palaeomagnetic data from the lake sediments (Turner and Thompson, 1981). This declination swing may therefore be a prominent feature of the field in northwestern Europe between 500 and 1000 BCE; however, it is one that our purely archaeomagnetic model fails to resolve and is a current limitation to the dating curve. Further archaeomagnetic data from the UK for this time, concentrating on reducing archaeomagnetic and dating uncertainties, would be required to confirm this declination swing. In addition, a re-examination of sediment palaeomagnetic data from UK lakes would also bring further insight into the timing and character of this possible declination swing.

The difference between GMADE2K.1 and the Zananiri et al. (2007) reference curve in inclination might seem surprising, but Lodge and Holme (2009) noticed that the European reference curves they used as input data were not always mutually consistent in the frame of a physically reasonable geomagnetic field model. Moreover, Lodge and Holme (2009) used a very smooth and by now outdated background model (Korte and Constable, 2005). They concluded that instead of using smoothed curves, it is preferable to use individual input data, as we have done in ARCH-UK.1. The difference between the ARCH-UK.1 and the Zananiri et al. (2007) reference curves is small. The curves mostly fall within each other's uncertainty limits (not shown in the figure). However, the

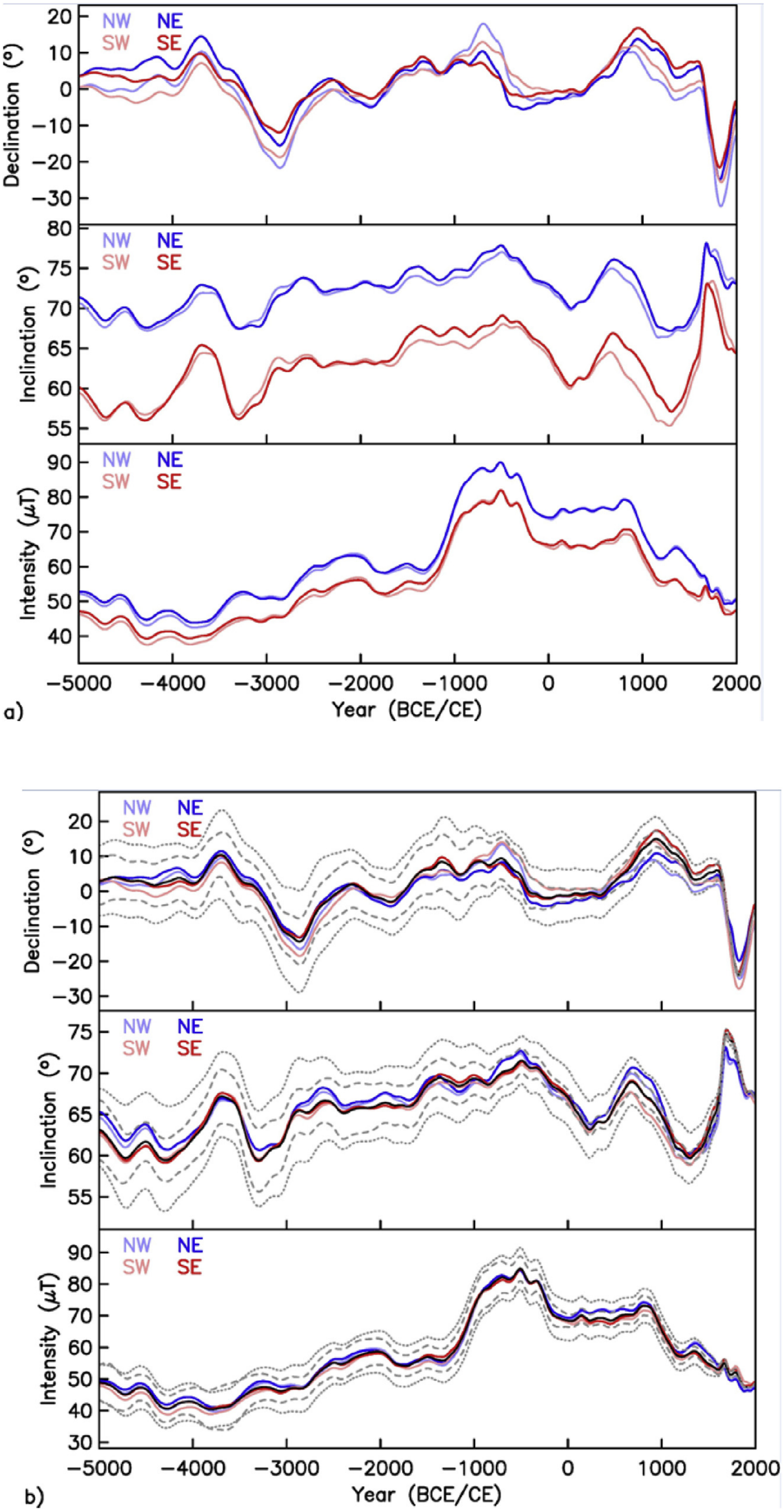


Fig. 7. (a) Declination (top), inclination (middle) and field intensity (bottom) predictions from ARCH-UK.1 for the four corners of the area displayed in Fig. 6: northwest (NW, light blue, 61°N, 11°W), northeast (NE, blue, 61°N, 2°E), southwest (SW, light red, 49°N, 11°W) and southeast (SE, red, 49°N, 2°E). (b) The same curves all reduced to Meriden (52.43°N, 1.62°W) by the tilted dipole assumption. The black line is the actual model prediction for Meriden with uncertainty estimates obtained from the ensemble model predictions as in Fig. 5 (dashed grey lines) and the more conservative estimates obtained from ensemble coefficient uncertainties (dotted lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

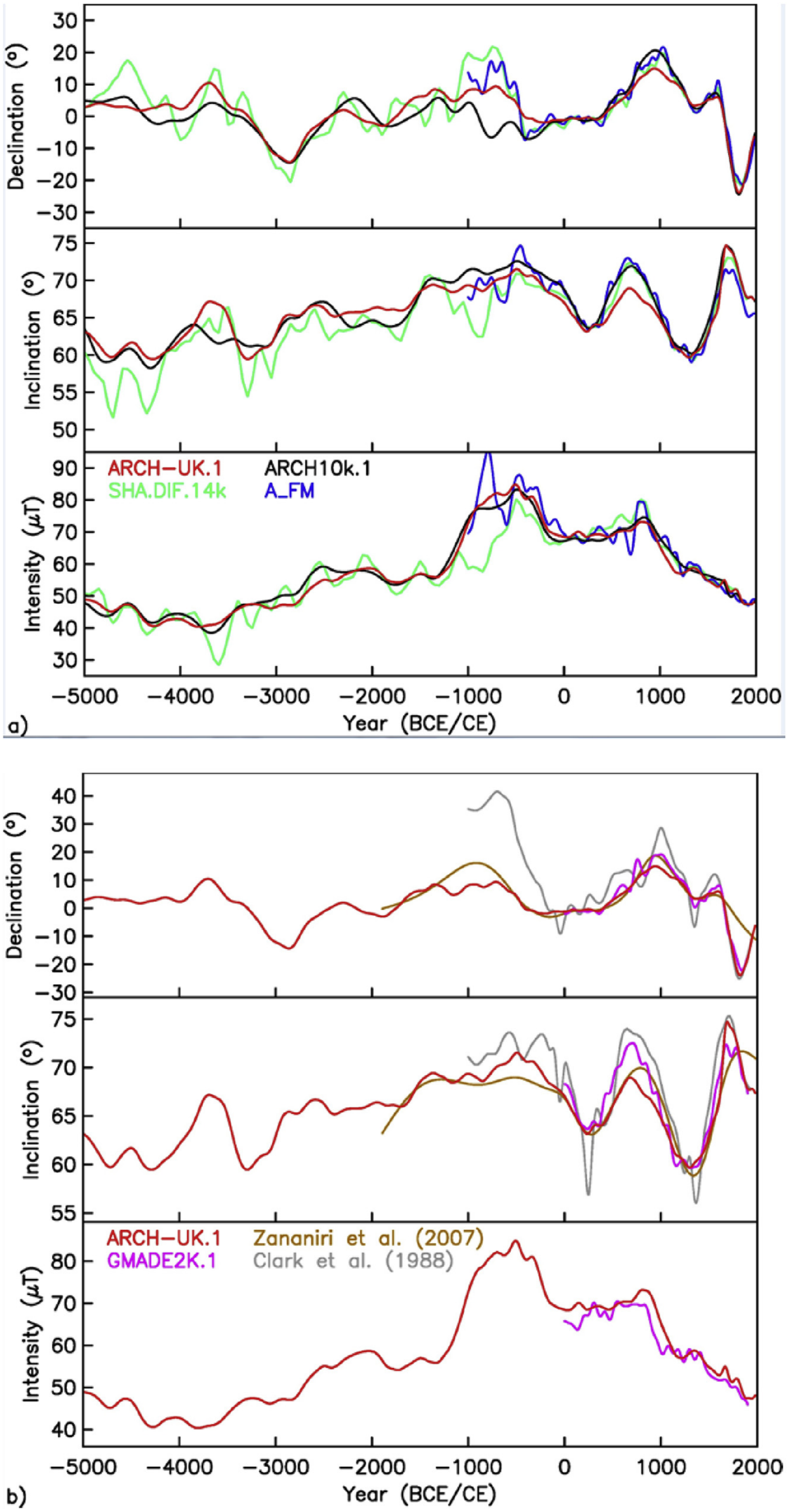


Fig. 8. Comparison of ARCH-UK.1 prediction for Meriden (red) to (a) previous global field archaeomagnetic field models A_FM (Licht et al., 2013; blue), SHA.DIF.14k (Pavón-Carrasco et al., 2014; green) and ARCH10k.1 (Constable at al. 2016; black), and (b) to previous UK reference curves by Clark et al. (1988; grey) and Zananiri et al. (2007, brown) and model GMADE2K.1 (Lodge and Holme, 2009; purple). Available uncertainty estimates have been omitted for clarity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Archaeomagnetic data for Context 4700 Structure 14 at Old Scatness Broch, Shetland.

Feature description	Fired clay in primary hearth	Sample number	AM61: Bradford
No. of samples taken/used in mean	22/22	Archaeological Date based on radiocarbon from stratigraphically related deposits	310BCE-50BCE
Mean characteristic declination at Meriden	−3.1°	Archaeomagnetic date using Zananiri et al., 2007	520BCE-126CE 410CE–650CE 1599CE-1698CE
Mean characteristic inclination at Meriden	67.2°	Archaeomagnetic date using ARCH-UK.1 and Matlab	266BCE-129CE 469CE-543CE
α_{95} of characteristic remanent magnetisation	2.4°		
k, Fisher precision estimate	154.7		

period where we have concentrated on improving the archaeological date ranges, 1000BCE-1BCE shows the most differences, which demonstrates the value of re-evaluating existing data. There are also significant differences in the historical times after 1600CE. These arise because ARCH-UK.1 is indirectly constrained by much more data in this time interval and might show higher temporal variability as it is forced to agree with the *gufm1* model (Jackson et al., 2000) while the Zananiri et al. (2007) curve is constrained by only few data in that time interval. The difference in the time interval 1000BCE–1BCE is comparable to the difference that is seen in the time interval where ARCH-UK.1 is indirectly constrained by additional historical data. Improvements from the updated and new data are noted at similar times as already observed in comparison to previous global models. Moreover, ARCH-UK.1 has slightly higher temporal resolution in addition to spanning a longer time interval and including all three vector components in a physically consistent way.

In order to use ARCH-UK.1 for archaeomagnetic dating, it can be incorporated into the Matlab programme developed by Pavón-Carrasco et al. (2011), which allows comparison between a measured archaeomagnetic direction and the new model (Appendix 1). The effects of the revisions made are illustrated by considering the example of an archaeomagnetic direction obtained from fired clay in the primary hearth in Structure 14 (Table 1, Fig. 9) excavated

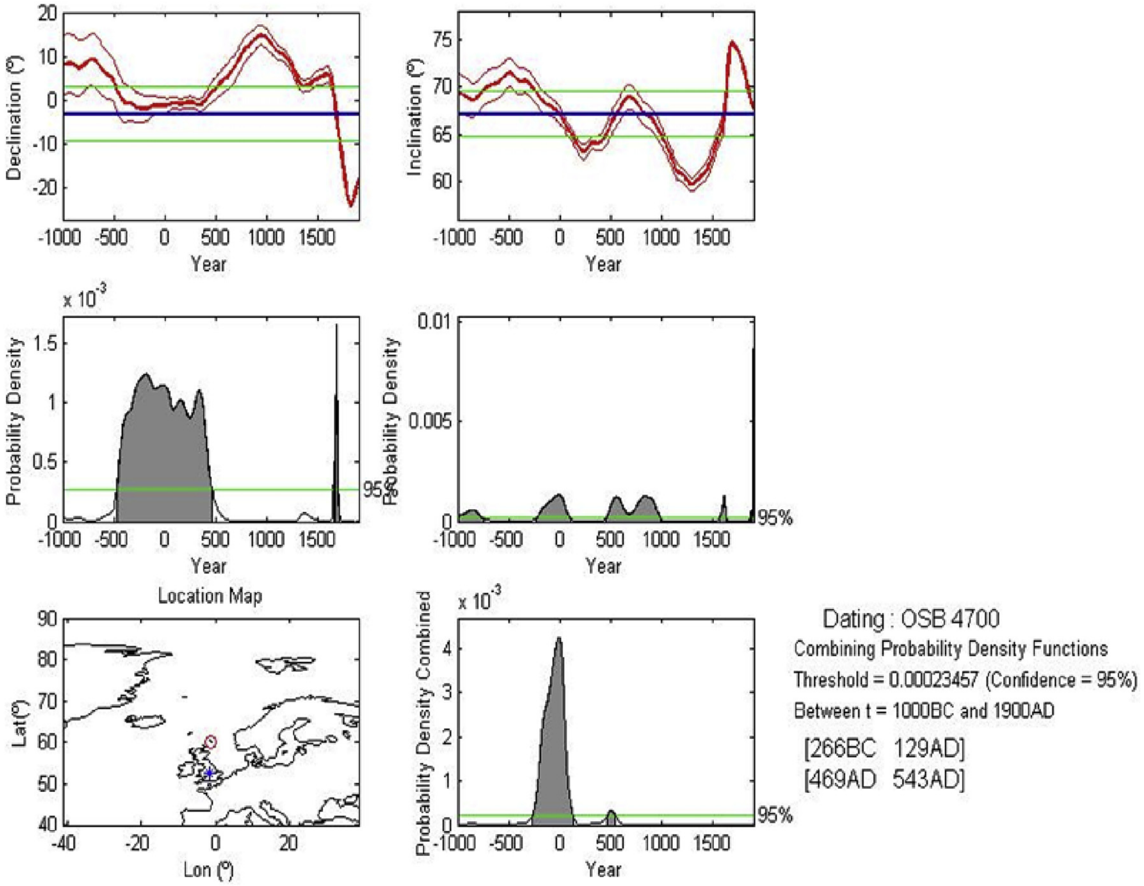


Fig. 9. Summary of the calibration data for AM61 using the ARCH-UK.1 calibration dataset (Appendix 1) and the Matlab programme developed by Pavón-Carrasco et al. (2011). Top row: master secular variation curves for the observation site (red bold curves with red error bands) of the declination (left), inclination (right) and the undated archaeomagnetic direction (blue line). Middle row: the individual probability density functions for the declination (left), inclination (right). The green lines indicate the 95% probability threshold. Bottom row: regional map (left) of the data location (red circle) and the master secular variation curve location (blue star); combined probability density marked with the green line of probability (centre); and archaeomagnetic dating information (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at Old Scatness Broch, Shetland (latitude 59.87°N, longitude 1.3°W: Outram and Batt, 2015; Outram, 2006). The previous reference curve (Zananiri et al., 2007) produces three possible date ranges. ARCH-UK.1 produces two possible ranges. The date range that is consistent with the archaeological information is 250 years more precise and closer to the date obtained from radiocarbon measurements, highlighting the impact of reassessment of the dataset.

5. Conclusions and further work

This research has collated and updated the largest collection of dated archaeomagnetic directions from a single country, resulting in a marked increase in the quantity and quality of archaeomagnetic data available for the UK. The data are now easily available to other workers for archaeological, archaeomagnetic and geomagnetic research, allowing regular review of the UK SV curves and highlighting aspects that need to be targeted to improve the method. In addition, the database demonstrates the effectiveness of archaeomagnetism in different situations, and therefore increases awareness of the technique to a wider audience.

A strategy for the re-evaluation of the independent dating evidence has been suggested and, when applied in the 1st millennium BCE, has demonstrated that the existing data can be improved significantly. Clearly reassessment of the dating evidence for other periods would further improve the precision of SV curves. Such reassessment requires collaboration between archaeologists (pottery specialists, period specialists, technology specialists) and archaeomagnetists to ensure that SV curves represent current archaeological understanding.

The data have been used to produce a detailed record of secular variation of the geomagnetic field in the UK, which has added considerable detail to previous studies. In particular, archaeomagnetic calibration curves have been produced that can be used for dating material from the UK from the present to 5000BCE. In order to further improve the SV curve we require more high quality archaeomagnetic data, ideally with a targeted sampling campaign to improve the precision in key periods, as well as investigating sites located in the northern and western extremes of the UK and Ireland. The analysis has specifically demonstrated the need for more data to be collected from before 500BCE and between 400CE and 800CE. Even if the material has no independent date at present, it is worth collecting as it may be datable in the future. Archaeological situations which allow the sampling of a number of stratigraphically related horizons, with associated independent dates would be particularly valuable.

It is not possible to state a generally expected precision for an archaeomagnetic date; in periods where geomagnetic change was rapid it will be possible to produce a more precise age range than for periods where changes were slower. However, it is possible to use the SV curves to check the likely precision before sampling, if the expected date is broadly known.

Many of the recent developments reported in this paper have been reliant on dialogue with archaeologists; to improve communication a website has been established (Outram, 2011) to provide clear, accessible, up-to-date information which addresses the questions raised by archaeologists. A better understanding of what archaeomagnetic analysis can offer leads to increased access to features for archaeomagnetic sampling; more data improve both precision and accuracy of the SV record and therefore improve the dating method itself and the data available for geomagnetic modelling.

Acknowledgements

The authors would like to dedicate this research to Professor Martin Aitken (1922–2017), who was instrumental in the development of archaeomagnetic dating and was still contributing to archaeomagnetic discussions when this paper went to press. Many grateful thanks are expressed to all those who have contributed data to the database of UK archaeomagnetic data over the years, particularly Dr Tony Clark at English Heritage, Prof Don Tarling at the University of Plymouth, Dr Mark Hounslow at the University of Lancaster, Dr Mimi Hill and Dr Neil Suttie at the University of Liverpool and Dr Mark Noel at Geoquest. Sam Harris at the University of Bradford is thanked for assistance with Fig. 9.

Funding: ZO was funded by an AHRC Knowledge Transfer Partnership (AH/G01020X/1) awarded to CMB and SJC was funded by a PhD studentship from NERC (NE/F008651/1) awarded to CMB. MCB was funded by DFG SPP 1488 grant KO2870/4-1 awarded to MK.

Reviewers for Journal of Archaeological Sciences are thanked for their detailed and helpful comments which have improved the manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2017.07.002.

References

Aitken, M.J., 1958. Magnetic dating – I. Archaeometry 1, 16–20.

Aitken, M.J., 1960. Magnetic dating. Archaeometry 3, 41–44.

Aitken, M.J., Allsop, A.L., Bussell, G.D., Winter, M.B., 1988. Determination of the intensity of the Earth's magnetic field during archaeological times: reliability of the Thellier technique. Rev. Geophys. 26 (1), 3–12. http://dx.doi.org/10.1029/RG026i001p00003.

Aitken, M.J., Weaver, G.H., 1962. Magnetic dating: some archaeomagnetic measurements in Britain. Archaeometry 5, 4–18.

Armit, I., 1991. The Atlantic Scottish iron age: five levels of chronology. Proc. Prehist. Soc. 121, 181–214.

Barton, C.E., 1982. Spectral analysis of palaeomagnetic time series and the global spectrum. Phil. Trans. R. Soc. Lond. A 306, 203–209.

Batt, C.M., 1998. Where to draw the line? The calibration of archaeomagnetic dates. Phys. Chem. Earth (and Solar System) 23, 991–995.

Batt, C.M., 1997. The British archaeomagnetic calibration curve: an objective treatment. Archaeometry 39, 153–168.

Batt, C.M., 1999. Preliminary investigations into the acquisition of remanence in archaeological sediments. In: Tarling, D.H., Turner, P. (Eds.), Palaeomagnetism and Diagenesis of Sediments, vol. 151. Special Publication of the Geological Society of London, pp. 9–19.

Bauer, L.A., 1896. On the secular motion of a free magnetic needle II. Phys. Rev. 3, 34–48.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.

Brown, M.C., Donadini, F., Korte, M., Nilsson, A., Lodge, A., Lengyel, S., Korhonen, K., Constable, C.G., 2015a. GEOMAGIA50.v3: 1. General structure and modifications to the archeological and volcanic database. Earth Planets Space 67, 83.

Brown, M.C., Donadini, F., Nilsson, A., Panovska, S., Frank, U., Korhonen, K., Schuberth, M., Korte, M., Constable, C.G., 2015b. GEOMAGIA50.v3: 2. A new paleomagnetic database for lake and marine sediments. Earth Planets Space 67, 70. http://dx.doi.org/10.1186/s40623-015-0233-z.

Bucur, I., 1994. The direction of the terrestrial magnetic field in France, during the last 21 centuries. Recent progress. Phys. Earth Planet. In. 87 (1–2), 95–109.

Casas, Ll, Shaw, J., Gich, M., Share, J., 2005. High quality microwave intensity determinations from an early C18th AD English brick kiln. Geophys. J. Int. 161, 653–661.

Clark, A.J., Tarling, D.H., Noel, M., 1988. Developments in archaeomagnetic dating in Britain. J. Archaeol. Sci. 15, 645–667.

Clelland, S.J., 2011. Developing Archaeomagnetic Dating in the British Iron Age. Division of Archaeological, Geographical and Environmental Sciences, University of Bradford unpublished PhD thesis.

Cong, Y.Z., Wei, Q.Y., 1989. Study of secular variation (2000 BC-1900 AD) based on comparison of contemporaneous records in marine sediments and baked clays. Phys. Earth Planet. In. 56, 69–75.

Constable, C., Korte, M., 2015. Centennial to Millennial-scale geomagnetic field variations. In: Schubert, G. (Ed.), Treatise on Geophysics, second ed., vol. 5, pp. 309–334.

Constable, C., Korte, M., Panovska, S., 2016. Persistent high paleosecular variation activity in Southern Hemisphere for at least 10 000 years. Earth Planet. Sci. Lett. 453, 78–86.

Cook, R.M., Belshé, J.C., 1958. Archaeomagnetism: a preliminary report on Britain.

Antiquity 32, 167–178.

Donadini, F., Korte, M., Constable, C., 2009. Geomagnetic field for 0-3ka: 1. New data sets for global modeling. Geochem. Geophys. Geosyst. 10, Q06007. http://dx.doi.org/10.1029/2008GC002295.

Ellis, C., Brown, A.G., 1998. Archaeomagnetic dating and palaeochannels sediments: data from the medieval channel fills at Hemington, Leicestershire. J. Archaeol. Sci. 25, 149–163.

Ertepinar, P., Langereis, C.G., Biggin, A.J., de Groot, L.V., Kulakoglu, F., Omura, S., Suel, A., 2016. Full vector archaeomagnetic records from Anatolia between 2400 and 1350 BCE: implications for geomagnetic field models and the dating of fires in antiquity. Earth Planet. Sci. Lett. 434, 171–186.

Fisher, R., 1953. Dispersion on a sphere. Proc. R. Soc. Lond. A 217, 295–305. http://dx.doi.org/10.1098/rspa.1953.0064.

Forum on Information Standards in Heritage, 2016. Chronological Guide for Recording Sites and Monuments. http://heritage-standards.org.uk/chronology/ (Accessed 15 September 2016).

Frank, U., Nowaczyk, N.R., Negendank, J.F.W., Melles, M., 2002. A paleomagnetic record from Lake Lama, northern Central Siberia. Phys. Earth Planet. In. 133, 3–20.

Gallet, Y., Genevey, A., Le Goff, M., 2002. Three millennia of directional variation of the Earth's magnetic field in western Europe as revealed by archeological artefacts. Phys. Earth Planet. Inter 131, 81–89.

Gallet, Y., Molist, M., Genevey, A., García, X., Thébault, E., Gómez, A., Le Goff, M., Robert, B., Nachasova, I., 2015. New Late Neolithic (c. 7000–5000 BC) archeointensity data from Syria. Reconstructing 9000 years of archeomagnetic field intensity variations in the Middle East. Phys. Earth Planet. In. 238, 89–103. http://dx.doi.org/10.1016/j.pepi.2014.11.003.

Genevey, A., Gallet, Y., Rosen, J., Le Goff, M., 2008. Evidence for rapid geomagnetic field intensity variations in Western Europe over the past 800 years from new French archeointensity data. Earth Planet. Sci. Lett. 284, 132–143. http://dx.doi.org/10.1016/j.epsl.2009.04.024.

Gentles, D., 1989. Archaeomagnetic Directional Studies of Large Fired Structures in Britain. Plymouth Polytechnic unpublished Ph.D. thesis.

Gómez-Paccard, M., Lanos, P., Chauvin, A., McIntosh, G., Osete, M.L., Catanzariti, G., Ruiz-Martínez, V.C., Núñez, J.I., 2006. The first Archaeomagnetic secular variation curve for the Iberian Peninsula. Geochem. Geophys. Geosyst. 7, Q12001,. http://dx.doi.org/10.1029/2006GC001476.

Hervé, G., Chauvin, A., Lanos, P., 2013. Geomagnetic field variations in Western Europe from 1500BC to 200AD. Part I: directional secular variation curve. Phys. Earth Planet. In. 218, 1–13.

Hill, M.J., Shaw, J., 1999. Palaeointensity results for historic lavas from Mt. Etna using microwave demagnetization/remagnetization in a modified Thellier-type experiment. Geophys. J. Int. 139, 583–590.

Hodder, I., 1992. Theory and Practice in Archaeology. Routledge, London.

Jackson, A., Finlay, C., 2015. Geomagnetic secular variation and its applications to the core. In: Schubert, G. (Ed.), Treatise on Geophysics, second ed., vol. 5, pp. 137–184.

Jackson, A., Jonkers, A.R.T., Walker, R.M., 2000. Four centuries of geomagnetic secular variation from historical records. Phil. Trans. R. Soc. Lond. 358, 957–990.

Jonkers, A.R.T., Jackson, A., Murray, A., 2003. Four centuries of geomagnetic data from historical records. Rev. Geophys. 41 http://dx.doi.org/10.1029/2002RG000115.

Jordan, D., Haddon-Reece, D., Bayliss, A., 1994. Radiocarbon Dates from Samples Funded by English Heritage and Dated before 1981. English Heritage, London.

Katari, K., Bloxham, J., 2001. Effects of sediment aggregate size on DRM intensity: a new theory. Earth Planet. Sci. Lett. 186, 113–122.

Korhonen, K., Donadini, F., Riisager, P., Pesonen, L.J., 2008. GEOMAGIA50: an archeointensity database with PHP and MySQL. Geochem. Geophys. Geosyst. 9 http://dx.doi.org/10.1029/2007GC001893.

Korte, M., Constable, C., 2005. Continuous geomagnetic field models for the past 7 millennia II: CALS7K. Geochem. Geophys. Geosyst. 6 (2), Q02H15. http://dx.doi.org/10.1029/2004GC000801.

Korte, M., Donadini, F., Constable, C.G., 2009. Geomagnetic field for 0-3 ka: 2. A new series of time-varying global models. Geochem. Geophys. Geosyst. 10, Q06008. http://dx.doi.org/10.1029/2008GC002297.

Kostadinova-Avramova, M., Kovacheva, M., Boyadzhiev, Y., 2014. Contribution of stratigraphic constraints of Bulgarian multilevel tells in the prehistory and comparison with archaeomagnetic observations. J. Archaeol. Sci. 43, 227–238.

Kovacheva, M., Boyadziev, Y., Kostadinova-Avramova, M., Jordanova, N., Donadini, F., 2009. Updated archeomagnetic data set of the past 8 millennia from the Sofia laboratory, Bulgaria. Geochem. Geophys. Geosyst. 10, Q05002. http://dx.doi.org/10.1029/2008GC002347.

Kovacheva, M., Kostadinova-Avramova, M., Jordanova, N., Lanos, P., Boyadzhiev, Y., 2014. Extended and revised archaeomagnetic database and secular variation curves from Bulgaria for the last eight millennia. Phys. Earth Planet. In. 236, 79–94.

Lanos, P., 2004. Bayesian inference of calibration curves: application to archaeomagnetism. In: Buck, C.E., Millard, A.R. (Eds.), Tools for Constructing Chronologies: Crossing Interdisciplinary Boundaries, Lecture Notes in Statistics 177. Springer, London, pp. 43–82.

Lanos, P., Kovacheva, M., Chauvin, A., 1999. Archaeomagnetism, methodology and applications: implementation and practice of the archaeomagnetic method in France and Bulgaria. Eur. J. Archaeol. 2, 365–392.

Lanos, P., Le Goff, M., Kovacheva, M., Schnepp, E., 2005. Hierarchical modelling of archaeomagnetic data and curve estimation by moving average technique. Geophys. J. Int. 160, 440–476.

Le Goff, M., Gallet, Y., 2004. A new three-axis vibrating sample magnetometer for continuous high-temperature magnetization measurements: applications to paleo- and archeo-intensity determinations. Earth Planet. Sci. Lett. 229, 31–43.

Lengyel, S.N., Eighmy, J.L., 2002. A revision to the U.S. Southwest archaeomagnetic master curve. J. Archaeol. Sci. 29, 1423–1433.

Licht, A., Hulot, G., Gallet, Y., Thébault, E., 2013. Ensembles of low degree archeomagnetic field models for the past three millennia. Phys. Earth Planet. In. 224, 38–67.

Linford, P., 2006. Archaeomagnetic Dating: Guidelines on Producing and Interpreting Archaeomagnetic Dates. English Heritage, Swindon.

Lodge, A., Holme, R., 2009. Towards a new approach to archaeomagnetic dating in Europe using geomagnetic field modelling. Archaeometry 51, 309–322.

Malin, S.R.C., Bullard, E., 1981. The direction of the Earth's magnetic field at London, 1570-1975. Phil. Trans. R. Soc. Lond. A 1981 (299), 357–423.

Márton, P., 2003. Recent achievements in archaeomagnetism in Hungary. Geophys. J. Int. 153, 675–690.

Neal, D.S., 1983. Excavations on a settlement at little Bay, Isles of Scilly. Cornish Archaeol. 22, 47–80.

Noel, M., Batt, C.M., 1990. A method for correcting geographically separated remanence directions for the purpose of Archaeomagnetic dating. Geophys. J. Int. 102, 753–756.

Nourgaliev, D.K., Heller, F., Borisov, A.C., Yasonov, P.G., Chernova, I.Y., Hajdas, I., 2005. Principle features (master curve) of geomagnetic field variations in Belorussia during the last 12 thousand years. Russ. J. Earth Sci. 7, 1–16.

Ojala, A.E.K., Tiljander, M., 2003. Testing the fidelity of sediment chronology: comparison of varve and paleomagnetic results from Holocene lake sediments from central Finland. Quat. Sci. Rev. 22, 1787–1803.

Ojala, A.E.K., Saarinen, T., 2002. Palaeosecular variation of the Earth's magnetic field during the last 10 000 years based on the annually laminated sediment of Lake Nautajarvi, central Finland. Holocene 12, 391–400.

Outram, Z., 2006. A Reassessment of the Iron Age Chronology of the Northern Isles: a Pilot Study at the Old Scatness Broch Site, Shetland. Unpublished PhD thesis. University of Bradford.

Outram, Z., 2011. Archaeomagnetism: Magnetic Moments in the Past. http://www.brad.ac.uk/archaeomagnetism/ (Accessed 28 September 2016).

Outram, Z., Batt, C.M., 2010. Dating at Old Scatness. In: Dockrill, S.J., Bond, J.M., Brown, L.D., Turner, V.E., Bashford, D., Cussans, J.E., Nicholson, R.A. (Eds.), Excavations at Old Scatness, Shetland Volume 1: the Pictish Village and Viking Settlement. Shetland Heritage Publications, Lerwick, pp. 99–130.

Outram, Z., Batt, C.M., 2015. Dating at Old Scatness. In: Dockrill, S.J., Bond, J.M., Turner, V.E. (Eds.), Excavations at Old Scatness, Shetland Volume 2: the Broch and Iron Age Village. Shetland Heritage Publications, Lerwick, pp. 161–204.

Pavón-Carrasco, F.J., Osete, M.L., Torta, J.M., De Santis, A., 2014. A geomagnetic field model for the Holocene based on archeomagnetic and lava flow data. Earth Planet. Sci. Lett. 388, 98–109.

Pavón-Carrasco, J., Rodríguez-González, J., Osete, M.L., Torta, J.M., 2011. A Matlab tool for archaeomagnetic dating. J. Archaeol. Sci. 38, 408–419.

Renfrew, C., 1973. Before Civilization: the Radiocarbon Revolution and Prehistoric Europe. Jonathan Cape Ltd., London.

Roberts, A.P., Tauxe, L., Heslop, D., 2013. Magnetic paleointensity stratigraphy and high-resolution Quaternary geochronology: successes and future challenges. Quat. Sci. Rev. 61, 1–16.

Schiffer, M.B., 1987. Formation Processes of the Archaeological Record. University of New Mexico Press, Albuquerque.

Schnepp, E., Lanos, P., 2005. Archaeomagnetic secular variation in Germany during the past 2500 years. Geophys. J. Int. 163, 479–490.

Schnepp, E., Leonhardt, R., Korte, M., Klett-Drechsel, J., 2016. Validity of archaeomagnetic field recording: an experimental pottery kiln at Coppengrave, Germany. Geophys. J. Int. 205, 622–635. http://dx.doi.org/10.1093/gji/.

Shaar, R., Ben-Yosef, E., Ron, H., Tauxe, L., Agnon, A., Kessel, R., 2011. Geomagnetic field intensity: how high can it get? How fast can it change? Constraints from Iron Age copper slag. Earth Planet. Sci. Lett. 301, 297–306.

Shaw, J., Yang, S., Rolph, T.C., Sun, F.Y., 1999. A comparison of archaeointensity results from Chinese ceramics using microwave and conventional Thellier's and Shaw's methods. Geophys. J. Int. 136, 714–718.

Shuey, R.T., Cole, E.R., Mikulich, M.J., 1970. Geographic correction of archaeomagnetic data. J. Geomagn. Geoelectr. 22, 485–489.

Snowball, I., Sandgren, P., 2002. Geomagnetic field variations in northern Sweden during the Holocene quantified from varved lake sediments and their implications for cosmogenic nuclide production rates. Holocene 12, 517–531.

Snowball, I., Zillén, L., Ojala, A., Saarinen, T., Sandgren, P., 2007. FENNOSTACK and FENNORPIS: varve dated Holocene palaeomagnetic secular variation and relative palaeointensity stacks for Fennoscandia. Earth Planet. Sci. Lett. 255, 106–116.

Sørensen, M.L.S., Thomas, R. (Eds.), 1989. The Bronze Age-Iron Age Transition in Europe. Aspects of Continuity and Change in European Societies c. 1200-500BC. Oxford, British Archaeological Reports (International Series) 483.

Stark, F., Cassidy, J., Hill, M.J., Shaw, J., Sheppard, P., 2010. Establishing a first archaeointensity record for the SW Pacific. Earth Planet. Sci. Lett. 298, 113–124.

Sternberg, R.S., 2008. Archaeomagnetism in Archaeometry- a semi-centennial review. Archaeometry 50, 983–998.

Stockhausen, H., 1998. Geomagnetic palaeosecular variation (0-13 000 yr BP) as recorded in sediments from three maar lakes from the West Eifel (Germany). Geophys. J. Int. 135, 898–910.

Suttie, N.A., 2010. Geomagnetic Field Archaeointensities from Britain and the Application of the Microwave Palaeointensity Method to Materials of Differing Dielectric Properties. Unpublished PhD thesis. University of Liverpool.

Tarling, D.H., 1983. Palaeomagnetism. Chapman and Hall, London.

Tarling, D.H., 1989. Geomagnetic secular variation in Britain during the last 2000 years. In: Lowes, F.J., Collinson, D.W., Parry, J.H., Runcorn, S.K., Tozer, S.D.C.A. (Eds.), Geomagnetism and Palaeomagnetism. Kluwer Academic Publishing, Dordrecht, pp. 55–62.

Tarling, D.H., Dobson, M.J., 1995. Archaeomagnetism: an error assessment of fired material observations in the British directional database. J. Geomagn. Geoelectr. 147, 5–18.

Tauxe, L., 2002. Palaeomagnetic Principles and Practice. Kluwer Academic Publishing, Dordrecht.

Tauxe, L., Steindorf, J.L., Harris, A., 2006. Depositional remanent magnetization: toward an improved theoretical and experimental foundation. Earth Planet. Sci. Lett. 244 (3–4), 515–529.

Tauxe, L., Yamazaki, T., 2007. Paleointensities. In: Schubert, G. (Ed.), Treatise on Geophysics. Elsevier, Amsterdam, pp. 509–563.

Taylor, R.E., 1987. Radiocarbon Dating: an Archaeological Perspective. Academic Press Inc., London.

Tema, E., Kondopoulou, D., 2011. Secular variation of the Earth's magnetic field in the Balkan region during the last 8 millennia based on archaeomagnetic data. Geophys. J. Int. 186, 603–614.

Thomas, R., 1983. Review of archaeointensity methods. Geophysical Surveys 5 (381–393), 0046–5763/83/0054-0381501.95.

Trigger, B.G., 2007. A History of Archaeological Thought, second ed. Cambridge University Press, Cambridge.

Turner, G.M., Thompson, R., 1981. Lake sediment record of geomagnetic secular variation in Britain during Holocene times. Geophys. J. R. Astron. Soc. 65, 703–725.

Turner, G.M., Thompson, R., 1982. Detransformation of the British geomagnetic secular variation record for Holocene times. Geophys. J. R. Astron. Soc. 70, 789–792.

Valet, J.P., 2003. Time variations in geomagnetic intensity. Rev. Geophys. 41, 1004.

Yamamoto, Y., Torii, M., Natsuhara, N., 2015. Archeointensity study on baked clay samples taken from the reconstructed ancient kiln: implication for validity of the Tsunakawa-Shaw paleointensity method. Earth Planets Space 67, 63. http://dx.doi.org/10.1186/s40623-015-0229-8.

Zananiri, I., Batt, C.M., Lanos, P., Tarling, D.H., Linford, P., 2007. Archaeomagnetic secular variation in the UK during the past 4000 years and its application to archaeomagnetic dating. Phys. Earth Planet. In. 160 (2), 97–107.