High-intensity geomagnetic field ‘spike’ observed at ca. 3000 cal BP in Texas, USA.

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Abstract

By observing the fluctuations in direction and intensity of the Earth’s magnetic field through time, we increase our understanding of the fluid motions of the Earth’s outer core that sustain the geomagnetic field, the geodynamo. Recent archaeomagnetic studies in the Near East have found extremely rapid increases - ‘spikes’ - in geomagnetic field intensity at ca. 3000 years cal BP. These observations have proved problematic for our current understanding of core-flow. However, until now, these geomagnetic spikes had not been observed outside of the Near East, where they have been preserved in metallurgical slag and fired, mud brick walls.

We present a new, fully oriented, geomagnetic secular variation and relative palaeointensity (RPI) record for the last 17,000 years from Hall’s Cave, Texas, whose complete, >3.8 meter thick sedimentary sequence spans from the present to 16,850±110 RC yr BP (Modern to 20,600 cal BP). Within the stable, cool climate of the cave, pedogenic and bioturbation processes are negligible to non-existent, thereby limiting post-depositional physical and geochemical alteration of the magnetic record. The sub-aerial and subterranean setting of the sedimentary sequence in Hall’s Cave enabled us to collect oriented palaeomagnetic cubes from a previously excavated stratigraphic section.

The palaeomagnetic samples yielded high-quality vectors. An age model for the sequence, determined using 15 AMS ^{14}C -dates on individual bones from microvertebrates, was combined with the palaeomagnetic data to construct a secular variation record. The record is in broad agreement with predictions by Holocene field models for the site's location. However, starting ca. 3000 years ago, the RPI data indicate an almost four-fold increase in geomagnetic field intensity lasting several hundred years. This record presents well-dated evidence, obtained using conventional techniques, for the existence of a geomagnetic intensity spike in North America that is contemporaneous with the shorter duration, decadal-scale spikes reported from the Near East.

1 Introduction

The behaviour of the Earth's magnetic field provides us with a window into the deep interior of the Earth. By observing the fluctuations in direction and intensity of the external field through time, we increase our understanding of the fluid motions of the Earth's outer core that sustain the geomagnetic field, the geodynamo (Donadini et al., 2010; Korte and Muscheler, 2012). Accurate reconstructions of the behaviour of the Earth's magnetic field through time require well-dated, globally distributed records of past magnetic field behaviour.

Sedimentary sequences can offer continuous, high-resolution records of geomagnetic field behaviour. However, the distribution of terrestrial sites is restricted by the limited number of sites with sufficiently high sedimentation rates, such as lakes. In some areas, sparsely distributed data precludes robust reconstruction of field behaviour (Korte et al., 2011). The majority of continuous terrestrial magnetic records that span the Holocene are obtained from lake sediment cores. In most cases, the cores are extracted without azimuthal orientation. This means that any magnetic declination record obtained from the cores can only describe relative changes in declination. Although relative declination records can be, and are, used in geomagnetic field models, the absence of oriented declination data and the need for calibration to nearby absolute declination

measurements introduces larger uncertainties into the model (Nilsson et al., 2014; Panovska et al., 2015, 2012). Continuous sequences with fully oriented samples that can record absolute declinations are therefore especially valuable.

Our knowledge of high-frequency variations in field direction and intensity has been greatly enhanced by numerous archaeomagnetic studies. These studies use archaeological materials that have been heated to high temperature, such as pottery and brick fragments, to reconstruct geomagnetic field behaviour over centennial and even decadal time-scales (Gallet and Le Goff, 2006; Gallet et al., 2014, 2008; Genevey et al., 2013; Hong et al., 2013). Detailed archaeointensity studies in Western Europe have documented a series of rapid geomagnetic field intensity variations over the last 1100 years (Genevey et al., 2013, 2009).

Archaeointensity studies in the Near East have identified a period of high intensity field strength around ~3000 cal BP suggesting a significant increase in field intensity by a factor of two from ~5450 to ~2650 cal BP (~3500 BCE to ~700 BCE) (Gallet and Le Goff, 2006; Gallet et al., 2006; Genevey et al., 2003). Lake sediment records from Sweden (Snowball and Sandgren, 2004; Snowball et al., 2007), palaeointensity estimates from radiocarbon dated lava flows on Hawaii (Pressling et al., 2007, 2006), and archaeomagnetic intensity estimates from South Korea (Hong et al., 2013) record similar, broadly synchronous highs in field intensity at ca. 3000 years cal BP, thereby implying a global intensity high during this period.

This interval has drawn particular interest following the discovery of even more dramatic palaeointensity highs identified in records from the Near East (Ben-Yosef et al., 2009; Ertepinar et al., 2012; Shaar et al., 2011). Recent investigations have demonstrated that copper slag (a metallurgical waste product of copper-smelting) can be a useful palaeomagnetic recorder that can offer decadal resolution and yield palaeointensity estimates accurate to within 6% (Ben-Yosef et al., 2008; Shaar et al., 2010). Palaeointensity studies on copper slag deposits from smelting sites in southern Jordan (Ben-Yosef et al., 2009) and southern Israel (Shaar et al., 2011) found evidence for

extremely high geomagnetic field intensities (higher than 100 μT , compared to modern field strengths of $\sim 50 \mu\text{T}$) corresponding to two, twenty-year long intervals at 2930 and 2840 cal BP (980 BCE and 890 BCE). The term 'geomagnetic spike' was used to describe these intervals, reflecting the unprecedented rapidity and amplitude of the geomagnetic field intensity variations (Ben-Yosef et al., 2009). Subsequently, archaeointensity measurements on a burnt mud-brick wall in Arslantepe, southeast Turkey suggested a high-intensity of 100.8 μT , providing further, independent evidence for the existence of a high-intensity event at 3000 cal BP (Ertepinar et al., 2012).

However, such short-lived, high-intensity events are difficult to reconcile with our current understanding of the geomagnetic dynamo (Livermore et al., 2014). The palaeointensity records from the Levant suggest intensity changes in the range of $\sim 4\text{-}5 \mu\text{T}/\text{year}$ (Ben-Yosef et al., 2009; Shaar et al., 2011). Assuming realistic estimates of flow velocity at the core-mantle boundary, modelled core-flows are incapable of generating such extreme and rapid intensity changes (Livermore et al., 2014).

These models suggest that the maximum rate of intensity change compatible with the currently accepted structure of core-flow is on the order of $0.6 \mu\text{T}/\text{year}$ (Livermore et al., 2014). Several hundreds of years rather than several decades would be required to achieve the high intensities observed in the Levant. The relatively unlikely coincidence of obtaining materials from Turkey that are contemporary with a short-lived 20-30 year event could suggest that the high intensity spike may be of a longer duration than implied by the Levantine data (Ertepinar et al., 2012; Livermore et al., 2014). However, to reduce the two short-lived decadal events to a single centennial scale, long-duration event would require a drastic and perhaps unrealistic reassessment of the age models and stratigraphy for the Levantine archaeological sites. Further progress on understanding the 'geomagnetic spike' or 'spikes' has been limited by the absence of any further records that could provide insight into geomagnetic field behaviour during this period (Livermore et al., 2014). The

spikes are insufficiently long for a significant effect to be apparent in records of cosmogenic nuclides, whose production is modulated by geomagnetic field intensity (Fournier et al., 2015).

In this study, we present a well-dated, fully-oriented palaeomagnetic record of the field direction and relative palaeointensity (RPI) from Hall's Cave, Texas, over the last 17.5 ka. The record includes significantly higher palaeointensities coincident with the 3000 cal BP interval, suggesting that the geomagnetic spike, so far only observed in the Near East, may also have been manifest in North America.

2 Study Site

Hall's Cave (30° 8' 10"N; 99° 32' 6"W) is in Kerr County, Texas, on the Edward's Plateau, a Cretaceous limestone platform covering an area of $9.7 \times 10^{10} \text{ m}^2$ (Cooke et al., 2003) (Fig. 1). The cave was formed in the Segovia Formation of the lower Cretaceous Edwards Group. Hall's Cave is a unique depository of sediments and soils eroded from several tens of hectares surrounding the cave. A 15 m wide, 3 m high entrance, formed by the collapse of a subterranean limestone cavern, provides access to a cavern with a 5-7 m high ceiling and sediments measuring at least 3.8 meters deep (Toomey, 1993) (Supplementary Fig. S1a,b). Although the Edwards limestone is covered today by a thin, discontinuous veneer of soil varying from zero to a few centimetres thick, strontium isotope data from Hall's Cave indicate that between 12 and 5 ka cal BP, local soils were at least 1.8 m thick (Cooke et al., 2003). Over the last 20,000 years or more, sediments and soils washed into the cave and formed a stratigraphic sequence that is at least 3.8 m thick. Within the uniform, cool, dark cave environment, pedogenic processes were inhibited, as was bioturbation by vertebrates and invertebrates (Ellwood and Gose, 2006; Toomey, 1993). The unusual sub-aerial and subterranean setting of the sedimentary sequence in Hall's Cave allowed us to collect oriented palaeomagnetic cubes from a previously excavated vertical section. Discrete *in situ* sampling from the stratigraphic

profile eliminated the problems of orientation and twisting that are common in lake cores (Bowles, 2007).

3 Materials and methods

3.1 Sampling

The sedimentary sequence exposed in Hall's Cave is exposed in three vertical walls remaining from palaeontological excavations first conducted by Rickard Toomey in 1986 (Toomey, 1993). Free-standing walls from Toomey's excavation pits 1d and 1e were approximately 2.5 metres high, with the originally ~ 4 metre deep pit having been infilled with sediments washed in during rains (Supplementary Fig. S1b,c). The 2.0 metre wide, north-facing wall was cleaned by removing ~ 5 cm from the existing face. Two vertical profiles, Columns A and B, spaced 20 cm apart horizontally were used for the palaeomagnetic sampling (Supplementary Fig. S2). Sample positions were measured vertically relative to an absolute datum (metal spike) drilled into the limestone wall west of the stratigraphic section. This absolute datum is ~ 1.8 m above the present sediment floor and was originally emplaced by Toomey in 1986. Our measurements refer to depths below this absolute datum (cm BD_{ABSOLUTE}) and are correlated with Toomey's (1993) measurements (cm BD_{TOOMEY}) used in his dissertation and by Cooke et al. (2003) and Elwood and Gose (2006) (Supplementary Fig. S3). The value 0 cm BD_{ABSOLUTE} = 184 cm BD_{TOOMEY}.

Hollow, Perspex acrylic cubes (1.5 x 1.5 x 1.5 cm) were pressed manually into the sediment, oriented *in situ* and photographed. The cubes were subsequently extracted from the section and sealed. Samples were collected at ~2 cm vertical intervals from both columns to ensure contiguous sampling. The samples are named according to their column and depth relative to the absolute datum. For example, HC-A-1740 is from column A at 174.0 cm BD_{ABSOLUTE}. The majority of samples were collected as full cubes. Within a few intervals, where there were higher concentrations of obstructing limestone clasts, small bones or both, the cubes could not be pushed completely into

the wall and they were extracted partially filled. However, the sediment inside these cubes remained consolidated and the magnetic record was not affected. Ninety-seven discrete samples were collected from column A and 92 were collected from column B. A high concentration of limestone clasts prevented the collection of palaeomagnetic cubes between ~360 and 400 cm below the cave datum. The uppermost 10 cm of the section is loose, unconsolidated sediment that has been disturbed by surface trampling during this study's and previous excavations.

3.2 Magnetic measurements

Following measurement of their natural remanent magnetization (NRM), the primary components of magnetism were isolated by subjecting samples to a 16-step alternating field (AF) demagnetization that ended at a maximum peak AF of 100 mT. All remanence measurements and demagnetization steps were performed using a 2G Enterprises DC-SQUID magnetometer equipped with an in-line tri-axial AF demagnetizer within a shielded room.

After measurement of the NRM, an anhysteretic remanent magnetization (ARM) was induced in all palaeomagnetic samples using a 100 mT peak AF field and a 50 μ T bias field. Following measurement of the ARM, each sample was AF-demagnetized and the remanence measured after peak alternating fields of 12, 20, and 60 mT. Similarly, all samples were given an isothermal remanent magnetization (IRM) at 1 T using a 2G pulse magnetizer. Following measurement of the IRM, the remanence was measured after peak AF of 12, 20, and 60 mT.

Hysteresis loops were measured for eleven representative samples that together span the full depth profile from columns A and B at room temperature using a Princeton Measurements vibrating sample magnetometer (VSM) with a maximum applied field of 1.5 T. The saturation magnetization (M_s), the saturation remanent magnetization (M_r) and the coercive force (B_c) were determined for each sample from the measured loops following subtraction of the paramagnetic component determined from the high-field susceptibility. Following the hysteresis cycles, the remanent coercive force (B_{cr}) was determined by stepwise demagnetization of an IRM acquired at 1.5 T. First-order

reversal curves (FORC) were also measured on two samples from column A, HC-A-2260 and HC-A-2630. FORC diagrams were processed using the FORCinel software package (Harrison and Feinberg, 2008). HC-A-2260 is a sample that records a significantly higher natural remanent magnetization, whilst HC-A-2630 is a sample that approximates the average magnetization and many of the other magnetic parameters measured.

Low-temperature, cryogenic experiments were conducted on subsamples from HC-A-2260 and HC-A-2630 using a Quantum Designs magnetic property management system (MPMS) cryogenic magnetometer. Low-temperature measurements enable the identification of diagnostic magnetic mineral transitions and are sensitive to magnetic mineral compositions and domain states. Significant variations in these magnetic properties could impair recovery of a reliable relative palaeointensity record. Two measurement protocols were conducted for each sample:

1. A field-cooled—zero-field-cooled (FC-ZFC) experiment, in which the subsample is cooled from room temperature to 20 K in a 2.5 T field, given a 2.5 T IRM at 20 K, and the magnetization measured during warming back to room temperature in zero field. The procedure is subsequently repeated, except the subsample is cooled from room temperature to 20 K in a zero field.

- 2.) A low-temperature cycling of room-temperature saturation isothermal remanent magnetization (RTSIRM), in which a 2.5 T IRM is imparted to each subsample at room temperature. The magnetization is then measured during cooling to 20 K and subsequent warming to room temperature in a zero field.

All magnetic measurements were conducted at the Institute for Rock Magnetism at the University of Minnesota.

4 Results

4.1 *Magnetic susceptibility*

The magnetic susceptibility (χ) of all samples was measured using a Magnon variable frequency susceptibility meter at a frequency of 920 Hz and peak field strength of 300 Am^{-1} . The magnetic susceptibility profile through the section is broadly similar to that given by Ellwood and Gose (2006) (Supplementary Fig. S3). Our samples were taken at a lower resolution than their 1 cm resolution which explains the absence of some short-duration events in our record. The magnetic susceptibility of the bulk samples varied between $0.2 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$ and $1.4 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$. Unlike Ellwood and Gose (2006), we did not sieve our samples to remove lithic clasts and bone fragments. Consequently, our bulk samples had slightly lower magnetic susceptibility than Ellwood and Gose's more homogenous, sieved samples. Regardless, the same general trends are evident from low values at the base of the sequence at 17.5 ka, up to a maximum at 3 ka, before decreasing again towards the modern day.

4.2 *Construction of age model*

The vertical positions of all the samples collected for this study were measured relative to a permanent datum in the cave wall's limestone. Our depths (cm $\text{BD}_{\text{ABSOLUTE}}$) were cross referenced to Toomey's (1993) depth scale (cm $\text{BD}_{\text{TOOMEY}}$) by using 6 tie-points derived from a combination of stratigraphic horizons and distinctive features in the magnetic susceptibility record in the Ellwood and Gose (2006) study (Supplementary Fig. S3). All depths quoted in the text are relative to the absolute cave datum and are expressed as cm $\text{BD}_{\text{ABSOLUTE}}$.

The chronology for the Hall's Cave section (Fig. 2) was constructed using 15 accelerator mass spectrometry (AMS) ^{14}C measurements. Following Wong et al. (2015) the youngest age (420 ± 60 years; reported as uncalibrated ^{14}C age) is taken from Toomey et al. (1993). The rest of the dates were measured on collagen from bone fragments at the Stafford Research Laboratories.

The ^{14}C dates were calibrated using OxCal version 4.2 (Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013). Ages used in the text are in calibrated years before present (cal BP) unless otherwise stated. To account for the uncertainties in the calibrated dates, an age

model for the section was calculated using Bayesian statistical analysis in Oxcal, using a 'Poisson-Sequence' routine. A potential hiatus was included in the model at 191 cm (<1 ka) corresponding to that discussed in Toomey (1993) and Wong et al. (2015). Each palaeomagnetic cube sampled a vertical thickness of 1.5 cm, which represents approximately 50 to 150 years, based on typical depositional rates of 1 to 3 cm per 100 years (Fig. 2).

4.3 Palaeomagnetic directions

Typical orthogonal demagnetization diagrams of representative samples are shown in figure 3. Many samples exhibited a minor viscous overprint from the modern field that was demagnetized by the 12 mT peak field. Following demagnetization of the overprint, the samples displayed well-defined, single-component magnetization vectors that pass through the origin. Most samples were almost completely demagnetized by the 60 mT AF step. Principal component analysis (PCA) was used to determine the characteristic remanent magnetization (ChRM) direction of the samples.

The majority of the samples older than 3 ka have directions with a maximum angular deviation (MAD) less than 5 (Fig. 4a). The directions for samples younger than 3 ka are less well-defined but the majority have MAD values less than 10. Within the top ~10 cm of the stratigraphic section, the directions appear to deviate significantly from the expected field direction for this location and do not agree between the two columns. This is especially evident in the declinations which are more than 60° away from geographic north. We attribute these anomalous directions to prior disturbance of the uppermost sediment layer. Beneath this layer, there is good agreement between directions obtained from column A and column B, indicating that some of the larger MAD values do not necessarily adversely affect the reliability of the field direction. By comparing samples from each column taken from the same depth, we can estimate the typical uncertainties in the inclination and declination obtained from an individual sample. The inclination (Fig. 4b) is more reproducible than the declination (Fig. 4c) between the columns and the typical inclination uncertainty is less than $\pm 9^\circ$, compared to that of $\pm 15^\circ$ for the declination.

4.4 *Relative palaeointensity*

Sedimentary records can record changes in the intensity of the geomagnetic field (Roberts et al., 2013; Tauxe, 1993; Valet, 2003). Estimates of relative changes in palaeointensity can be obtained by normalising the measured sample NRM by laboratory-induced magnetizations to account for variations in magnetic grain concentration between samples (Tauxe, 1993). Successful recovery of RPI variations requires that the magnetic mineralogy and grain size of the samples remains constant with depth (Tauxe, 1993). Consequently, rock magnetic parameters were measured to assess whether any significant variations occurred in magnetic mineralogy or grain size.

4.4.1 *Rock magnetic parameters*

The NRM of the Hall's Cave samples exhibit consistent demagnetization properties and record single, well-defined components of magnetization that suggest little change in magnetic mineralogy (Fig. 5a), that is, sediment mineralogy was constant. Hysteresis loops were measured for eleven representative samples from columns A and B. All samples plot within a narrow range of hysteresis ratios (Fig. 5b). The average M_r/M_s ratio is 0.18 ± 0.01 and that of B_{cr}/B_c is 2.86 ± 0.08 . The limited variation in hysteresis parameters indicates that the magnetic mineralogy is constant through time and between the columns. The samples lie within the pseudo-single domain (PSD) region of the Day plot (Day et al., 1977). The average B_{cr} of the eleven samples, 30 ± 5 mT, is typical of magnetite and its partially oxidised equivalents.

Banerjee et al. (1981) outlined how the ratio of anhysteretic remanence magnetic susceptibility (χ_{ARM}) to low-field magnetic susceptibility (χ) may be used to investigate first-order variations in magnetic grain size. Low-field susceptibility is relatively more sensitive to a coarser magnetic grain fraction than the anhysteretic remanence magnetic susceptibility, which is more sensitive to the finer grain size fraction (King et al., 1982). The calculated χ_{ARM}/χ ratios agree well between the two columns and decrease from the bottom of the section to the top (Fig. 6b). From 420 cm to 330 cm, χ_{ARM}/χ is relatively constant at ~ 8.6 , before dropping to ~ 7.7 at 330 cm and steadily decreasing to

~6.5 at the top of the section. The ratio of the saturation isothermal remanence (SIRM) to the low-field magnetic susceptibility ($SIRM/\chi$) has a similar trend to χ_{ARM}/χ (Fig. 6c). The steady decrease in these ratios could reflect a slight but progressive increase in magnetic grain size.

4.4.2 Normalization of palaeointensity

The measured NRM, ARM and IRM intensities are presented in figure 7. We obtain estimates of RPI by calculating the NRM-ARM and NRM-IRM regression (slope) in the 12-60 mT peak AF interval (Channell et al., 2002) (Fig. 8). Linear correlation coefficients of 0.99 for almost all samples indicated that the slopes are well-defined and that the coercivity spectra of the ARM and IRM are well-matched with that of the NRM. As expected, the r values for the NRM-ARM regression are slightly better than those of the NRM-IRM regression, indicating that the NRM coercivity spectrum is more similar to that of the ARM than the IRM. Therefore, we use the NRM-ARM slope as our preferred normalization (Brachfeld and Banerjee, 2000; Levi and Banerjee, 1976). Normalization of the NRM can be achieved by subtly different protocols. A simple normalization may also be achieved by dividing the NRM at a single demagnetization step by the ARM or IRM at the equivalent demagnetization step. Using either the 12 mT or 20 mT AF step produced curves that were indistinguishable from those using the slope method. All of the different normalization approaches produced similar RPI curves, with agreement both between the different normalization methods and between columns A and B. This is consistent with the fact that all the samples, apart from three in column A, have an almost constant ARM/IRM ratio with depth (Fig. 6d). The samples with increased magnetizations in the uppermost 10 cm are those that are affected by sediment disturbance and record anomalous directions. We therefore exclude these samples from our final reconstruction of secular variation.

4.4.3 Rock magnetism and the 3000 cal BP spike

The efficiency of remanence acquisition in sediments is controlled by the magnetic moment and size of the magnetic grains. Single domain (SD) grains are small ($< 0.08 \mu\text{m}$) and have large magnetic

moments relative to their size while multi-domain (MD) grains are larger and have relatively lower net magnetic moments. SD grains can therefore be more efficiently aligned by a magnetic torque to the ambient magnetic field. To assess whether the high relative palaeointensity centred at 226 cm is an artefact introduced by a reduction in grain size or change in magnetic mineralogy, rock magnetic measurements were made on two samples for which hysteresis loops had already been measured. One sample was from within the intensity spike (HC-A-2260) and one sample was from an interval of approximately average intensity (HC-A-2630). The AF demagnetization behaviour of the two samples' respective NRM is very similar, indicating that the coercivity distributions carrying the NRM are also similar (Fig. 5a). Furthermore, the demagnetization behaviour of the sample from within the spike is also not unusual when compared to the range of behaviours exhibited by all the other samples from column A (grey filled region).

The FORC diagrams for the two samples are almost indistinguishable (Fig. 5c and d) and show that both samples are dominated by a single population of small PSD to SD magnetic grains with a symmetric interaction distribution about the $H_u = 0$ axis that includes grains with coercivities up to 60 mT.

Low-temperature experiments also indicate that the magnetic mineralogy is essentially the same between the two samples. The FC-ZFC and RTSIRM experiments show a decrease in magnetization at ~120 K, characteristic of the Verwey crystallographic transition in magnetite (Fig. 5e-h). There may be a minor contribution of haematite, indicated by the slight separation of the FC and ZFC curves until ~260 K, corresponding to the temperature of the haematite Morin transition (262 K) (Morin, 1950).

The similarity of the hysteresis parameters, demagnetization behaviour, FORC diagrams and low-temperature experiments for the two samples show that the high intensity NRM centred at 226 cm is not the result of a change in the properties of the magnetic mineralogy or coercivity distribution.

5 Discussion

5.1 Comparison with field models

The measured inclinations at Hall's cave agree well with those predicted for the site by the geomagnetic field models CALS10k.1b (Korte et al., 2011), pfm9k.1b (Nilsson et al., 2014), and SHA.DIF.14K (Pavón-Carrasco et al., 2014) apart from within the uppermost part of the sequence (< 250 years ago) (Fig. 9). Millennial-scale variability predicted by the models accords well with that measured at Hall's Cave and individual centennial-scale events can be correlated between the Hall's Cave record and the SHA.DIF.12K model, which is constructed solely from archaeomagnetic data (Pavón-Carrasco et al., 2014). The level of agreement between the measured directions and the model increases our confidence in the measured record. Beyond 10 ka, where the uncertainty in the SHA.DIF.14K model increases, the measured inclinations diverge from the model and consistently indicate steeper inclinations. This would suggest that the model predictions are less reliable within this older interval. The declination record from Hall's Cave has a greater associated uncertainty than that of the inclination. Nevertheless, the average declination is usually within uncertainty of the model predictions even if higher-frequency variation is obscured by noise.

To compare the RPI record from Hall's Cave with that predicted by the SHA.DIF.14K model, we multiply the NRM-ARM regression by a constant factor such that the average field intensity for the record up to 14 ka is the same as that of SHA.DIF.14K (44 mT) (Fig. 9c). In general terms, there is a steady decrease in RPI between 16 and 9 ka in the Hall's Cave record. From 9 ka to 3.5 ka, there is relatively little variation in the RPI about the average and both SHA.DIF.14K and the Hall's Cave record show a progressive increase in intensity. There is a minor spike in intensity up to 75 mT, centred at 5.25 ka, and lasting several hundred years which is not seen in the SHA.DIF.14K model. A broad low between 10 and 8 ka in the Hall's Cave record is similarly not replicated in the model.

A dramatic and rapid increase in palaeointensity is recorded at the Hall's Cave centred at 2.84 ka. The spike is recorded in multiple samples from both column A and column B and suggests a four-

fold increase in field intensity within less than several hundred years. Although there is some minor fluctuation in field direction prior to and during the intensity spike, it is not outside of the typical range of field directions observed in the rest of the record. However, the observed directions at Hall's Cave within the spike interval diverge slightly from those predicted by SHA.DIF.14K.

Following the spike, from 3-0 ka, the RPI record from Hall's Cave suggests lower palaeointensity values than predicted for the site by SHA.DIF.14K. To assess whether these low intensity estimates are plausible, archaeointensity data were obtained for a region centred on the Hall's Cave site and bounded by 15 and 45°N and 85 and 115°W from the GEOMAGIA50.v3 database (Brown et al., 2015) (Fig. 10). The data include archaeointensity results from Mexico and the American Southwest. The intensity data were filtered to return intensity estimates from the last 17 ka, which had an age uncertainty (1σ) less than 200 years and for which cooling rate and anisotropy corrections had been made. There is a broad range of archaeointensity estimates within the region including some that are lower than the predicted curve. The Hall's Cave RPI record is within uncertainty of many of the archaeointensity results.

5.2 Timing and character of the intensity spike

The geomagnetic intensity spike at Hall's Cave occurs in samples dating between 3000 and 2640 cal BP (~1050 to 690 BC). Based on the age model, the highest intensity sample dates 2843±144 cal BP (893±135 BC). The age of the spike interval at Hall's Cave overlaps with that of spikes dated at 2930 and 2840 cal BP (980 and 890 BC) in the southern Levant (Ben-Yosef et al., 2009; Shaar et al., 2011), and with a 3000 cal BP (1050 BC) intensity high observed in archaeomagnetic results from Turkey (Ertepinar et al., 2012).

The results from Hall's Cave contain no evidence for multiple spikes equivalent to the double spike feature in the archaeointensity record from the Levant (Ben-Yosef et al., 2009; Shaar et al., 2011). However, the duration of the single spike in the Hall's Cave record is approximately 400 years; each sample recording the spike represents approximately 75 years. This presents two possibilities:

1) the samples recording high intensities integrate the double spike into a single, high-intensity feature or 2) the high-intensity event is different in North America in the Near East. The timing of the spike at Hall's Cave is consistent with the high-intensity event occurring simultaneously in both the Near East and North America (Fig. 10). Even accounting for the uncertainty in the age model and the resolution of the samples, it is unlikely that the event could be offset by more than 100 years.

5.3 Implications of the geomagnetic spike at Hall's Cave

The existence of short-duration, high-intensity geomagnetic spikes is difficult to reconcile with current models of the source region of the magnetic field, fluid flow at the outer surface of the Earth's core (Livermore et al., 2014).

The geomagnetic spike recorded at Hall's Cave is associated with a maximum field intensity up to five times the average field intensity. Based on the geomagnetic field model SHA.DIF.14K (Pavón-Carrasco et al., 2014) the average field intensity for the Hall's Cave site for the last 14 ka is 44 μT . Assuming a single-spike structure, the RPI change recorded at Hall's Cave corresponds to changes in field intensity of up to 170 μT over 270 to 300 years, a rate of change of 0.56-0.62 $\mu\text{T}/\text{year}$. This rate of change is eight times slower than that suggested by the Levantine data ($\sim 4\text{-}5 \mu\text{T}/\text{year}$) and is within the upper-bound of instantaneous magnetic intensity change of $0.62 \pm 0.02 \mu\text{T}/\text{year}$ estimated for a purely-toroidal, core-surface flow (Livermore et al., 2014). It is also less than the variation rates of up to 0.8 $\mu\text{T}/\text{year}$ estimated for European regions during the Medieval period (Gómez-Paccard et al., 2012). Livermore et al. (2014) assumes that the geomagnetic spike is the result of localised fluid flow at the surface of the Earth's core. Following the Livermore et al. (2014) calculations, the location of Hall's Cave is sufficiently distant from the Near East sites that the surface core-flow, and corresponding intensity changes, at the two locations would be independent of one another. However, the apparently coincident timing of the spike at Hall's Cave and in the Near East suggests that there is some teleconnection between the two locations, which are $\sim 11,000$ km apart. Assuming the possibility of unrelated, coincident spikes at two independent locations is unlikely, one

explanation may be that the interaction distance of changes in the surface core-flow has been underestimated.

Shaar et al. (2015) suggested that the highest rates of geomagnetic field intensity change within the historical record are concentrated in preferred locations. They observed that two lobes of high temporal variability in the Southern Hemisphere were paired with similar but slightly less active lobes at roughly the same longitude in the Northern Hemisphere. The eastern Northern Hemisphere lobe overlaps with the location of the Near East studies that record the geomagnetic spike at 2900-3000 cal BP. The location of Hall's Cave is just within the western Northern Hemisphere lobe that is the mirror image of the presently active region in South America and spans much of the western North Atlantic. The northern and southern lobes in the Americas may together represent the manifestation of a columnar convection structure within the fluid outer core whose growth and migration may be linked to the greater field activity at the surface (Shaar et al., 2015). The existence of a geomagnetic spike in the western Northern Hemisphere lobe as well as the eastern lobe supports Shaar et al. (2015), who suggested that the geomagnetic spike could be associated with the lobes and that the level of field activity within the Northern Hemisphere could have been significantly higher in the past.

The Hall's Cave record is evidence that the change in fluid flow resulting from increased dynamo efficiency in the Near East lobe is mirrored by the North American lobe. If the mechanisms driving convection in these posited structures are connected, anomalies associated with one structure could be observed in the other. Alternatively, contemporaneous spikes in intensity in two widely separated locations may be evidence that the spikes are global, not local events. Because there are no dramatic field direction changes during the intensity spike, its cause may be an increase in dipole strength rather than a regional non-dipole contribution.

6 Conclusion

Our palaeomagnetic investigation on the sediment sequence at Hall's Cave has yielded an exceptionally well-dated, centennial-scale record of geomagnetic secular variation for the last 17 ka. The sediments recorded high quality palaeomagnetic vectors that were replicated in two different vertical sampling profiles and agree well with palaeomagnetic directions predicted for the site's geographic location using global field models. At ca. 3000 years cal BP, the RPI data from Hall's Cave indicate an almost four-fold increase in geomagnetic field intensity lasting ~400 years. This geomagnetic 'spike' is contemporaneous with shorter duration, decadal-scale spikes reported from the Near East and is the first evidence for this geomagnetic 'spike' outside of the Near East. The rate of field intensity change recorded at Hall's Cave is within the maximum possible suggested by surface-core flow modelling, unlike those recorded in the Near East. However, the presence of contemporaneous spikes in two sites separated by 11,000 kilometres implies a degree of teleconnection that is difficult to explain within our current understanding of core-dynamics.

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579

Figure Captions

Fig. 1: **Location of Hall's Cave.** Elevation relative to modern sea level (rmsl). HC: Hall's Cave, Texas. L: Levantine Sites, Khirbat en-Nahas and Timna-30 (Shaar et al., 2011). AT: Aslantepe, Turkey (Ertepinar et al., 2012).

Fig. 2: **Age model for Hall's Cave.** The age model is constructed from 15 AMS ^{14}C measurements. The 95% confidence intervals for each calibrated age are represented by the individual error-bars. The 95% confidence interval for the Bayesian age model, calculated using OxCal version 4.2 (Bronk Ramsey, 2009), is represented by the shaded, orange band. The uppermost age scale is in uncalibrated radiocarbon ka (RC ka) while the lower scale is in calibrated ka (cal ka).

Fig. 3: **Typical orthogonal demagnetization diagrams of representative samples demagnetized using an alternating field (AF).** The top (bottom) row of diagrams are samples from Column A (B). Open (closed) circles represent the projection of the magnetic vector onto the vertical (horizontal) plane. Characteristic remanent magnetization vector parameters are given in the inset boxes, where D is the declination, I is the inclination, and MAD is the maximum angular deviation.

Fig. 4: **Characteristic remanent magnetization (ChRM) directions.** (a) Maximum angular deviation (MAD), (b) inclination and (c) declination of ChRM directions obtained from samples from column A and B (HC-A and HC-B) against depth (relative to the cave datum). The horizontal grey bar indicates the interval corresponding to the geomagnetic intensity 'spike' (see Fig. 9).

Fig. 5: **Rock magnetic parameters.** (a) Demagnetization of the natural remanent magnetization (NRM) of samples by the stepwise application of alternating fields (AF) normalized to each sample's initial NRM. The shaded grey band represents the 2σ variation of all samples' demagnetization behaviour from column A, excluding samples from within the spike in natural remanent magnetization. (b) A Day plot showing the hysteresis parameters of 11 representative samples from

columns A and B where M_{rs} is the saturation remanent magnetization, M_s is the saturation magnetization, B_{cr} is the remanent coercive force and B_c is the coercive force. All samples plot within a narrow range of hysteresis parameters within the pseudo-single domain (PSD) field. For (c-h), figures on the left relate to sample HC-A-2260 (within the intensity spike) and those on the right to sample HC-A-2630 (a sample with average intensity). (c, d) First-order reversal curve (FORC) diagrams processed using FORCinel (Harrison and Feinberg, 2008). Smoothing was achieved for both samples using the VARIFORC protocol (Egli, 2013) and smoothing parameters of $Sc0 = Sb0 = 3.5$, $Sc1 = Sb1 = 7$. (e,f) FC-ZFC low-temperature experiments (filled circles on FC, open circles on ZFC). (g,h) RTSIRM experiments (filled circles on cooling, open circles on warming).

Fig. 6: Rock magnetic parameters. (a) Low-field magnetic susceptibility (χ), (b) the ratio of ARM susceptibility to low-field susceptibility (χ_{ARM}/χ), (c) the ratio of saturation isothermal remanent magnetization (SIRM) to χ , and the ratio of the maximum anhysteretic remanent magnetization to isothermal remanent magnetization (ARM/IRM) of all samples from columns A and B. The horizontal grey bar indicates the interval corresponding to the geomagnetic intensity 'spike' (see Fig. 9).

Fig. 7: Remanent magnetizations. Initial magnetizations prior to the application of an alternating field are indicated by the darkest lines with circles for (a) the natural remanent magnetization (NRM), (b) the anhysteretic remanent magnetization (ARM), and (c) the isothermal remanent magnetization (IRM). Lines without circles show the magnetizations resulting from step-wise application of alternating fields (AF) with progressively decreasing peak fields. The NRM was demagnetized step-wise using peak alternating fields of 3, 6, 9, 12, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, and 100 mT while the ARM and IRM were demagnetized at peak fields of 12, 20, and 60 mT.

Fig. 8: Relative palaeointensity estimates. The regression (slope) of the natural remanent magnetization (NRM) to (a) the anhysteretic remanent magnetization (ARM) and (b) the isothermal remanent magnetization within the 12-60 mT peak AF demagnetization interval, normalized to the average value for each.

Fig. 9: **Comparison of palaeomagnetic field reconstruction to model predictions.** (a) Inclination and (b) declination of characteristic remanent magnetization vector of samples from columns A (closed circles) and B (open circles). A composite record in which the directions of samples collected from the same depth are averaged is shown as a solid black line. The vertical grey bar indicates the interval corresponding to the geomagnetic intensity 'spike'. (c) RPI derived from the regression of NRM/ARM normalized to an average of 44 mT, of samples from columns A (closed circles) and B (open circles). A composite record in which the intensities of samples collected from the same depth are averaged is shown as a solid black line. The 95% confidence interval of the predicted inclinations, declinations and palaeointensities by the SHA.DIF.14K field model are indicated by the grey shaded bands.

Fig. 10: **Comparison of relative palaeointensity variations to archaeointensity data.** The Hall's Cave composite record (black line) is compared to archaeointensity data from the GEOMAGIA50.v3 database (see Section 5.1 for details). Error bars on GEOMAGIA data indicate 1σ uncertainty. Previously reported observations of the geomagnetic spike are represented by grey bars in the top panel. The additional black bars for Ben-Yosef et al. (2009) and Shaar et al. (2011) represent the two spikes present in their record.

Figure 1

Figure 2

Figure 3

Figure 4

Interval corresponding to the geomagnetic intensity 'spike' (see Fig. 9).

Figure 5

Figure 6

Figure 7

Interval corresponding to the geomagnetic intensity 'spike' (see Fig. 9).

Figure 8

Interval corresponding to the geomagnetic intensity 'spike'.

Figure 9

■ Interval corresponding to the geomagnetic intensity 'spike'.

Figure 10