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Core-flow constraints on extreme archeomagnetic intensity changes

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ABSTRACT

Recent studies (Ben-Yosef et al., 2009; Shaar et al., 2011) propose extreme archeomagnetic intensity changes (termed spikes) in the range ∼4–5 μT/year c.a. 1000 BC in the Near East, around 40 to 50 times larger than values typical of the present-day. In order to investigate whether such extreme changes are consistent with a model of the source region of the magnetic field, namely the fluid flow at the surface of Earth's core, we construct upper bounds for instantaneous magnetic intensity change at an arbitrary site on the Earth's surface. These bounds are constrained by the amount of kinetic energy available to sustain the change, taken here to be a prescribed value for the root-mean-squared surface velocity of 13 km/yr as inferred from the current state of the core. Further, we focus attention on two end-members of optimised core surface flow structure: unrestricted and purely-toroidal. As the derivation of the bounds demands complete knowledge of the geomagnetic field at the core surface, we model the unknown field by means of a Monte Carlo approach, extending to high degree the CHAOS-4 (epoch 2010 AD) and CALS10k1.b (epoch 1000 BC) geomagnetic field models.

Using 2000 realisations for each family of stochastic field models, we find that optimised core flows are always large-scale and that they tend to generate a non-dipole, quadrupole-dominated secular variation at the Earth's surface. The dependence of the upper bounds as a function of site location reflects the large-scale structure of the intensity itself: stronger field permits more rapid change. For the site in the Near East, purely-toroidal flows have upper bounds of approximately 0.62 ± 0.02 μT/year, whereas unrestricted flows increase this bound to 1.20 ± 0.02 μT/year. We favour the former as more geophysically sound, on the account of a large body of previous results from core surface flow inversions and consistency with the existence of a stratified layer at the top of the core. Even if we allow for a generous threefold increase in the prescribed rms velocity (and a concomitant threefold increase in the bound), we conclude that the reported occurrences of extreme intensity changes as suggested in the Near East are not compatible with the commonly accepted structure of core–surface flow. However, it may be that an explanation for spikes lies beyond our current perception of core-dynamics and future work would be further motivated by seeking corroborative evidence of rapid intensity change from sites elsewhere on Earth's surface; we therefore also discuss the form that the secular variation would take in the case of simultaneous archeomagnetic spikes.

1. Introduction

Over the last few years there has been considerable effort focused on studies of geomagnetic field intensity (F) variations over the past several millennia, mainly analysing the thermoremanent magnetization carried by archeological artifacts heated at the time of their manufacture or use. These studies led to the emergence of increasingly detailed composite intensity variation curves for European regions (e.g. De Marco et al., 2008; Kovacheva et al., 2009; Gómez-Paccard et al., 2012; Genevey et al., 2013; Hervé et al., 2013), as well as for the Middle East, where many opportunities of sampling recently allowed the recovery of the geomagnetic intensity fluctuations over the past millennia BC (e.g., Thébault and Gallet, 2010; Gallet et al., in press). The results highlighted a series of regional centennial-scale intensity maxima. In particular, Genevey et al. (2009, 2013) showed the existence in Western Europe of three intensity peaks during the last millennium (during the 12th century, the second half of the fourteenth century and around 1600 AD) that the reconstructed time-varying global archeomagnetic field models are unable to capture, because of their still limited temporal resolution (Korte et al., 2011; Licht et al., 2013). The peaks observed in Western Europe are associated with intensity variation rates of $dF/dt \sim 5$–10 μT per century (or 50–100 nT/yr), comparable to variation rates presently

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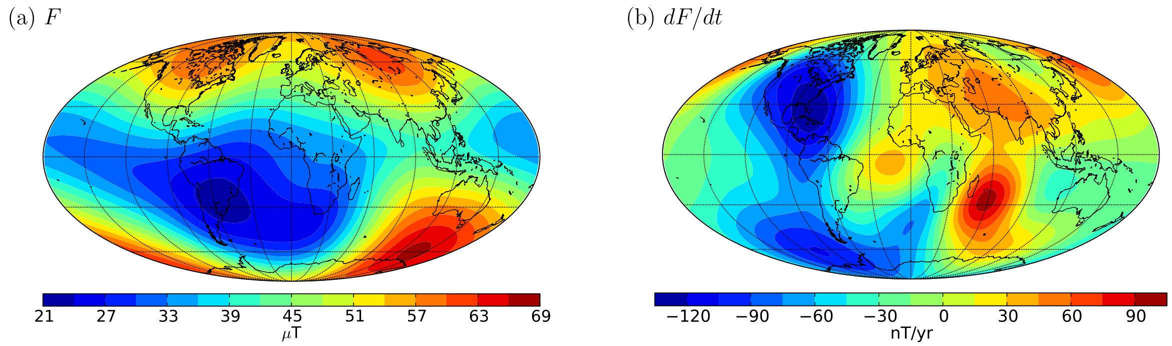

Fig. 1. Contours of (a) F and (b) dF/dt from CHAOS-4 at epoch 2010 to degree 13 on the Earth's surface. The maximum rate of change of intensity is currently $\sim$100 nT/yr.

prevailing in many regions (as shown in Fig. 1). This rate from Genevey et al. (2009, 2013) is determined from an averaged curve and the existence of episodes with larger intensity variation rates cannot be excluded. Such a possibility was proposed by Gómez-Paccard et al. (2012) for Western Europe from rough comparisons between pairs of intensity data, although the derived rates did not take into account uncertainties in the intensity or age. These authors suggested variation rates larger than $\sim$10 μT per century (100 nT/yr) during the Medieval era with values up to 50–80 μT per century (500–800 nT/yr) — such high rates obviously not persisting for the entire period.[1] While variations close to $\sim$100 nT/yr presently exist only in the Indian ocean and the Americas, values larger than $\sim$150 nT/yr appear very unusual.

The best evidence for very rapid intensity variations at a rate much larger than $\sim$100 nT/yr was most probably provided by archeointensity data obtained from the Near East. Recent archeomagnetic studies conducted in Anatolian, Syrian and Levantine regions made it possible to assemble the main intensity variation patterns over the last three millennia BC: see Fig. 2(a); (Genevey et al., 2003; Gallet and Le Goff, 2006; Gallet et al., 2006, 2008, in press; Gallet and Al-Maqdissi, 2010; Ben-Yosef et al., 2008, 2009; Shaar et al., 2011; Ertepinar et al., 2012). These changes are marked by several relative intensity maxima, among which three occurred during the Bronze Age ($\sim$3000–1200 BC), with variation rates again of $\sim$50–100 nT/yr (e.g. Thébault and Gallet, 2010; Gallet et al., in press). But the latter appear very minor compared to the rates reported for the very beginning of the first millennium BC (beginning of the Iron Age; Fig. 2(b)). These data were principally obtained from paleomagnetic analyses of metallurgical residues (slag) in the Levant (Ben-Yosef et al., 2008, 2009; Shaar et al., 2011), and more recently from baked-clay fragments collected from a kiln discovered at Arslantepe (Turkey; Ertepinar et al., 2012). Furthermore, a selection of the available data over a wider geographic area (see Fig. 1 in Shaar et al., 2011, with data selected between 20° N and 50° N in latitude and between 10° E and 50° E in longitude) does not change the main message conveyed by Fig. 2: the beginning of the first millennium BC was characterised in the Near East (and elsewhere) by the highest geomagnetic field intensities ever observed during the Holocene and beyond. There was a suggestion of this phenomenon in the analysis of global and regional compilations of geomagnetic field intensity data (e.g. Yang et al., 2000; Genevey et al., 2008; Knudsen et al., 2008), but not with such a high intensity level. The key information obtained by Ben-Yosef et al. (2009) and Shaar et al. (2011) is that these extreme geomagnetic intensities, larger than 100 μT, were reached in a very short time interval ($\sim$10–20 years), which led to the concept of a "geomagnetic intensity spike" (Ben-Yosef et al., 2009). Two such events have been proposed so far, at $\sim$980 BC and $\sim$890 BC (Fig. 2(b); from Fig. 7 by Shaar et al., 2011). Fig. 2(b) shows that regional intensity variations as extreme as $\sim$30 μT (Shaar et al., 2011, considering solely the data from archeological site Timna-30), even possibly $\sim$50 μT (Ben-Yosef et al., 2009, further considering the data from site Khirbat en-Nahas, abbreviated in what follows to "KEN"), beyond the previously assumed intensity level ($\sim$75 μT) would have occurred in approximately a decade. Figs. 2(c) and 2(d) show smooth fits[2] through the data (orange curve: Timna-30 and KEN datasets, red: Timna-30 only); we present separate analyses as only the intensity recorded at Timna-30 is independently verified by a measurement of comparable magnitude nearby (Ertepinar et al., 2012). In both cases Fig. 2(d) shows similar rates of change of intensity of up to 4–5 μT/yr during the two proposed spike-events.

These archeomagnetic spikes, which have not been found elsewhere, in particular in eastern Europe (for instance neither in the Bulgarian nor Greek data sets; De Marco et al., 2008; Kovacheva et al., 2009; Tema and Kondopoulou, 2011), pose a number of questions, in particular on the precise geographical extension and time-scale of the spike events, on the relative contribution of the dipolar and non-dipolar field components to these features, as well as on the reliability of the extreme intensity data, although the latter have met strict quality criteria, or on the dating precision of these data. The kiln studied by Ertepinar et al. (2012) at Arslantepe yielded a spike-like intensity value ($\sim$100 μT), thereby confirming the extremely high intensity level during the early Iron Age. However, Ertepinar et al. (2012) emphasized the fact that the dating uncertainties for this kiln are 300 yr. It may be that the date at which the oven was fired happened to coincide with the proposed 20–30 yr spike, although this may be regarded as too much of a coincidence. Should the dates not coincide, this would favour not a spike but a centennial-scale intensity peak, albeit extreme, like other maxima so far observed in the Near East and in Europe.

Considering the importance of intensity spikes, and more generally of episodes characterised by rapid intensity changes for deciphering the geomagnetic field behaviour during the Holocene, we decided in the present study to approach the topic from a different perspective: that of asking what intensity variation rates in the

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[1] Although we have reported intensity variation rates expressed per century to be consistent with the cited literature, in view of the short time-scales under consideration in this study, hereafter we will only refer to rates expressed per year.

[2] We generated 100 realisations (thin blue lines) of data bootstrapped from Shaar et al. (2011) and Ben-Yosef et al. (2009), based on a uniform distribution of ages (within the bounds given) and normally distributed intensity (with the mean and standard deviation as given). We fitted uniformly-weighted cubic splines through the data using the Matlab routine *SPAPS*, where the tradeoff between the fit to the data and the smoothness was chosen so that the maximum $|dF/dt|$ was at most 10 μT/yr, a factor of 100 higher than typical archeomagnetic intensity change. The solid orange line shows the average spline, the red shows the equivalent average restricted to the Timna-30 dataset.