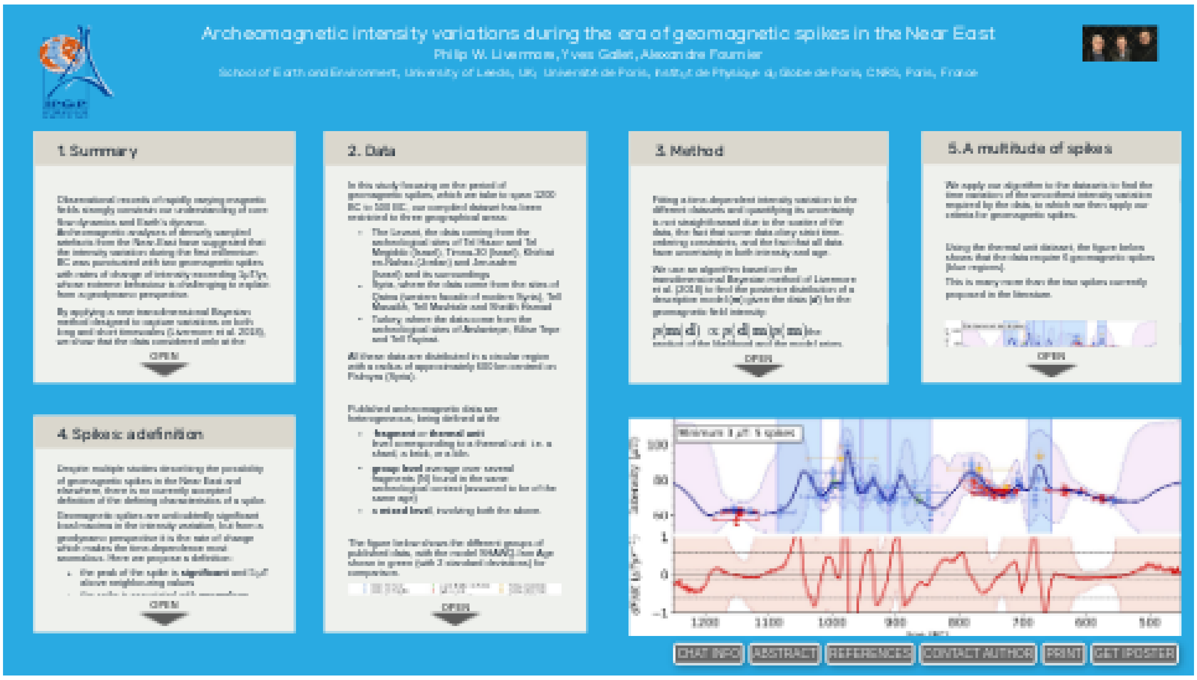
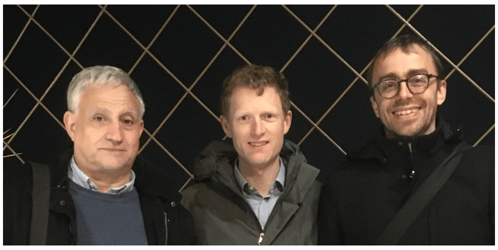
Archeomagnetic intensity variations during the era of geomagnetic spikes in the Near East



Philip W. Livermore, Yves Gallet, Alexandre Fournier

School of Earth and Environment, University of Leeds, UK; Université de Paris, Institut de Physique du Globe de Paris, CNRS, Paris, France



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1. SUMMARY

Observational records of rapidly varying magnetic fields strongly constrain our understanding of core flow dynamics and Earth's dynamo. Archeomagnetic analyses of densely sampled artefacts from the Near-East have suggested that the intensity variation during the first millennium BC was punctuated with two geomagnetic spikes with rates of change of intensity exceeding 1μT/yr, whose extreme behaviour is challenging to explain from a geodynamo perspective.

By applying a new transdimensional Bayesian method designed to capture variations on both long and short timescales (Livermore et al. 2018), we show that the data considered only at the fragment (thermal-unit) level require a complex intensity variation with no less than six spikes.

However, the nature of the inferred intensity evolution and the number of spikes detected are fragile and highly dependent on the specific treatment of the archeomagnetic data. No spikes are observed when the data are considered only at the level of a group of fragments from the same archeological context, with a minimum of three different artefacts per context. Furthermore, the number of spikes decreases to zero when increasing the error budget for the intensity at the fragment level: only 1 spike is observed with an intensity error budget of 5μT, and no spikes are observed with an intensity error budget of 6 μT.

Thus, depending on the choices made, the Near-Eastern data are compatible with a broad range of time-dependence, from six spikes at one extreme to zero spikes on the other.

4. SPIKES: A DEFINITION

Despite multiple studies describing the possibility of geomagnetic spikes in the Near East and elsewhere, there is no currently accepted definition of the defining characteristics of a spike.

Geomagnetic spikes are undoubtedly significant local maxima in the intensity variation, but from a geodynamo perspective it is the rate of change which makes the time-dependence most anomalous. Here we propose a definition:

- the peak of the spike is **significant** and 5 μT above neighbouring values
- the spike is associated with **anomalous rates of change** of the intensity F**,** taken to be values of | dF/dt | > 0.12 μT/yr
- **rates of change are beyond simple physical explanation,** taken to mean that at some point during the spike, | dF/dt | > 0.6 μT/yr

The width of the spike can also be determined by consideration of these criteria.

The threshold of 0.12 μT/yr is the maximum current rate of change of intensity as determined from the latest IGRF model (Alken et al., 2020) while that of 0.6 μT/yr from Livermore et al. (2014).

For more details, see Livermore et al. (2020).

2. DATA

In this study focusing on the period of geomagnetic spikes, which we take to span 1200 BC to 500 BC, our compiled dataset has been restricted to three geographical areas:

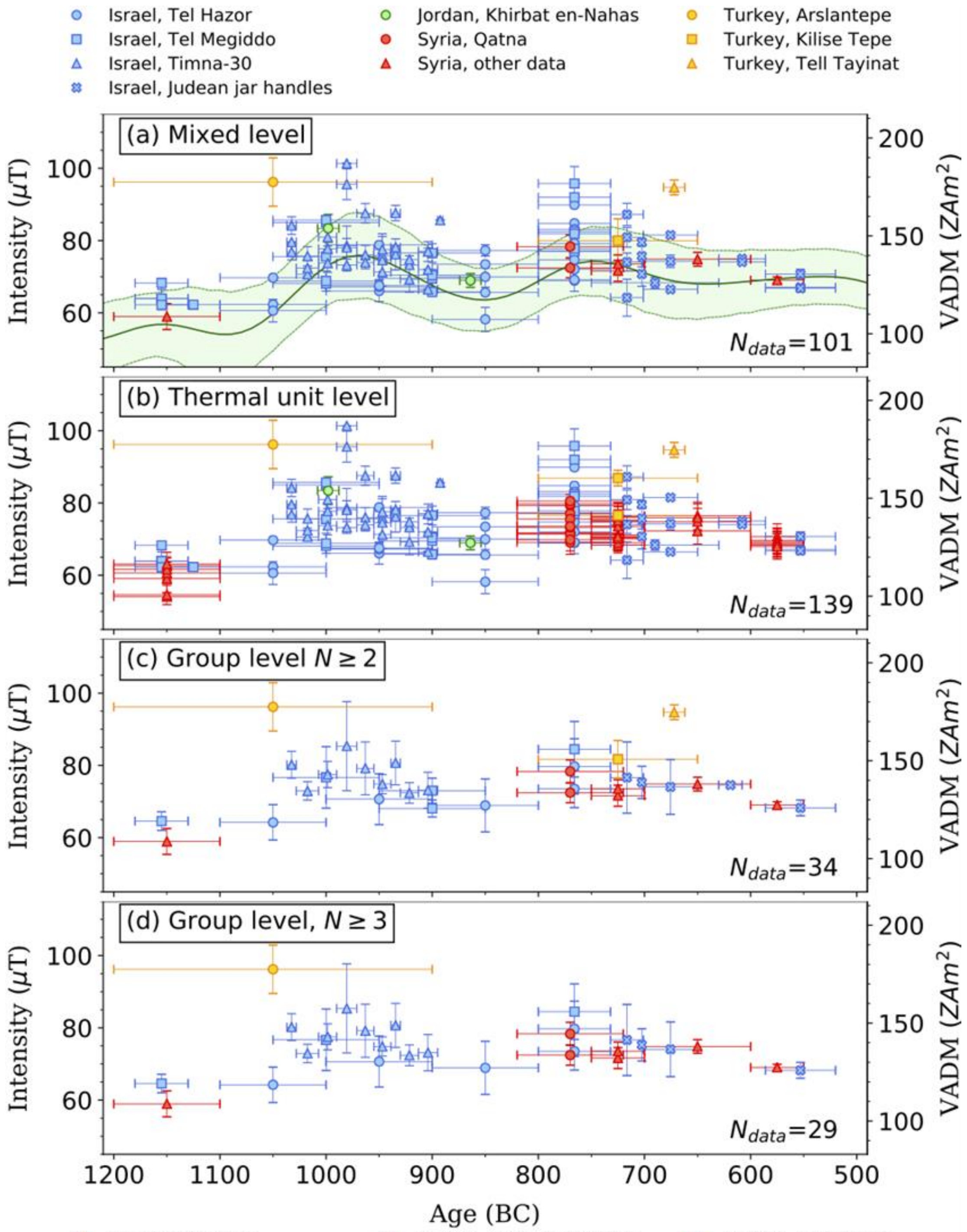
- The Levant, the data coming from the archeological sites of Tel Hazor and Tel Megiddo (Israel), Timna-30 (Israel), Khirbat en-Nahas (Jordan) and Jerusalem (Israel) and its surroundings
- Syria, where the data come from the sites of Qatna (western facade of modern Syria), Tell Masaikh, Tell Mashtale and Sheikh Hamad
- Turkey, where the data come from the archeological sites of Arslantepe, Kilise Tepe and Tell Tayinat.

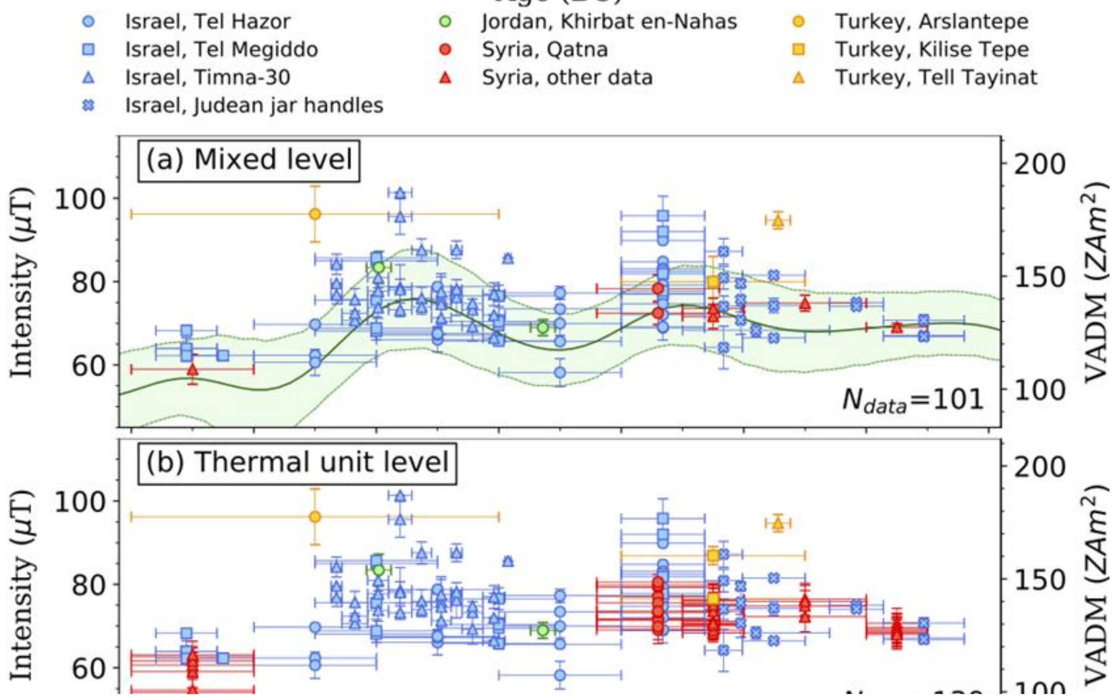
All these data are distributed in a circular region with a radius of approximately 600 km centred on Palmyra (Syria).

Published archeomagnetic data are heterogeneous, being defined at the

- **fragment** or **thermal unit** level corresponding to a thermal unit i.e. a shard, a brick, or a kiln.
- **group level** average over several
  fragments (N) found in the same archeological context (assumed to be of the same age)
- a **mixed level**, involving both the above.

The figure below shows the different groups of published data, with the model SHAWQ-Iron Age shown in green (with 2 standard deviations) for comparison.


Israel, Tel Hazor
Israel, Tel Megiddo
Israel, Timna-30
Israel, Judean jar handles
Jordan, Khirbat en-Nahas
Syria, Qatna
Syria, other data
Turkey, Arslantepe
Turkey, Kilise Tepe
Turkey, Tell Tayinat
(a) Mixed level
N_{data}=101
(b) Thermal unit level
N_{data}=139
(c) Group level $N \geq 2$
N_{data}=34
(d) Group level, $N \geq 3$
N_{data}=29
Intensity (μT)
VADM (ZAm^2)
Age (BC)
1200
1100
1000
900
800
700
600
500
60
80
100
100
150
200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(a) Mixed level
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(b) Thermal unit level
Intensity (μT)
VADM (ZAm^2)

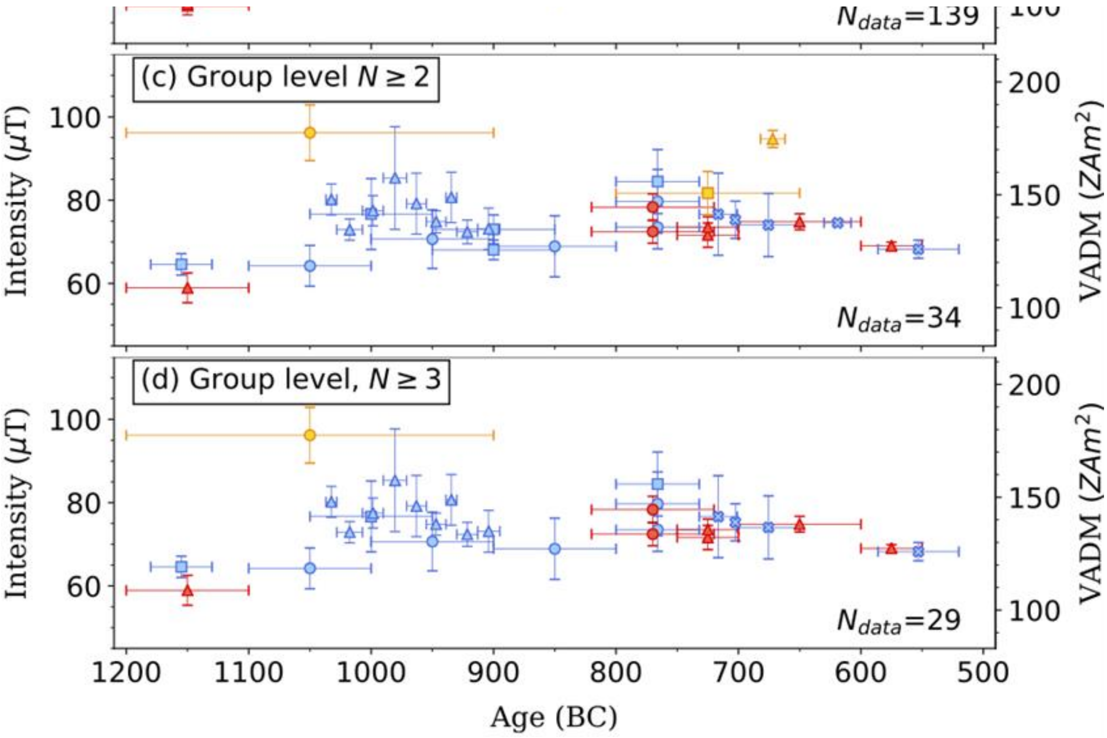


Figure: the different datasets that describe the Near-East intensity variation.

3. METHOD

Fitting a time-dependent intensity variation to the different datasets and quantifying its uncertainty is not straightforward due to the scatter of the data, the fact that some data obey strict time-ordering constraints, and the fact that all data have uncertainty in both intensity and age.

We use an algorithm based on the transdimensional Bayesian method of Livermore et al. (2018) to find the posterior distribution of a descriptive model (***m***) given the data (***d***) for the geomagnetic field intensity:

$p(\mathbf{m}|\mathbf{d}) \propto p(\mathbf{d}|\mathbf{m})p(\mathbf{m})$the product of the likelihood and the model priors. The Monte-Carlo Markov Chain algorithm produces a large ensemble of models
whose statistics converge to those of the joint posterior distribution of the unknown model. Each model is piecewise linear, but their median (as used in the plots on this poster) is smooth.

There is no subjective smoothing parameter but
instead the method relies on the innate parsimony of Bayesian methods. The method will produce rapid intensity changes only when required by the data. Any rapid changes localised in time will not affect the
preference for simple time-dependence elsewhere. This is very important because of the likely range of timescales that may describe the intensity evolution, ranging from the proposed decadal duration of a spike, to the typical centennial timescale of secular variation.

The code to reproduce these examples is open source and available here (http://github.com/plivermore/AH-RJMCMC1/).

5. A MULTITUDE OF SPIKES

We apply our algorithm to the datasets to find the time variation of the smoothest intensity variation required by the data, to which we then apply our criteria for geomagnetic spikes.

Using the thermal unit dataset, the figure below shows that the data require 6 geomagnetic spikes (blue regions).

This is many more than the two spikes currently proposed in the literature.

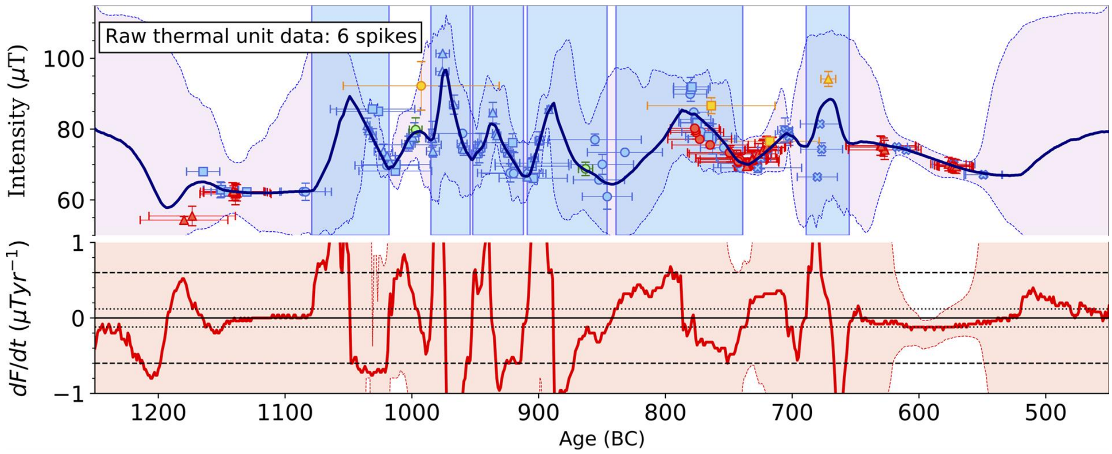


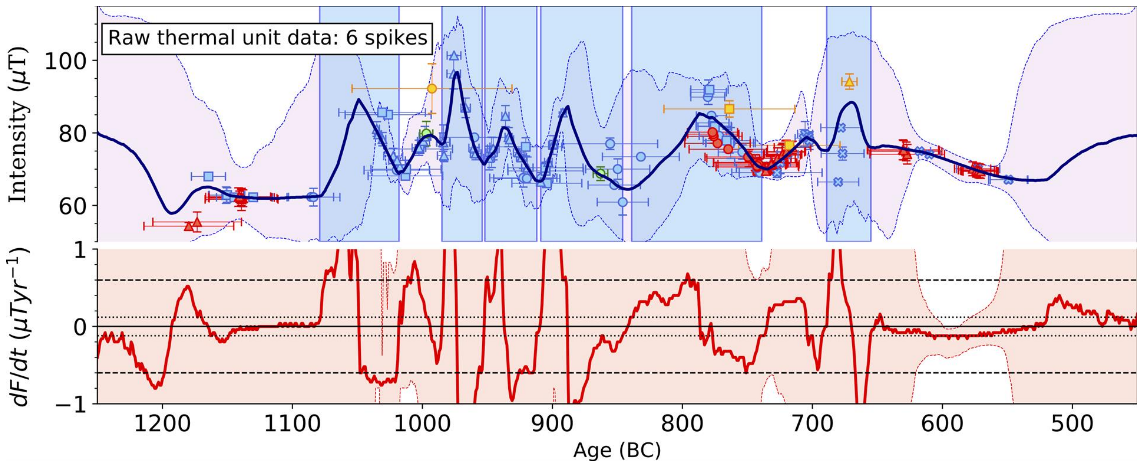
Figure: The median of the posterior distribution of the intensity curve compatible with the thermal unit dataset (upper panel) with its rate of change (lower panel). The six geomagnetic spikes are marked on by the blue panels, whose width reflects the width of the spike. The curves may be regarded at the smoothest such curves consistent with the data. The data shown are the posterior median intensity and age of the samples, with error bars indicating a single standard deviation.

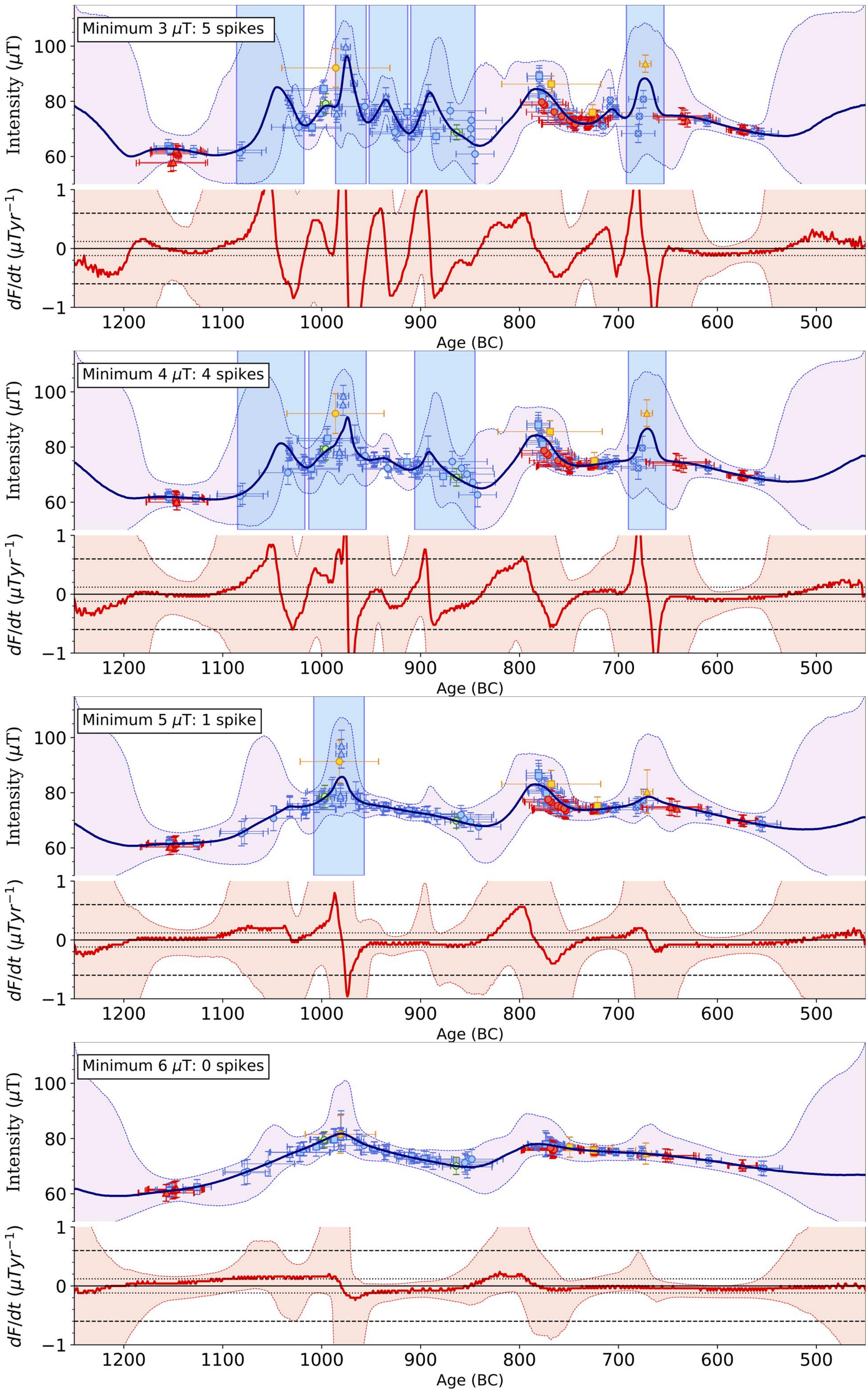
Increasing the minimum error budget for the intensity associated with the thermal unit dataset results in ever smoother models. The slideshow below shows how the number of spikes decreases as the error budget increases.

The number of spikes decreases to zero when increasing the error budget: only 1 spike is observed with an intensity error budget of 5 µT, and no spikes are observed with an intensity error budget of 6 µT.

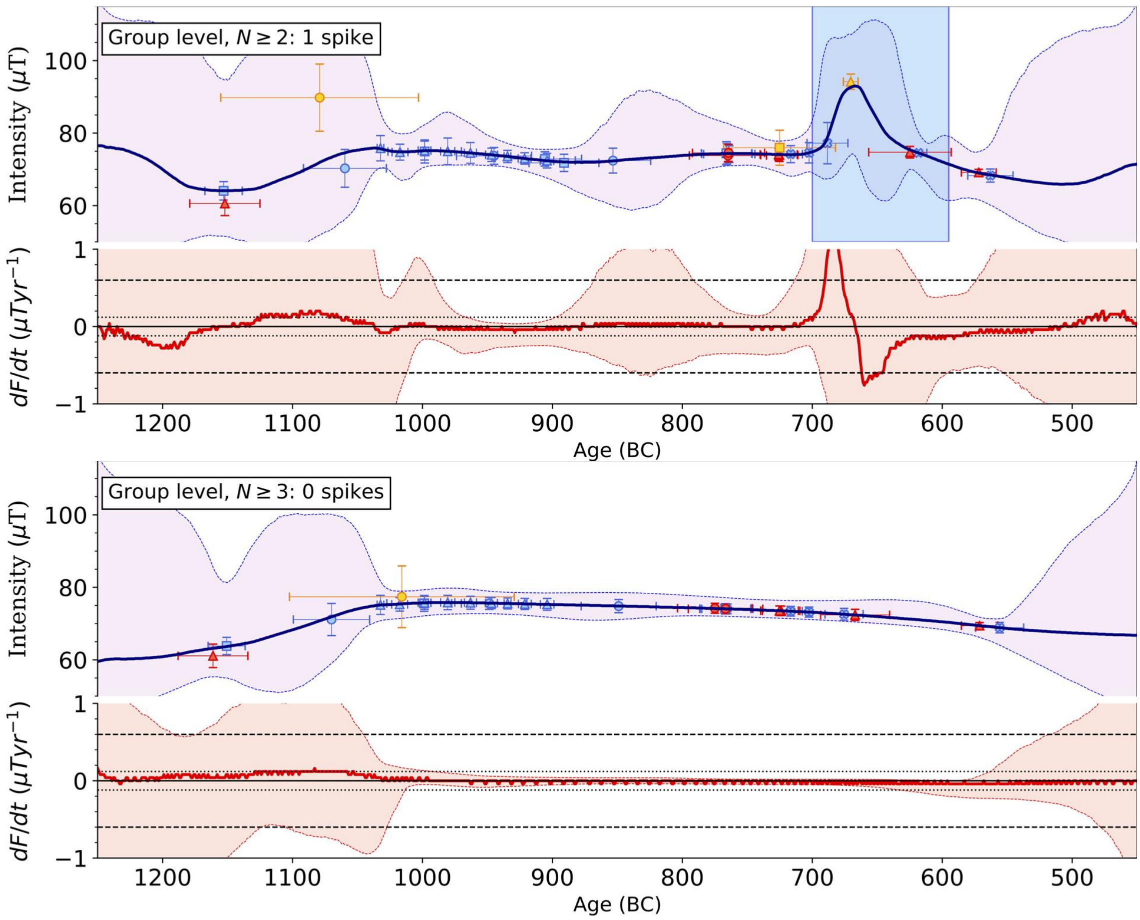
The group-level data sets (with the published intensity error estimates) are consistent with 1 spike (N ≥2) and 0 spikes (N ≥3).

An error of 6 µT at the fragment level produces a model with strong similarity with the reconstruction from the SHAWQ-Iron Age global model (Osete et al, 2020) with modest rates of change of ~0.2-0.3 µT/yr.





Minimum 3 μT: 5 spikes
Minimum 4 μT: 4 spikes
Minimum 5 μT: 1 spike
Minimum 6 μT: 0 spikes
Intensity (μT)
dF/dt (μTyr⁻¹)
Age (BC)



Group level, N ≥ 2: 1 spike
Intensity (μT)
dF/dt (μTyr⁻¹)
Age (BC)
Group level, N ≥ 3: 0 spikes
Intensity (μT)
dF/dt (μTyr⁻¹)
Age (BC)

ABSTRACT

Observational records of rapidly varying magnetic fields strongly constrain our understanding of core flow dynamics and Earth's dynamo. Archeomagnetic analyses of densely sampled artefacts from the Near-East have suggested that the intensity variation during the first millennium BC was punctuated with two geomagnetic spikes with rates of change of intensity exceeding 1 μT/y, whose extreme behaviour is challenging to explain from a geodynamo perspective. By applying a new transdimensional Bayesian method designed to capture variations on both long and short timescales, we show that the data considered only at the fragment (thermal-unit) level require a complex intensity variation with six spikes, each with a duration between ~30-100 years. However, the nature of the inferred intensity evolution and the number of spikes detected are fragile and highly dependent on the specific treatment of the archeomagnetic data. No spikes are observed when the data are considered only at the level of a group of fragments from the same archeological context, with a minimum of three different artefacts per context. Furthermore, the number of spikes decreases to zero when increasing the error budget for the intensity within reasonable levels of 3-6 μT and the data age uncertainty up to 50 years. Thus, depending on the choices made, the Near-Eastern data are compatible with a broad range of time-dependence, from six spikes at one extreme to zero spikes on the other, the latter associated with much more modest rates of change of ~0.2-0.3 μT/y, comparable to secular variation at other periods and in other regions.

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