Six centuries of geomagnetic intensity variations recorded by royal Judean stamped jar handles

Erez Ben-Yosef[a,b,1], Michael Millman[a,b], Ron Shaar[c], Lisa Tauxe[d,1], and Oded Lipschits[a,b]

[a]Department of Archaeology and Ancient Near Eastern Cultures, Tel Aviv University, Tel Aviv 69978, Israel; [b]Institute of Archaeology, Tel Aviv University, Tel Aviv 69978, Israel; [c]The Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem 91904, Israel; and [d]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0220

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Earth's magnetic field, one of the most enigmatic physical phenomena of the planet, is constantly changing on various time scales, from decades to millennia and longer. The reconstruction of geomagnetic field behavior in periods predating direct observations with modern instrumentation is based on geological and archaeological materials and has the twin challenges of (*i*) the accuracy of ancient paleomagnetic estimates and (*ii*) the dating of the archaeological material. Here we address the latter by using a set of storage jar handles (fired clay) stamped by royal seals as part of the ancient administrative system in Judah (Jerusalem and its vicinity). The typology of the stamp impressions, which corresponds to changes in the political entities ruling this area, provides excellent age constraints for the firing event of these artifacts. Together with rigorous paleomagnetic experimental procedures, this study yielded an unparalleled record of the geomagnetic field intensity during the eighth to second centuries BCE. The new record constitutes a substantial advance in our knowledge of past geomagnetic field variations in the southern Levant. Although it demonstrates a relatively stable and gradually declining field during the sixth to second centuries BCE, the new record provides further support for a short interval of extreme high values during the late eighth century BCE. The rate of change during this "geomagnetic spike" [defined as virtual axial dipole moment > 160 ZAm^2 (10^{21} Am^2)] is further constrained by the new data, which indicate an extremely rapid weakening of the field (losing ~27% of its strength over *ca.* 30 y).

archaeomagnetism | archaeointensity | levantine archaeomagnetic curve | paleosecular variation | archaeomagnetic spikes

Reconstruction of geomagnetic secular variation during the Holocene has implications for various fields of research, from geophysics and other planetary sciences to biology and archaeology. Such reconstructions are based predominantly on heat-impacted geological and archaeological materials, whose thermal remanent magnetization (TRM) holds information on the geomagnetic field vector at the time of their last cooling. As evidence for fluctuating field behavior, including short (decadal) periods of rapid changes, is constantly growing (1–5), using records with excellent time resolution has become increasingly of interest.

To improve the accuracy and precision of age constraints associated with estimates of ancient geomagnetic field strength, the current study exploits a set of archaeological artifacts whose ages are exceptionally well constrained. This set is composed of well-studied ceramic jars from Judah/Yehud/Judea (Jerusalem and its vicinity), which bear royal stamp impressions on their handles (6–10). The stamped jars were part of the ancient administration of this region for about 600 y, between the late eighth and late second centuries BCE. As the types of stamp impressions changed with time according to the political situation, the jar handles provide an excellent record for geomagnetic intensity in the Levant during this time.

The geomagnetic intensity record of the Levant has recently improved with new data from Israel, Jordan, Syria, and Cyprus (ref. 4 and references therein). These data indicate two very short episodes of extremely high field values [virtual axial dipole moments (VADMs) in excess of 160 ZAm^2] during the 10th and 8th centuries BCE, which are referred to as the "Iron Age spikes" (2–4). However, as the unusually high field values, accompanied by apparently rapid changes in field strength, raise difficulties in core-flow models, the existence of the spikes has been questioned (11), and a scholarly debate has emerged (5, 12). Thus, an additional aim of the current study is to further investigate this phenomenon, using jar handles bearing successive seal types from the eighth century BCE, the time of the later Iron Age spike.

Materials and Methods

Sampling. The focus of the current research is on royal Judean stamped jar handles that were found in surveys and excavations in Jerusalem and the hill country of Judah. As the archaeological context of these artifacts has no direct relation to the place of their firing (i.e., the location where magnetization was acquired), the entire assemblage is treated here as though coming from one central location in Judah. This location was chosen to be the archaeological site of Tel Sochoh (31.682°N, 34.975°E), which several studies suggest was the production place of one of the major jar groups (the lmlk stamp type; lmlk stands for the Hebrew למלך, meaning "to/of the king") (6, 7, 13). That said, as all of the stamped jars investigated in this study were produced within the boundaries of the political formations ruling the Judean region throughout the first millennium BCE (~31.2°N to 32.2°N), the maximum expected uncertainty in estimated VADM is less than 1 ZAm^2.

Age estimates of the jar handles (Fig. 1 and Table 1) are based on the typology of the stamp impressions found on them, which, except for one general type

Significance

Understanding the geomagnetic field behavior in the past, and, in particular, its intensity component, has implications for various (and disparate) fields of research, including the physics of Earth's interior, atmospheric and cosmologic sciences, biology, and archaeology. This study provides substantial data on variations in geomagnetic field intensity during the eighth to second centuries BCE Levant, thus significantly improving the existing record for this region. In addition, the study provides further evidence of extremely strong field in the late eighth century BCE ("geomagnetic spike"), and of rapid rates of change (>20% over three decades). The improved Levantine record is an important basis for geophysical models (core–mantle interactions, cosmogenic processes, and more) as well as a reference for archaeomagnetic dating.

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Data deposition: All data from our paleomagnetic experiments are provided in the MagIC online database (https://earthref.org/MagIC/DOI/10.1073/pnas.1615797114/). The MagIC Database is a National Science Foundation-supported database for all paleomagnetic and archaeomagnetic data.

[1]To whom correspondence may be addressed. Email: ltauxe@ucsd.edu or ebenyose@post.tau.ac.il.

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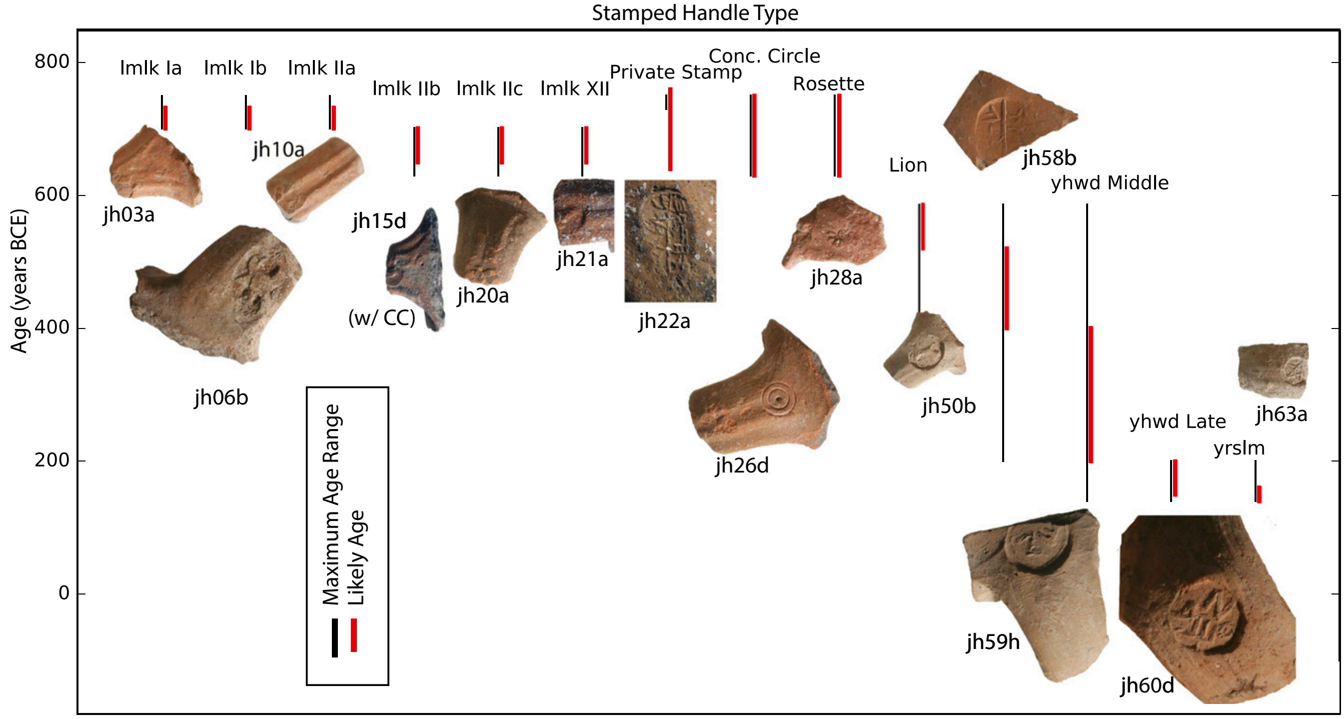

Fig. 1. Six centuries of royal Judean stamped handles: basic typology of the seal impressions and their ages (lmlk, yhwd, and yrslm stand for the Hebrew למלך, יהוד, and ירשלם respectively) (see Table 1 for references). CC, concentric circles; Conc., concentric.

(the incised concentric circles), were done by stamping a seal onto the wet clay just before firing. More than a century of research of these artifacts has resulted in good to excellent chronological constraints. These are based on their stratigraphic context (sharply confined by destruction layers at 701 BCE and 586 BCE), stylistic considerations, the study of the script (Hebrew or Aramaic), and relevant historical events (e.g., refs. 6, 7, 14, and 15). Although there is relatively broad scholarly agreement on the age ranges labeled "likely" in Table 1 (and used as a reference for our results), the maximum possible time intervals are also provided, with the references for the relevant literature.

Extensive detail about the artifacts used in this study is provided in *SI Appendix, Details of Samples Used in This Study*, including the context of their discovery, stamp impression typology, photographs, and references. Most of the handles used in this study were retrieved from the collections of the Ramat Rahel Expedition (16) and the Tel Sochoh survey (17). Each artifact, referred to here as a "sample," is identified by a five-character label that includes the name of the study (jh = Judean Handles), the type/subtype of the stamp impression (e.g., 50 = the lion type), and the sample running number (in letters). For the paleomagnetic experiments, five to six small (~2 mm) pieces were chipped from each sample. These chips are referred to here as "specimens" and are indicated by running numbers; for example, specimen jh50b3 is the third specimen from the second lion type sample in this study.

Table 1. Age ranges of the Judean stamped handled

Stamp type	Max age range, BCE	Max age (Refs.)	Likely age range, BCE	Likely age (Refs.)
lmlk Ia	750–701	(38–46)	732–701	(6, 7, 34, 47)*
lmlk Ib	750–701	(38–46)	732–701	(6, 7, 34, 47)*
lmlk IIa	750–701	(38–46)	732–701	(6, 7, 34, 47)*
lmlk IIb	701–630	(39, 47)	701–650	(6, 7, 34, 47)
lmlk IIc	701–630	(39, 47)	701–650	(6, 7, 34, 47)
lmlk XII	701–630	(39, 47)	701–650	(6, 7, 34, 47)
Private stamps	750–630	(39, 47)	704–701	(6, 7, 34, 47)
Concentric circle incisions	750–630	The dates refer to the firing of the jars (the incision was done after firing)	750–630	(41, 45, 48–50)
Rosette	630–586	(7, 8, 41, 51–54)	630–586	(41, 45, 48–50)
Lion	586–320	Limited stratigraphic evidence that this type did not persist to the end of the Persian Period	586–520	(55, 56)
yhwd early	586–200	(15, 57)	520–400	(58, 59)
yhwd middle	586–140	In some cases, this type has been found together with the early and later types (but possibly in fills)	400–200	(58, 59)
yhwd late	200–140	(60–62)	200–150	(58, 59)
yrslm	200–140	(60, 61, 63, 64)	160–140	(65)

*Ref. 34 argues for a likely start date at *ca.* 715 BCE.

Paleomagnetic Experiments. Paleointensity experiments were carried out in the Paleomagnetic Laboratory of Scripps Institution of Oceanography, University of California, San Diego, using laboratory-built computer-controlled paleomagnetic ovens and a 2G-SRM-760 three-axis superconducting magnetometer. Laboratory procedures and data analyses were done in the same manner as described in Shaar et al. (4). The procedure followed the experimental protocol of Tauxe and Staudigel (18) with routine partial TRM (pTRM) checks at every second temperature step (19). A remanence tensor for anisotropy corrections was calculated from TRMs acquired in six orthogonal positions, or with anhysteretic magnetizations acquired in nine positions. Corrections for cooling rate effects were done assuming a logarithmic relationship between TRM overestimation from ratios of laboratory versus original cooling rates (20), and cooling time from 500 °C to 200 °C approximations of 0.1 h, 3.7 h, and 6 h for the laboratory-fast, laboratory-slow, and ancient cooling times. In all experiments, the field during "in-field cooling" in the oven was 60 μT. Data analysis was done with the Thellier graphical user interface (GUI) program (21), which is part of PmagPy software (22), using the automatic interpretation technique described in detail in Shaar et al. (4, 23). The acceptance criteria follow Shaar et al. (4) and are described with references in *SI Appendix*.

Results

All data from our paleomagnetic experiments are provided in the MagIC online database (https://earthref.org/MagIC/). Out of 211 specimens, 158 passed the threshold values of the criteria used to establish paleomagnetic reliability (*SI Appendix*, *Selection Criteria Applied in This Study*), a success rate of 74%. This relatively high success rate for ceramic material (cf. 24), together with the strictness of the threshold values used in this study (cf. 25), demonstrates the high quality of the Judean jars as a paleomagnetic recorder.

Fig. 2 illustrates typical behavior of specimens during the paleomagnetic experiments. Most specimens have a single component magnetization and a blocking temperature compatible with magnetite. In addition, the original (or "natural") remanent magnetization (NRM) of the fired clay is relatively strong, in the range of 10^{-5} Am^2/kg, allowing the use of very small fragments (~20 mg) in the (destructive) archaeomagnetic experiments, which is especially important when working on rare archaeological materials such as inscribed clay.

Applying a minimum of three successful specimens and a maximum SD of 3 μT or 8%, 27 out of the 67 samples measured yielded reliable paleomagnetic results (Table 2). These new data add to previously published geomagnetic intensity values for the Levant during the first millennium BCE (Fig. 3).

Discussion

Our paleomagnetic experiments yielded excellent geomagnetic intensity values for all of the stamp impression types and subtypes defined in Table 1 and shown in Fig. 1, except for one

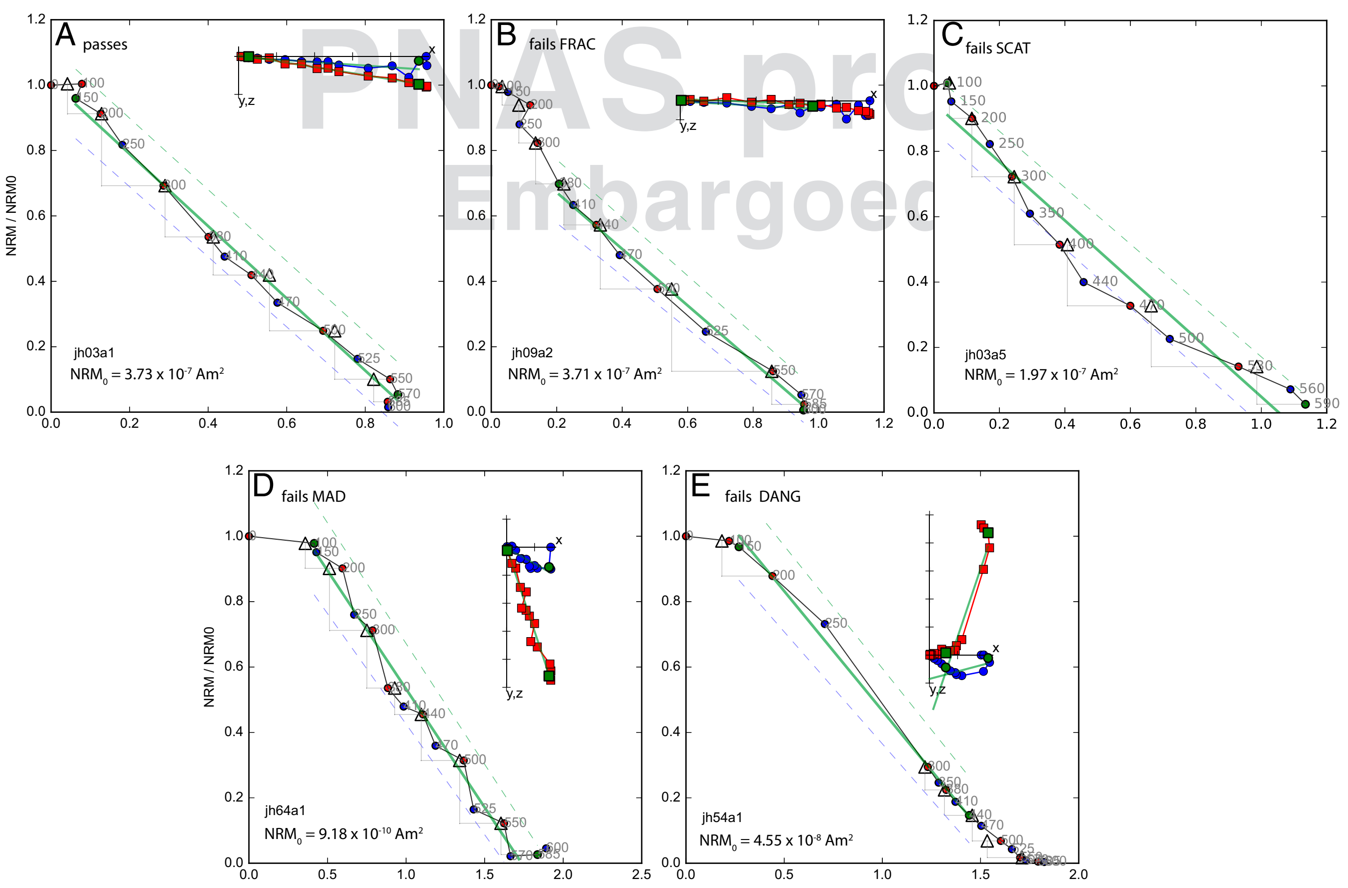

Fig. 2. Examples of behavior of specimens during the paleointensity experiment. Arai plots (36) show NRM lost (NRM/NRM0) versus pTRM gained (TRM/NRM0). Blue symbols are from in-field cooling followed by zero-field cooling (IZ steps), and red symbols are from zero-field cooling followed by in-field cooling (ZI steps). Triangles are the pTRM check steps. Green line is the best-fit line through the data. The (absolute value of the) slope of this line multiplied by the laboratory field gives the ancient field value. The dashed lines are the "SCAT" box. *Insets* are Zijderveld (37) diagrams whereby the remanences measured after zero-field cooling are plotted as X, Y (blue circles) and X, Z (red squares). Experiment (*A*) passed all selection criteria, (*B*) failed the FRAC criterion, (*C*) failed the SCAT criterion, (*D*) field the MAD criterion, and (*E*) failed the DANG criterion. (See *SI Appendix* for detailed description of the criteria used.)

Table 2. Geomagnetic intensity results of samples with $n \geq 3$ and SD ≤ 3 μT or 8%

Stamp type	Sample	Specimens	n	Int., μT	Int. σ	VADM, ZAm^2	VADM σ
lmlk Ia	jh03a	jh03a6:jh03a1:jh03a3	3	61.9	4.92	118	9.41
lmlk Ib	jh06b	jh06b1:jh06b2:jh06b3	3	84.1	2.98	161	5.7
lmlk IIa	jh12a	jh12a4:jh12a5:jh12a3	3	78	2.61	149	4.99
lmlk IIa	jh10a	jh10a3:jh10a4:jh10a5	3	71.4	2.38	137	4.55
lmlk IIb	jh15d	jh15d4:jh15d3:jh15d1	3	64.1	0.0595	123	0.114
lmlk IIc	jh20a	jh20a5:jh20a4:jh20a1:jh20a3	4	71.6	1.64	137	3.14
lmlk XII	jh21a	jh21a1:jh21a2:jh21a3:jh21a4:jh21a5	5	78.6	0.787	150	1.51
Private stamp	jh24a	jh24a1:jh24a3:jh24a2	3	76.7	1.03	147	1.97
Private stamp	jh24d	jh24d4:jh24d5:jh24d2:jh24d1	4	73	2.83	140	5.41
Private stamp	jh24c	jh24c3:jh24c2:jh24c1:jh24c5	4	68.2	3.29	130	6.29
Conc. circle	jh25b	jh25b3:jh25b5:jh25b4	3	65.9	1.44	126	2.75
Rosette	jh27a	jh27a2:jh27a3:jh27a1:jh27a4	4	72.3	0.0793	138	0.152
Rosette	jh28a	jh28a1:jh28a3:jh28a2	3	71.4	0.0779	137	0.149
Lion	jh55a	jh55a4:jh55a1:jh55a2	3	68.2	1.27	130	2.43
Lion	jh56a	jh56a4:jh56a2:jh56a3:jh56a1	4	64.7	0.119	124	0.228
Lion	jh57b	jh57b2:jh57b3:jh57b1:jh57b4	4	64.4	1.04	123	1.99
yhwd early	jh58b	jh58b1:jh58b3:jh58b2:jh58b4	4	73.6	1.18	141	2.26
yhwd early	jh58a	jh58a4:jh58a1:jh58a2:jh58a3	4	72.9	1.82	139	3.48
yhwd early	jh58h	jh58h3:jh58h2:jh58h1:jh58h4	4	70.2	1.21	134	2.31
yhwd early	jh58j	jh58j1:jh58j3:jh58j2:jh58j4	4	65.7	2.51	126	4.8
yhwd middle	jh59l	jh59l4:jh59l2:jh59l3:jh59l1	4	70.3	0.0718	134	0.137
yhwd middle	jh59e	jh59e4:jh59e1:jh59e3:jh59e2	4	66.7	0.0728	128	0.139
yhwd middle	jh59h	jh59h2:jh59h3:jh59h1:jh59h4	4	59.9	4.7	115	8.99
yrslm	jh62a	jh62a4:jh62a3:jh62a2:jh62a1	4	56.1	0.0955	107	0.183
yrslm	jh65a	jh65a1:jh65a3:jh65a4	3	55.8	0.0533	107	0.102
yrslm	jh63a	jh63a2:jh63a3:jh63a1:jh63a4	4	50.9	2.89	97.4	5.53

Conc., concentric; Int., intensity; n, number of successful specimens.

("Late yhwd"). The new data cover a period of *ca*. 600 y, from the late eighth to the late second centuries BCE. In general, the results indicate a gradual decrease in the field's intensity during the seventh to second centuries BCE, in agreement with the trends of the recent paleosecular variation models PFM9K of Nilsson et al. (26) and CALS10K.2 and HOL.OL1.A1 of Constable et al. (27), and previously published data of Gallet et al. (28). Following the peak, there is a trough around 0 CE identified by Ben-Yosef et al. (29) (~77 ZAm^2 VADM). In general, however, it is evident that the secular variation models predict significantly weaker fields and a much smoother behavior than our data suggest.

Discrepancies between models and experimental data have been observed in other recent publications of studies from the southern Levant (e.g., ref. 4), Cyprus (23), and other regions (e.g., refs. 30 and 31), and they are most notable in the early Iron Age of the Eastern Mediterranean (*ca*. 1200–700 BCE) when the field fluctuated rapidly, with intensity peaks reaching more than 150% of the model-predicted values (Fig. 3 for the eighth century BCE). As the models are based on the extensive data published over decades of research, it is evident that they are smoothed by "noise" in the data. These sources of noise include both faulty intensity estimations (inappropriate experimental protocol and/or selection criteria) and erroneous dating. The latter issue has been underappreciated until recently, when more collaborative projects were introduced and effort began in tackling the intricate problem of dating archaeological contexts and artifacts. Thus, the next generation of models needs to take into account regional datasets that are scrutinized for quality of their individual samples. The Levantine curve presented here (Fig. 3) includes only such data, and our research on the Judean stamped jar handles underscores the advantages of working with inscribed clay materials to tackle the dating issue.

In addition to the noise in the database, rapid secular variations are not represented in the geomagnetic field models because of their extremely short durations. To detect rapid changes such as those observed for the eighth century BCE southern Levant (Fig. 3), it takes an extensive quantity of data obtained from materials that represent a time sequence of only several decades. Not only are such efforts rare in common archeaomagnetic research, but the archaeological record itself often is not continuous and is biased toward major events of destruction or abandonment. Several ways to overcome this issue have been suggested in previous research, including working with materials from waste piles and industrial debris (2, 29).

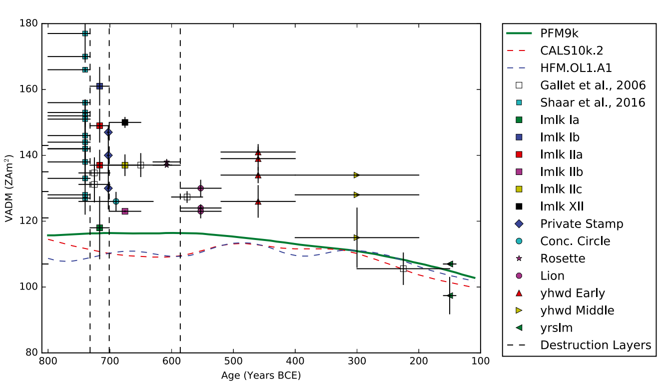

Fig. 3. Six centuries of geomagnetic intensity in the Levant [this study (Table 1), Shaar et al. (4), and Gallet et al. (28)]. The reference curves (solid green, dashed red, and blue lines) are, respectively, from PFM9K model of Nilsson et al. (26) and HOL.OL1.A1 and CALS10k.2 of Constable et al. (27), respectively. The vertical lines represent key chronological markers: the Assyrian campaign to the southern Levant in 734–732 BCE, the destruction of Judean cities by Assyria in 701 BCE, and the destruction of Jerusalem by Babylon in 586 BCE. All data, including results of the current study, are available in the MagIC database (https://earthref.org/MagIC/).

Our new data support the existence of an interval of extremely high field intensity during the late eighth century BCE. These high values are in agreement with recently published data by Shaar et al. (4) and represent one of the Levantine Iron Age "geomagnetic spikes." These anomalies, first reported by Ben-Yosef et al. (2), were defined by Cai et al. (32) as "a sharp increase in the field intensity to more than twice the present value (~160 ZAm^2 VADM) in less than 500 years." Following this definition and the current data available for the Levant (4), there is evidence for at least two such spikes, one during the 10th century BCE [cf. refs. 2 and 3; note that evidence of a 9th century BCE spike failed the more rigorous selection criteria applied in the current study (30)] and the other during the 8th century BCE. Both the 10th-century and 8th-century BCE spikes occurred during a time span of generally high field values worldwide (33), which appears to promote rapidly fluctuating and unstable fields (see discussion in *Results*). The data of the current study add information on the eighth century BCE spike, as it provides strong evidence of the rapidly decreasing intensity over the interval after 732 BCE, an interval not covered by previous studies (Fig. 3). Age constraints from archaeological contexts and stamped jar handles during the second half of the eighth century BCE southern Levant are exceptionally tight, as the region was influenced by Assyrian interventions that resulted in excellent chronological markers in the archaeological record (10). These include military campaigns that left destruction layers of the major Israelite and Judahite cities (in 734–732 BCE, 722–720 BCE, and 701 BCE, Fig. 3). Moreover, the interaction with Assyria and preparation for possible conflicts had direct bearing on the administration of Judah, which is reflected in changes in the stamp impressions on the jar handles (Table 1 and references therein). Thus, the data indicate a sharp drop of ~27% in field intensity over 31 y (732–701 BCE), or—if accepting Na'aman's (34) chronology—over 14 y (715–701 BCE). This well-constrained time interval of the decaying eighth century BCE spike is important evidence that should be taken into account as part of the ongoing discussion on this phenomenon, its sources, and its effects (e.g., refs. 11 and 12; note that the rates here are around ~0.75/1.5 μT/y, within the limits of the suggested models).

Recently, more evidence of extremely high field values around the time of the Levantine Iron Age spikes (~3,000 y B.P.) was found in nearby regions, including Turkey (30) and Georgia (35). Altogether, the available data suggest that this is a regional phenomenon, similar in scale to the current South Atlantic Anomaly (cf. ref. 4); however, the exact geographic expanse of this phenomenon has yet to be investigated, and the fact that these are very short-lived features that can be easily missed suggests that there is much more to discover. As demonstrated here, special archaeological materials such as inscribed clay are one of the keys for increasing time resolution in future research.

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