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

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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 לְמֶלֶךְ, 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.

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