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Geomagnetic intensity spike recorded in high resolution slag deposit in Southern Jordan

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ABSTRACT

In paleomagnetism, periods of high field intensity have been largely ignored in favor of the more spectacular directional changes associated with low field intensity periods of excursions and reversals. Hence, questions such as how strong the field can get and how fast changes occur are still open. In this paper we report on data obtained from an archaeometallurgical excavation in the Middle East, designed specifically for archaeomagnetic sampling. We measured 342 specimens from 72 samples collected from a 6.1 m mound of well stratified copper production debris at the early Iron Age (12th–9th centuries BCE) site of Khirbat en-Nahas in Southern Jordan. Seventeen samples spanning 200 yr yielded excellent archaeointensity results that demonstrate rapid changes in field intensity in a period of overall high field values. The results display a remarkable spike in field strength, with sample mean values of over 120 μT (compared to the current field strength of 44 μT). A suite of 13 radiocarbon dates intimately associated with our samples, tight control of sample location and relative stratigraphy provide tight constraints on the rate and magnitude of changes in archaeomagnetic field intensities.

1. Introduction

Study of the ancient geomagnetic field has widespread implications for a variety of disciplines including physics of the Earth's interior (e.g., Christensen and Wicht, 2007), tectonics (e.g., Torsvik et al., 2008), the early history of the Earth (e.g., Tarduno et al., 2006), biostratigraphy (e.g., Opdyke and Channell, 1996), and archaeomagnetic dating (e.g., Lanos, 2003). Our understanding of the geomagnetic field is based on data obtained from historical measurements (e.g., Jackson et al., 2000; Jackson, 2003), archaeological and geological samples (e.g., Korte and Constable, 2005) and numerical simulations (e.g., Glatzmaier and Roberts, 1996). However, despite centuries of research, we still lack sufficient information regarding such fundamental properties of its behavior as the maximum field strength or its maximum rate of change. Therefore, reliable data from tightly controlled chronostratigraphic contexts are still essential for enhancing our knowledge.

Encouraged by the results of Ben-Yosef et al. (2008a,b) we designed a high resolution sampling strategy for archaeointensity investigation and, aiming at a probable period of a high intensity field around the 10th century BCE (Genevey et al., 2003; Pressling et al., 2006; Ben-Yosef et al., 2008a), applied it as part of the excavation project of the University of California, San Diego and the Department of Antiquities of Jordan, reported by Levy et al. (2008). The excavation penetrated one of the numerous 'slag mounds' at the site of Khirbat en-Nahas (latitude 30.681°N, longitude 35.437°E, Fig. 1), one of the largest ancient copper production centers in the Southern Levant. Three months of careful excavation into approximately 6.1 m of archaeological accumulation exposed a complex sequence of fine industrial debris layers and resulted in a large inventory of samples from a well controlled context. We recorded the x, y and z coordinates of each sample using a 'total station' (precision of less than 5 cm) and included detailed descriptions of their setting in relation to the general division of excavation units (square, strata, loci and baskets). As the site is characterized mostly by pyrotechnological refuse and is located in an arid region where organic material is frequently preserved, it was relatively easy to obtain suitable charcoal samples closely associated with samples for archaeointensity experiments. Radiocarbon measurements of these samples are the basis for the age constraints of the archaeointensity data, as explained below.

2. Archaeointensity experiments

Samples for archaeointensity experiments include copper slag fragments, pieces of smelting furnaces (burned clay) and tuyères (clay

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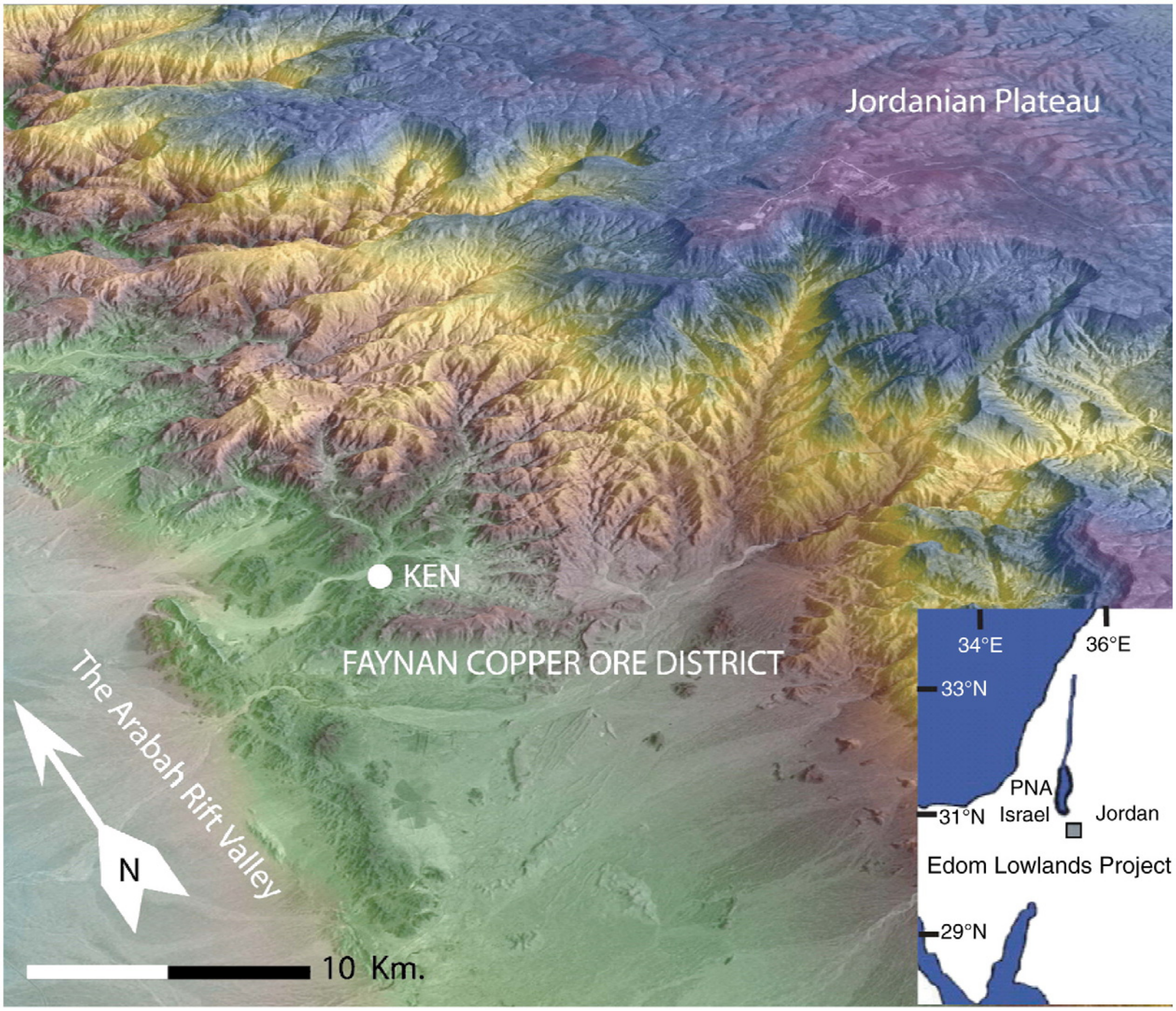

Fig. 1. Faynan Copper Ore District in Southern Jordan, with the archaeological site of Khirbat en-Nahas (KEN), the largest Iron Age copper production center in the Southern Levant. False color 3D satellite image courtesy of Richard Cleave, ROHR, Nicosia, Cyprus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

nozzles of bellow pipes), as well as a few pottery sherds. Ben-Yosef et al. (2008a) demonstrated the reliability of copper slag and associated clay material as archaeointensity recorders and summarized the advantages of its exploitation for reconstructing geomagnetic field intensities for the period of the last seven millennia, starting with the introduction of metallurgy in human history. Their conclusions are based on testing slag material under controlled conditions (known field intensities were recovered from re-melted slag materials), and on results from a large collection of slag samples that were compared to burned clay from the same contexts and to other datasets from the Levant. All of the samples in the current study were divided into 4–12 specimens that were subjected to the Thellier–Thellier based IZZI paleointensity protocol (Tauxe and Staudigel, 2004), including ‘pTRM checks’ and ‘pTRM tail checks’. Representative results from slag material are shown in Fig. 2 and examples of pottery, tuyère and furnace fragments are shown in Fig. 3. Heating steps followed by cooling either in zero field or a controlled lab field (30, 50 or 70 μT) enables graphic depiction (an ‘Arai plot’ — see Figs. 2a–c and 3a–c for examples) of the remaining original magnetization (natural remanent magnetization, NRM) versus field acquired remanence for each temperature level (partial thermal remanent magnetization, pTRM gained). The absolute value of the slope relating the two, when multiplied by the laboratory field allows calculation of the ancient magnetic field. The pTRM checks and tail checks are also graphically illustrated for facilitating evaluation of specimen quality (shown as triangles and squares respectively in the plots shown in Figs. 2a–c and 3a–c).

To further illustrate the behavior of each specimen in the archaeointensity experiment we show the evolution of the directional results as equal area projections with vector end-point diagrams (see Figs. 2d–f and 3d–f for examples). In the equal area projections, we show the change in natural remanent directions as circles and squares and the directions of the pTRMs acquired in each in-field step as triangles. If the pTRMs are acquired in a direction deflected from the laboratory field direction (center of the diagram), then there is cause for worry about the anisotropy of the TRM. Here we use a new paleointensity statistic, γ, defined by Tauxe (2009), which is the angle between the applied field and the best-fit line through the pTRM data.

Many specimens, including nearly all of those with significantly deflected pTRMs, were treated to anisotropy of anhysteretic remanence (AARM) experiments (some deflected specimens were not subjected to this treatment because they broke during or prior to the AARM experiment). In addition, 57 specimens were also subjected to a TRM anisotropy experiment (ATRM). There was no significant difference between the ATRM and the AARM corrected results.

In addition to the standard paleointensity experiment, we tested representative specimens for non-linearity of TRM acquisition (Selkin et al., 2007) (see, e.g., S10265 in Fig. 2). After correction for non-linear TRM acquisition when applicable (B_{nlc} in Fig. 2), specimens were also