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A new approach for geomagnetic archaeointensity research: insights on ancient metallurgy in the Southern Levant

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ABSTRACT

We present results from an archaeointensity investigation based on a relatively unexploited recording medium, copper slag deposits. Together with a recently improved experimental design for the archaeointensity experiment, we demonstrate the applicability of this medium, as well as other archaeometallurgical artifacts, for the study of the ancient geomagnetic field intensity. In addition to archaeointensity data from well-dated archaeological contexts, we obtained reliable archaeointensity results from poorly dated or contentious archaeometallurgical sites in the Southern Levant. These results shed new light on the dating of these sites, among them the copper smelting installation of Timna 39b – a site that has important implications for the beginning of metallurgy during the fifth millennium BCE. The paper also aims to introduce archaeointensity research to the archaeologist scholar, and to encourage further collaboration between the disciplines in future research.

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1. Introduction

Archaeointensity research, the study of the intensity of the geomagnetic field as recorded by archaeological artifacts, has produced a vast amount of data since the 1950s (Donadini et al., 2006; Thellier and Thellier, 1959). The data for the Middle East obtained to date are inconsistent and highly scattered (Fig. 1), principally as a result of different materials used, varying experimental methods, different standards for evaluating the reliability of the laboratorial results and poor time constraints. This inconsistency, together with low data resolution in certain periods, influences the accuracy and predictability of derived geomagnetic field models (notably CALSK7.2, see Korte and Constable, 2005a,b; Korte et al., 2005, and dashed line in Fig. 1). In search of increasing reliability of archaeointensity data we conducted a systematic investigation of a virtually unexploited recording medium, namely copper slag deposits. Together with a recently improved experimental design for the archaeointensity experiment, we demonstrated the suitability of this medium, as well as other materials from archaeometallurgical context, for archaeointensity studies (Ben-Yosef et al., in press).

As part of applying and testing the new approach to archaeointensity investigation we obtained highly reliable archaeomagnetic results from hundreds of specimens that originate from archaeometallurgical sites in the Southern Levant. These results shed new light on the dating of some sites in the Timna valley, including the controversial site of Timna 39b, situated in Israel's southern Negev desert. In the following we present the methodological concepts of archaeointensity research, the advantages of copper slag deposits as an archaeointensity recorder and the archaeointensity results obtained in the first stages of the current study. We also discuss the implication of our results on dating of archaeometallurgical sites and explore some applications of archaeointensity studies in the archaeological research in general.

2. Archaeointensity research

Although the Earth's magnetic field has been recognized for nearly 2000 years (Kono, 2007), it is still one of the least

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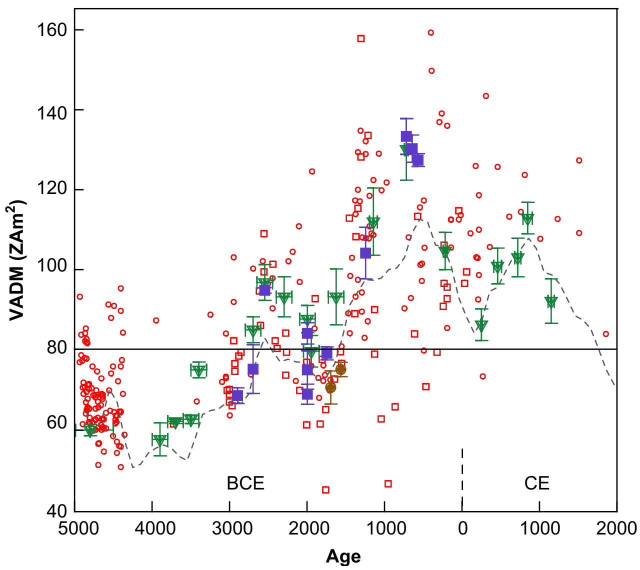

Fig. 1. Examples of archaeointensity data from the Near and Middle East for the last seven millennia, the period since the inception of copper smelting (after Ben-Yosef et al., in press). The magnetic field strength is expressed as Virtual Axial Dipole Moment ($Z = 10^{21}$). Large green triangles are data from Syria of Genevey et al. (2003), blue squares are from Gallet and Le Goff (2006) and brown dots are the Syrian data from Gallet et al. (2006). Open red circles and squares are compilation of 11 other sources, mostly based on fired clay (see Ben-Yosef et al., in press for references). Predicted VADM values for Syria by CALS7K.2 of Korte and Constable (2005a) are shown as dashed line. The recent dipole value is shown as a solid black line (~80 ZAm^2) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

understood geophysical phenomena. Its behavior provides insights on the inner workings of the Earth, including geodynamics of the early planet and changes in boundary conditions through time. Its strength modulates the amount of cosmic radiation hitting the Earth, thus contributing to factors such as the production of cosmogenic isotopes in the atmosphere (including radiocarbon, e.g. Frank, 2000; Kitagawa and Plicht, 1998; Peristykh and Damon, 2003) and potentially even climatic changes (e.g. Courtillot et al., 2007; Gallet et al., 2005).

The geomagnetic field is dynamic and undergoes random changes. Small-scale variations (known as "secular variations") occur constantly, independent of the larger scale directional changes of reversals and excursions (e.g. Yamazaki and Oda, 2004). They show similar characteristics over an areal extent in the order of 10^3 km, and they consist of significant non-dipolar components whose magnitudes are debated (e.g. Constable et al., 2000; Courtilot et al., 1992). Reconstructing geomagnetic field behavior for the last several millennia focuses on studying its secular variations, and thus depends strongly on position. Improved prediction of geomagnetic field vectors awaits more sophisticated archaeosecular variation models, based on reliable data from various regions of the world.

Comprehensive investigation of the geomagnetic field requires full vector information for a known point in time (Fig. 2). For the directional components there are instrumental records for the last 400 years, and for the intensity we have records since 1830s, all included in the GUFM model of Jackson et al. (2000). Reconstructing the geomagnetic field prior to the instrumental recording depends on geological and archaeological recorders. In most cases, these recorders are volcanic rocks and archaeological artifacts that acquired a thermal remanent magnetization (TRM) after cooling from Curie temperature (usually in the range of 300–600 °C). Materials like basaltic rocks, pottery sherds and fired clay bricks are examples of paleomagnetic and archaeomagnetic recorders, which preserve the properties of the geomagnetic field from the last moment of cooling.

While reconstructing the directional properties of the geomagnetic field is a relatively easy procedure, extracting the ancient intensity is a complex and laborious process (Valet, 2003). In principle, it is possible to determine the intensity for ancient magnetic fields because the primary mechanisms by which rocks and artifacts become magnetized can be approximately linearly related to the ambient field for low fields such as the Earth's. Thus, we have by assumption

$$M_{NRM} \cong \alpha_{anc} H_{anc}$$

and

$$M_{lab} \cong \alpha_{lab} H_{lab}$$

where α_{lab} and α_{anc} are dimensionless coefficients; M_{NRM} and M_{lab} are natural (i.e. original) and laboratory remanent magnetizations, respectively; and H_{anc} and H_{lab} are the magnitudes of the ancient and laboratory fields, respectively. If α_{lab} and α_{anc} are equal, we can divide the two equations and rearrange terms to get

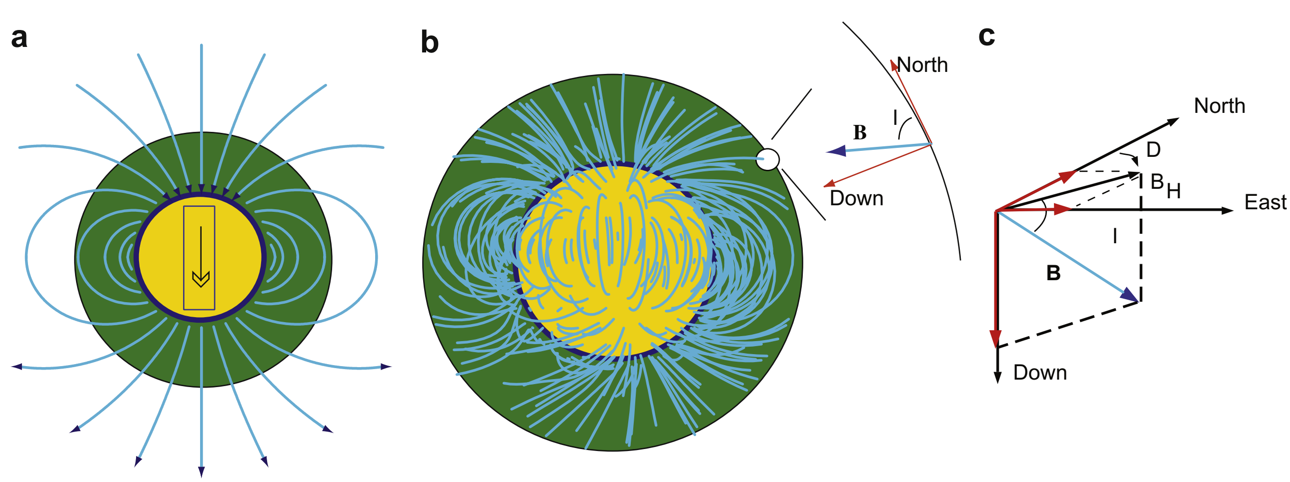

Fig. 2. The Earth's magnetic field and its elements. (a) Magnetic field lines as predicted by a simple model of geocentric axial dipole; (b) magnetic field lines predicted from the international geomagnetic reference field from 1980 in the Earth's mantle (green) (Courtesy of R.L. Parker). The core is the source of the field and is shown in yellow. The field is somewhat more complicated than that shown in (a) owing to non-axial dipole contributions to the field. The enlarged circle represents the vector of the geomagnetic field (B) for the specific location on the Earth's surface (I = inclination angle); (c) three elements of the geomagnetic field's vector: inclination angle (I), declination angle (D) and intensity, represented by the length of line B (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

$$H_{anc} = \frac{M_{NRM}}{M_{lab}} H_{lab}$$

In other words, if the laboratory remanence has the same proportionality constant with respect to the applied field as the ancient one, the remanences are linearly related to the applied field, and the natural remanence (NRM) is composed solely of a single component, all one needs to do to get the ancient field is measure M_{NRM}, give the specimen a laboratory proxy remanence M_{lab} and multiply the ratio between them by H_{lab}.

In practice, the estimation of paleointensity is not so simple. The remanence acquired in the laboratory may not have the same proportionality constant as the original remanence (e.g. the specimen has altered its capacity to acquire remanence or was acquired by a mechanism not reproduced in the laboratory). The assumption of linearity between the remanence and the applied field may not hold true. Or, the natural remanence may have multiple components acquired at different times with different constants of proportionality.

A sophisticated experimental design is needed for validating the basic assumptions of the method, for tracking changes in the magnetic characteristic of a specimen throughout the experiment and for evaluating the reliability of the intensity results. For materials with thermal remanent magnetization, the most common experimental design derives from the basic "Thellier–Thellier" experimental protocol (Thellier, 1938; Thellier and Thellier, 1959).

2.1. Thellier–Thellier experimental design and data interpretation

The theoretical basis for how ancient magnetic fields might be preserved was clarified with the Nobel Prize-winning work of Néel (1949, 1955). The theoretical basis for the experiments, including detailed description and comparison with other methods was recently reviewed by Tauxe and Yamazaki (2007). Here we present only the basic principles of the laboratory work and data interpretation as a background for the archaeological discussion.

The basic experiment involves heating specimens up in stages, progressively replacing the NRM with partial thermal remanences (pTRMs) in the hope of establishing the ratio M_{NRM}/M_{lab} prior to the onset of alteration. This step-wise approach relies on the assumptions that pTRMs acquired by cooling between any two temperature steps are independent of those acquired between any other two temperature steps, and that the total TRM is the sum of all independent pTRMs.

There are several options for ordering the sequential steps. For simplicity, the method of Coe (1967) is presented here. In the first step the specimen is heated to some temperature and cooled in zero field. The measurement of the specimen will give us

$$M_{first} = M_{NRM\_remaining}$$

As an illustration, we plot $M_{NRM\_remaining}$ for a series of temperature steps as the blue line in Fig. 3a. In the second step the specimen is heated again to the same temperature and cooled in the laboratory field, H_{lab}. The measurement of the combined remanence (what is left of the natural remanence plus the new laboratory pTRM) is

$$M_{second} = M_{NRM\_remaining} + \mathrm{pTRM}$$

Simple vector subtraction allows the determination of the pTRM for this temperature step. The pTRM of each temperature stage is plotted as the red line in Fig. 3a. Then, we plot the pTRMs against the relevant $\mathrm{NRM}_{remaining}$, and the result is a useful diagram ('Arai plot', Nagata, 1961) for analyzing the behavior of the specimen throughout the experiment (Fig. 3b). The proportion between the pTRM and the $\mathrm{NRM}_{remaining}$ should be constant, and the slope of the line is the desired proportionality constant

$$\mathrm{slope} = \frac{\mathrm{NRM} - \mathrm{NRM}_{remaining}}{\mathrm{pTRM}} \Rightarrow H_{anc} = H_{lab} \times \mathrm{slope}$$

Additional steps in the same or lower temperatures provide tests for various reliability checks in the experiment. For example, repeating a lower temperature step and checking the pTRM acquired ("pTRM check") indicates if the ability to acquire a pTRM has changed during the experiment. Demagnetizing the specimen after

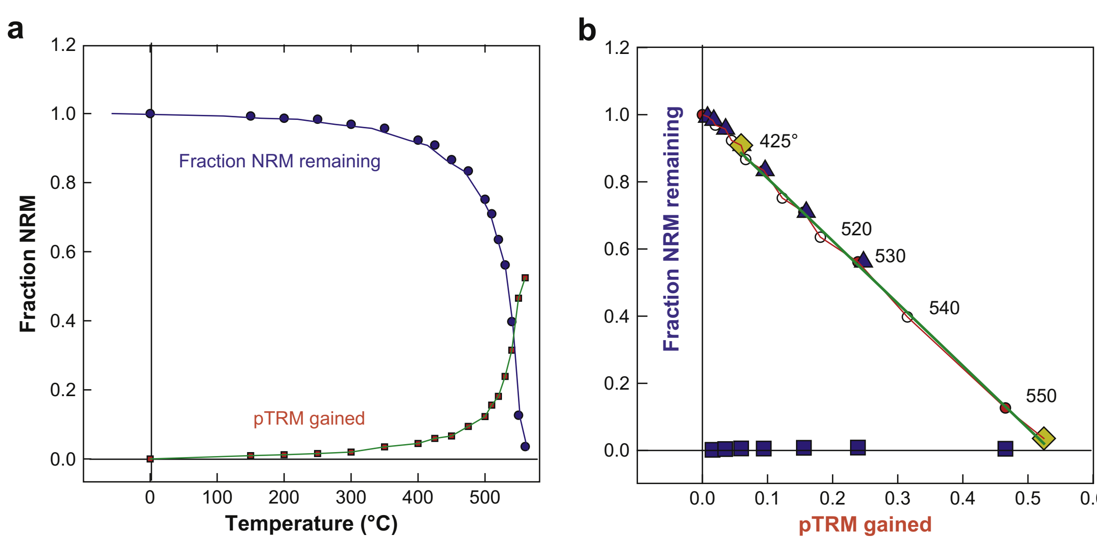

Fig. 3. A graphic representation of the "Thellier–Thellier" type experiment. The figures represent one specimen (IS07a01) and the fractional pTRM it obtained in the laboratory throughout the experiment. Each point stands for a different temperature step. (a) A plot showing the gradual destruction and replacement of NRM (the original [natural] remanent magnetization) by laboratory partial TRM for each temperature step. The fraction $\mathrm{NRM}_{remaining}$ after cooling in zero field is the blue line with circles and the pTRM gained when the specimen is cooled in a laboratory field is the green line with the red squares. (b) An "Arai plot": the $\mathrm{NRM}_{remaining}$ at each temperature step is plotted against the pTRM gained. The absolute value of the slope of the line connecting temperature steps (1.871) is reflects the ratio of NRM/TRM. When multiplied by the lab field (30 μT), the slope gives the absolute archaeointensity (56 μT). The linearity of this line and other parameters are used to determine the reliability of the archaeointensity result. In addition, the plot shows the pTRM checks (blue triangles, expected to be in the same location of the corresponding temperature step, e.g. at 530 °C) and the pTRM-tail checks (blue square, expected to be close to zero). For further discussion see text and Ben-Yosef et al. (in press) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

it acquired a pTRM in the same temperature ("pTRM-tail check") checks whether the blocking temperature is equal to the unblocking temperature, an important prerequisite for reliable intensity results. These tests can be represented on the Arai plot (Fig. 3b).

Interpretation of the results has to take into account numerous factors, and should be done for each specimen separately. First, the segment of the experiment, which represents the ancient magnetic field should be identified, usually using standard demagnetization vector end-point diagrams for determining the original magnetic component and Arai plot for spotting alteration. Then the reliability of the relevant segment should be evaluated, using aspects such as the linearity of the line in the Arai plot, the results of the relevant pTRM and pTRM-tail checks, the number of data points in the relevant segment and others. Many of these aspects can be quantified, and different combinations are used as "selection criteria" for determining a reliable intensity results (see review in Tauxe, 2006). The criteria used and their acceptance values vary among different studies, and they depend on the experimental protocols, the materials used and the personal methodology of the researcher.

There are several other considerations regarding the reliability, precision and accuracy of the intensity results. For example, if the specimen is anisotropic with respect to the acquisition of thermal remanence, the anisotropy tensor must be determined and intensity corrected (e.g. Aitken et al., 1981; Selkin et al., 2000). Moreover, because the approach to equilibrium is a function of time, slower cooling results in a larger TRM; hence differences in cooling rate between the original remanence acquisition and that acquired in the laboratory will lead to erroneous results (e.g. Fox and Aitken, 1980). Compensating for differences in cooling rate is relatively straight forward if the original cooling rate is well known and the sample behaves according to single-domain theory. This theory derives its name from the distribution of atomic magnets within the macroscopic sample, where no domains of mutually contradicting magnetization might cancel each other. Alternatively, one could take an empirical approach in which the specimen is allowed to acquire a pTRM under varying cooling rates, an approach useful for cooling periods of up to a day or 2. For pottery fragments, originally cooled inside kilns, the overestimation was shown experimentally to be by as much as 15–20% with an original cooling time of a day (from the Curie temperature) and an experimental cooling time of half an hour (Genevey and Gallet, 2002).

Finally, the intensity results should be evaluated in the sample level, according to the agreement between different specimens from the same original sample (i.e. the standard deviation cut-off). Usually a minimum number of "well-behaved" specimens per sample (N) is also determined as an additional cut-off value.

2.2. Representation of geomagnetic intensity results – a comment about units

The Système international (SI) basic unit for representing magnetic induction (B) is tesla (T). Induction is often used interchangeably with the term magnetic field (H), with units of A/m because in cgs units there is no difference between field and induction. While there is a significant difference in SI units (a factor of μ_0, or $4\pi \times 10^{-7}$ henries/m), most researchers for simplicity, continue to refer to the induction as the magnetic field but quote values in tesla. For the Earth's magnetic field, which is relatively weak, it is convenient to use μT. The field varies strongly as a function of latitude, as expected from an essentially dipolar field (which is twice as strong at the poles than at the equator). Therefore, when comparing data from different localities (i.e. different longitudes/latitudes) in the same region, it is useful to 'reduce' them to a reference latitude, by simple manipulation (e.g. Odah et al., 1995)

$$B_{\text{reduced}} = B_{\text{site}} \left(\frac{4 - 3\cos^2 \lambda_{\text{reduced}}}{4 - 3\cos^2 \lambda_{\text{site}}} \right)^{\frac{1}{2}}$$

whereλ is the latitude.

A more common way to compare geomagnetic intensity data from different localities and regions is by presenting them as virtual axial dipole moment (VADM)

$$\text{VADM} = \frac{4\pi r^3}{\mu_0} B_{\text{ancient}} \left(1 + 3\cos^2 \theta \right)^{-\frac{1}{2}}$$

where r = Earth's radius [~6,372,000 m]; μ_0 = permeability of free space constant; and θ = co-latitude. Magnetic moments (as the VADM) are measured in Am^2 so magnetic fields (A/m) can be thought of as volume normalized magnetic moments. Conversion to VADM eliminates the effect of the dipole on intensity and allows the possibility of regional differences derived from sources of non-dipole moments to be assessed. Represented as VADM, the current geomagnetic intensity is 77.8 ZAm^2 (Zeta = 10^{21}).

2.3. The contribution of archaeology to geomagnetic intensity research

Understanding the behavior of the geomagnetic field's intensity over the last millennia is a key for studying various related phenomena, such as solar activity (e.g. Usoskin et al., 2006), the production of radiocarbon and other cosmogenic isotopes (e.g. Peristykh and Damon, 2003), the mechanisms of the geomagnetic field itself (e.g. Constable et al., 2000) and perhaps even climate changes (e.g. Courtillot et al., 2007). Moreover, the geomagnetic field has significantly reduced in strength over the last few decades, leading to speculation that it could collapse entirely as it undergoes a reversal of polarity (Constable and Korte, 2006; Hulot et al., 2002). The decay of the field has been observed since the beginning of instrumental recording over 160 years ago (Bloxham, 2003), yet a better understanding of the geomagnetic intensity throughout the last millennia is needed for assessing the nature of the recent change.

For the last millennia, as for the entire Holocene, the best source for reconstructing the secular variations of the geomagnetic field derives from the archaeological context (Folgheraiter, 1899; Thellier, 1938). Since the innovation of pyrotechnological industries in the Neolithic, heated materials are abundant in the archaeological record. The most commonly used archaeomagnetic recorders are artifacts of baked clay, typically pottery sherds, fired mud bricks and kilns' walls (e.g. Fig. 8). The primary advantage of these recorders is the ability to determine their age by the archaeological context. For young (<50 kyr) volcanic rocks, another frequent paleomagnetic target, age determination is a hard task and depends on the association of rare organic materials trapped in or under the rock. Sediments can also be used for study of the ancient geomagnetic field (e.g. Tauxe and Yamazaki, 2007; Valet, 2003), but paleointensity information is at best relative and the time scales are sometimes difficult to constrain.

The success rate of paleointensity experiments frequently does not exceed 10–20% (Valet, 2003). It appears that archaeointensity experiments get higher success rates, especially when using a pre-experiment selection procedure (e.g. Genevey et al., 2003), although many publications do not present the failed data or the virtual success rates. Thus, novel materials are needed as part of the efforts to improve the success rates of these extremely time consuming experiments.

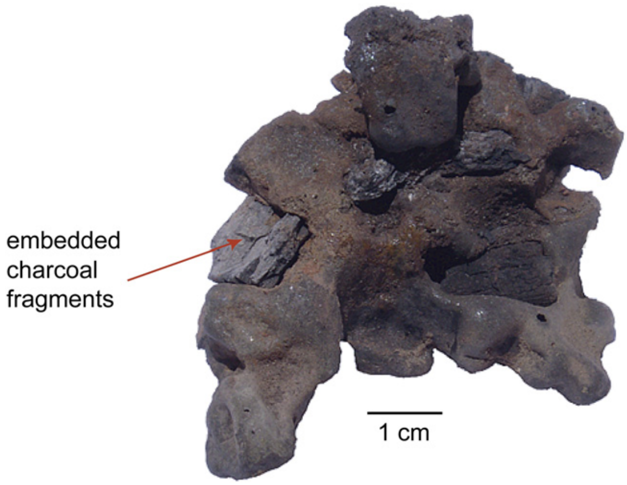

Fig. 4. Embedded charcoal in a slag sample. The charcoal enables a direct dating of the sample, without relying on the archaeological context.

3. Archaeointensity in archaeometallurgical context

3.1. Copper slag as an archaeointensity recorder

Copper slag samples have several distinct advantages as archaeointensity recorders. Frequently it is easy to collect charcoal samples from the same context of the slag and retrieve radiocarbon dates, independently from the dating of the more general archaeological locus assigned by the archaeologists. The latter is often based on complex stratigraphic and typological considerations that are not always under consensus. In some cases, typically with association to advanced copper production technologies, pieces of charcoal can be found embedded in the slag sample itself, providing the possibility for even more direct dating (Fig. 4). As copper production and smelting was widespread in time and space, particularly in the Old World beginning in the fifth millennium BCE, the use of slag for archaeointensity research is especially promising.

Although slag samples vary in chemical composition, appearance, size, mineralogy and texture depending on the raw ore and flux mixture and the specific technique of smelting used, they usually carry a strong magnetic remanence (Ben-Yosef et al., in press). This feature of slag enables the use of very small specimens in the archaeointensity experiments. In addition, abundant glassy parts in most of the slag samples increase the probability for single-domain magnetic particles and thus "well-behaved" specimens throughout the experiment.

In many copper production sites slag deposits are found in multilayer mounds of debris (Fig. 5) representing repeated phases of smelting, enabling a high resolution archaeointensity investigation of specific periods. However, full vector analysis of the ancient geomagnetic field is rarely possible, as most of the samples are not in their original cooling position. *In situ* furnaces with slag attached (Fig. 6) can be sampled for full vector reconstruction, although they are scarce in the archaeological record. In addition, the inclination angle might be retrieved from tapping slag samples with clear horizontal surfaces (Fig. 7a, b).

Typically there is no need for cooling rate correction for copper slag samples. Tapping slag, common since the first millennium BCE, poured out of the furnace during the copper smelting process, cooled rapidly in rates likely to be comparable to laboratory conditions (e.g. Merkel, 1990). However, furnace slag cools inside the furnace and is likely to have cooled slower than the tapping slag. Nonetheless, in antiquity furnaces were frequently broken apart so that those carrying out the smelting could have rapid access to the slag and the copper prills embedded in it (e.g. Hauptmann, 2007). Even if the furnaces were left intact and the slag allowed to cool *in situ*, the furnaces were quite small (typically around 0.5 m in diameter or smaller) and the slag material would have been cool to the touch within a few hours. The most sizable over-estimation might occur with furnace slag samples containing magnetic carriers with low blocking temperatures (e.g. copper–magnesian ferrites). Yet, that could result in overestimates of a few percent at most.

As part of the current study we measured 210 furnace copper slag specimens and 149 tapping copper slag specimens from sites in Israel and Jordan (see examples of samples in Fig. 7). The results demonstrate the suitability of copper slag material for archaeointensity experiments, and establish this medium as one of the most efficient geomagnetic intensity recorders. For a thorough discussion of the experiments and results, including analysis of slag anisotropy and magnetic characteristics, see Ben-Yosef et al. (in press).

3.2. Other artifacts from archaeometallurgical context: implications for archaeointensity research

Ancient metal production industries are a source of various types of samples suitable for the archaeointensity experiments (Fig. 8). Slag from bronze (Ben-Yosef et al., in press) and of iron production industries (Gram-Jensen et al., 2000) have proven to yield reliable archaeointensity results. These observations can probably be extended to any type of slag, including glass production industries; however, further research is needed. In addition to the slag material there is a large variety of samples derived from

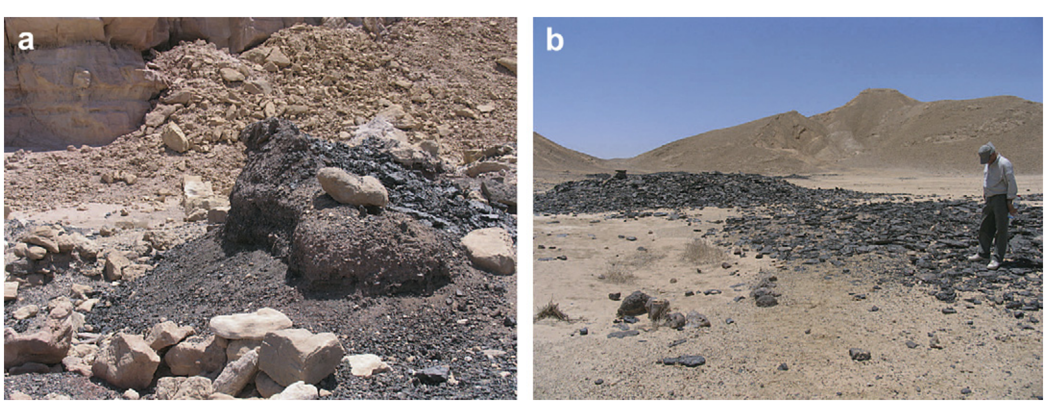

Fig. 5. Slag deposits in the Southern Levant. (a) A ~2 m profile of a partially excavated slag mound in the site of Timna 30, representing probably the Late Bronze Age II, Iron Age I and Iron Age II; (b) abundant slag mounds in Beer-Ora Valley (Timna 28). The slag deposits represent intensive copper production in the Early Islamic period.

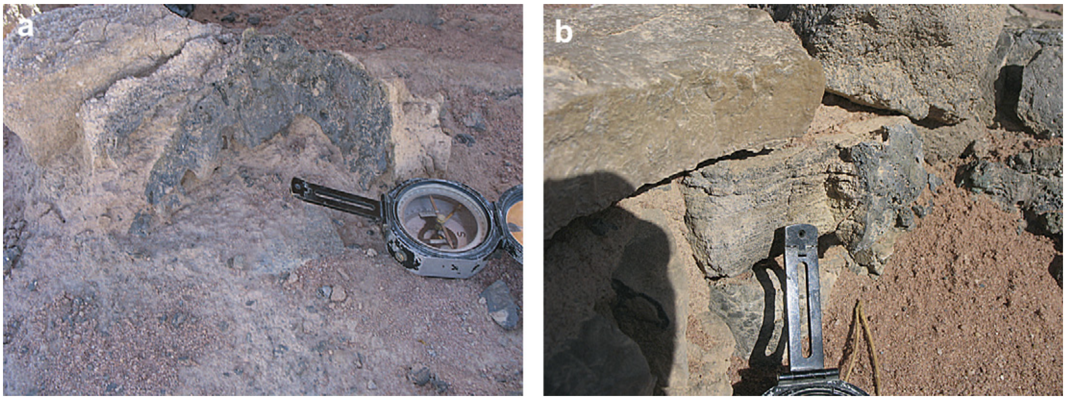

Fig. 6. Slag attached to the walls of *in situ* furnaces enables sampling for full geomagnetic vector analysis. (a) The lower part of furnace "Z" in site Timna 2 is a clay-lining "pit in the ground" (Rothenberg, 1990b); (b) the stone built furnace "E" in site Timna 2 with slag attached (Rothenberg, 1990b).

clay found in archaeometallurgical contexts. These include crucibles, tuyères, bellow pipes, moulds and furnace's linings, as well as other associated clay artifacts. These "technological" or refractory ceramics were typically exposed to extremely high temperatures (>1100 °C) and in many cases have unique tempering and complex structures making them resistant to the smelting and melting processes. Thus, clay samples from archaeometallurgical context are distinct from the commonly used baked clay artifacts such as pottery sherds (typically baked between 400 and 800 °C) and fired mud bricks.

As part of the current study we also measured 28 specimens derived from five samples of refractory ceramics from archaeometallurgical sites in the Southern Levant (Ben-Yosef et al., in press). The experiments yielded successful results for 25 specimens ($\sim$89% success rate), and for all of the samples (using rigorous selection criteria of more than two specimens [$N > 2$] and a standard deviation [σ] $\leq$ 10%). Although the number of clay samples was small, the results indicate that they are highly suitable for archaeointensity studies. We hope to test this observation with a much larger sample of refractory clay objects in the future.

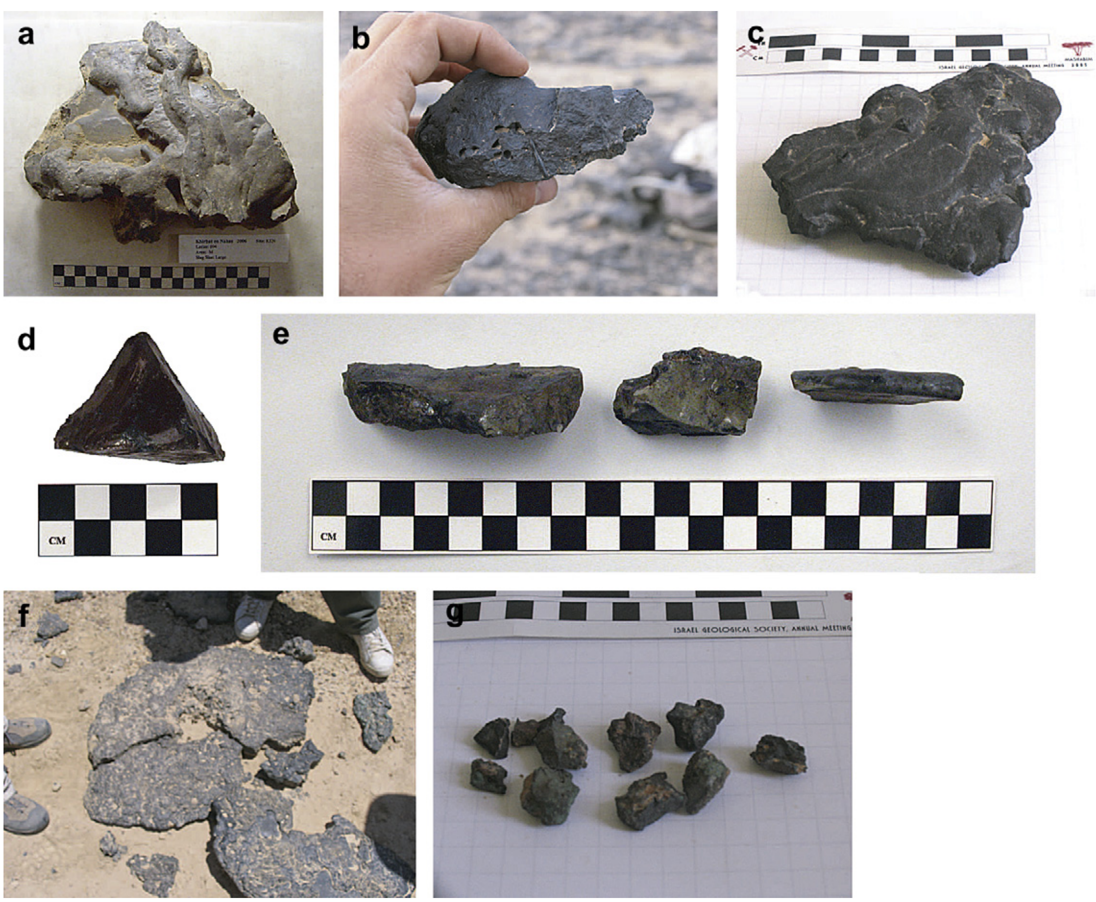

Fig. 7. Examples of slag samples. (a) Broken tapping slag with flow textures, looking at its top (Khirbat en-Nahas, Jordan). Flat areas indicate the horizontal position of the slag when cooling, enabling the reconstruction of the geomagnetic inclination angle. (b) Broken tapping slag with "slag droplet" embedded (Khirbat al-Jariya, Jordan). The droplets indicate the horizontal position of the sample when cooling, enabling the reconstruction of the geomagnetic inclination angle. The glassy texture makes the droplet itself a good source for archaeointensity experiments. (c) Intact tapping slag sample Khirbat Hamra Ifdan, Jordan. (d, e) Glassy fragments of tapping slag (Khirbat en-Nahas, Jordan). (f) "Slag cake" (Beer-Ora Valley, Israel). (g) Broken furnace slag from site Timna 39b.

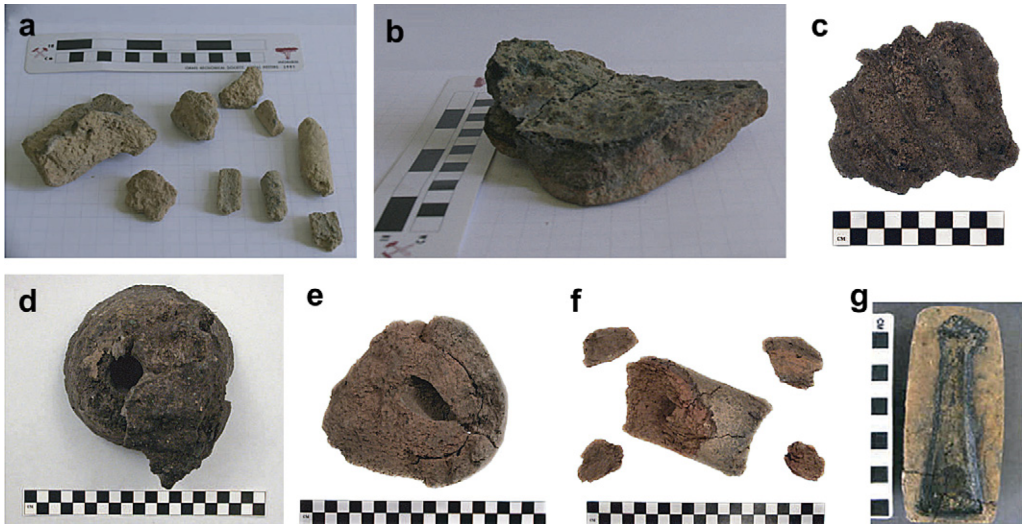

Fig. 8. Examples of baked clay artifacts from archaeometallurgical context. (a) Clay rods ("lady fingers") and furnace fragments from site Fenan 15, Jordan (Early Bronze Age II–III). (b) Clay crucible with slag coating, Tell Gerisa, Israel (Iron Age I). (c) Clay furnace fragment, Khirbat en-Nahas, Jordan (Iron Age II). (d) Tuyère fragment with slag coating Khirbat en-Nahas, Jordan (Iron Age II). (e) Tuyère fragment, back side, Khirbat en-Nahas, Jordan (Iron Age II). Note the composite structure of clay material. (f) Bellow tube fragment, Khirbat en-Nahas, Jordan (Iron Age II). (g) Clay mould for casting copper ax, Khirbat Hamra Ifdan, Jordan (Early Bronze IV) (after Levy et al., 2002).

4. Archaeometallurgy in the Southern Levant and the problem of dating

The copper ore districts of southern Israel and Jordan are some of the richest ancient mining and metal production regions in the Old World, comprising widespread evidence of archaeometallurgical sites and slag deposits. Together they provide key areas for understanding the role of technology on social change and an exciting new sample set for archaeointensity research for the time span of the last seven millennia.

The first evidence of copper production in the Southern Levant goes back as early as the fifth millennium BCE (e.g. Görsdorf, 2002; Levy and Shalev, 1989; Rothenberg and Merkel, 1998) and corresponds with the period of metallurgical innovation throughout the ancient Near East (e.g. Hauptmann, 2000, 2007). The archaeometallurgical sites in the region span almost all of the archaeological periods from the beginning of metal production in the Chalcolithic period, although at different resolutions (e.g. Avner, 2002; Rothenberg, 1999b), through the Mamluk period, in the 13th century CE (Hauptmann, 2007).

The main centers of copper production in the Southern Levant are Faynan and Timna, located along either side of the Wadi Arabah (the Arava Valley) (Fig. 9). They are situated in the vicinity of natural exposures of rich copper ore that are typically part of sandstone and dolomite host layers (Hauptmann, 2007). Except for few other copper smelting sites located near small exposures of copper ore along the Wadi Arabah and in the Sinai Peninsula, other sites of copper industry required transportation of the ore for a relatively long distance. The Chalcolithic site of Shiqmim (Shalev and Northover, 1987) and the Early Bronze Ia site of Ashqelon-Afridar (Segal et al., 2004) are examples of copper production industries that transported copper ore from Faynan, more than 150 km away.

The region of Timna has been intensively investigated by Beno Rothenberg, the director of the Arava archaeological expedition, between the years 1959 and 1990 (e.g. Rothenberg, 1962, 1999a,b, 1990b). As part of this work more than 300 copper mining and production sites were documented (Wilson, 1983), some of which were excavated. Intermittent archaeological research in Timna continues to the present by the Israeli Antiquities Authority and University College London.

The archaeometallurgy of the Faynan district was systematically investigated by Andreas Hauptmann and a team from the Deutsches Bergbau-Museum Bochum (DBM) between the years 1983 and 1993 (e.g. Hauptmann, 2007). Their work included surveys, small-scale excavations and complementary laboratory analysis of the archaeometallurgical finds. Since 1997 the area has been the focus of intensive investigation as part of the Edom Lowland Regional Archaeology Project of the University of California San Diego (UCSD) and the Department of Antiquity Jordan (DOAJ) under the direction of Thomas Levy and Mohammad Najjar (e.g. Levy, 2006). As one of the largest center of copper production in the eastern Mediterranean, the Faynan district is a prolific source for archaeometallurgical studies. Moreover, the current UCSD-DOAJ research in this area provides samples from well-defined context, usually with dating constrained by radiocarbon measurements.

In Timna, however, the situation with regard to the dates of many sites is much more complex – in part because the excavations mostly took place over 25 years ago. In spite of the intensive research and the abundance of surveyed and excavated sites, only scarce radiocarbon dates are available (Avner, 2002 see in particular Table 2 which covers all the periods). The paucity of radiocarbon dates generates a significant challenge for dating sites in the desert areas of the Wadi Arabah. These ancient sites, being remote from the populated centers of the Mediterranean and semi-arid regions where agriculture is relatively easy to practice, show distinct regional characteristics in the material culture. The ceramic typology for this region is much less refined, especially in the early periods form the Chalcolithic to the Iron Age (Avner, 2002; Rothenberg and Glass, 1992), thus hampering the possibility for high resolution contextual dating. In some periods, such as the Chalcolithic and Early Bronze, there are very little stylistic changes in the ceramic assemblage. This results, inter alia, in difficulty for identifying desert sites to the Chalcolithic period in many of the early sites in the Wadi Arabah, both in the Faynan area (e.g. Adams, 1998; Genz, 1997) and in the outskirts of Aqaba (e.g. Görsdorf, 2002; Khalil, 1987, 1992, 1995; Khalil and Eichmann, 1999). In the Jordanian sites the ambiguity in dating was eventually resolved using high precision radiocarbon measurements. In Timna, however, the dating of some of the sites is still highly controversial, such as the copper smelting furnace of site Timna 39b (e.g. Rothenberg, 1990a and see below; Rothenberg and Merkel, 1998).

The difficulty of establishing high resolution dates based on the material culture in the region of Timna led Rothenberg and glass to develop a different and more crude typological/chronological

Fig. 9. The major copper production centers in the Southern Levant.

scheme for the desert sites divided into three assumed phases of the "Sinai-Arabah Copper Age" (Rothenberg and Glass, 1992). In addition to distinctive ceramic and lithic types, each phase was characterized also by an archaeometallurgical typology, including slag types (Rothenberg, 1990b). For example, slag features such as glassy textures, viscosity, amount of left-over copper, mineralogy and chemistry, were considered as chronological markers.

The reliability of archaeometallurgical typology as a dating tool was questioned by members of the Arava archaeological expedition themselves and other scholars (e.g. Avner, 2002), and it became clear that the technological development was not unilinear. Moreover, the chemical composition of slag varies according to the original ore and flux mixture, which depends primarily on the geographical location rather than on the advances in technologies. Nevertheless, the archaeometallurgical typology was used for dating many sites, such as N3 (Segal et al., 1998) and 250b (Rothenberg and Shaw, 1990a,b). These were dated to the Chalcolithic according to a similar "technological horizon" as Site 39b, a contentious site in itself.

In many of the earliest archaeometallurgical sites it is difficult or impossible to retrieve radiocarbon samples. Slag samples, as archaeointensity recorders, might hold the key for solving some of the dating problems and clarify the archaeological picture of the dawn of metallurgy in the region. Since the archaeointensity curve for the Southern Levant is yet in low resolution, a comparison with results from well-dated archaeometallurgical sites is in cases necessary. As part of the current study we investigated slag also from sites of the more populated areas of the Beersheva Valley (Shiqmim), the western Negev (Ashqelon-Afridar) and the central coastal plain of Israel (Tell Dor and Tell Gerisa). In the latter we investigated Iron Age I bronze melting sites (Ilan, 1999). However, before focusing on the problem of the fifth millennium BCE, it is important to examine the archaeointensity results for the entire seven millennia trajectory.

5. Seven millennia of geomagnetic intensity changes in the Southern Levant

5.1. Research methodology

As part of an investigation into slag material as an archaeointensity recorder and in an effort to improve the resolution and reliability of the geomagnetic intensity curve for the last seven millennia, we collected slag, furnace and crucible fragments from

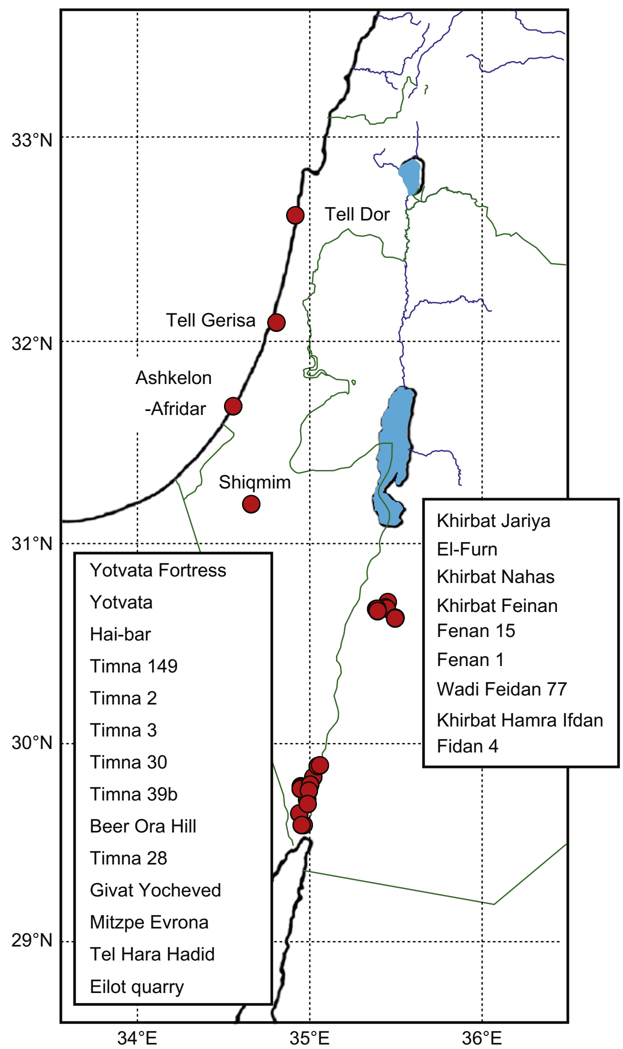

Fig. 10. Archaeometallurgical sites that were sampled in the current study.

27 archaeometallurgical sites in Israel and Jordan (Fig. 10, Table 1). Most of the samples were collected during a field survey from a variety of archaeological contexts, and others were taken from collections of previous archaeological excavations with the exact locations well known (e.g. the sites of Shiqmim and Khirbat Hamra Ifdan), providing the best reference for further analysis.

The main criteria used for choosing the sites were (1) dating quality, with priority given to sites that have well-established archaeological dating or reliable results from radiocarbon measurements; (2) sites from periods that have distinct geomagnetic archaeointensity trends in previous studies, such as the conspicuous peak in the Iron Age (ca. 3000 years ago) and the low in the Chalcolithic – Early Bronze Age (ca. 5500 years ago); and (3) sites in which paleointensity data might help to solve questions concerning the history of metallurgical technology, such as Timna 39b.

All of the dates assigned to our samples are based on prior archaeological investigation of the sites. We have not measured radiocarbon samples in this stage of the research, although in many cases associated charcoal pieces are abundant and might be used in the future. The archaeological context constraining the age information of the sample collection (see Table 1) is of variable quality, depending on the collection method and the previous archaeological work. We have developed a scheme for characterizing the age uncertainty of a sample based on the complex reality of archaeological investigation in our research area. While the age assigned might be precise (i.e. having a small deviation from the mean), the archaeological context tying a given sample to a given age may be weak or controversial. In order to characterize the context itself, we make use of various objective categories that relate to the methods of the original dating (e.g. radiocarbon measurements versus ceramic typology), the characteristic of the site (e.g. presenting multi-periods or single period) and our sample collection strategy (e.g. from confined excavated loci or surface survey).

To summarize the relative reliability of our samples ages, we have assigned each age a number from 1 to 6 whereby 1 is considered as excellent and 5 as poor. Controversial sites are assigned a number 6. For the purposes of geomagnetic field modeling, only the samples with age reliability of 1 and 2 should be considered. The results from the rest of the samples are part of the discussions on the quality of slag as an archaeointensity recorder (Ben-Yosef et al., in press) and on the dating of the sites from which they were collected (below).

In this study, every coherent fragment (piece of slag or clay) that we collected is called "sample", and every chip of a sample is called "specimen". From each sample we isolated four to 12 specimens ranging from 2 to 7 mm in diameter. The full name of a specimen designates its location. JS stands for Jordan, IS stands for Israel and the next two digits represent the site. The sample piece is designated with a letter and the specimen number with the last two digits. For example, specimen JS01b03 is the third specimen from the b sample from the Wadi Fidan 4 site in Jordan (JS01). We catalogued and stored all of our samples in the paleomagnetic laboratory of the Institute of Earth Sciences in the Hebrew University of Jerusalem, and they constitute a large inventory for future research.

The specimens were inserted into non-magnetic glass tubes (1 cm in diameter) and went through a Thellier–Thellier type experiment, using a sophisticated experimental protocol (the "IZZI" protocol, see Tauxe and Staudigel, 2004; Yu and Tauxe, in press; Yu et al., 2004). A detailed description of the experiments, the selection criteria used and our methodology in determining the cut-off values together with comprehensive results and statistical analyses are given in Ben-Yosef et al. (in press).

5.2. Results

Our archaeointensity curve (Fig. 11a and Table 2) is based on well-dated samples (age quality 1 and 2) with at least three successful specimens ($N \geq 3$) that are in good agreement with each other (σ cut-off = 20% of the mean or within 5 μT). Fig. 11b and Table 3 show the additional samples that passed the experimental and statistical requirements, but originated from a poorly dated or controversial context (age quality 3–5). For perspective, we plot the recently published data set from archaeointensity investigation of Syrian sites (Gallet et al., 2006; Gallet and Le Goff, 2006; Genevey et al., 2003) together with the predicted VADM for the region from the CALS7K.2 model of Korte and Constable (2005a).

In total, 30 samples out of 80 show reliable geomagnetic intensity results, therefore representing a success rate (on a sample basis) of 37.5%. At the specimen level, 236 out of 400 passed the experimental requirements, giving a general success rate of ~60%. Comparing between specimens of furnace and tapping slag in terms of success rate shows a slight preference towards furnace slag. The success rate of baked clay from archaeometallurgical context was extremely high (89% in the specimens level and 100% in the sample level), although the total number of specimens is only 28. Bronze melting slag show similar success rate to furnace copper slag, but in this case the number of specimens is limited, making this inference tentative.

Table 1
Archaeometallurgical sites and samples in this study

Site name	Lat/Long	Age[a]	C[b]	Co[c]	Q[d]	S#[e]	SN[f]	Type[g]	S[h]	Ref.[i]
Southern Wadi Arabah (Timna area, Israel)										
Timna 39b	29.763/34.994	−4200 ± 250	–	S	6	10	IS11 IS24	FS	*	6,11–13, 33
Hai-Bar	29.830/35.020	−3400 ± 1100	–	S	5	6	IS01	FS	*	1
Yotvata fortress	29.890/35.058	−3860 ± 500	*	S	2	1	IS17	FS	–	17,8,6
Yotvata	29.885/35.046	−2650 ± 350	–	S	5	1	IS15	FS	*	1
		0 ± 100	–	S	1	1	IS16	TS	*	1
Eilot Quarry	29.589/34.952	−2650 ± 350	–	S	5	1	IS19	FS	*	20,1
Beer-Ora Hill	29.717/34.985	−1785 ± 20	*	S	2	4	IS07	FS	*	6
Timna 149	29.792/35.001	−2150 ± 150	–	S	2	3	IS03	FS	*	2,3,5,6
					6	6	IS02	FS	*	
Timna 2	29.784/34.948	−1225 ± 75	*	S	2	4	IS05 IS06	TS	*	10
Timna 3	29.779/34.952	−1225 ± 75	–	S	2	3	IS08	TS	*	5
Timna 30	29.771/34.947	−860 ± 60	*	S	3	2	IS09	TS	*	10
Timna 28	29.716/34.984	850 ± 150	*	S	2	2	IS04	TS	*	4,7,9
Tell Hara-Hadid	29.589/34.965	800 ± 150	–	S	3	5	IS10	TS	–	1
Givat-Yocheved	29.648/34.939	800 ± 150	*	S	6	1	IS18	TS	*	9,18,10
Mitzpe Evrona	29.695/34.987	800 ± 150	–	S	3	1	IS25	TS	–	9
Faynan area, Jordan										
Fidan 4	30.673/35.385	−3250 ± 250	*	S	1	3	JS01	FS/C	*	27,28
Fenan 15	30.629/35.497	−2600 ± 300	–	S	1	2	JS04	FS/C	*	28
Khirbat Hamra Ifdan	30.663/35.393	−2450 ± 150	*	E	1	1	JS09	FS	–	31
		−2100 ± 100	*	E	1	1	JS08	FS	*	31
		−1000 ± 200	–	S	4	1	JS06	TS	–	32
Khirbat al-Jariya	30.707/35.452	−1030 ± 110	*	S	1	2	JS02	TS/C	*	28
Khirbat en-Nahas	30.681/35.437	−850 ± 50	*	S	1	3	JS03	TS	–	28,29
Wadi Feidan 77 ('Khirbat Glueck')	30.674/35.391	−1000 ± 200	–	E	3	1	JS07	FS	–	32
Fenan 7	30.630/35.495	−900 ± 100	–	S	5	1	JS10	TS	–	28
Fenan 1	30.626/35.495	160 ± 145	*	S	2	1	JS11	TS	–	28
El-Furn	30.675/35.447	1250 ± 50	–	S	1	1	JS05	TS	*	28
Other sites in Israel										
Shiqmim	31.195/34.639	−4275 ± 50	*	E	1	3	IS14	FS/C	*	14–16
Ashqelon-Afridar	31.679/34.556	−3475 ± 125	*	E	4	3	IS20C	FS/C	*	21–24
Tell Gerisa	32.091/34.806	−1100 ± 100	–	E	3	1	IS21	BS	*	25
Tell Dor	32.617/34.916	−1100 ± 100	–	E	1	1	IS22	BS	–	26

[a] Negative numbers are BCE.
[b] ^{14}C dates available (calibrated with OxCal).
[c] Collection method: S, surface collection during survey; E, collection from excavation.
[d] Age reliability scores: 1, excellent; 2, moderate to excellent; 3, moderate; 4, moderate to poor; 5, poor; 6, controversial.
[e] Number of samples measured from the site.
[f] Sample names.
[g] Type (crude categories): FS, furnace slag; TS, tapping slag; C, clay; BS, bronze production slag.
[h] Successful experiment results for the site (according to our criteria, see Ben-Yosef et al., in press).
[i] Most relevant references: [1] Avner (personal communication, 2006); [2] Rothenberg and Shaw (1990b); [3] Rothenberg and Shaw (1990a); [4] Rothenberg (1999b); [5] Rothenberg and Glass (1992); [6] Avner (2002); [7] Sharon et al. (1996); [8] Segal and Carmi (1996); [9] Avner and Magness (1998); [10] Rothenberg (1990b); [11] Rothenberg (1978); [12] Rothenberg (1990a); [13] Muhly (1984); [14] Gilead (1994); [15] Shalev and Northover (1987); [16] Burton and Levy (2001); [17] Meshel (1993); [18] Willies (1990); [20] Avner and Naor (1978); [21] Segal and Carmi (2004); [22] Gophna (2004); [23] Golani (2004); [24] Yekutieli (personal communication, 2006); [25] Herzog (personal communication, 2006); [26] Ilan (1999); [27] Adams (1999); [28] Hauptmann (2000); [29] Levy et al. (2004); [31] Levy et al. (2002); [32] Levy (personal communication, 2007); [33] Burleigh and Hewson (1979).

Our archaeointensity curve shows acceptable agreement with the data set from Syria (Gallet et al., 2006; Gallet and Le Goff, 2006; Genevey et al., 2003 see Fig. 11a). As this region is close to the Southern Levant and as these researchers used samples from careful archaeological contexts and modern, strict, experimental procedures, we consider the comparison useful, and the different data sets as complementary.

The intensity of the geomagnetic field fluctuated rapidly over the last 7000 years. Major trends observed in previous studies were confirmed with our new results. This includes the conspicuous peak in intensity around 3000 years ago, now shown to be even higher during the Iron Age I, and the relatively long period of low intensity prior to 5000 years ago (Chalcolithic – Early Bronze Age I). Two less prominent peaks are corroborated around 4500 years ago (Early Bronze Age II–III) and 1200 years ago (Early Islamic). Our data suggest a slightly lower trough 2000 years ago (Early Roman).

Not surprisingly, the details of the archaeointensity curve do not agree precisely with the smoother depiction of the global model of Korte and Constable (Korte and Constable, 2005a) (see Fig. 11a). Nevertheless, most of the major trends of the geomagnetic intensity are reflected in the model. It seems to us that the reasons for the discrepancy are the current low resolution of the global model and the use of some less rigorously obtained data as constraints. The published data include a variety of approaches, materials, and quality controls on paleointensity and dating, hence may contain a less than optimal recording of the geomagnetic field.

6. Implications on dating of archaeometallurgical sites

Samples with reliable archaeointensity readings from poorly dated or controversial sites can contribute for constraining the age of their context. The results of the current research provide some insights into the dating of certain archaeometallurgical sites in the Southern Levant, mainly in the region of Timna. This includes the controversial site of Timna 39b.

6.1. Timna 39b

The site of Timna 39b is considered by its excavator, Beno Rothenberg, to be the most ancient copper smelting installation

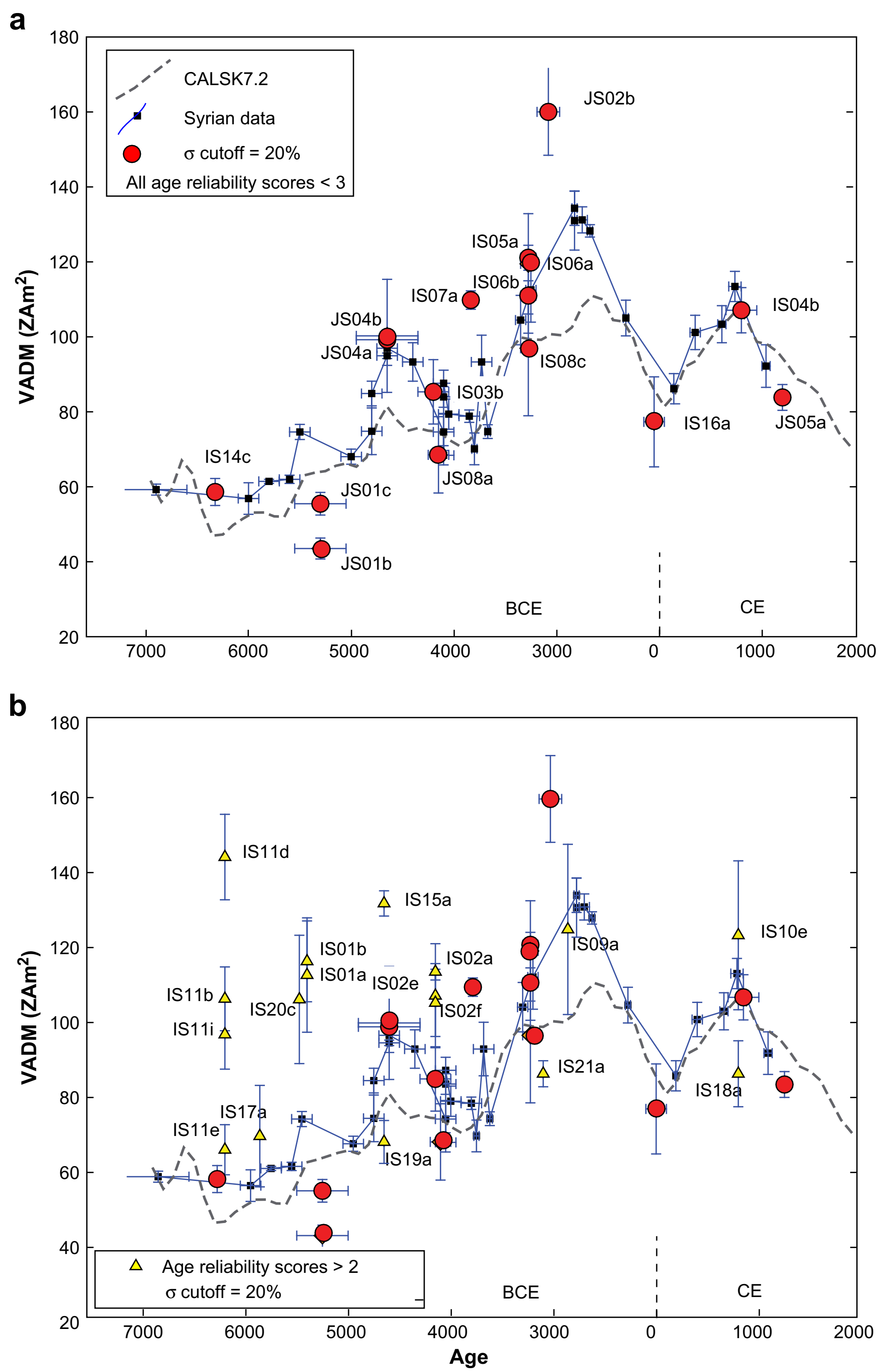

Fig. 11. Summary of all acceptable sample intensities (with standard deviation cut-off values of 20% of the mean and $N \geq 3$). (a) All samples have an age reliability index better than 3 (Table 2). (b) Same as in (a) but including samples with uncertain ages (triangles). Small blue squares are data from Syria (Gallet et al., 2006; Gallet and Le Goff, 2006; Genevey et al., 2003). Predicted VADM values for Syria by CALSK7K.2 of Korte and Constable (2005a) are shown as dashed line (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

ever found anywhere (Rothenberg, 1990a and many other publications). Since its discovery (1960) and excavation (1965), there has been a ceaseless debate regarding its age (e.g. Avner, 2002; Craddock, 2001), which has not reached a satisfactory resolution so far.

The site is located in the southeastern part of Timna Valley, on top of a small hill facing the Wadi Arabah plain. It was excavated together with a domestic site situated ca. 130 m to the southeast, on the lower slopes of the hill (Timna 39a). The final report (Rothenberg, 1978) connects the two sites and concludes that both are dated to the early phase of the Chalcolithic. Site 39a, a household unit with scarce evidence of ore and metal processing, was first dated primarily by the lithic assemblage (Bercovici, 1978). The Chalcolithic age was confirmed later by radiocarbon measurement yielding the date of 5485 ± 45 BP (4351 ± 98 BCE 95.4% probability using OxCal 4.0) (Rothenberg and Merkel, 1998). Site 39b is a "pit in the ground" smelting furnace, surrounded by many fragments of small furnace slag with homogeneous visual characteristics (Fig. 12). It is 30–40 cm in diameter and ca. 40 cm in depth,

Table 2
Reliable archaeointensity results from well-dated archaeometallurgical sites in the Southern Levant (Fig. 11)

Sample	Site	Age	+/−	Q	N	$B_{ancient}$	%σ	VADM	1σ
IS03b	Timna 149 hillside	−2150	150	2	3	44	10.1	85.5	8.59
IS04b	Timna 28	850	150	2	5	52	12.0	102	12.2
IS05a	Timna 2	−1225	75	2	3	62	2.7	121	3.32
IS06a	Timna 2	−1225	75	2	6	61	11.2	120	13
IS06b	Timna 2	−1225	75	2	4	55	9.3	108	10.1
IS07a	Ora Hill	−1785	20	2	3	56	2.2	110	2.45
IS08c	Timna 3	−1225	75	2	4	50	18.6	97	18.0
IS14c	Shiqmim	−4275	50	1	3	31	6.1	58.7	3.6
IS16a	Yotvata Nabataean	0	100	2	3	40	15.5	77	12
JS01b	Wadi Fidan 4	−3250	250	1	4	23	6.4	43.6	2.8
JS01c	Wadi Fidan 4	−3250	250	1	5	29	5.4	55.6	3.02
JS02b	Khirbat Jariya	−1030	110	1	3	83	7.2	160	11.6
JS04a	Fenan 15	−2600	300	1	4	52	15	100	15.1
JS04b	Fenan 15	−2600	300	1	3	51	1.5	99.3	1.44
JS05a	El-Furn	1250	50	1	3	43	4.1	83.9	3.44
JS08a	Khirbat Hamra Ifdan	−2100	100	1	5	36	14.8	68.6	10.2

For discussion on selection criteria applied see Ben-Yosef et al. (in press), and text (*Q*, age reliability scores; *N*, number of successful specimens; age, negative numbers are BCE).

although its partially stone lining suggests an upper structure of additional 40 cm (Rothenberg, 1978). It was dated to the early phase of the Chalcolithic primarily by relying on the typology of the lithics uncovered in the small excavation around the furnace, the slag and furnace characteristics and the supposed connection to Site 39a (Rothenberg, 1978, 1990a; Rothenberg and Merkel, 1998).

Critical reservations regarding the early date of the furnace in Site 39b were raised, even before the publication of the final report, by Muhly (1973, 1976). He extended his criticism later on (Muhly, 1984), and was followed by various of other scholars (e.g. Adams, 1998; Avner, 2002; Craddock, 2001; Hanbury-Tenison, 1986; Weisgerber and Hauptmann, 1988). In general, these objections for this early date are based on two aspects of the archaeometallurgical research of the site. The first is related to a comprehensive understanding of the metal production in the Chalcolithic (e.g. Shalev, 1994), which claims that copper smelting was practiced within villages, which could have been located far away from the ore. This is the case in Beersheva valley (e.g. Gilead et al., 1992; Levy and Shalev, 1989), and in recently discovered industries near Aqaba (Hauptmann et al., 2004). The second aspect is related to the quality of the archaeological evidence (see updated summary and discussion in Avner, 2002).

The main arguments regarding the quality of the archaeological evidence include reassessment of the technology, reservations of the models employed by the investigators and a previously unpublished radiocarbon date from the furnace itself. The furnace structure and the characteristics of the slag were used by Rothenberg as evidence for a suggested technology that is even earlier than the Chalcolithic of Beersheva Valley (Rothenberg and Merkel, 1998). However, revisiting of the evidence suggests an advanced, presumably late industry (e.g. Avner, 2002). The supposed connection between Site 39a and the furnace is not decisive, and the original publication of the lithic assemblage did not distinguish between the two sites (Bercovici, 1978) creating ambiguity in the interpretation. Most surprising is the radiocarbon date from the furnace, yielding the result of 1945 ± 309 BP (Burleigh and Hewson, 1979) (761BCE–645CE, 95.4% probability, using OxCal 4.0). Rothenberg, who characterizes this date as "Late Bronze Age" (Rothenberg, 1990a), explains the date as being derived from refill of the excavation pit that was brought from a different location. Others suggest the possibility of reusing the smelting location and/or installation in the course of more than one period (Avner, 2002).

Revisiting the site in 2004–2005, we collected 10 samples of furnace slag from the furnace itself and its close vicinity. Four samples (based on 16 specimens) passed all of our rigorous selection criteria and yielded reliable archaeointensity results. They clearly show three distinct groups of ancient geomagnetic intensity (Fig. 13), implying at least three periods of copper production in the site of Timna 39b. The group showing the lowest intensity (66 ± 7 ZAm^2 VADM) might indeed represent copper smelting during the Chalcolithic. It is within a one standard deviation agreement with the archaeointensity results obtained for the

Table 3
Reliable archaeointensity results from poorly dated or controversial archaeometallurgical sites in the Southern Levant (Fig. 11b)

Sample	Site	Age	+/−	Q	N	$B_{ancient}$	%σ	VADM	1σ
IS01a	Hai-bar	−3400	1100	5	3	57.9	13.5	113	15.3
IS01b	Hai-bar	−3400	1100	5	4	59.7	9.2	117	10.8
IS02a	Timna 149 hilltop	−2150	150	6	3	58.3	1.9	114	2.19
IS02e	Timna 149 hilltop	−2150	150	6	5	55	12.9	108	13.9
IS02f	Timna 149 hilltop	−2150	150	6	7	54	8.5	106	8.97
IS09a	Timna 30	−860	60	3	3	64	18.1	125	22.7
IS10e	Tell Hara-Hadid	800	150		4	63	16.1	124	19.9
IS11b	Timna 39b	−4200	250	6	3	54.6	8.0	107	8.51
IS11d	Timna 39b	−4200	250	6	4	73.9	7.9	145	11.4
IS11e	Timna 39b	−4200	250	6	4	34	10.0	66.5	6.68
IS11i	Timna 39b	−4200	250	6	5	49.7	9.5	97.3	9.25
IS15a	Yotvata (EB)	−2650	350	5	3	67.7	2.6	132	3.37
IS18a	Givat Yocheved	800	150	6	6	44	10.1	86.8	8.8
IS19a	Eilot quarry	−2650	350	5	3	35	8.4	68.6	5.73
IS20c	Ashkelon-Afridar	−3475	125	4	9	55.8	16.1	107	17.1
IS21a	Tell Gerisa	−1100	100	3	3	45.7	4.0	86.8	3.47

For discussion on selection criteria applied see Ben-Yosef et al. (in press), and text (*Q* = age reliability scores; *N*, number of successful specimens; age, negative numbers are BCE).

Fig. 12. The copper smelting installation in site Timna 39b and the excavated area surrounding it.

Chalcolithic site of Shiqmim (58 ± 4 ZAm^2 VADM) and is consistent with the general low intensity throughout this period. Nevertheless, this group is compatible with copper smelting in other periods, mainly the Early Bronze Age I. The middle group, as well, might represent several different periods of copper production including Early Bronze Age II–III, Middle and Late Bronze Age, and Byzantine – Early Islamic periods. The latter corresponds to the radiocarbon measurement from the site. The group with the highest intensity (145 ± 11 ZAm^2 VADM) fits best to the Iron Age I period, the latest phase of the intensive copper production in Timna region under the Egyptian influence (Rothenberg, 1999b).

The archaeointensity results from Site 39b provide additional support for Rothenberg's early Chalcolithic dating, although they do not decisively prove it. Moreover, there might be a difference between the dating of copper production in the site and the dating of the installation found *in situ* today. While our results support the idea that smelting activities occurred in more than one period, the installation itself might represent only the latest one.

We do not find the evidence of copper production near the origin of the ore during the Chalcolithic to be unique. The evidence of metallurgical activities in the Chalcolithic site of Timna 39a (Rothenberg, 1978), together with other small sites in the Timna region such as N3 (Segal et al., 1998), F2 (Rothenberg, 1999a; Rothenberg and Merkel, 1995) and 250b (Rothenberg and Shaw, 1990a) might suggest small-scale domestic copper production in periods as early as the Chalcolithic, although this evidence is problematic (e.g. Avner, 2002; Hauptmann and Wagner, 2007) and more research is needed. Moreover, in the light of other sites in the Wadi Arabah, the connection between sites 39a and 39b is a reasonable supposition. In many cases, the "cold industry" of crushing the ore and flux and processing slag was done at the foot of the hill, while the pyrotechnological industry, taking advantage of the wind, was done on the top of the hill (e.g. Avner, 2002; Site 189a: Avner and Naor, 1978; Site 201a: Rothenberg, 1999a,b). There is no doubt that the vast majority of data for Chalcolithic smelting in the southern Levant comes from the Beersheva region and supports the model of specialized industry far from the ore source. However, the new archaeointensity data points to more than one mode of production during the fifth millennium BCE.

6.2. *Archaeometallurgical sites from later periods*

The site of Timna 149 (Rothenberg, 1999a; Rothenberg and Glass, 1992; Rothenberg and Shaw, 1990a,b) is located in the northeastern part of the Timna Valley, and considered by its excavator to be a key site for understanding the development of metallurgy in the Early Bronze Age IV (ca. 2200–2000 BCE). The site consists of two separate parts, one on top of a hill facing the Wadi Arabah and the other on a plain to the west of the hill. The latter was excavated during 1984 and 1990, and dated by indicative ceramics from well-defined context to the Early Bronze Age IV. The excavated area contains two shallow lines of walls, ground stones, slag fragments and clay rods, and was interpreted as a preparation

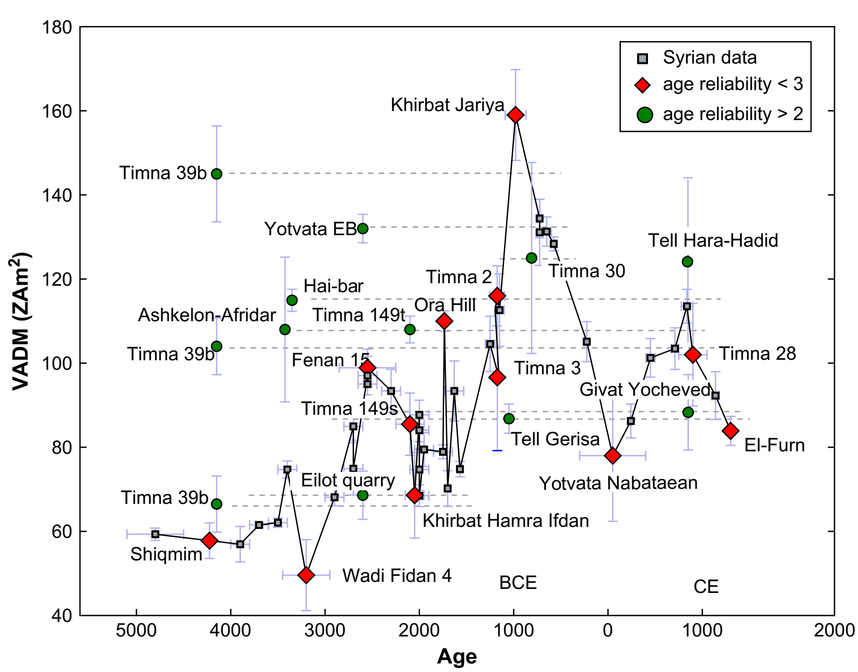

Fig. 13. Curve combining Syrian (Gallet et al., 2006; Gallet and Le Goff, 2006; Genevey et al., 2003) and Southern Levantine results (this study). We averaged results to the site level, excluding Timna 39b where three distinct groups of data were obtained. Also shown are reliable archaeointensity results from poorly dated or controversial sites (green circles; 149t = hilltop, 149s = hillside) (see text for discussion) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

camp for the smelting process which took place on the top of the hill. In addition, the excavation suggests slag processing and probably a secondary melting for the production of ingots (Rothenberg and Shaw, 1990b). The date of the finds from the hilltop is much less secure and based primarily on the supposed connection to the excavated site of the hillside. They include slag fragments and stones that were interpreted as part of sophisticated furnaces that replaced the earlier "pit in the ground" type. According to the excavator, they represent a progress in copper production attributed to this period (e.g. Rothenberg and Shaw, 1990a).

Our archaeointensity results (Fig. 13) show clearly that there is no connection between the metallurgical activities of the hillside and the hilltop. While results from the former are indeed in agreement with data from previous studies and fit well in the Early Bronze Age IV, the results from the hilltop are distinct and represent a different period. This period is most probable the Late Bronze IIB (13th century BCE), when the copper production activity in the area reached a climax under the Egyptian influence. Several other periods are also compatible with our results, including Early Islamic (638–1099 CE) and Early Bronze Age II–III (ca. 3000–2200 BCE) (Fig. 13).

The alleged sophistication of the furnaces on the hilltop and the claims for industrial scale of copper production, with a breakthrough in technology (e.g. first appearance of tapping slag) are contentious, still regardless of their date (e.g. Avner, 2002). The conclusion about metallurgical activities during the Early Bronze Age IV should be reassessed under the light of the recently discovered large scale industry from this period in Faynan district (Levy et al., 2002), as well as the interpretation of the finds from the excavated industry in the hillside. We suggest that the industry of the hillside included smelting in addition to preparation and processing activities. The clay rods, considered by the excavators to be components of crucible manufacturing (Rothenberg and Shaw, 1990b), might be part of the smelting installation, as suggested for the same type of finds from Faynan district (Hauptmann, 1989, 2000). In Faynan, however, the clay rods are part of wind-driven furnaces common in the Early Bronze II period.

The samples from the site of Timna 30 were collected from layer I, considered by the excavator to represent the most advanced ancient copper smelting technology (Rothenberg, 1999b). The site was excavated (Bachmann, 1980; Rothenberg, 1980, 1999b, 1990b) and layer I was dated by Egyptian ceramic to the 22nd dynasty, in particular to the reign of Shishanq I. A radiocarbon date yield even later date from the 8th century BCE (Rothenberg, 1990b, footnote 71).

The advanced technology represented in layer I and the uniqueness of the Iron Age II period raised some reservations concerning the date (e.g. Avner and Magness, 1998, footnote 7). Our archaeointensity results fit well in the Iron Age II, both to the period of Shishanq I as well as to the 8th century BCE. Because of the high peak in the geomagnetic intensity in this period, it is difficult to assign this layer to any other period.

The site of Givat Yocheved (also known as Nahal Amram and Timna 33) is located 15 km south of Timna Valley, near an intensive mining district. It consists of several structures and mounds of broken tapping slag. The Arava expedition dated the site to the New Kingdom (14th–12th centuries BCE) (Rothenberg, 1967, 1990b, footnote 23), a date that was confirmed with a radiocarbon measurement from the bottom of the slag mound (Rothenberg, 1990b, footnote 21). However, based on the advanced metallurgical technology evidenced at the site, other scholars date the site to the Early Islamic period (Avner and Magness, 1998) and point out another radiocarbon measurement from the same site, yielded a date from the 8th–9th centuries CE (Burleigh and Hewson, 1979).

Our archaeointensity results (Fig. 13) fit neither of the suggestions above, and indicate most probably copper smelting in the Early Roman period. A date from the Middle Bronze Age or earlier (Fig. 13) is inconsistent with the advanced tapping technology, and the Early Roman period is compatible with the intensive mining of copper ore from this period in the close vicinity (Avner and Magness, 1998; Willies, 1990). However, the site very likely represents more than one period, including the New Kingdom and Early Islamic as well.

The site of Eilot Quarry was surveyed in the 1970s (Avner and Naor, 1978). Its original Early Islamic date was changed to Early Bronze Age according to new finds of lithic and ceramics (Avener, personal communication, 2006). Our archaeointensity results (Fig. 13) support the early date and constrain it to the Early Bronze Age I/early phase of Early Bronze Age II.

Our results from Tell Hara-Hadid (IS10e, Fig. 13) support its Early Islamic date. This site is a large mound of tapping slag located a few kilometers north of Elat. It was previously dated by ceramics collected in a survey (not published yet).

The sites of Hai-Bar and Yotvata-EB in the Timna region are considered to be early according to the slag type and archaeometallurgical typology. According to our archaeointensity results (Fig. 13), both are dated to later periods. Hai-Bar can most probably be dated to the Late Bronze Age – Iron Age I, the climax of copper production in the area under the Egyptian influence. Nevertheless, other periods are also possible for this site, such as the Early Islamic. The results from Yotvata-EB indicate Iron Age II smelting activities, a date which makes it the second known site from this period in the southern part of the Wadi Arabah. The revised dating of these sites demonstrates that slag and archaeometallurgical typology cannot be used as a chronological marker, and that the advancement in copper production technologies was accompanied by continuation of small-scale production using less sophisticated techniques.

The site of Ashqelon-Afridar (Gophna, 2004) is a large scale Early Bronze Age I settlement, located in the southern part of the coastal plain of Israel. The excavation encountered ample archaeometallurgical remains (Segal et al., 2004), representing melting and casting activities, as well as smelting of copper ores. Our samples originated in area 10, excavated by Yekutieli in 1998. Although the finds from this area were dated to the Early Bronze Age Ia and show similar characteristic to the finds from nearby area E (Golani, 2004), the specific samples (IS20a,b) came from an insecure context of refill in pits. Our archaeointensity results suggest a later date for this phase of metallurgical activities associated with the pits, most probably Early Bronze Age II–III (Fig. 13).

Our archaeointensity results from Tell Gerisa (Fig. 13) suggest a different date than Iron Age I. The excavations are not yet published, hampering any further discussion.

7. Conclusions

7.1. Archaeointensity in the Levant – new horizons

The results from the current study demonstrate the suitability of copper slag material in archaeointensity research (see also Ben-Yosef et al., in press). Together with the application of a sophisticated experimental protocol (the "IZZI" protocol of Tauxe and Staudigel, 2004), we introduced a new and promising tool for studying the behavior of the geomagnetic intensity during the last seven millennia. The abundant archaeometallurgical sites in the Southern Levant provide an invaluable source of samples for archaeointensity research. Together with complementary sites in Cyprus (e.g. Balthazar, 1990) and Anatolia (e.g. Yener, 2000), slag deposits present a relatively high time resolution for the periods since the dawn of metallurgy.

We added 15 reliable archaeointensity results from well-dated contexts to the archaeointensity curve of the Levant. They are in good agreement with previously published data from Syria (Gallet et al., 2006; Gallet and Le Goff, 2006; Genevey et al., 2003), and emphasize some of the heretofore observed trends in the geomagnetic intensity behavior. Further reliable archaeointensity data from well-dated archaeological context are needed for improving the resolution of the highly fluctuating curve. Such a high resolution curve, in turn, might be used in the archaeological research.

7.2. Archaeointensity as a dating tool

The resolution of the current available archaeointensity curve is poor and its application as a dating tool is limited. In most cases, other archaeological methods of dating, such as radiocarbon or material culture typologies, are more probable to yield accurate results. However, in certain sites, where radiocarbon samples are unavailable and the material culture typology is problematic or in low resolution, the archaeointensity curve might be used as a reference for dating. This is the case in many of the archaeometallurgical sites in the southern Wadi Arabah where the material culture cannot provide a decisive date. Our reliable archaeointensity results from such sites were compared to results from well-dated samples and to the available archaeointensity curve, providing several insights regarding the archaeometallurgy of this region.

A significant conclusion is the nonlinear development of copper smelting technologies. Our results show clearly that ancient technologies were still in use in later periods, along with the advanced large scale production industry. Slag and archaeometallurgy typology cannot, therefore, be used as a chronological marker. They might, however, be related to social and political structures, implying differential accessibility to resources of knowledge and power.

In addition, metal production activities in site Timna 39b occurred in more than one period, most probably including the Chalcolithic. The site of Timna 149 had hosted copper smelting in the Early Bronze Age IV only in the excavated hillside part, while the remains on the hilltop are from a distinct period, probably related to the proliferation of copper industry during the New Kingdom.

Archaeointensity research focuses only on one component of the geomagnetic field. Combining data from high resolution curves of inclination and declination changes provide a strong dating tool for the archaeologist, based on a statistical matching of the three different components (Lanos, 2003). Applications of such a dating technique provide excellent results (e.g. Jordanova et al., 2004; Kovacheva et al., 2004) and demonstrate the need for further reliable archaeomagnetic data in the Southern Levant (see also Le Goff et al., 2002).

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