Geomagnetic field intensity behavior in the Middle East between ∼3000 BC and ∼1500 BC

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Geomagnetic field intensity behavior in the Middle East between ~3000 BC and ~1500 BC

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[1] An archeointensity study was carried out on 14 sites of Syrian baked clay artifacts, archeologically dated between ~2500 BC and ~1600 BC. Using an experimental protocol involving high-temperature magnetization measurements, well-defined mean intensity values were derived for 13 different sites with three to nine results obtained at the fragment level per site. Results of similar ages are coherent and the new data set is in good agreement with previous archeointensity results obtained from the same region. All together these data allow one to refine the evolution of the geomagnetic field intensity in the Middle East during the third and the second millennium BC. In particular, they show the occurrence of three periods of rather sharp intensity increase at ~2600 BC, ~2200 BC and ~1600 BC possibly at the times of climatic cooling in the eastern North Atlantic, further suggesting a connection between the Earth's magnetic field and multi-decadal climatic events.
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1. Introduction

[2] The incredible richness of the cultural past in the Middle East makes it possible to study the secular variation of the Earth's magnetic field in this region over millennial scales. Moreover, such research is facilitated by the active archeological excavations conducted in this area, providing many opportunities for sampling well-dated baked clayed artifacts suitable for archeomagnetic analyses. Over the past several years, our efforts have yielded numerous (more than 40) geomagnetic field intensity values from Syrian and Iranian pottery and baked brick fragments spanning the past eight millennia [*Genevey et al.*, 2003; *Gallet and Le Goff*, 2006; *Gallet et al.*, 2006]. The new data set supplements other archeointensity results principally obtained by *Nachasova and Burakov* [1995, 2000] from Central Asia, allowing one to describe the main features of the regional geomagnetic field intensity variations.

[3] A new interest for these investigations arose from the recently suggested connection, at least in western Eurasia, between geomagnetic variations and multi-decadal climatic events [*Gallet et al.*, 2005, 2006; *Courtillot et al.*, 2007]. Deciphering this potential link, possibly through a global or a regional influence of the Earth's magnetic field on the galactic cosmic ray flux interacting with the atmosphere, clearly requires the construction of a better resolved record of the geomagnetic field intensity variations in Western Eurasia as in other regions. For this reason, we present in this paper new archeointensity data from Syria dated between ~2500 BC and ~1600 BC.

2. Sampling Sites

[4] Our fragments were collected from four different Syrian archeological sites (Figure 1): Mari, Ebla, Terqa and Tell Marsaikh. Mari (Tell Hariri, $\lambda = 34.5°$N, $\Phi = 40.9°$E) and Ebla (Tell Mardikh, $\lambda = 35.8°$N, $\Phi = 36.8°$E) are among the most famous historical places in the Mesopotamian and Eastern Mediterranean areas. Mari, located along the middle course of the Euphrates river in southeastern Syria, was a major Mesopotamian city from ~2900 BC to ~1750 (following the middle chronology) [e.g., *Brinkman*, 1977] when it was destroyed by the Babylonian troops of King Hammurabi. Its importance relied on the control that Mari had on commerce via the Euphrates river between the Sumerian region, to the south, and northern Mesopotamia. Three different phases of construction, related in the literature to three successive cities (from the oldest City 1 to City 3) separated by abandonment and/or destruction levels [*Margueron*, 2004], were recognized based on intensive excavations which started more than 70 years ago [*Parrot*, 1935]. The eight new groups of fragments are dated of the beginning and end of City 2 (~2500 BC and ~2300 BC) and City 3 (~2000 BC and ~1800 BC, respectively). More details on their archeological contexts can be found in Table 1 and will be further discussed in the text below.

[5] Excavations in Ebla, located ~55 km to the south of Alep in northwestern Syria, began in the mid-sixties and have continued without interruption since that time [e.g., *Matthiae et al.*, 1995]. The place of Ebla was occupied before 3000 BC. At the beginning of the second half of the third millennium BC, Ebla was a powerful trading center, connecting the commercial exchanges between the Euphrates river and the Mediterranean Sea, which dominated a vast territory to the west of Mesopotamia. This flourishing time abruptly ended when the troops of Akkadian King Sargon (~2300 BC at the end of the period referred as to the Early Bronze IVA) and soon after Narâm-Sîn ruined the city. During the following Early Bronze IVB period, the influence of Ebla remained limited but a second prosperous era started during the 20th century BC (Middle Bronze I) and lasted about four centuries. The city was again totally

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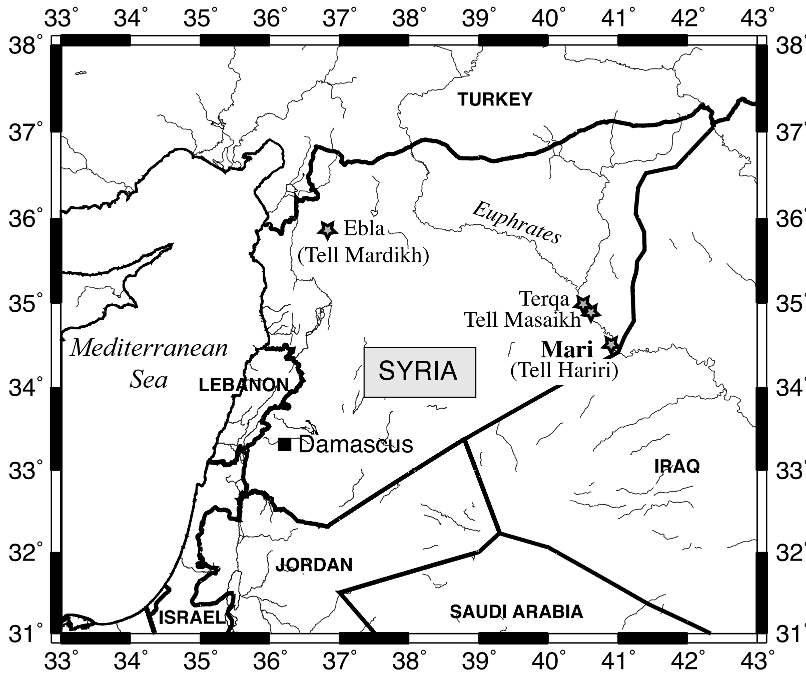

Figure 1. Location map of the Syrian archeological excavations where the groups of baked clay fragments analyzed in this study were collected.

destroyed by the Hittites around 1600 BC (end of Middle Bronze II). Afterward, only a small occupation resumed in this place until the first millennium AD. We analyzed four groups of pottery fragments dated to the Early Bronze IVA (~2300 BC) and IVB (~2150 BC) periods and to the Middle Bronze I and II periods (Table 1).

[6] In addition, two other archeomagnetic sites consisting of Paleo-Babylonian (~1800 BC) potsherds were collected in Terqa and Tell Masaikh, two places situated in south-eastern Syria ~30 km to the north of Mari [e.g., *Rouault*, 2001].

3. Acquisition of New Archeointensity Data

[7] The fragments were analyzed using the laboratory-built Triaxe magnetometer allowing continuous magnetization measurements of individual small cylindrical samples at high temperatures [*Le Goff and Gallet*, 2004]. Paleointensity determinations were derived from the experimental procedure described in detail by *Le Goff and Gallet* [2004] and *Gallet and Le Goff* [2006]. This procedure involves an automatically-running measurement cycle that includes the demagnetization of the ancient natural remanent magnetization (NRM), the acquisition of a new laboratory thermoremanent magnetization (TRM) in known field conditions and its subsequent demagnetization. Measurements were performed over a single large temperature interval between generally 150°C to 250°C (temperature step referred as to T1) and 450° to 520°C (temperature step referred as to T2). For each sample, a mean archeointensity value was obtained from numerous estimates of the ratio R'(Ti) between the NRM and TRM fractions unblocked between T1 and a

Table 1. New Archeointensity Results[a]

Archeological Excavation	Site	Archeological Context	Type Fragment	Age, BC	Intensity (site) μT	Nb Fragment
Mari	SY18	Roy. Palace, begin. City 2	bricks, wall	2550 ± 100	50.1 ± 0.6	6 (7)
Mari	SY19	Roy. Palace, begin. City 2	bricks, wall	2550 ± 100	52.1 ± 1.2	3 (8)
Mari	SY35	Roy. Palace, end City 2	Oven fragments	2350 ± 50	49.4 ± 2.4	6 (8)
Ebla	SY45	Roy. Pal. G, Early Br. IVA	ceramics	2300 ± 50	55.3 ± 2.0	9 (13)
Ebla	SY46	Houses HH, Early Br. IVB	ceramics	2150 ± 50	53.7 ± 2.2	5 (10)
Mari	SY36	Ghost Pal., begin City 3	bricks, door coffering	2050 ± 100	47.2 ± 1.7	5 (7)
Mari	SY29	Orient. Pal., begin City 3	bricks, door coffering	2000 ± 100	47.6 ± 2.2	7 (8)
Mari	SY33	Orient. Pal., begin City 3	bricks, door coffering	2000 ± 100	49.3 ± 1.7	5 (8)
Ebla	SY47	Pits HH, Middle Bronze I	ceramics	1950 ± 50	48.8 ± 2.3	6 (8)
Mari	SY26	Great Roy. Pal., end City 3	bricks, pavement	1825 ± 75	41.0 ± 0.9	6 (6)
Mari	SY31	Great Roy. Pal., end City 3	bricks, pavement	1825 ± 75	38.4 ± 2.7	5 (6)
Tell Masaikh	SY16	Paleo-Babylonian resid	ceramics	1825 ± 75	42.5 ± 2.6	6 (6)
Terqa	SY17	Paleo-Babylonian resid.	ceramics	1825 ± 75	44.0 ± 2.5	5 (6)
Ebla	(SY48)	Houses B, Middle Bronze II	ceramics	1600 ± 50	(53.7 ± 5.5)	4 (10)

[a]New mean Syrian archeointensity data at the site level obtained using the Triaxe protocol. Mean intensity μT, mean Triaxe intensity value in μT obtained at the site level and its standard deviation; nb fragment, number of data used for the computation of the site-mean intensity value. The total number of studied fragments per site is given between brackets. For complete table (with intensity results at the sample level), see auxiliary material.

running temperature Ti increasing from T1 to T2 with a temperature step of ~5°C. The R'(Ti) data are not affected by TRM anisotropy because the TRM is imparted within a few degrees of the NRM direction. Our previous studies have shown that the R'(Ti) values are also corrected for the cooling rate dependence of TRM acquisition. Direct comparisons were made between intensity determinations obtained from the same Mesopotamian fragments using the classical *Thellier and Thellier* [1959] method revised by *Coe* [1967] and the new Triaxe protocol [*Genevey et al.*, 2003; *Gallet and Le Goff*, 2006]. The agreement both at the sample and site levels was found to be mostly within ±5%, which validates the methodology developed for the Triaxe.

[8] 111 fragments from 14 archeomagnetic sites were studied here. In this collection, 78 samples (one per fragment) fulfilled the same selection criteria as those defined by *Gallet and Le Goff* [2006] and *Gallet et al.* [2006]. This gives a success rate of ~70%, which again demonstrates the very good suitability of Syrian baked clay artifacts, whose magnetic mineralogy is dominated by titano-magnetite in the pseudo single range, for archeointensity studies [*Genevey et al.*, 2003; *Gallet and Le Goff*, 2006]. Among the 33 rejected samples, 10 are from sites SY45 and SY48 both collected in Ebla (Table 1). They were eliminated because of significant re-firing of the fragments after their initial baking, thus preventing the analysis of their primary magnetization over a well isolated magnetization segment. But for the other fragments from the same sites, although most of them were also subjected to partial re-firing, it was nevertheless possible to determine archeointensity values meeting our selection criteria (Figure 2 and auxiliary material).[1] These two sites are dated to the two phases of destruction of Ebla, first by the Akkadians and second by the Hittites; their complex thermal behavior appears to vividly reflect these historical events. It is worth pointing out that the samples from site SY35 collected in Mari and dated to the end of City 2, which was also destroyed by the Akkadians, show only a single magnetization component (Figure 2). Compared with the previous case, this can be understood because this site, consisting of fragments from a kiln, was found just under the floor of a room of the Royal Palace, which was indeed destroyed during the sack of Mari (P. Butterlin, personal communication, 2006). This archeomagnetic site therefore predates shortly the end of City 2 and was not involved in its destruction.

[9] Thirteen archeomagnetic sites yielded suitable mean archeointensity values. The different R'(Ti) data from six sites are reported in Figure 2. Only site SY48 fails our selection criterion based on the dispersion of the data at the site level: i.e. a mean intensity value is rejected if its standard deviation computed from a minimum of three samples is >5 μT or >10% of the mean [*Genevey et al.*, 2003; *Gallet et al.*, 2006]. For this site, the relatively large dispersion is principally due to one sample among four which gives a significantly lower intensity value (46.6 μT versus 59.6 μT, 52.6 μT and 56.0 μT; Table 1). This sample is also different from the others because it is the only one having a single magnetization component. An explanation might be that this sample has a different age (predating the destruction of Ebla), therefore casting doubt on the temporal homogeneity of this site. As will be shown below, a mean intensity value computed from the three other samples (56.1 ± 3.5 μT) would have been in very good agreement with previous data around 1600–1500 BC (Figure 3). Nevertheless, the data dispersion obtained for the other archeomagnetic sites is rather limited, their standard deviation being in most cases ≤2.5 μT (Table 1).

4. Discussion

[10] All together the data obtained by *Genevey et al.* [2003], *Gallet and Le Goff* [2006], *Gallet et al.* [2006] and from this study allow one to make several tests of consistency among the results available in the ~2500–1700 BC time interval. Four mean archeointensity values are now available for the beginning of City 2 (~2500 BC). This period saw the re-foundation of Mari after the abandonment of City 1 during approximately one century [*Margueron*, 2004]. The archeomagnetic results are very close to each other (Figure 3). Two archeomagnetic sites dated of the end of City 2 give concordant intensity values as well. A similar consistency is observed between several data obtained for the period referred as to the beginning of City 3. This period, around 2000 BC, related to the end of the Neo-Sumerian third Dynasty of Ur (Early Bronze IVB), was marked by the construction of the so-called "Small" Oriental Palace and by the re-construction of the "Great" Royal Palace (GRP) [*Margueron*, 2004]. Our fragments were collected from the former building, which probably accommodated the regnant dynasty while the GRP was under construction (SY29, SY33; Table 1), and from a short-lived palace (the "Ghost" Palace; SY36) which immediately preceded the GRP and was totally erased to allow its construction [*Margueron*, 2004]. Special care was paid to this sampling because previous archeomagnetic sites archeologically dated as the same age gave very different intensity results with "high" and "low" values (Figure 3a). The three new archeointensity data are almost identical and are similar to the high values previously obtained by *Genevey et al.* [2003] and *Gallet and Le Goff* [2006] (one site from the Small Oriental Palace and another one from the GRP). Moreover, the archeomagnetic site SY47 from Ebla dated around the same age (20th century BC) provides a similar high value which strengthens the possibility that the low intensity values in fact indicate a late phase of construction –or a renovation- in the GRP (small horizontal arrows in Figure 3). Further considering the intensity values obtained for the end of City 3 and also those of Paleo-Babylonian age from Terqa and Tell Masaikh (~1800 BC), it appears that the GRP was in use during a period of significantly decreasing geomagnetic field intensity. Hence, we observe that one of the lowest intensity value found in Mari was obtained from a construction made under the King Shamsi Adad I, very shortly before the final destruction of the city [*Gallet et al.*, 2006].

[11] We now have 31 mean archeointensity results fulfilling our selection criteria for the ~3000–1500 BC time interval. The satisfactory consistency tests described above give us confidence as to their reliability. This data set shows several distinct periods of large intensity fluctuations: between ~2800 BC and ~2600 BC, between ~2200 BC and

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL031991.

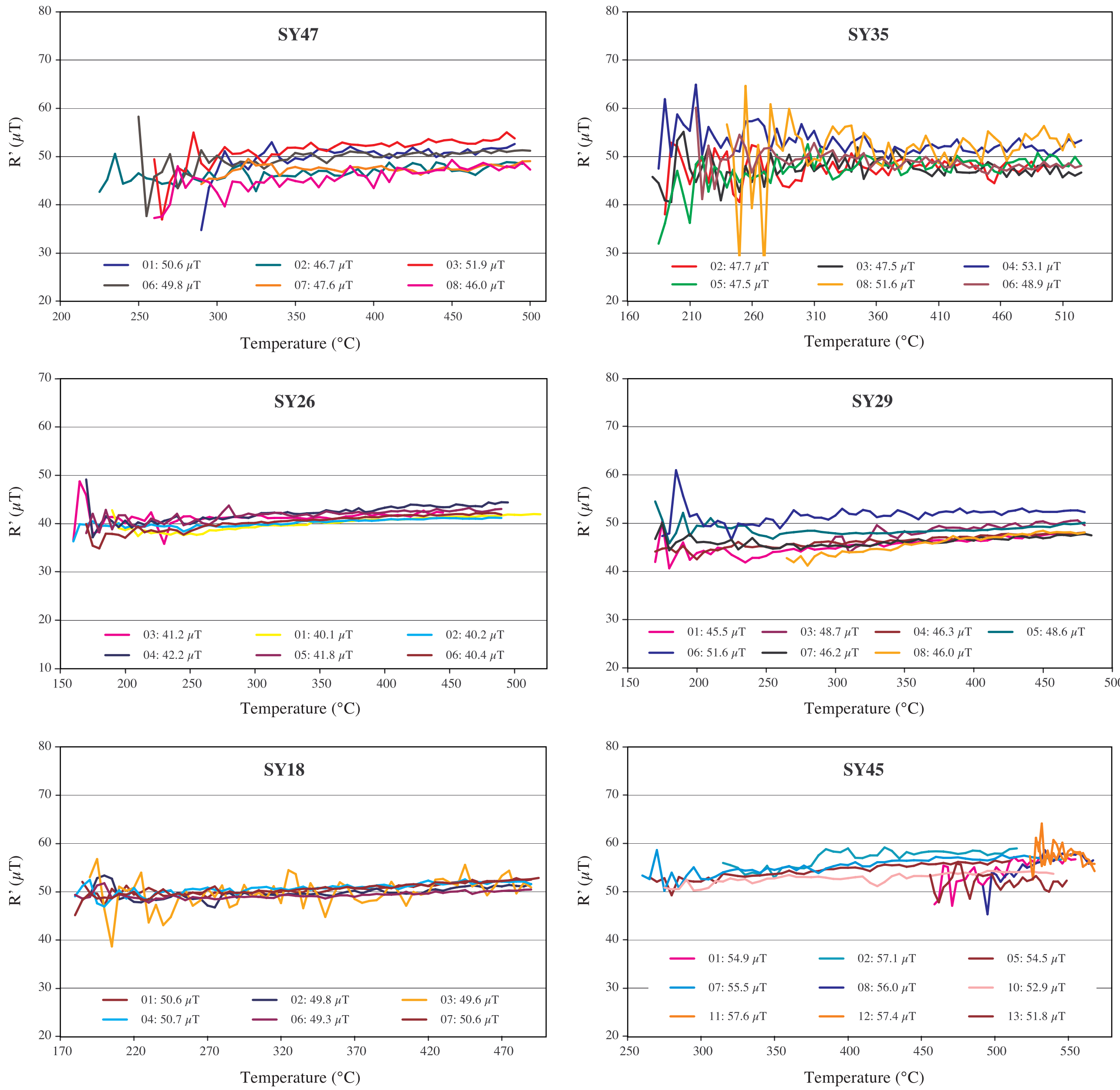

Figure 2. R'(Ti) data from six new archeomagnetic sites. One sample was analyzed per fragment providing each individual R'(Ti) curve in the different panels, and each site comprises several fragments (>3) [*Le Goff and Gallet*, 2004; *Gallet and Le Goff*, 2006].

~1750 BC and around the 17th century BC (Figure 3a). The second half of the third millennium BC is marked by more limited variations, probably characterized by a "V" shape with a rather sharp intensity increase around 2300–2200 BC. The two relative intensity maxima are respectively given by the data for the beginning of City 2 of Mari and those of Early Bronze age from Ebla (SY45 and SY46), while the minimum is defined by the two results obtained for the end of City 2 of Mari (SY 35, Table 1, and Lot 14 from *Gallet et al.* [2006]). The "V" shape evolution during the period that roughly corresponds to the Akkadian empire (~2400–2200 BC) needs further confirmation, but this will be quite difficult because of the restricted amplitude of these variations (~5 μT in Mari). However, the general evolution deduced from Syrian data is very close to the one previously obtained by *Nachasova and Burakov* [2000] from Central Asia (Figure 3b; see also *Genevey et al.* [2003]). The main differences arise from the positive gradients of the geomagnetic field variations at ~2700 BC, ~2300 BC and ~1700 BC, which appear stronger when considering our data set. We note that the curve of *Nachasova and Burakov* [2000] was obtained using sliding windows of 75 years shifted by 50 years, which perhaps smoothed out the sharpest variations in this record. Nevertheless, these geomagnetic events, called "archeomagnetic jerks" by *Gallet et al.* [2003], may be of particular interest because they are remarkably coincident in time with the occurrence of cooling periods in the eastern North Atlantic found by *Bond et*

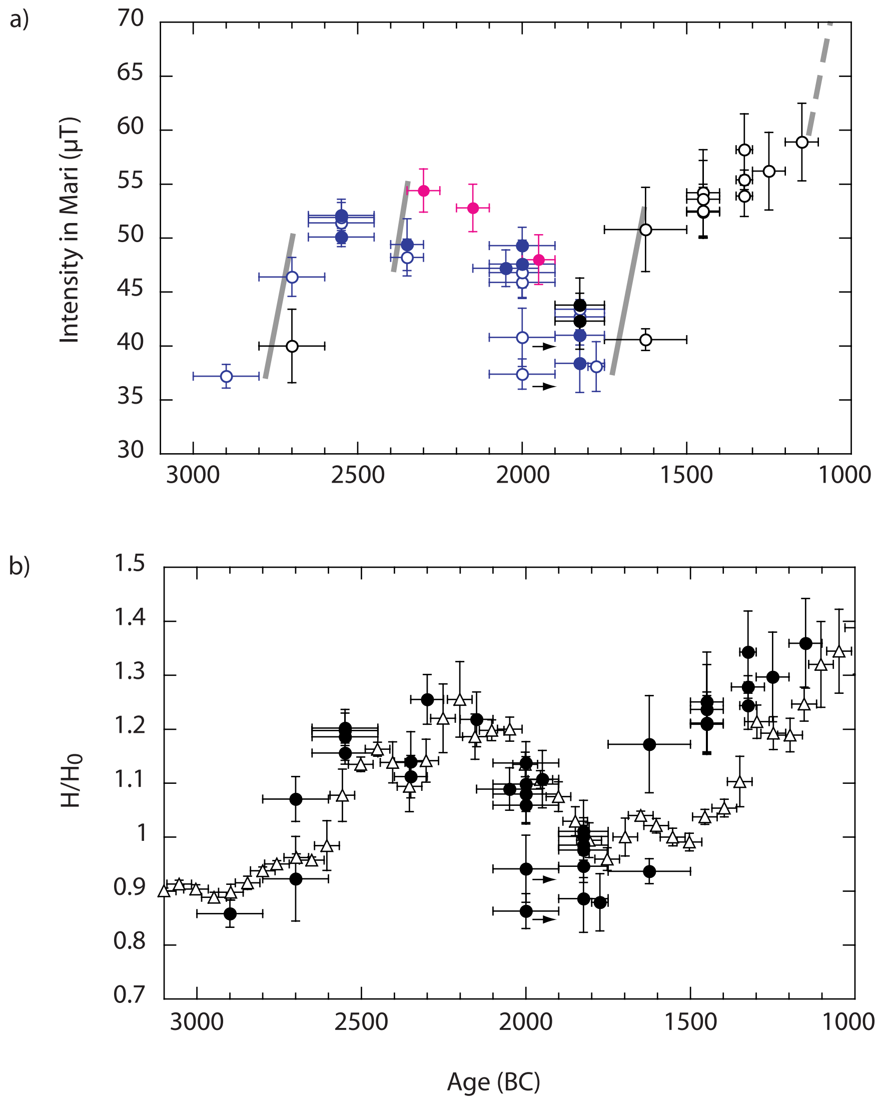

Figure 3. Variations of the Earth's magnetic field intensity in the Middle East between ~3000 BC and ~1000 BC. (a) Archeointensity values obtained by *Genevey et al.* [2003], *Gallet and Le Goff* [2006], and *Gallet et al.* [2006] (open symbols), and from this study (filled symbols). Blue symbols, data from Mari; pink symbols, data from Ebla; black symbols, data from other archeological sites. Results are adjusted to the latitude of Mari (λ = 34.5°N). The small horizontal arrows show two values that should be shifted towards younger ages. The grey lines underline periods of sharp geomagnetic field intensity increase. (b) Comparison between our intensity results (black dots) and data from Central Asia (open triangles) smoothed over 75-year long intervals shifted every 50 years [*Nachasova and Burakov*, 2000]. Each result is reported as a ratio between the ancient field intensity and the intensity given at the latitude of the studied site by an axial dipole field with the present field moment [e.g., *Creer et al.*, 1983].

al. [2001] from petrologic markers in deep sea sediments (but see discussion by *Bard and Delaygue* [2008] and *Courtillot et al.* [2008]), suggesting some connection between the Earth's magnetic field and climate over multi-decadal time scales [*Gallet et al.*, 2005, 2006]. In this respect, the geomagnetic field intensity behavior in the Middle East during the third and the second millennia BC as derived from the Syrian data is clearly reminiscent of that of the climatic fluctuation curve obtained by *Bond et al.* [2001]. Moreover, although not further documented in the present study, a fourth rapid intensity increase occurred around the transition between the second and the first millennia BC, when the geomagnetic field in Western Eurasia probably reached its highest intensity over the entire Holocene, which also correlates well with a cooling episode observed in the North Atlantic and in Western Europe [*Gallet et al.*, 2006]. This set of coincidences encourages us to pursue our efforts for determining the detailed evolution of the geomagnetic field intensity in Western Eurasia during the past few millennia.

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References

Bard, E., and G. Delaygue (2008), Comment on "Are there connections between the Earth's magnetic field and climate?," *Earth Planet. Sci. Lett.*, *265*, 302–307.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, and G. Bonani (2001), Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136.

Brinkman, J. A. (1977), Mesopotamian chronology of the historical period, in *Ancient Mesopotamia:Portrait of a Dead Civilization*, edited by A. Oppenheim, pp. 335–348, Univ. of Chicago Press, Chicago, Ill.

Coe, R. (1967), Paleo-intensities of the Earth's magnetic field determined from Tertiary and Quaternary rocks, *J. Geophys. Res.*, *72*, 3247–3262.

Courtillot, V., Y. Gallet, J.-L. Le Mouël, F. Fluteau, and A. Genevey (2007), Are there connections between the Earth's magnetic field and climate?, *Earth Planet. Sci. Lett.*, *253*, 328–339.

Courtillot, V., Y. Gallet, J.-L. Le Mouël, F. Fluteau, and A. Genevey (2008), Response to comment on "Are there connections between the Earth's magnetic field and climate?", *Earth Planet. Sci. Lett.*, *265*, 308–311.

Creer, K., P. Tucholka, and C. Barton (Eds.) (1983), *Geomagnetism of Baked Clay and Recent Sediments*, 324 pp., Elsevier, New York.

Gallet, Y., and M. Le Goff (2006), High-temperature archeointensity measurements from Mesopotamia, *Earth Planet. Sci. Lett.*, *241*, 159–173.

Gallet, Y., A. Genevey, and V. Courtillot (2003), On the possible occurrence of archeomagnetic jerks in the geomagnetic field over the past three millennia, *Earth Planet. Sci. Lett.*, *214*, 237–242.

Gallet, Y., A. Genevey, and F. Fluteau (2005), Does Earth's magnetic field secular variation control centennial climate change?, *Earth Planet. Sci. Lett.*, *236*, 339–347.

Gallet, Y., A. Genevey, M. Le Goff, F. Fluteau, and S. A. Eshraghi (2006), Possible impact of the Earth's magnetic field on the history of ancient civilizations, *Earth Planet. Sci. Lett.*, *246*, 17–26.

Genevey, A., Y. Gallet, and J.-C. Margueron (2003), Eight thousand years of geomagnetic field intensity variations in the eastern Mediterranean, *J. Geophys. Res.*, *108*(B5), 2228, doi:10.1029/2001JB001612.

Le Goff, M., and Y. Gallet (2004), A new three-axis vibrating sample magnetometer for continuous high-temperature magnetization measurements: applications to paleo- and archeointensity determinations, *Earth Planet. Sci. Lett.*, *229*, 31–43.

Margueron, J. C. (2004), *Mari Métropole de l'Euphrate au IIIe et au début du IIe millénaire av. J.-C.*, edited by A. Picard and J. Picard, 575 pp., Assoc. pour la Diffus. de la Pensée Fr., Paris.

Matthiae, P., F. Pinnock, and G. Scandone-Matthiae (1995). *Ebla: Alle Origini Della Civiltà Urbana: Trent'anni di Scavi in Siria*, 542 pp., Electa, Milan, Italy.

Nachasova, I., and K. Burakov (1995), Archeointensity of the geomagnetic field in the fifth millennium BC in northern Mesopotamia, *Geomagn. Aeron., Engl. Transl.*, *35*, 398–402.

Nachasova, I., and K. Burakov (2000), The geomagnetic field intensity in Central Asia from 6000 to 3000 BC, *Izv. Phys. Solid Earth*, *36*, 358–363.

Parrot, A. (1935), *Les fouilles de Mari. Première campagne (hiver 1933–34) –Rapport préliminaire*, 140 pp., Libr. Orientaliste Paul Geuthner, Paris.

Rouault, O. (2001), Terqa et sa région (6e-1er millénaire av. J.-C.): Recherches récentes, *Akkadica*, *122*, 1–26.

Thellier, E., and O. Thellier (1959), Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique, *Ann. Geophys.*, *15*, 285–376.

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