Paleointensity of the Geomagnetic Field in Egypt from 4000 BC to 150 AD Using the Thellier Method

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A total of 170 ceramic specimens from 16 archaeological sites representing 16 well determined ages from 4000 BC to 150 AD were investigated using the Thellier method. These paleointensities were compared with data from countries near Egypt after reduction to a common latitude to determine a secular variation curve of the geomagnetic field for the time period from 4000 BC to 150 AD. The field intensity increases from about 30 μT around 3500 BC to a maximum of 70 μT at about 400 BC when it starts to decrease until 150 AD. The Thellier double heating method was used together with the following additional test measurements: a) during the Thellier experiments the laboratory field F_{Lab} pointed in the direction of stable NRM, b) magnetic susceptibility was measured after each double heating step to check for chemical alteration, c) a TRM check was made, by repeating the pTRM induction at a lower temperature, d) recent samples which were fired in a known field were used to test the reliability of our experimental setup and method. Based on rock magnetic measurements magnetite was identified as the predominant carrier of magnetization in the ceramics and bricks.

1. Introduction

One prerequisite for paleointensity determinations is that the fired objects, which are usually made of clay (i.e. ceramics, bricks, and other artifacts) were heated during manufacturing to a temperature above the Curie temperature T_c . During cooling the samples acquire a thermoremanent magnetization (TRM) which records the geomagnetic field intensity and direction that was present at the time of firing. The paleointensity of the geomagnetic field can be determined when the TRM is proportional and parallel to the ambient field. Since the introduction of the Thellier method potential problems became obvious and many experiments were carried out showing that the statements above are only valid to some extent. Faulty paleointensities may result from the differences between the conditions in which the objects were originally fired and today's laboratory conditions. The magnetic minerals in the archaeological material may undergo chemical alterations during the Thellier double heating process. Chemical alteration, the anisotropy of magnetic susceptibility and the cooling rate during the Thellier experiment influence the determined paleointensity value.

The paleointensity of the geomagnetic field in Egypt over a long time span from 4000 years BC to 150 years AD was determined using the method of Thellier and Thellier (1959) with a few additional precautionary measures. Previous paleointensity determinations of the geomagnetic field in Egypt were made by Athavale (1969), Games (1980), Hussain (1983, 1987), Aitken *et al.* (1984), and Walton (1986).

Several field trips were made with archaeologists and ceramicists to excavations of ancient graves, mostly in Upper Egypt. We were allowed to select the most suitable samples for paleointensity measurements from a big variety of archaeological materials. Only the bases and necks with handles were selected from the pottery to be able to distinguish between vertical and horizontal walls. Homogeneously

Fig. 1. A sketch map of Egypt showing the sites of samples. 1: Minia El Kamh, 2: El Giza, 3: Beni Suef, 4: El Minia, 5: Naga Hamadi, 6: El Ballas, 7: Qena, 8: Qift, 9: Luxor, 10: El Kharga, 11: Isna, 12: Idfu, 13: Aswan.

Table 1. Paleointensities measurements of the ceramics samples which were drilled parallel to the stable NRM. Ceramics and ovens are marked with C and bricks with B. F_{sample} is the mean paleointensity for 2–4 specimens. F_{site} is the site mean paleointensity. A dash means no reliable results.

Age	Site	Sample	Type	F_{specimen} (μT)	F_{sample} (μT)	N	F_{site}
4000 BC	Hiw, Naga Hamadi (26.0°N, 32.3°E)	16-1	C	42 42 44 42	42.5	12	42.5
		16-2	C	44 45 43 44	44.0		
		16-3	C	42 40 40 42	41.0		
3476 BC	El Odwa, Idfu (25.0°N, 32.8°E)	12-1	C	32 32 32	32.0	9	32.0
		12-2	C	33 32 32	32.3		
		12-3	C	—	—		
		12-4	C	32 31.5 32	31.8		
3000 BC	El-Kom Al-Ahmer, Idfu (25.0°N, 32.8°E)	14-1	C	50 50 50 50	50.0	17	49.7
		14-2	C	48 49 53 48	49.5		
		14-3	C	46 49 48	48.0		
		14-4	C	50 50 50	50.0		
		14-5	C	49 52 52	51.0		
2560 BC	Beni Suef (29.1°N, 31.1°E)	26	C	50 48	49.0	2	49.0
2160 BC	Al-Qurna, Luxor (25.7°N, 32.6°E)	17-1	C	50 55 55 54	53.5	16	54.0
		17-2	C	54 50 57 52	53.3		
		17-3	C	57 55 55 56	55.8		
		17-4	C	58 52 52 51	53.3		
2150 BC	Al-Qurna, Luxor (25.7°N, 32.6°E)	6	C	47.2 47	47.1	2	47.1
1990 BC	Al-Qurna, Luxor (25.7°N, 32.6°E)	7-1	C	—	—	—	—
		7-2	C	—	—		
1436 BC	Abul Goud, Luxor (25.7°N, 32.6°E)	8-2	C	58 58 59 57	58.0	12	57.2
		8-3	C	57 58 59 56	57.5		
		8-4	C	57 56 52 59	56.0		

1430 BC	Abul Goud, Luxor (25.7°N, 32.6°E)	11	B	56 55	55.5	2	55.5
1349 BC	Al-Qurna, Luxor (25.7°N, 32.6°E)	22	C	45 45	45.0	6	45.8
		5-2	C	46 46 49 45	46.5		
1300 BC	Gabanet El-Asmak, Isna (25.3°N, 32.5°E)	1-1	C	65 62 64 60	62.8	16	64.2
		1-2	C	63 65 64 66	64.5		
		2	C	66 64 63 63	64.5		
		3	C	65 64 67 64	65.0		
1300 BC	Addir El-Kharby, El Ballas (26.0°N, 32.7°E)	19-1	C	66 62 64 68	65.0	12	63.2
		19-2	C	60 62 62 61	61.3		
		19-3	C	62 65 66 60	63.3		
1130 BC	El Karnak, Luxor (25.7°N, 32.6°E)	9-1	B	63 63 64 62	63.0	12	63.0
		9-2	B	64 69 62 62	64.3		
		9-3	B	60 62 64 61	61.7		
350 BC	Tall AL-Shorafa, Idfu (25.0°N, 32.8°E)	15-1	C	66 64 66 67	65.8	12	66.3
		15-2	C	67 67 67 67	67.0		
		15-3	C	65 66 68 66	66.1		
200 BC	El Hazayer, Qift (25.9°N, 32.8°E)	10-1	B	48 50 53 51	50.5	8	51.5
		10-2	B	56 53 51 50	52.5		
200 BC	El Hager, Idfu (25.0°N, 32.8°E)	13-1	C	46 55 55	52.0	10	54.3
		13-2	C	55 55 57 55	55.5		
		13-3	C	54 56 56	55.3		
200 BC	Dandara, Qena (26.2°N, 32.7°E)	18-1	C	57 57 57	57.0	12	55.2
		18-2	C	54 55 55 54	54.5		
		18-3	C	55 54 56	55.0		
		18-6	C	54 54	54.0		
100–150 AD	Sibrata, Libya (32.8°N, 13.1°E)	4-1	C	55 55	55.0	4	55.0
		4-2	C	55 55	55.0		
150 AD	Naga El-Hager, Aswan (24.1°N, 33.0°E)	0	C	44 44	44.0	2	44.0
1990 AD	Minia Al-Kamah, El Sharqia (30.6°N, 31.2°E)	20	C	39 39	39.0	4	39.3
		20-1	C	39 40	39.5		

fired thick ceramic sherds and bricks were collected similar to the ones used by Rogers *et al.* (1979). One ceramic sample came from Sibrata (Libya) for a comparison with the ceramics made in Egypt.

The accuracy of dating the samples is one of the critical problems in archaeomagnetic studies, especially if we want to understand the detailed behaviour of the geomagnetic field over a short time period. The precision of ^{14}C dating and the accuracy of thermoluminescence for samples older than 2000 years is not sufficiently accurate. The uncertainties in these age determinations would not give the resolution needed to determine the often rapid changes of the geomagnetic field intensity. The ages of our samples were determined with an accuracy of better than ± 10 years by the archaeologists from the very accurate chronology, type of manufacture of the ceramics, construction patterns at the excavated sites and from dated objects in the graves like coins and drawings. The archaeological sites, from which the samples were collected, have been thoroughly studied by egyptologists and ceramicists (e.g. Boak and Peterson, 1931; Boak, 1933; Bresciani, 1968). Figure 1 is a map showing the sampling sites and Table 1 contains the ages of the samples and the coordinates of the sampling sites.

2. Sample Preparation

Anisotropy of magnetic susceptibility κ is potentially a large source of error in palaeointensity measurements. To minimize the effects of anisotropy of magnetic susceptibility on the pTRM intensities in the Thellier experiments, samples required a certain orientation with respect to $F_{\text{Lab.}}$. Often ceramics possess an anisotropy of magnetic susceptibility (AMS) with a maximum κ parallel and a minimum κ

Table 2. The rock magnetic properties of the archaeological samples. $M_s(T)$: Thermomagnetic curves and Curie temperature. IRM: acquisition of isothermal remanent magnetization. (a): Magnetite-like phase; (b): Mixture of magnetite-like phase and high-coercivity hematite-like phase; (c): High-coercivity hematite-like phase and small amount of magnetite-like phase. Hysteresis-parameters: M_{rs} : saturation remanence; M_s : saturation magnetization; H_c : coercive force. Anisotropy of magnetic susceptibility: the degree of anisotropy is κ_1/κ_3 , where κ_1 is the maximum susceptibility. X-ray diffraction: Mag.: magnetite; hem.: hematite; qtz.: quartz; mus.: muscovite. Underlined minerals have well defined peaks in the X-ray diffractogram.

Age	Sampl. No.	T_c from $M_s(T)$ curves	IRM type	M_{rs} Am ² /kg	M_s Am ² /kg	M_{rs}/M_s	H_c mT	Degree of aniso.	X - ray	Microscopic observation
4000 BC	16	$\approx 565^\circ\text{C}$	b	0.05	0.17	0.29	11.0	1.038	<u>mag.</u> + hem. + qtz. + mus.	normal
3476 BC	12	$\approx 200 - 470^\circ\text{C}$ and $\approx 577^\circ\text{C}$	b	0.09	0.39	0.23	8.0	1.040	qtz. + mus + mag. + hem.	-small amount of mag. & hem. -small grain size
3000 BC	14	mixture of mainly para + ferrimagnetic	c	0.01	0.07	0.14	3.5	1.064	<u>mag.</u> + hem. + qtz. + mus.	normal
2160 BC	17	mixture of mainly para + ferrimagnetic	b	0.03	0.17	0.18	6.5	1.048	<u>mag.</u> + hem. + qtz. + mus.	normal
1990 BC	7	$\approx 420 - 430^\circ\text{C}$	b	0.06	0.19	0.32	7.5	1.063	qtz. + mus. + mag. + hem.	
1436 BC	8	mixture of mainly para + ferrimagnetic	a	0.02	0.06	0.33	11.5	1.054	<u>mag.</u> + mus. + qtz. + hem.	normal
1349 BC	5	very weak sample	b	0.01	0.07	0.14	5.0	1.082	<u>mag.</u> + hem. + qtz. + mus.	-no mag. grains were observed
1300 BC	2	$\approx 570^\circ\text{C}$	b	1.64	5.92	0.28	11.0	1.031	<u>mag.</u> + <u>mus.</u> + hem. + qtz.	normal
	19	$\approx 560^\circ\text{C}$	b	0.06	0.41	0.15	6.2	1.043	<u>mag.</u> + <u>hem.</u> + mus. + qtz.	-hem. grains $\geq 10\mu\text{m}$ -mag. grains (10-50 μm)
1130 BC	9	mixture of mainly para + ferrimagnetic	a	0.03	0.14	0.21	4.5	1.005	<u>mag.</u> + mus. + qtz. + hem.	normal
330 BC	15	$\approx 580^\circ\text{C}$	a	0.04	0.14	0.29	23.0	1.043	<u>mag.</u> + hem. + mus. + qtz.	normal
200 BC	10	mixture of mainly para + ferrimagnetic	b	0.09	0.22	0.41	12.0	1.006	<u>mus.</u> + qtz. + mag. + hem.	-small amount of mag. and hem.
200 BC	13	$\approx 580^\circ\text{C}$	a	0.09	0.31	0.29	17.0	1.082	<u>mag.</u> + qtz. + mus. + hem.	normal
	18	$\approx 570^\circ\text{C}$	c	0.02	0.09	0.22	9.5	1.028	<u>mag.</u> + hem. + qtz. + mus.	normal
125 AD	4	mixture of mainly para + ferrimagnetic	a	0.25	1.08	0.23	6.0	1.068	qtz. + mus. + mag. + hem.	-small amount of mag. and hem.
130 AD	0	$\approx 565^\circ\text{C}$	b	1.06	4.84	0.22	9.0	1.045	<u>mag.</u> + <u>hem.</u> + qtz. + mus.	normal
1990 AD	20	$\approx 568^\circ\text{C}$	c	0.11	0.39	0.28	9.5	1.010	<u>hem.</u> + <u>mag.</u> + qtz. + mus.	-big amount of hem. -size (0.4-10) μm

perpendicular to the plane of a ceramic sherd. To overcome this problem we collected only thick ceramics and bricks in which case a large AMS due to the manufacturing process is less likely. Measurements of anisotropy of magnetic susceptibility were carried out on 17 samples. Maximum, intermediate and minimum susceptibilities (κ_1 , κ_2 , κ_3) were determined for each sample to obtain the degree of anisotropy κ_1/κ_3 (Nagata, 1961) and the mean susceptibility $(\kappa_1 + \kappa_2 + \kappa_3)/3$. Unfortunately, the orientation of the AMS ellipsoid with respect to the sample coordinates is not known. The degrees of anisotropy is less than 1.08 for our samples (Table 2). Therefore the thick ceramics and bricks do not possess a significant anisotropy of κ compared to the one detected by Rogers *et al.* (1979). The low degree of anisotropy shows that it is preferable to carry out paleointensity measurements on thick ceramics and bricks.

The ancient vases and ceramic objects were rotated on a disc during the manufacturing process. It

is therefore reasonable to assume that the magnetic particles orient themselves with their long axes in the direction of rotation. This would result in $\kappa_{\max}$ along the direction of rotation and two minimum directions perpendicular to it. Magnetic anisotropy affects both the TRM which is acquired during the initial firing of the archaeological ceramics and the pTRM which is acquired during the Thellier experiment in the laboratory. Our samples were orientated and drilled in such a way, that the direction of stable NRM coincided with the direction of $F_{\text{Lab.}}$ during the Thellier experiment. Under these circumstances the pTRM is acquired with the same anisotropy present as the original TRM was.

The samples could be placed in the furnace only with their cylinder axes (z-axes) in the direction of $F_{\text{Lab.}}$. This required that the direction of stable natural remanent magnetization (NRM) points along the z-axis of the sample. In other words, we had to drill the specimens parallel to the direction of stable NRM. The drilled samples were embedded in plaster of Paris to obtain standard 1-inch cylinders. An oriented pilot specimen was drilled from this embedded sherd and alternating field (AF) demagnetized to determine declination D and inclination I of the stable NRM. Most of the samples were found to have a single stable direction of magnetization.

A device was designed to orientate the mother archaeological samples. This instrument consists of two plates made of aluminum with two protractors, one between the two plates and the other on the upper plate. To prepare the samples so that $F_{\text{Lab.}}$ points parallel to the direction of stable NRM, the sample is rotated by the angle of declination on the tilted plate so that the horizontal component of NRM points parallel to the edge of the tilted plate. The plate is then raised by an angle $90^\circ - I$, where I is the inclination of the pilot specimen's magnetization. The direction of stable NRM is then exactly vertically downward. Three or four specimens were typically drilled from a mother sample. Their cylinder axes were parallel to the direction of stable NRM and therefore parallel to $F_{\text{Lab.}}$.

3. Paleointensity Measurements

The Thellier and Thellier (1959) method with slight modifications was used for the paleointensity determinations. In total there were 170 specimens from 50 mother samples representing 16 independently determined ages. A $F_{\text{Lab.}}$ of $50 \mu\text{T}$ was applied to all specimens during the Thellier experiments. Magnetic susceptibility of the samples was measured after each double heating step to ensure that it remained constant throughout the experiment as a test for chemical alterations. An additional test for chemical alteration was done on 20 specimens which is named pTRM check after Coe (1967). After double heating the samples to 400°C and getting the NRM-pTRM pair values, the sample was again double heated to 300°C and the NRM-pTRM pair was determined. This last pair (NRM-pTRM)₃₀₀ represents NRM remaining after the heating to 400°C and pTRM gained at 300°C . Ideally this point lies at the same NRM value as after the 400°C step and at the same pTRM value as after the first 300°C pTRM acquisition if no chemical alteration had occurred (Fig. 2). This step was repeated for temperatures 500°C and sometimes 600°C . Only 4 out of 20 samples were found to have deviations of pTRM₃₀₀-pTRM₄₀₀ of more than 10%. If there was indication of chemical alteration at a certain temperature, we rejected this point and the following ones from the linear least squares fit to the data. Only 20 specimens were subjected to the pTRM check due to time constraints.

The results of the paleointensity experiments in terms of the ancient field F_{sample} , based on 50 samples (170 specimens), are listed in Table 1. In Fig. 3 we show eight representative examples of paleointensity measurements as NRM versus TRM plots. The paleointensities obtained from two recent specimens of sample 20 (1990 AD) are shown in Fig. 4. Both specimens have paleointensities of $39 \mu\text{T}$ which compares reasonably well with the actual field at the site which was $42 \mu\text{T}$. The difference of 7% may be due to a VRM or to a difference in cooling rate (Walton, 1987), since there were no anisotropy or chemical alteration effects determined for these two samples. Another explanation for the discrepancy could be the presence of pseudo-single-domain or multidomain magnetite, both of which have unblocking temperatures of TRM far above the blocking temperatures of that pTRM (e.g. Shcherbakov *et al.*, 1993).

Fig. 2. Arai plot of NRM versus TRM with pTRM check after Coe (1967). The laboratory field F_{Lab} was $50 \mu T$. a) sample 17 from Luxor (2160 BC), the slope of the linear least squares fit is 1.24. b) sample 19 from El Ballas (1300 BC), the slope of the linear fit is 1.0.

Fig. 3. NRM versus TRM plots for a) 4 samples from Sibrata, Libya (100-150 AD) and b) 4 samples from Gabbanet El Asmak, Isna (1300 BC).

Fig. 4. NRM versus TRM plot of 2 recent samples from Minia El Kamh (1990 AD) using different laboratory fields $F_{Lab.}$ during the Thellier experiment. a) for sample 20 $F_{Lab.} = 80 \mu T$ and the slope of the linear fit is 0.49. b) for sample 20-1 $F_{Lab.} = 50 \mu T$ and the slope of the linear fit is 0.78.

Fig. 5. Secular variation curve of the geomagnetic field in Egypt based on the results of this investigation. Small crosses show paleointensities for each specimen. Small stars show mean paleointensities of single samples (F_{sample} in Table 1), each sample consisting of 2–4 specimens. Mean paleointensities of samples from the same site are shown by solid squares (F_{site} in Table 1). The data are not reduced yet to a common latitude.

4. Secular Variation of the Geomagnetic Field in Egypt

The behaviour of the earth's magnetic field through the archaeological ages of this study can be represented in form of a secular variation curve. Reliable paleointensity data are necessary for understanding the secular variation of the geomagnetic field in the region surrounding the eastern Mediterranean. These data can then be used for evaluating different secular variation models. The conditions for studying the secular variation of the geomagnetic field using archaeological samples are better in Egypt than elsewhere in the world, since the historical archaeological record from pre-historic through Pharaonic, Greco-Roman and Islamic ages is well dated and well preserved due to a favourable climate.

Figure 5 is a plot of the secular variation curve for the geomagnetic field in Egypt for the time between 4000 BC and 2000 AD based on our determinations of the paleointensity for 170 specimens which are represented by crosses (F_{specimen} in Table 1). The mean value of the ancient geomagnetic field for each sample (F_{sample} in Table 1) was determined from 2 to 4 specimens and is represented by a star in Fig. 5. The mean value for each site (F_{site} in Table 1), which was determined from 1 to 5 samples, is represented by a black square in Fig. 5. Starting with a field intensity of $44 \mu\text{T}$ at 4000 BC the geomagnetic field decreased to a minimum value of $32 \mu\text{T}$ around 3500 BC. Between 3500 BC and 3000 BC the field increased rapidly to about $52 \mu\text{T}$ and from then on more gradually up to a maximum of $67 \mu\text{T}$ at 1300 BC. There is a gap in our field intensity data until 350 BC when the field began to decrease to about $50 \mu\text{T}$ at 150 AD (Fig. 5). The secular variation curve based on our data suggests that the magnetic field in Egypt varied by at least a factor of two over the last 6000 years and generally remained above the present day value of $42 \mu\text{T}$.

For comparison with our results, we used published paleointensity data from areas close to Egypt.

Fig. 6. Secular variation curve of the geomagnetic field intensity during the last 6000 years. Solid squares (■) represent reduced site mean values (F_{red}) for samples from the same site from this study after reduction to $\phi = 28^\circ\text{N}$. Published data from countries around the eastern Mediterranean reduced to the middle latitude of Egypt 28°N are shown by the following symbols: $\times$ (Kovacheva, 1980), $\Delta\Delta$ (Hussain, 1983, 1987), $\blacktriangle$ (Aitken *et al.*, 1984) and $\circ\circ$ (Walton, 1986) and (Walton and Balhatchet, 1988).

These data are from south-east Europe (Kovacheva, 1980), from Egypt (Hussain, 1983, 1987; Aitken *et al.*, 1984; Walton, 1986) and from Athens and Corinth (Walton and Balhatchet, 1988). These published data together with the data from this study were used for construction of a secular variation curve of the geomagnetic field in Egypt during the last 6000 years (Fig. 6). All data were reduced to the middle geographic latitude of Egypt (28°N) according to the virtual axial dipole equation (Creer *et al.*, 1983):

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

where F_{reduced} is the paleointensity after reduction to middle latitude of Egypt, F_{site} is the paleointensity at the site, $\phi_{\text{reduced}} = 28^\circ\text{N}$ and ϕ_{site} is the geographic latitude of the site.

All paleointensity data from this study and from neighbouring countries before and after reduction to a common latitude are summarized in the Appendix. The compilation of paleointensities in Fig. 6 shows that there is moderate agreement between the various data sets. One possibility is that the geomagnetic field in Egypt has fluctuated quite rapidly over the investigated period from 4000 BC to 1990 AD. Another possibility is, that some of the non-egyptian samples are not as precisely dated as our ceramics. More likely there are systematic differences between the various data sets. The paleointensities of Walton (1986) and Walton and Balhatchet (1988) are generally lower than our data and the results of Kovacheva (1980). The paleointensities of Aitken *et al.* (1984) are in good agreement with our data. Nevertheless, there are several maxima and minima with the highest value of the paleofield around 78 μT at approximately 460 BC (Hussain, 1987) and a minimum in the field intensity with $\approx 29 \mu\text{T}$ around 100 AD (Walton and Balhatchet, 1988). During the last 2500 years the Earth's magnetic moment generally decreases.

5. Rock Magnetic Measurements

A good knowledge of the magnetic mineralogy of archaeological materials is necessary to judge the reliability of archaeomagnetic data. Rock magnetic studies provide information about the composition of the magnetic carriers, their approximate grain size distribution and their chemical alteration state.

Each specific composition of a magnetic mineral has a unique T_c , so that the determination of this temperature is diagnostic of a specific kind of magnetic mineral. The Curie temperature T_c is usually determined from the thermal variation of saturation magnetization (M_s). Thermomagnetic curves were measured on 17 archaeological ceramics and bricks (Table 2). All thermomagnetic curves indicate the presence of magnetite (Fig. 7a) or a mixture of mainly paramagnetic minerals with a small amount of ferrimagnetic minerals (Fig. 7b). Most of the $M_s(T)$ curves are reversible, suggesting that the samples are suitable for the Thellier experiments since they do not show any chemical alterations during heating to 700°C. One exception is sample 12-3 (Fig. 7c) which showed a distribution of T_c between 460–470°C most likely due to titanomagnetite. The curve in Fig. 7c shows a peak at $\approx 500^\circ\text{C}$ from the inversion of titanomagnetite to magnetite with a higher M_s and with $T_c \approx 570^\circ\text{C}$. Such irreversible behaviour of the $M_s(T)$ curve means that this sample is unsuitable for Thellier experiments (Ade-Hall *et al.*, 1968; Schweitzer, 1975). Sample 7 (Fig. 7d) has also a low T_c of ≈ 420 – 430°C which may be due to the presence of titanomagnetite in addition to paramagnetic minerals. Samples 12-3 and 7 showed erratic behaviour during the paleointensity determination (Table 1) and were therefore not given in the Appendix.

The acquisition curves of isothermal remanent magnetization (IRM) of 17 archaeological samples can be divided into three groups. The first type revealed a "magnetite-like" phase (Fig. 8a, type "a" in Table 2) which reached saturation in a field of $\approx 220 \text{ mT}$ (for magnetite typically 200–300 mT). The second type shows a low coercivity "magnetite-like" phase which saturates in a field of $\approx 200 \text{ mT}$. A further minor increase of the IRM is due to a high coercivity phase which could be hematite or goethite (Fig. 8b, type "b" in Table 2). The third type (Fig. 8c, type "c" in Table 2) is a mixture of a high coercivity phase (hematite or goethite) and a smaller amount of a low coercivity "magnetite-like" phase. The low coercivity fraction

Fig. 7. Thermomagnetic curves of 4 archaeological samples. a) Sample 0 from Aswan, b) sample 14 from Idfu, c) sample 12-3 from Idfu, d) sample 7 from Luxor.

in Fig. 8c saturates in a field of ≈ 150 mT, followed by a substantial increase of IRM above 150 mT without reaching saturation due to the presence of the high coercivity phase.

Room temperature hysteresis loops were measured with a vibrating sample magnetometer (VSM). Figure 9 shows the hysteresis loops of 2 archaeological samples and indicates the presence of a low coercivity phase ("magnetite-like" phase) reaching saturation in fields of ≈ 150 –200 mT and a high coercivity phase (hematite or goethite) or a paramagnetic phase which does not reach saturation (Fig. 9a). Figure 9b shows the presence of a high coercivity phase together with paramagnetic minerals and a magnetite-like phase. Hysteresis loops show that all samples contain either magnetite or a mixture of magnetite plus a different amounts of hematite. Table 2 summarizes all the rock magnetic characteristics such as saturation remanence M_{rs} , the ratio M_{rs}/M_s , and coercive force H_c . All samples contain possibly pseudo-single-domain (PSD) grains. The ratio M_{rs}/M_s can also be interpreted as a mixture of single domain (SD) and superparamagnetic grains or SD plus multidomain (MD) grains.

All 17 archaeological samples were investigated twice by X-ray diffraction. One powdered specimen

Fig. 8. IRM curves of 3 archaeological samples. a) Sample 8 from Luxor, type a. b) Sample 12-3 from Idfu, type b. c) Sample 18 from Qena, type c.

was left in its original state and the other was mixed with Silicon as a standard for calibration of the spectrum. X-ray diffraction indicated that all 17 samples contain magnetite, hematite, quartz and muscovite in different quantities (Table 2). The X-ray analysis of sample 4 from Libya shows a large amount of muscovite and quartz, a small amount of magnetite and a very small amount of hematite. Sample 20 (recent, 1990 AD) is characterized by a large amount of hematite. Only sample 5 contains a very small amount of magnetic minerals while sample 12 contains large amounts of quartz and a small amount of a "magnetite-like" phase and hematite.

Microscopic observations are very useful to study the shape and size of the magnetic grains and to determine the percentage of each mineral type. The microscopic observations of the 17 polished sections reveal that the samples contain magnetite in various amounts and a wide variety of grain sizes, and a small amount of hematite with small grain sizes. Sample 4 shows a large amount of quartz and muscovite, and a small amount of magnetite and hematite. Sample 20 (1990 AD) reveals a large amount of quartz and of idiomorphic and pseudo-hexagonal hematite grains from $0.1\ \mu\text{m}$ to $10\ \mu\text{m}$ in size. Sample 12 contains a

Fig. 9. Hysteresis loops of 2 archaeological samples. a) Sample 8 from Luxor, b) sample 16 from Naga Hamadi.

Fig. 10. Reflected light micrograph of sample 13 from Idfu. The large magnetite grain has a diameter of 120 μm .

large amount of quartz, a small amount of magnetite (probably titanomagnetite with grain sizes from 0.3 to 0.7 μm), and a very small amount of hematite. Sample 5 has a small content of magnetic minerals and no magnetite was detected. Figure 10 shows an example of a 120- μm -size magnetite grain in sample 13 from Idfu.

6. Conclusions

From the above mentioned rock magnetic measurements of the 17 archaeological samples, one can conclude that most of the 17 investigated samples contain magnetite plus varying amounts of hematite. Rock magnetic investigations showed that samples 12-3 and 7 contain titanomagnetite. These two samples were excluded from the paleointensity results following the suggestion of Schweitzer (1975) not to use paleointensities of samples containing titanomagnetite. The NRM versus TRM plots from the Thellier experiments of samples 12-3 and 7 showed irregular and uninterpretable results. The remaining samples which contain mainly magnetite had interpretable paleointensity results. The recent sample 20 shows the same behaviour as the archaeological samples, but contains large amounts of hematite. Sample 4 from Libya has similar rock magnetic behaviour as the Egyptian samples but its magnetization is lower than that of the other samples.

A few commonly used tests were performed together with the classic Thellier and Thellier (1959) method to ensure the reliability of the paleointensity values. Thin sherds often have a higher anisotropy of magnetic susceptibility than thick sherds (Rogers *et al.*, 1979). Therefore thick, homogeneously fired and well dated sherds were collected for our investigation. One pilot sample was drilled from the mother sample to determine the direction of stable NRM by AF demagnetization. We recommend to drill all specimens from the mother sample such that F_{Lab} can be applied parallel to the direction of stable NRM to minimize the effect of anisotropy of magnetic susceptibility on paleointensities. Measuring susceptibility after each double heating step helps to recognize chemical alterations of the sample when κ deviates from its initial value. Nevertheless, a constant κ throughout a Thellier experiment is no guarantee for the absence of chemical changes in the magnetic mineralogy. Therefore we used as a supplementary method, the pTRM check after Coe (1967), to test for chemical alteration during the paleointensity experiment.

Figure 5 represents the paleointensity secular variation curve of the geomagnetic field in Egypt based on our present data without reduction to a common latitude. The site mean paleointensities (black squares in Fig. 5) do not show large scatter and could form the base for future paleointensity determinations in Egypt which may lead to a reference curve for archaeomagnetic chronology. Unfortunately the scatter in the data gets bigger when one compares the data from this study with data presently available for the countries near Egypt. A comparison with paleointensities from the eastern Mediterranean after reduction to the middle latitude of Egypt (Fig. 6) shows only a rough trend for the geomagnetic field intensity. The field increases from a low value of about 30 μT around 3500 BC to maximum values of 65 μT to 70 μT around 400 BC followed by a decrease down to the present day intensity of 42 μT .

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APPENDIX

The archaeological samples, their ages, types of manufacture (C means ceramics, oven, or furnaces; and B means bricks), site name, number of specimens (No.), latitude (ϕ) and longitude (λ) from this study the published data before and after reduction to the middle latitude of Egypt (28°N). The published data are from Kovacheva (1980), Hussain (1983, 1987), Aitken *et al.* (1984), Walton (1986) and Walton and

Balhatchet (1988). The following abbreviations are used: Kova.: for Kovacheva, Huss.: for Hussain, Aitk.: for Aitken, Walt.: for Walton, F_{sample} : for sample mean, F_{site} : for site mean, and $F_{\text{red.}}$: for reduced site mean. The intensities of the ancient field are in μT .

Age	Site	Samp. Name	Type	$\phi(N)$	$\lambda(E)$	No.	Site mean F_{site}	Reduced. site mean $F_{\text{red.}}$	Author
4000 BC	Hiw, Naga Hamadi	16-1,2,3	C	26.0°	32.3°	12	42.5	43.6	this study
4000 BC	S.E.Europe	S.E.1	C	42.9°	24.5°	24	42.0	35.0	Kova.80
3900 BC	S.E.Europe	S.E.2	C	43.9°	22.7°	26	46.0	37.9	Kova.80
3800 BC	S.E.Europe	S.E.3	C	43.6°	22.3°	18	52.0	43.0	Kova.80
3476 BC	El Odwa, Idfu	12-1,2,4	C	25.0°	32.8°	9	32.0	33.3	this study
3300 BC	Monshaat Abu Omar	Mo - 1	C	30.8°	32.0°	2	46.0	44.4	Huss.83
3300-2900 BC	Monshaat Abu Omar	Mo - 2	C	30.8°	32.0°	2	38.0	36.6	Huss.83
3200 BC	S.E.Europe	S.E.4	C	44.9°	19.8°	8	53.0	43.3	Kova.80
3100 BC	Monshaat Abu Omar	Mo - 3	C	30.8°	32.0°	3	43.0	41.5	Huss.83
3100 BC	KurKur	Kr - 1	C	30.0°	31.0°	5	36.2	35.3	Huss.87
3100-3000 BC	Monshaat Abu Omar	Mo - 4	C	30.8°	32.0°	2	37.0	35.7	Huss.83
3000 BC	El-Kom Al-Ahmer, Idfu	14-1,2,3,4,5	C	25.0°	32.8°	17	49.7	51.7	this study
3000 BC	Turra	Tu - 1	C	30.0°	31.0°	3	46.8	45.6	Huss.87
3000 BC	S.E.Europe	S.E.5	C	43.7°	22.9°	15	40.0	33.1	Kova.80
2780 BC	Turra	Tu - 2	C	30.0°	31.0°	3	36.5	35.6	Huss.87
2560 BC	Beni Suef, Beni Suef	26	C	29.1°	31.1°	2	49.0	48.3	this study
2500 BC	Turra	Tu - 3	C	30.0°	31.0°	7	49.0	47.7	Huss.87
2200 BC	Lahoun	L - 1	C	29.5°	30.6°	5	36.4	35.7	Huss.87
2160 BC	Al-Qurna, Luxor	17-1,2,3,4	C	25.7°	32.6°	16	54.0	55.6	this study
2150 BC	Al-Qurna, Luxor	6	C	25.7°	32.6°	2	47.1	48.6	this study
2100 BC	S.E.Europe	S.E.6	C	42.2°	24.8°	3	63.0	52.9	Kova.80
2000 BC	S.E.Europe	S.E.7	C	42.6°	26.0°	3	57.0	47.7	Kova.80
1990 BC	Turra	Tu - 4	C	30.0°	31.0°	8	57.0	55.5	Huss.87
1900 BC	S.E.Europe	S.E.8	C	42.6°	26.0°	3	62.0	51.9	Kova.80
1800 BC	S.E.Europe	S.E.9	C	41.5°	25.4°	3	69.0	58.4	Kova.80
1750-1700 BC	Tell El-Dab'a	Dab'a 1	C	30.9°	32.3°	2	36.5	35.2	Aitk.84
1700 BC	S.E.Europe	S.E.10	C	42.2°	24.3°	6	51.0	42.8	Kova.80
1630-1590 BC	Tell El-Dab'a	Dab'a 2	C	30.9°	32.3°	2	41.8	40.3	Aitk.84
1550-1401 BC	Thebes	Theb 1	C	26.0°	33.0°	1	49.9	51.2	Aitk.84
1504-1492 BC	El Karnak, Luxor	Karn 1	C	25.7°	32.6°	2	47.1	48.6	Aitk.84
1436 BC	Abul Goud, Luxor	8-2,3,4	C	25.7°	32.6°	12	57.2	58.9	this study
1430 BC	Abul Goud, Luxor	11	B	25.7°	32.6°	2	55.5	57.2	this study
1400 BC	Madi	M - 1	C	29.5°	30.6°	9	66.7	65.4	Huss.87
1400 BC	Biahmu	B - 1	C	29.5°	30.6°	4	61.5	60.3	Huss.87
1400-1350 BC	Kiman Faris	Kf - 1	C	29.5°	30.6°	6	60.0	58.8	Huss.83

1400 BC	S.E.Europe	S.E.11	C	42.2°	24.8°	2	77.0	64.7	Kova.80
1353-1335 BC	Tell El Amarna	Amar 1	C	28.0°	30.6°	4	53.8	53.8	Aitk.84
1350 BC	Tal El Amarna, El Minia	Egypt-1,4,5,6	C	28.0°	30.6°	7	44.5	44.5	Walt.86
1349 BC	Al-Qurna, Luxor	5-2 - 22	C	25.7°	32.6°	6	45.8	47.2	this study
1306-1290 BC	El Karnak, Luxor	Karn 2	C	25.7°	32.6°	2	51.65	53.2	Aitk.84
1300 BC	Gabane: El-Asmak, Isna	1-1,2 - 2 - 3	C	25.3°	32.5°	16	64.2	66.5	this study
1300 BC	Addir El-Kharby, El Ballas	19-1,2,3	C	26.0°	32.7°	12	63.2	64.9	this study
1250-1150 BC	El Karnak, Luxor	Karn 3	C	25.7°	32.6°	2	58.7	60.5	Aitk.84
1200 BC	S.E.Europe	S.E.12	C	42.2°	24.8°	4	56.0	47.0	Kova.80
1130 BC	El Karnak, Luxor	9-1,2,3	B	25.7°	32.6°	12	63.0	64.9	this study
1100-950 BC	El Karnak, Luxor	Karn 4	C	25.7°	32.6°	3	58.4	60.2	Aitk.84
1000 BC	S.E.Europe	S.E.13	C	42.3°	25.7°	7	67.0	56.2	Kova.80
900-850 BC	Athens	Ath.1	C	38.0°	23.8°	1	57.0	50.3	Walt.88
900 BC	S.E.Europe	S.E.14	C	45.2°	20.1°	18	65.0	52.9	Kova.80
875-825 BC	Corinth	Cor.1	C	37.9°	22.9°	1	49.0	43.2	Walt.88
800-750 BC	Athens	Ath.2	C	38.0°	23.8°	1	54.0	47.6	Walt.88
800 BC	S.E.Europe	S.E.15	C	43.5°	22.3°	6	75.0	62.1	Kova.80
775-740 BC	Athens	Ath.3	C	38.0°	23.8°	1	51.0	45.0	Walt.88
750-720 BC	Corinth	Cor.2	C	37.9°	22.9°	1	59.0	52.0	Walt.88
750-700 BC	Athens	Ath.4	C	38.0°	23.8°	1	54.0	47.6	Walt.88
650-600 BC	Athens	Ath.5	C	38.0°	23.8°	1	58.0	51.1	Walt.88
650-600 BC	Corinth	Cor.3	C	37.9°	22.9°	1	60.0	52.9	Walt.88
625-600 BC	Corinth	Cor.4	C	37.9°	22.9°	1	60.0	52.9	Walt.88
600 BC	Khus Abu Zeid	Kh - 1	C	30.0°	31.0°	5	69.9	68.1	Huss.87
600 BC	S.E.Europe	S.E.16	C	44.1°	17.5°	5	81.0	66.7	Kova.80
575 BC	Corinth	Cor.5	C	37.9°	22.9°	1	69.0	60.8	Walt.88
575-540 BC	Athens	Ath.6	C	38.0°	23.8°	1	40.0	35.3	Walt.88
570-530 BC	Corinth	Cor.6	C	37.9°	22.9°	1	61.0	53.8	Walt.88
550 BC	Khus Abu Zeid	Kh - 2	C	30.0°	31.0°	4	59.3	57.8	Huss.87
500 BC	S.E.Europe	S.E.17	C	41.5°	25.4°	2	76.0	64.3	Kova.80
475-450 BC	Athens	Ath.7	C	38.0°	23.8°	1	61.0	53.8	Walt.88
470-420 BC	Corinth	Cor.7	C	37.9°	22.9°	1	67.0	59.1	Walt.88
460 BC	Khus Abu Zeid	Kh - 3	C	30.0°	31.0°	2	79.9	77.9	Huss.87
450 BC	Khus Abu Zeid	Kh - 4	C	30.0°	31.0°	7	73.4	71.5	Huss.87
425 BC	Corinth	Cor.8	C	37.9°	22.7°	1	60.0	52.9	Walt.88
420-370 BC	Corinth	Cor.9	C	37.9°	22.9°	1	55.0	48.5	Walt.88
400 BC	Athens	Ath.8	C	38.0°	23.8°	1	57.0	50.3	Walt.88
400 BC	S.E.Europe	S.E.18	C	43.7°	22.6°	10	78.0	64.5	Kova.80

360-330 BC	Corinth	Cor.10	C	37.9°	22.9°	1	55.0	48.5	Walt.88
350 BC	Tall AL-Shorafa, Idfu	15-1,2,3	C	25.0°	32.8°	12	66.3	69.0	this study
350-320 BC	Corinth	Cor.11	C	37.9°	22.9°	1	59.0	52.0	Walt.88
350-150 BC	Kiman Faris	Kf - 2	C	29.5°	30.6°	3	43.0	42.2	Huss.83
320 BC	Khus Abu Zeid	Kh - 5	C	30.0°	31.0°	6	69.7	67.9	Huss.87
300 BC	Corinth	Cor.12	C	37.9°	22.9°	1	55.0	48.5	Walt.88
300 BC	S.E.Europe	S.E.19	C	44.9°	15.8°	11	60.0	49.0	Kova.80
200 BC	El Hazayer, Qift	10-1,2	B	25.9°	32.8°	8	51.5	52.9	this study
200 BC	El Hager, Idfu	13-1,2,3	C	25.0°	32.8°	10	54.3	56.5	this study
200 BC	Dandara, Qena	18-1,2,3,6	C	26.2°	32.7°	12	55.2	56.5	this study
200-146 BC	Corinth	Cor.13	C	37.9°	22.9°	1	55.0	48.5	Walt.88
175-140 BC	Athens	Ath.9	C	38.0°	23.8°	1	52.0	45.9	Walt.88
160-146 BC	Corinth	Cor.14	C	37.9°	22.9°	1	50.0	44.1	Walt.88
100-50 BC	Kiman Faris	Kf - 3	B	29.5°	30.6°	9	58.0	56.9	Huss.83
100 BC	S.E.Europe	S.E.20	C	43.7°	23.1°	5	62.0	51.2	Kova.80
75-50 BC	Athens	Ath.10	C	38.0°	23.8°	1	50.0	44.1	Walt.88
50 BC-25 AD	Athens	Ath.11	C	38.0°	23.8°	1	45.0	39.7	Walt.88
50 AD	Babylon Wall	Ba - 1	B	30.0°	31.0°	11	56.2	54.8	Huss.87
100 AD	S.E.Europe	S.E.21	B	42.8°	25.2°	45	60.0	50.1	Kova.80
100-120 AD	Athens	Ath.12	C	38.0°	23.8°	1	33.0	29.1	Walt.88
100-150 AD	Sibrata, Libya	4-1,2	C	32.8°	13.1°	4	55.0	51.7	this study
117 AD	Kom Oushim	Ko - 1	B	29.5°	30.6°	1	64.6	63.3	Huss.83
117-200 AD	Kom Oushim	Ko - 2	B	29.5°	30.6°	3	60.8	59.6	Huss.83
128-159 AD	Kom Oushim	Ko - 3	B	29.5°	30.6°	2	52.0	51.0	Huss.83
147-170 AD	Kom Oushim	Ko - 4	C	29.5°	30.6°	4	53.3	52.2	Huss.83
150 AD	Naga EL-Hager, Aswan	0	C	24.1°	33.0°	2	44.0	46.3	this study
200-265 AD	Athens	Ath.13	C	38.0°	23.8°	1	42.0	37.0	Walt.88
200 AD	S.E.Europe	S.E.22	B	43.2°	24.6°	93	62.0	51.5	Kova.80
225-250 AD	Athens	Ath.14	C	38.0°	23.8°	1	42.0	37.0	Walt.88
300 AD	Abu Serga Cave	As - 1	B	30.0°	31.0°	3	54.4	53.0	Huss.87
300 AD	S.E.Europe	S.E.23	B	42.8°	24.7°	14	59.0	49.2	Kova.80
350-375 AD	Athens	Ath.15	C	38.0°	23.8°	1	44.0	38.8	Walt.88
400 AD	Bin Azra Temple	Bz - 1	B	30.0°	31.0°	6	64.9	63.2	Huss.87
400 AD	S.E.Europe	S.E.24	B	42.9°	23.8°	26	57.0	47.5	Kova.80
500 AD	S.E.Europe	S.E.25	B	42.7°	25.6°	60	62.0	51.8	Kova.80
600 AD	S.E.Europe	S.E.26	B	43.0°	25.6°	5	71.0	59.1	Kova.80
650 AD	Athens	Ath.16	C	38.0°	23.8°	1	46.0	40.6	Walt.88
700 AD	Amro-Bu Al Aas Mosque	O - 1	B	30.0°	31.0°	10	57.5	56.0	Huss.87
800 AD	S.E.Europe	S.E.27	B	43.2°	27.8°	5	68.0	56.5	Kova.80

900 AD	S.E.Europe	S.E.28	B	43.2°	26.7°	28	77.0	64.0	Kova.80
1000 AD	S.E.Europe	S.E.29	B	41.2°	23.0°	4	87.0	73.9	Kova.80
1100 AD	S.E.Europe	S.E.30	B	42.8°	23.6°	11	57.0	47.6	Kova.80
1173 AD	Bin Hadra Monastery	H - 1	B	24.0°	32.8°	8	54.0	56.9	Huss.83
1200 AD	S.E.Europe	S.E.31	B	43.4°	26.7°	10	50.0	41.5	Kova.80
1300 AD	S.E.Europe	S.E.32	B	43.0°	24.4°	28	53.0	44.1	Kova.80
1400 AD	S.E.Europe	S.E.33	B	43.9°	24.3°	6	54.0	44.5	Kova.80
1450 AD	Anba Matta Monastery	M - 1	B	24.0°	32.8°	11	49.0	51.6	Huss.83
1500 AD	S.E.Europe	S.E.34	B	42.7°	25.4°	21	58.0	48.5	Kova.80
1600 AD	S.E.Europe	S.E.35	B	42.8°	24.4°	10	71.0	59.3	Kova.80
1700 AD	S.E.Europe	S.E.36	B	42.4°	24.6°	19	47.0	39.4	Kova.80
1795 AD	Amro-Bn Al Aas Mosque	O - 2	B	30.0°	31.0°	3	43.0	41.9	Huss.87
1800 AD	S.E.Europe	S.E.37	B	42.9°	25.8°	22	46.0	38.3	Kova.80
1990 AD	Minia Al-Kamah, El Sharqia	20 - 20-1	C	30.6°	31.2°	4	39.3	38.0	this study

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