Improvement of the secular variation curve of the geomagnetic field in Egypt during the last 6000 years

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A total of 115 ceramic specimens out of 41 samples from 9 archeological sites in Giza, Fayoum, Benisuef, El Minia, Malawy, and Sohag were collected. They represent 14 well-determined ages covering the last 6000 years. Rock magnetic properties such as Curie temperature and hysteresis loops have been measured for these samples to identify the magnetic carrier; it is found to be fine-grained magnetite. All specimens were investigated using the classic Thellier double heating technique (Thellier and Thellier, 1959) and the modification after Odah *et al.* (1995) to obtain the paleointensity data. These paleointensities and the previous results of Odah *et al.* (1995) were used to improve the secular variation curve of the geomagnetic field in Egypt for the last 6000 years. This curve shows a maximum of 72.8 μT at about 250 AD and a minimum of 33 μT at about 3500 BC. It also shows a general decrease of the magnetic moment during the last 2000 years.

1. Introduction

Egypt, with its long and well-documented history, provides well-dated archeological materials suitable for paleointensity studies. Previous paleointensity studies in Egypt were carried out by Athavale (1969), Games (1980), Hussain (1983, 1987), Aitken *et al.* (1984), Walton (1986), Odah (1993), and Odah *et al.* (1995). Odah et al. (1995) have constructed a preliminary secular variation curve for the geomagnetic field in Egypt for the time between 4000 BC and 2000 AD. This curve contains only 13 ages and needs more measurements to be more acceptable. The results in this curve are based on applying the classic Thellier's (1959) double heating method with a certain modification to obtain reliable paleointensity data. The modification during the Thellier experiments is that the laboratory field is applied in the direction of the stable NRM (e.g., Rogers *et al.*, 1979; Odah *et al.*, 1995).

Several field trips have been carried out accompanying the archeologists and ceramists to a) West of Khofo and south east of Sphenix, Pyramids, Giza; b) Saqara, Giza; c) Fag El Gamous, Fayoum; d) Ahnasia, Benisuef; e) Beni Hasan, El Minia; f) Tona El Gabel, Malawy; g) Tell Al Amarana, Malawy; h) Atrebis, Sohag; and i) Abydos, Sohag. Only the homogeneously fired thick ceramic sherds were collected. Thin ceramics were avoided since they have anisotropy of magnetic susceptibility (Rogers *et al.*, 1979). The ages of our samples were determined with a great accuracy by the Egyptian archeologists and the archeological foreign missions that excavate in the sites. The archeological sites, from which the samples were collected, have been thoroughly studied by many egyptologists and ceramicists (e.g., Boak, 1933; Bresciani, 1968; O'Connor, 1997 and others). 115 specimens out of 41 samples from 9 archeological sites (representing 14 well-dated ages) were collected. The sites are shown in Fig. 1 and listed in Table 1.

2. Rock Magnetic Measurements

For paleomagnetic and archeomagnetic studies, identification of the magnetic mineralogy of the samples helps to evaluate the intensity results. Two experiments have been undertaken to investigate the magnetic mineralogy of the ceramic samples. Thermomagnetic curves and hysteresis loops were measured on one sample from each site. The magnetic mineralogy of these ceramic samples is dominated by magnetite-type minerals.

In each sample, the magnetic mineral has a unique Curie temperature, so that the determination of this temperature is diagnostic of a specific kind of magnetic mineral. The thermomagnetic behaviour of the samples was investigated by measuring the magnetization of crushed sample in a strong field (about 0.7 Tesla) during thermal cycling from room temperature to 700°C and cooling back to room temperature. The Curie temperatures for these samples ranged from 570°C to 580°C which is typical of magnetite. The thermomagnetic curves do not show any chemical alterations during heating and both heating and cooling curves are very similar. This clearly shows that magnetite is stable up to high temperatures. Figure 2(a) shows the thermomagnetic curve of sample S7 from Saqara, Giza with Curie temperature of about 580°C indicating the presence of magnetite.

Room temperature hysteresis loops were measured using a vibrating sample magnetometer (VSM). All hysteresis loops indicate the presence of either a low coercivity phase ("magnetite-like" phase) reaching saturation in fields

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Table 1. Paleointensity measurements of the ceramic samples.

Age	Site	Sample	$F_{specimen}$ (μT)			F_{sample} (μT)	N	F_{site} (μT)	F_{red} (μT)
2750 BC	Saqara, Giza	S1	51.3	51.1	51.5	51.3	9	51.5 ±	50.2 ±
± 150	29.9°N, 31.2°E	S2	51.9	51.9	51.6	51.8		0.26	0.26
		S3	51.4	51.4	51.4	51.4			
2650 BC	S. E. Sphenix,	Sph1	—	—	—	—	9	No	No
± 100	Pyramids, Giza	Sph2	—	—	—	—		results	results
	29.5°N, 31.1°E	Sph3	—	—	—	—			
2625 BC	Abydos, Sohag	Ab1	50.8	49.1	50.1	50.0	6	50.0 ±	51.2 ±
± 60.5	26.2°N, 31.9°E	Ab2	50.0	50.0	50.1	50.0		0.0	0.0
2500 BC	Fag El Gamous,	F1	45.2	—	46.2	46.2	7	46.0 ±	45.2 ±
± 100	Fayoum	F2	46.3	—	46.0	46.1		0.26	0.26
	29.4°N, 31.0°E	F3	45.7	45.9	45.5	45.7			
2295 BC	West of Khofo	Kh1	54.0	52.0	53.0	53.0	9	52.2 ±	51.2 ±
± 15	Pyramids, Giza	Kh2	50.9	50.7	52.2	51.4		0.8	0.8
	29.5°N, 31.1°E	Kh3	52.2	52.4	52.3	52.2			
2240 BC	Saqara, Giza	S4	53.5	54.0	54.1	54.0	8	53.7 ±	52.4 ±
± 50	29.9°N, 31.2°E	S5	53.1	53.2	53.2	53.2		0.44	0.44
		S6	53.7	—	54.0	53.9			
1958 BC	Abydos, Sohag	Ab3	40.9	41.3	42.5	41.6	7	41.6 ±	42.6 ±
± 172	26.2°N, 31.9°E	Ab4	41.5	41.3	41.8	41.5		0.06	0.06
		Ab5	—	41.55	—	41.6			
1365 BC	Tell Al Amarana,	Am1	66.0	67.0	65.7	66.2	9	67.5 ±	67.9 ±
± 50	Malawy	Am2	68.5	68.0	68.6	68.4		1.14	1.14
	27.6°N, 30.9°E	Am3	67.8	67.8	67.9	67.8			
595 BC	Saqara, Giza	S7	51.3	51.3	51.9	51.5	8	52.0 ±	50.7 ±
± 50	29.9°N, 31.2°E	S8	51.9	54.0	53.2	53.0		0.84	0.84
		S9	51.6	—	51.6	51.6			
250 BC	Beni Hasan,	Bn1	69.3	69.1	68.6	69.0	9	68.4 ±	68.5 ±
± 25	El Minia	Bn2	68.8	68.0	67.8	68.2		0.49	0.49
	27.9°N, 30.9°E	Bn3	68.2	67.8	68.2	68.1			
250 AD	Tona El Gabel,	To1	72.0	72.3	71.7	72.0	9	72.1 ±	72.3 ±
± 50	Malawy	To2	71.9	71.9	72.2	72.0		0.17	0.17
	27.8°N, 30.7°E	To3	72.3	72.6	72.0	72.3			
550 AD	Ahnasia, Benisuef	Ah1	—	57.9	—	57.9	7	57.7 ±	56.9 ±
± 25	29.1°N, 30.9°E	Ah2	57.9	57.5	57.4	57.6		0.15	0.15
		Ah3	57.3	57.9	57.9	57.7			
750 AD	Atrebis, Sohag	At1	61.6	61.0	61.0	61.2	9	61.0 ±	62.2 ±
± 25	26.5°N, 31.7°E	At2	61.0	61.1	61.5	61.2		0.35	0.35
		At3	60.8	60.7	60.3	60.6			
950 AD	Atrebis, Sohag	At4	52.5	52.5	53.0	52.7	9	53.0 ±	54.1 ±
± 50	26.5°N, 31.7°E	At5	53.4	53.4	53.3	53.4		0.35	0.35
		At6	53.0	52.7	53.3	53.0			

Where $F_{specimen}$ is the paleointensity measurement for each specimen, F_{sample} is the mean paleointensity for 1–3 specimens, N is the number of specimens in the site, F_{site} is the site mean paleointensity from 2–3 samples and $F_{red.}$ is the reduced site mean to the middle altitude of Egypt (28°N).
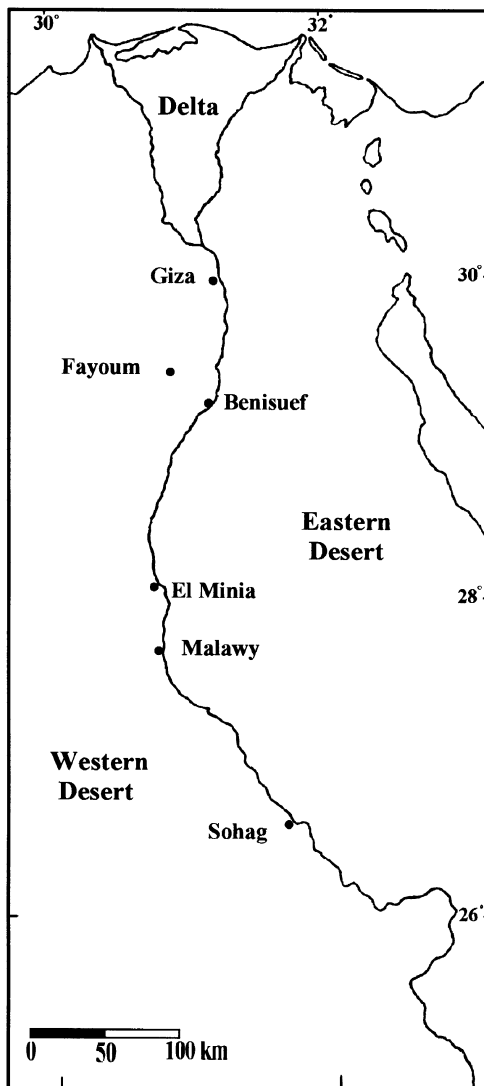
Fig. 1.   Location map of the studied archeological areas.

Fig. 2.   Rock-magnetic measurements of sample S7 from Saqara, Giza:
(a) Thermomagnetic curve with Curie temperature of about 580°C (mag-
netite) (b) Hysteresis loop shows the presence of low coercive phase ("mag-
netite-like" phase).

of about 150–200 mT or the presence of high coercivity phase
(hematite or geothite) reaching saturation in fields of about
500–700 mT and/or a paramagnetic phase. The hysteresis
rock magnetic characteristics such as the saturation rema-
nence M_{rs} ranges from 0.02 to 1.7 Am^2/kg, the ratio M_{rs}/M_s
ranges from 0.1 to 0.4, and the coercive force H_c ranges from
7 to 12 mT. This can be interpreted as a mixture of single do-
main (SD) and multidomain (MD) grains. Figure 2(b) shows
a hystersis loop of sample S7 from Saqara, Giza. This loop
indicates the presence of a low coercive phase ("magnetite-
like" phase) reaching saturation in a field about 300 mT. The
mean hysteresis parameters of this loop are: M_{rs} of 0.21,
M_{rs}/M_s of 0.34 and H_c of 11.7 mT.

3.   Paleointensity Measurements

All samples were prepared in the same way as in Odah *et
al.* (1995) so that the cylinder axes of the specimens were ori-
ented parallel to the direction of the stable NRM and therefore
parallel to $F_{Lab.}$. This method together with the modification
was used for the paleointensity determinations in this study.
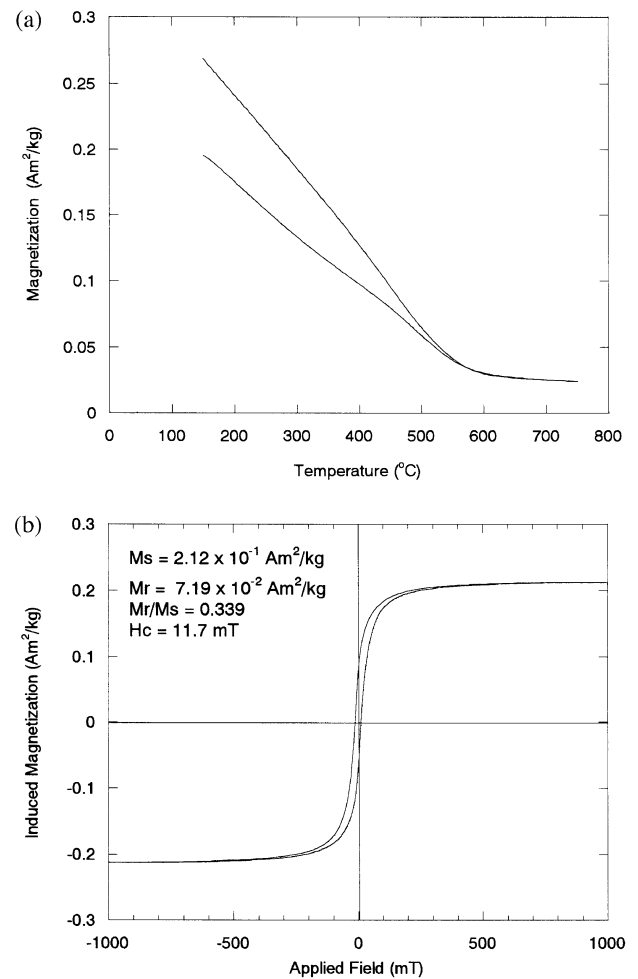115 specimens from 41 samples representing 14 well-dated

ages were measured. The $F_{Lab.}$ during Thellier experiments
was constant for all samples and equal to 50 μT.

In the case of the archeological materials, a common prob-
lem is the effect of weathering causing chemical changes.
The Arai diagrams of most samples show a linear relation-
ship over a large part of the entire temperature range. This
means that there is no chemical alterations in our samples.
Figures 3(a) and (b) show two Arai diagrams of NRM ver-
sus pTRM for samples Ab1-1 from Abydos, Sohag and S4-1
from Saqara, Giza. No cooling rate correction was applied to
the data. The results of the paleointensity of the specimens,
mean for sample, and mean for site from this work are listed
in Table 1.

4.   Secular Variation Curve of the Geomagnetic Field in Egypt

The behaviour of the earth's magnetic field through the
archeological ages can be represented in the form of secu-
lar variation curve. Figure 4 represents a plot of the secular
variation curve of the geomagnetic field through the archeo-
logical ages in Egypt for the time between 2750 BC ± 150
and 950 AD ± 50 based only on the determinations of the
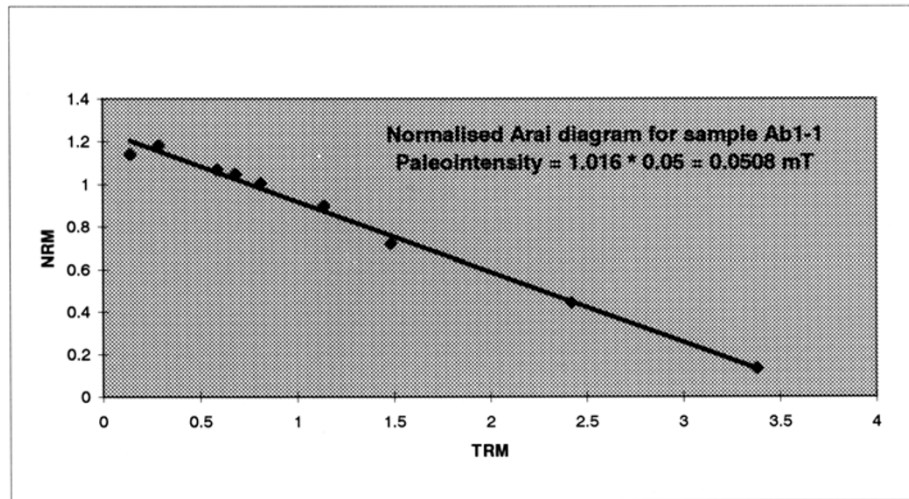
(a)
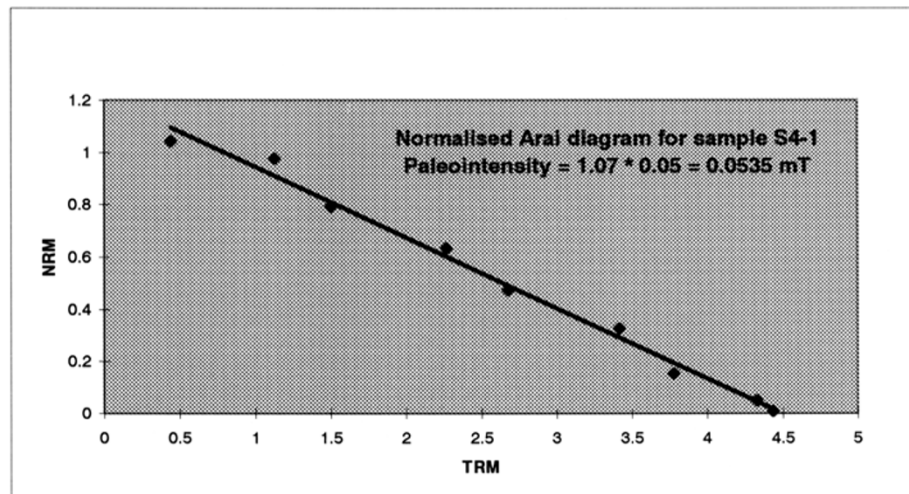
(b)

Fig. 3. Normalized Arai diagram for two sample: (a) sample Ab1-1 from Abydos, Sohag. (b) sample S4-1 from Saqara, Giza.
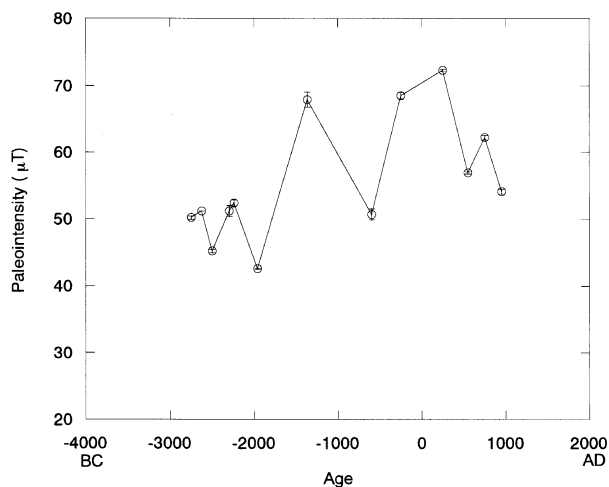

Fig. 4. Secular variation curve of the geomagnetic field in Egypt during the last 6000 years based only on the results of this study. The data are reduced to the middle latitude of Egypt.

paleointensity from this study. The mean value of the ancient geomagnetic field for each site is reduced to the middle geographic latitude of Egypt (28°N) according to the virtual axial dipole equation (Creer *et al.*, 1983). The reduced mean value for each site $F_{red.}$ is plotted versus age starting with an intensity of 50.2 μT at 2750 BC $\pm$ 150 and ending with a 54.1 μT at 950 AD $\pm$ 50. The curve shows a minimum value of a 42.6 μT at about 1958 BC $\pm$ 172 and the maximum values 67.9 μT at 1365 BC $\pm$ 50 and of 68.5 and 72.3 μT between 250 BC $\pm$ 25 and 250 AD $\pm$ 50.

5.   Discussion and Conclusions

Odah *et al.* (1995) carried out some rock magnetic and microscopic studies for the archeological ceramic samples from Egypt. These studies indicated that the main magnetic carrier is single to pseudo-single domain magnetite. The ceramic collection in this study has thermomagnetic curves and hysteresis loops (Figs. 2(a) and (b)) similar to that in Odah *et al.* (1995). This may indicates that magnetite is the main magnetic carrier in the archeological ceramics in Egypt.
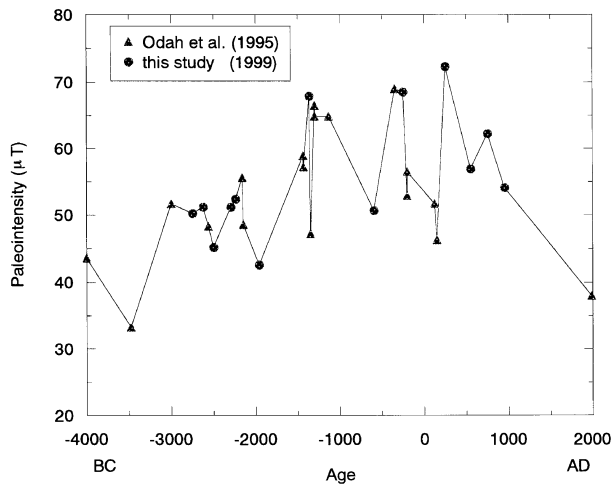
Fig. 5. Secular variation curve of the geomagnetic field in Egypt during the last 6000 years based on the results of this study together with the results of Odah *et al.* (1995). The data are reduced to the middle latitude of Egypt.

This result is typical for the baked earth that is usually used in Egyptian ceramics. The fine grains in the baked earth are usually totally oxidized during the manufacturing of the ceramics. No chemical alterations are thus expected during the Thellier double heating experiments. Thellier (1977) suggested that backed earth is the most suitable material for paleointensity determinations using the Thellier method.

The classic Thellier experiment (1959) with the modification of Odah *et al.* (1995) was used for paleointensity determinations. The external field was applied in the direction of the stable NRM. This cancels the effect of the magnetic anisotropy in the ceramic materials (Hussain, 1987; Odah *et al.*, 1995). The paleointensity results from this study were plotted against age to show the secular variation of the geomagnetic field in Egypt during this period (Fig. 4). Figure 5 shows the secular variation curve of the geomagnetic field in Egypt for the last 6000 years based on the paleointensity determinations from the two studies (present study and Odah *et al.*, 1995) after reduction to the middle latitude of Egypt. This curve starts with a field intensity of 43.6 μT at 4000 BC and ends with a field of 38 μT at 1990 AD. This curve has minimum field intensity values of 33.3 μT at about 3476 BC, of 42.6 μT at 1958 BC $\pm$ 172 and of 38 μT at 1990 AD. The maximum field values are represented at about 1350 BC $\pm$ 50

(67.9 μT), 250 BC $\pm$ 25 (68.5 μT) and 250 AD $\pm$ 50 (72.3 μT). This curve is suitable for archeomagnetic chronology because the $F_{\text{Lab.}}$ is parallel to the stable NRM and due to the accuracy of dating of the archeological ceramics. The results demonstrate the necessity of using such well-dated materials in paleointensity studies of the geomagnetic field to fill the gaps in this curve where more data are needed to define the curve more precisely.

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