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GEOMAGNETIC INTENSITY IN UPPER EGYPT BETWEEN 2900 BC AND 800 AD

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ABSTRACT

The intensity of the geomagnetic field in Upper Egypt in the period between 2900 BC and 800 AD has been measured using Thelliers' method. Thirty four ceramic samples were collected from Elephantine excavations in Aswan and Ramesseum, Karnak, and Habu city in Luxor. The collection represents 20 well-dated ages, which have been determined with great accuracy by the well-documented Egyptian history and the archaeological foreign missions that excavate in the investigated sites. Rock magnetic measurements indicated that the magnetic carrier is magnetite. The present paleointensity results are consistent with the previous paleointensities from Egypt and are added to the secular variation curve of the geomagnetic field in Egypt for the last 6000 years (Odah. 1999). This curve shows a general increase in the intensity between 4000 BC and 500 BC, followed by a decrease continuing to the present.

INTRODUCTION

Since the study of the Thellier and Thellier (1959), great advances in the production of large data sets of the ancient geomagnetic field intensity have been curried out, with the accelerating pace especially during the last 20 years. Nevertheless, the amount of the intensity data is still insufficient compared with the directional data.

The River Nile valley is one of the birthplaces of the Egyptian culture. There are lots of human relics, tombs, kilns, graves in this valley especially in Upper Egypt (Luxor and Aswan). The long history of Egypt, from the Pre-historic through Pharaonic, Greco-Roman, and Islamic, provides well dated archeological materials that are suitable for archaeomagnetic and paleomagnetic studies. These materials include backed earth, ceramics and bricks. Paleointensity determinations were first measured in Egypt by Athavale (1969). Since the early 1980s, subsequent determinations were carried out by Games (1980), Hussain (1983, 1987), Aitken et al. (1984), Walton (1986), Odah (1993), Odah et al. (1995), and Odah (1999). 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. Odah (1999) has improved this secular variation curve by adding data for 13 different ages. The results in the improved secular variation curve (Odah, 1999) which included the results of Odah et al. (1995) are based on applying the results obtained by the classic Thellier's (1959) double heating method with the laboratory field applied in the direction of the stable NRM (e.g. Rogers et al. 1979; Odah et al. 1995). In the present study, 22 ceramic samples from Elephantine in Aswan and 12 ceramic samples from Ramesseum, Karnak and Habu city in Luxor were collected. The collection of the ceramics was done in cooperation with archeologists and ceramists. Only homogeneously baked thick ceramic sherds were collected similar to those used by Rogers et al. (1979). The accuracy of dating of the archeological samples is one of the critical problems in archeomagnetic studies. The ages of the collected samples in this study were determined with a high accuracy by the archeological foreign missions that excavated in the collected-samples sites from the very accurate chronology, type of manufacture of the ceramics, construction pattern at the excavated sites, from dated objects in the graves like coins and drawings and sometimes by using ^{14}C dating. The investigated archeological sites have been thoroughly studied by many Egyptologists and ceramists (e.g. Boak, 1933; Bresciani, 1968; O'Connor, 1997 and others).

Figure 1 is a location map showing the investigated archaeo-logical sites in Upper Egypt (Luxor and Aswan) and Table (1) contains the ages of the ceramics and the coordinates of the sampling sites. In the present study, cylindrical samples with diameter of 7.5 mm and an average length of 7–10 mm were used in the modified Therllier method (Coe, 1967), incorporating pTRM check.

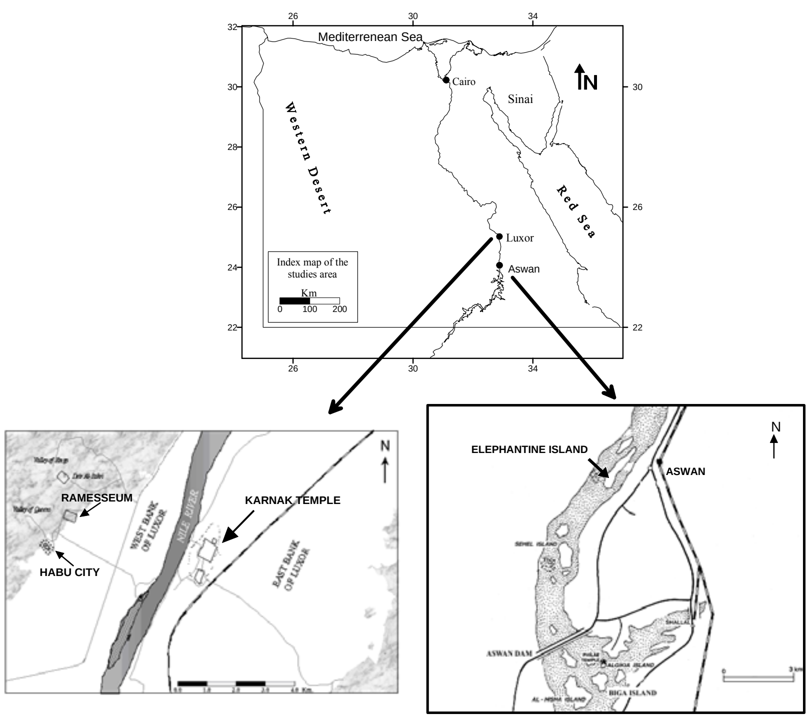


Fig. 1: A Location map showing the investigation archaeological sites in Upper Egypt (Luxor and Aswan)

Table 1: Paleointensity measurements of the ceramic samples (1 – 22) from Elephantine (24^{o} $05^{\backslash}$ N and 32^{o} $53^{\backslash}$ E), Aswan, samples (23 – 27) from Ramesseum (25^{o} $45^{\backslash}$ N and 32^{o} $36^{\backslash}$ E), samples (28 – 32) from Karnak (25^{o} $43^{\backslash}$ N and 32^{o} $40^{\backslash}$ E) and samples (33 – 34) from Habu city (25^{o} $43^{\backslash}$ N and 32^{o} $36^{\backslash}$ E), Luxor. Where $F_{specimen}$ is the paleointensity measurement for each specimen, F_{sample} is the mean paleointensity for 4-5 specimens and F_{red} is the reduced sample mean to the middle latitude of Egypt (28^{o}). All paleointensities are in μT.

No.	Age	$F_{specimens}$	F_{sample}	F_{red}	No.	Age	$F_{specimens}$	F_{sample}	F_{red}
1	2845 BC ± 75	38.7 39.0 38.5 38.6	38.7 ± 0.2	40.6 ± 0.2	18	465 BC ± 60	81.3 81.0 81.5 81.4	81.3 ± 0.2	85.4 ± 0.2
2	2709 BC ± 60	37.3 36.9 37.1 36.9	37.1 ± 0.2	39 ± 0.2	19	167 BC ± 165	65.0 65.4 65.1 65.4	65.2 ± 0.2	68.5 ± 0.2
3	2621 BC ± 40	52.1 52.5 52.1 52.5	52.3 ± 0.2	54.9 ± 0.2	20	500 AD ± 50	54.6 54.0 54.1 54 6	54.3 ± 0.3	57 ± 0.3
4	2520 BC ± 55	46.5 46.0 46.1 46.2	46.2 ± 0.2	48.5 ± 0.2	21	725 AD ± 50	66.6 66.4 66.7 66.5 66.6	66.6 ± 0.2	70 ± 0.2
5	2394 BC ± 70	48.2 48.3 48.2 48.1	48.2 ± 0.1	50.6 ± 0.1	22	800 AD ± 50	65.8 65.9 65.3 65.8	65.7 ± 0.3	69 ± 0.3
6	2237 BC ± 90	49.0 49.3 49.1 49.3 49.2	49.2 ± 0.2	51.7 ± 0.2	23	1373 BC ± 25	58.9 58.3 58.6 58.2	58.5 ± 0.3	60.5 ± 0.3
7	2087 BC ± 50	53.0 53.5 53.4 53.0	53.2 ± 0.3	55.9 ± 0.3	24	1456 BC ± 40	61.5 61.0 61.1 61.6	61.3 ± 0.3	63.4 ± 0.3
8	1939 BC ± 100	-	-	-	25	1257 BC ± 35	61.0 60.8 60.5 60.4	60.7 ± 0.3	62.8 ± 0.3
9	1749 BC ± 35	39.4 39.0 39.1 38.9	39.1 ± 0.2	41.1 ± 0.2	26	904 BC ± 25	-	-	-
10	1595 BC ± 45	55.3 55.1 55.2 55.4	55.3 ± 0.1	58 ± 0.1	27	725 AD ± 50	65.3 65.0 65.3 65.2	65.2 ± 0.2	67.5 ± 0.2
11	1456 BC ± 120	60.6 60.3 60.2 60.4 60.5	60.4 ± 0.2	63.4 ± 0.2	28	1939 BC ± 105	-	-	-
12	1133 BC ± 65	61.3 61.5 61.1 61.3	61.3 ± 0.2	63.3 ± 0.2	29	1133 BC ± 65	60.9 61.0 61.5 61.4 61.2	61.2 ± 0.3	63.3 ± 0.3
13	860 BC ± 180	66.5 66.1 66.2 66.4	66.3 ± 0.2	69.6 ± 0.2	30	505 BC ± 160	-	-	-
14	860 BC ± 120	66.6 66.9 66.3 66.7	66.6 ± 0.3	69.9 ± 0.3	31	20 AD ± 50	42.8 42.9 43.3 43.0	43.0 ± 0.2	44.5 ± 0.2
15	690 BC ± 30	-	-	-	32	1373 BC ± 175	60.4 60.2 60.8 60.2	60.4 ± 0.3	62.5 ± 0.3
16	568 BC ± 75	82.3 82.3 82.4 82.3	82.3 ± 0.1	86.5 ± 0.1	33	860 BC ± 120	66.5 66.7 67.0 66.6	66.7 ± 0.3	69.0 ± 0.3
17	568 BC ± 135	82.2 82.3 82.4 82.3	82.3 ± 0.1	86.5 ± 0.1	34	1456 BC ± 50	61.0 61.4 61.6 61.2	61.3 ± 0.3	63.4 ± 0.3

ROCK MAGNETIC MEASUREM-ENTS

A general knowledge of the magnetic properties of the samples is necessary to judge the reliability of archeomagnetic data. Rock magnetic experiments provide information about the identification of the magnetic carriers (magnetite, maghemite, hematite, goethite or iron-sulphides), the domain structures and sizes of the remanence carriers, and information about coercivities or blocking temperatures. This information contributes to our knowledge about the magnetization carried by the rock and may help to evaluate the intensity results and to assess whether the samples are suitable for Thelliers' method. Six samples from Elephantine (Aswan), 2 samples from Ramesseum, 2 from Karnak, and 1 sample from Madient Habu (Luxor) were subjected to rock magnetic measurements. Thermomagnetic curves and hysteresis loops were obtained, and the Day plot was made from hysteresis properties to estimate the domain size of the magnetic carrier. All rock magnetic measurements were carried out using a PMC MicroMag 3900 vibrating sample magnetometer (VSM) in the department of Earth and Planetary Science, University of Tokyo, Japan. The magnetic mineralogy of these samples is dominated, in terms of intensity of magnetization, by magnetite-type minerals.

Fig. (2): Thermomagnetic curve of sample 7 from Elephantine, Aswan with Curie temperature of about 590 °C (magnetite)

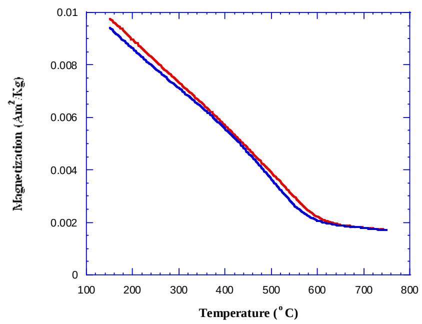
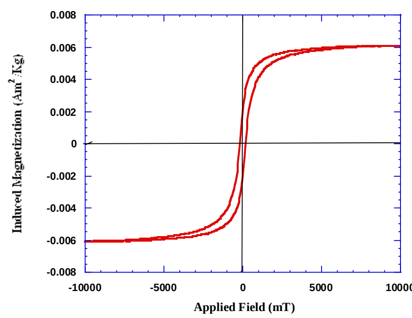


Fig. (3): Hysteresis loop of sample 29 from Karnak, Luxor shows the presense of low coercive phase ("magnetite-like" phase)

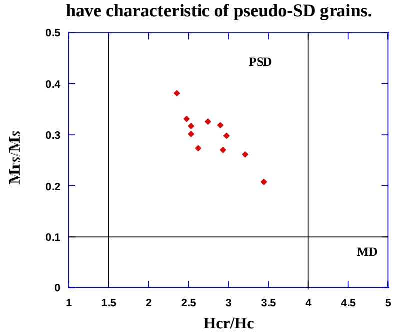


Curie point determinations are the most effective method for distinguishing between magnetic minerals where each specific composition of a magnetic mineral has a unique T_c. All the 11 samples show the thermomagnetic curve of magnetite. Figure 2 shows the thermomagnetic curve of sample 7 from Elephantine, Aswan with a Curie temperature of about 590 °C, which is typical for magnetite.

The concept of hysteresis is fundamental when describing and comparing the magnetic properties of rocks. The hysteresis loops were measured with the 11 samples under a maximum magnetizing field of 1000 mT. These hysteresis loops reveal the presence of magnetite. Figure 3 shows the hysteresis loop of sample 29 from Karnak, Luxor. It shows the presence of a low coercivity phase ("magnetite-like" phase). The mean parameters are: the saturation magnetization *Ms* is 6.1 memu, the maximum saturation remanence *Mr* is 2.1 memu, *Mr/Ms* is 0.34 and the bulk coercivity *Hc* is 17.3 mT.

In order to obtain insight into the distribution of the magnetic domain of the samples and according to the hysteresis ratios *Mr* / *Ms*, Day et al. (1976 and 1977) divided the Day plot into regions from SD (single domain, highest *Mr* / *Ms*), PSD (pseudo-single domain), to MD (multi domain, lowest *Mr* / *Ms*) behaviour and suggested that hysteresis parameters could be used to infer magnetic grain size. Figure 4 shows a plot of *Mr* / *Ms* versus *Hrc* / *Hc* of the 11 samples. The critical values of SD-PSD and PSD-MD state transition are represented by lines. One can see a clustering of the samples within the PSD grain size range indicating that the magnetic grain size of the 11 samples is small enough to be in the PSD state and these samples can be used for paleointensity experiments.

Fig. (4): Day et al. (1977) diagram shows that the samples have characteristic of pseudo-SD grains.



PALEOINTENSITY DETERMIN-ATIONS

All the paleointensity measurem-ents were carried out in the Institute for Study of the Earth's Interior, Okayama University, Japan. To determine the paleointensity of all the collected samples, the modified version of Coe (1967) of the Thellier's method (Thellier and Thellier, 1959) was used. The paleointensity determinations made by the Thellier method were based on the stepwise thermal demagnetization behaviour of the NRM, pTRM check for alteration and the linearity of the NRM-TRM plot. All of the heating treatments were undertaken in air using a Natsuhara's - Giken TDS-1 thermal demagnetizer. 116 specimens out of 34 samples (22 from Aswan and 12 from Luxor) have been measured. Double heating procedures were applied to the samples on more than 10 sequences. The applied magnetizing field was 50 µT for all samples. Susceptibility measurements at room temperature were carried out after each double heating process using a Bartington MS-2 susceptibility meter to detect any chemical alteration of the samples by heating. In addition, the pTRM (partial thermoremanent magnetization) check (Coe, 1967) was carried out about 5 times to all samples in the sequences of the double heating process. In the Arai diagram (NRM-TRM), where the remaining NRM was plotted versus the acquired TRM for each heating step, the least square fit was applied to the data points. No cooling rate correction has been applied to the results. This effect may cause paleointensities to be overestimated by up to 10% (Fox and Aitken 1980; Aitken et al., 1991). Most of the samples show a stable susceptibility during the temperature range of the experiment. The Arai diagrams of most samples show a linear relationship over a large part of the entire temperature range and a successful pTRM checks. Figures 5, 6 and 7 show three typical successful examples of Arai diagrams of NRM versus pTRM for samples 5 and 12 from Elephantine, Aswan and sample 27 from Ramesseum, Luxor. The data points of NRM in the three samples (5, 12 and 27) are not consistent to the linear fitting because they may have been disturbed by the viscous magnetization. Only 5 samples out of the 34 samples had bad results and were rejected. The results of the paleointensity of the specimens, mean of the samples, and mean of the age are listed in Table 1.

Fig. (5): Normalised Arai diagram for sample 5 from Elephantine, Aswan

Paleointensity = 50 * 0.964 = 48.2 µT

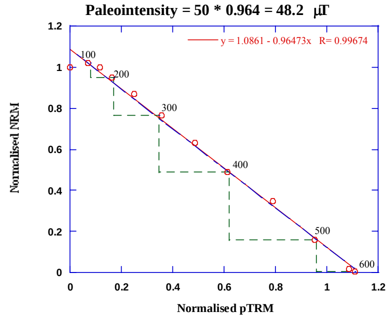


Fig. (6): Normalized Arai diagram for sample 12 from Elephantine, Aswan.

Paleointensity = 50 * 1.23 = 61.5 µT

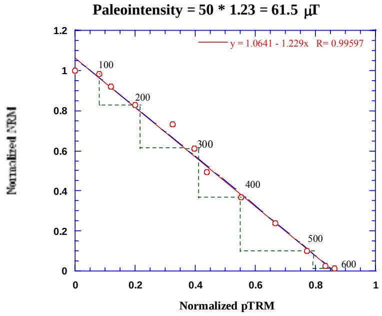
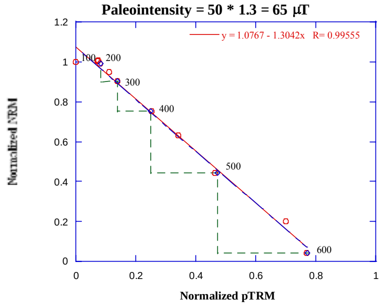


Fig. (7): Normalized Arai diagram for sample 27 from Ramesseum, Luxor.

Paleointensity = 50 * 1.3 = 65 µT



SECULAR VARIATION CURVE OF THE GEOMAGNETIC FIELD IN EGYPT

The behaviour of the Earth's magnetic field through the archaeological ages can be represented in the form of secular variation curve. The secular variation of the geomagnetic field paleointensity is an important source to understand the dynamics of the core powering the geodynamo. In this work, we tried to have the best conditions during collecting the samples (type and date) and during the laboratory measurements to determine accurate paleointensity of the geomagnetic field from archaeological materials from Egypt covering the period between 2900 BC and 800 AD. These paleointensity results were reduced to the mean latitude of Egypt (28^{o} N) according to the virtual axial dipole equation (Creer et al., 1983). The reduced paleointensities have been plotted against age to construct the secular variation curve of the geomagnetic field in Egypt covering the period between 2900 BC and 800 AD based on the determinations of the paleointensity from this study (Fig. 8). This curve starts with an intensity of 40.6 µT at 2845 ± 75 BC and ends with a 69 µT at 800 ± 50 AD. It shows four minimum paleointensity values of 39, 40.6, 41.1 and 44.5 µT at 2709 ± 60 BC, 2845 ± 75 BC, 1749 ± 35 BC and 20 ± 50 AD. It shows two maximum paleointensity values of 85.4 and 86.5 µT at 465 ± 60 BC and 568 ± 135 BC. A general trend of increasing the field intensity from 2900 BC reaching the maximum clear peak of the field strength around 500 BC and then a general trend of decreasing to 800 AD is seen.

DISCUSSION AND CONCLUSIONS

Odah et al., (1995) and Odah (1999) carried out some rock magnetic measurements and microscopic studies for the Egyptian archaeological materials (ceramics and bricks). They indicated the presence of dominant fine-grained (SD-PSD) magnetite. In this study, the thermomagnetic curves, hysteresis loops and Day plot were used to characterize the samples and gave similar results; and the curves are similar to those in the previous two studies. This may confirm that magnetite is the main magnetic mineral in the Egyptian ceramics and bricks.

**Fig. (8): Secular variation curve of the geomagnetic field in Upper Egypt based on the results of this study.
The data are reduced to the middle latitude of Egypt.**

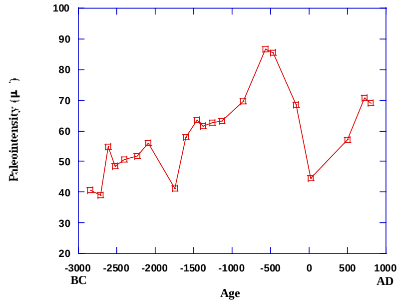
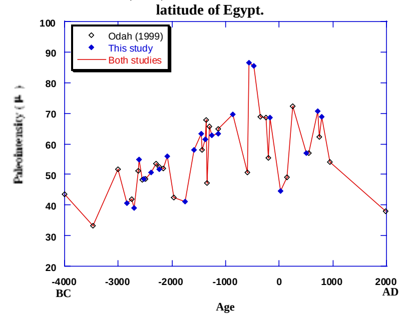


Fig. (9): Secular variation curve of the geomagnetic field in Egypt during the last 6000 years based on the results of this study and the results of Odah (1999). The data are reduced to the middle latitude of Egypt.



The Egyptian ceramics and bricks were made from baked earth. These fine grains in the ceramics and bricks were homogeneously oxidized or reduced when they were heated during manufacture. These materials were fired to a much higher temperature than the Curie temperature of magnetite and hematite and left to cool down in air resulting in a stable chemical composition. Therefore, no chemical alterations are expected during Thellier experiment. Thellier (1977) suggested that backed earth is a suitable material for paleointensity determination using the Thellier method.

In this study, the paleointensity determinations by the modified version of the Thelliers' method were applied to all samples with a laboratory field of 50 µT. To monitor the chemical alteration, pTRM checks were applied during the Thellier experiments and room temperature susceptibility was measured after each double heating process. Most of the samples show successful Arai diagrams (Figs. 5-7). The determined paleointensity results of this study are regarded as reliable and were plotted against age to provide the secular variation curve of the geomagnetic field in Egypt between 2900 BC and 800 AD (Fig. 8).

Odah (1999) has constructed a secular variation curve of the geomagnetic field in Egypt during the last 6000 years based on his study and constructed another one based on both his study and the results of Odah et al. (1995).

Figure 9 shows the secular variation of the geomagnetic field in Egypt during the last 6000 years based on the results of this study and the results of Odah (1999). This curve starts with a field intensity of 43.6 µT at 4000 BC and ends with a field intensity of 38 µT at 1990 AD. It shows a maximum clear peak of the field intensity around 500 BC and two minimum field intensity values of 33.3 and 38 µT at about 3476 BC and 1990 AD. The curve starts with low field intensity even weaker than the present value especially around 3476 BC and increasing to the maximum peak around 568 BC, followed by a general decrease continuing to the present. There are some short period fluctuations at about 800 AD, 150 BC, 550 BC and 1200 BC. There is generally good agreement between observations of Odah (1999) and those obtained from the present study, with the general increase from 4000 BC up to about 568 BC and then a general decrease to the present, but with a high peak around 568 BC which was well determined from the present study.

The results of the present study provide some new data of the ancient geomagnetic field intensity of Upper Egypt for the period between 2900 BC and 800 AD. These data agree well with those previously obtained by Odah et al., (1995) and Odah (1999). The results demonstrate the need of using such well-dated materials to fill the gaps in this curve where more data are needed to define the curve more precisely, especially the short period fluctuations to confirm either they are real features of the geomagnetic field or just results of error in age assignments, and to be suitable for archaeomagnetic chronology.

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REFERENCES

Aitken, M. J., Allsop, A. L., Bussell, G. D. and Winter, M. B. (1984): "eomagnetic intensity in Egypt and Western Asia during the second millennium BC.", Nature, vol. 310, pp. 305-306.

Aitken, M. J., Pesonen, L. J. and Leino, M. (1991): "The Thellier palaeointensity techniques: minisamples versus standard size", J. Geomag. Geoelect., vol. 43, pp. 325-331.

Athavale, R. N. (1969): "Intensity of the geomagnetic field in prehistoric Egypt", Earth Planet. Sci. Lett., vol. 6, pp. 221-224.

Boak, A. E. R. (1933): "The temples, coin hoards, botanical and zoological reports, seasons 1924-1931", Univ. Michigan Press.

Bresciani, E. (1968): "Messione die scavo medint Madi, Rapporto preliminiare della campagne di scavo 1966 e 1967".

Coe, R. S. (1967): "Paleo-intensities of the Earth's magnetic field determined from tertiary and quaternary rocks", J. Geophys. Res., vol. 72, pp.3247-3262.

Creer, K. M., Tucholka, P. and Barton, C. E. (1983): "Geomagnetism of Baked Clays and Recent Sediments, Elsevier, Amsterdam, 324 p.

Day, R., Fuller, M. and Schmidt, V. A. (1976): "Magnetic hysteresis properties of synthetic titanomagnetite", J. Geophys. Res., vol. 81, pp. 873-880.

Day, R., Fuller, M. and Schmidt, V. A. (1977): "Hysteresis properties of titanomagnetite: grain size and composition dependence", Phys. Earth Planet. Inter., vol. 13, pp. 260-267.

Fox, J. M. W, and Aitken, M. J. (1980): "Cooling-rate dependence of thermoremanent magnetization", Nature, vol. 283, pp. 462-463.

Games, K. P. (1980): "The magnitude of the archeomagnetic field in Egypt between 3000 and 0 BC.", Geophys. J. R. astr. Soc., vol. 63, pp. 45-56.

Hussain, A. G. (1983): "Archeological investigation in Egypt: Inclination and field intensity determination", J. Geophys., vol. 53, pp. 131-140.

Hussain, A. G. (1987): "The secular variation of the geomagnetic field in Egypt in the last 5000 years", Pageoph., vol. 125, pp. 67-90.

O'Connor, D. (1997): "The Early Dynastic Project: Report on Abydos", New York University.

Odah, H. (1993): "Archaeomagnetic studies in some localities in A. R. Egypt", Ph.D. thesis. Fac. of Sci. Mansoura University, Egypt.

Odah, H. (1999): "Improvement of the secular variation curve of the geomagnetic field in Egypt during the last 6000 years. Earth Planets Space", vol. 51, pp. 1325-1329.

Odah, H., Heider, F., Hussain, A. G., Hoffmann, V., Soffel, H. and ElGamili, M. (1995): "Paleointensity of the geomagnetic field in Egypt from 4000 BC to 150 AD using the Thellier method", J. Geomag. Geoelectr., vol. 47, pp. 41-58.

Rogers, J., Fox, J. M. W. and Aitken, M. J. (1979): "Magnetic anisotropy in ancient pottery", Nature, vol. 227, pp. 644-655.

Thellier, E. (1977): "Early research on the intensity of the ancient geomagnetic field", Phys. Earth Planet. Inter., vol. 13, pp. 241-244.

Thellier, E. and Thellier, O. (1959): "Sur l'intensite' du champ magne'tique terrestre, en France, a l'epoque gallo-romaine. Compt. Rend., vol. 222, pp. 905-907.

Walton, D. (1986): "Alteration and its effects on the reproducibility of archaeomagnitudes from Tel-El-Amarana", J. Geomag. Geoelectr., vol. 38, pp. 1349-1352.