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Archaeointensity results from two ceramic kilns from N. Greece

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Abstract: *Fired structures are abundant in Northern Greece and can be used for accurate estimations of the Earth's ancient magnetic field components. Two kilns belonging to the Classic-Hellenistic period have been sampled in Amphipolis and archaeointensity measurements have been performed on a set of 12 samples. Together with detailed rock magnetic studies, three reliable archaeointensity values (one from each kiln and one from a brick) have been obtained, in good correlation with the Bulgarian reference archaeomagnetic curve.*

Key Words: *Archaeomagnetism**,** Magnetic Properties, Kiln.*

INTRODUCTION

Knowledge of the Earth's ancient magnetic vector obtained from fired structures is very important. Firstly, to help theoreticians in order to refine their models of the dynamo in the earth's outer core which is thought to be responsible for the generation of the main field (Veitch *et al*., 1984). Secondly, for archaeomagnetic dating.

The archaeomagnetic studies can reveal the past geomagnetic field variations on the basis of remanent magnetization carried by archaeologically dated objects of baked clay (Aitken, 1983). The geomagnetic field vector is described by 3 elements: the angles of magnetic inclination (I) and declination (D) determining the direction of the ancient field, and its intensity (F) usually represented as a ratio between the ancient value F^A and the value F^D (for the site's latitude) of the present day axial dipole's strength. If the curves of the secular variation of the geomagnetic field elements are well established for a given territory they can be used as an archaeomagnetic scale of time for dating purposes (Creer *et al*, 1983).

The present study is a first step to the investigation of the geomagnetic field intensity during the Classic - Hellenistic period in Greece**.**

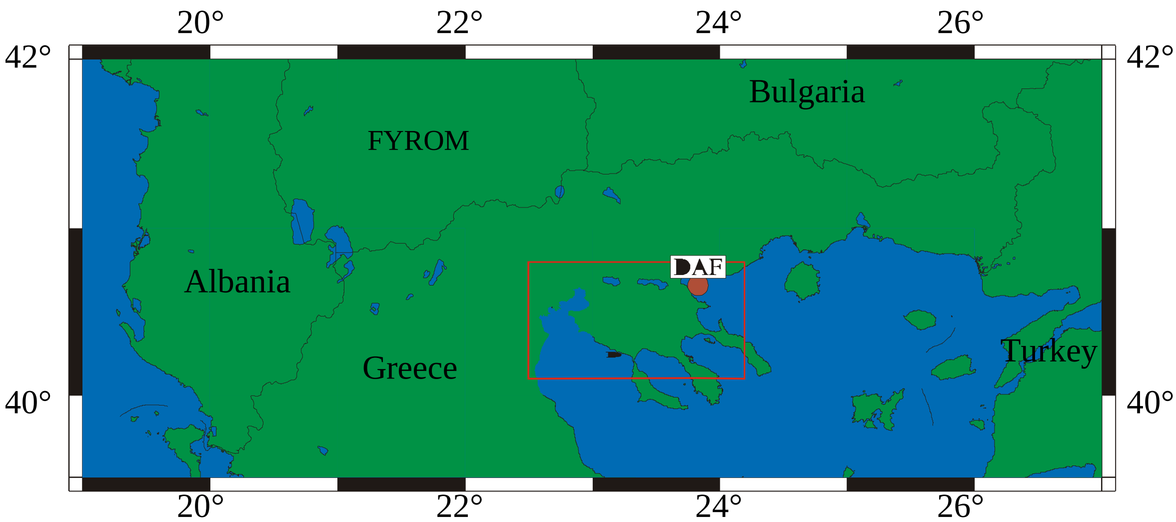

FIG. 1. Map of archaeological site Amfipoli.

SAMPLING

We visited the site of Amfipolis (N.Greece, Fig.1) in 1997. Excavations of the early seventies had revealed the existence of two ceramic kilns, one near the "North Wall" and the other near the "Gymnasium". The ages attributed by archaeologists excavating the site were ranging between 500 BC and 100 AD.

a) North Wall: the kiln is in contact with the wall and has a shape of an irregular trapeze, with maximum dimension of 4.35 m. On the floor, which is partly destroyed, traces of intense firing are observed. 12 non-oriented hand samples have been used for the intensity study. At the same time 12 hand samples were retrieved by means of a modified 'disk' method (Tarling, 1983). This technique consists of bonding 2 x 2 cm plastic squares on suitable parts of the structure, the orientation being achieved by solar bearings and a bubble-inclinometer. The specimen is then labeled and broken off. This method yields irregularly shaped specimens with a typical mass of 20 grams that are given the form of 2.5x2.5 cm cylinders (Evans and Kondopoulou, 1998).

b) Gymnasium (Fig. 2): only non-oriented samples (6) were collected because of the bad condition of the kiln. Due to this bad condition the kiln had been excavated later than the previous one. Care was given in order to sample only the undisturbed part of the kiln.

FIG. 2. Archaeological kiln.

MEASUREMENTS

Standard palaeomagnetic and rock magnetic investigations were carried out to characterize changes in the mineralogy of remanence-carrying minerals and to determine concentration and grain size variations of these minerals.

Remanent magnetization was measured with an astatic magnetometer, a JR-4 magnetometer and a MINISPIN magnetometer. Alternating field demagnetization was done on a MOLSPIN-MSA2 AF-demagnetizer. The magnetic susceptibility was measured using a KLY-2 susceptibility meter (sensitivity of 4 x 10^{-6} SI). Frequency-dependent magnetic susceptibility (χ_{FD} %) was calculated from measurements of bulk susceptibility using a Bartington MS2 susceptibility meter at low (0.47 kHz) and high (4.7 kHz) frequencies. Thermal demagnetization of saturation remanence (SIRM) in a field-free space was carried out on 1 cm^3 cubic samples using a non-standard spinner thermomagnetometer with continuous registration (Burakov, 1977). The thermomagnetic analysis (TMA) has been used to identify the ferromagnetic minerals present. Some specimens were given an isothermal remanent magnetization (IRM) with a pulse magnet and a maximum field of 2.5 T. The results of the AF demagnetization of the NRM and SIRM were used to perform the Lowrie-Fuller test for determining the domain state.

MAGNETIC ANISOTROPY

The AMS of minerals consists of two components: the magnetocrystalline anisotropy and the shape anisotropy (Halgedahl, 1989; Merrill, 1989; O'Reilly 1989).

The magnetic susceptibility, K, is defined by the ratio between the induced magnetization of the material and the inducing magnetic field. The anisotropy of magnetic susceptibility is represented by a symmetric second-rank tensor with K_1, K_2 and K_3 as its principal axes ($K_1>K_2>K_3$). The bulk magnetic susceptibility, K, is the arithmetic mean of the principal susceptibilities [$K_m = (K_1 + K_2 + K_3) / 3$]. The total anisotropy, P, is given by $P\% = 100 \times [(K_1/K_3) - 1]$ and the linear and planar anisotropy components are respectively given by $L\% = 100 \times [(K_1/K_2) - 1]$ and $F\% = 100 \times [(K_2/K_3) - 1]$. The ellipsoid shape is represented by the parameter $T = 2 \times (\ln K_2 - \ln K_3) / (\ln K_1 - \ln K_3) - 1$ (Jelinek, 1983). The shape parameter T varies from +1 for a perfect oblate ellipsoid to –1 for a perfect prolate ellipsoid.

ARCHAEOINTENSITY METHOD

The experiments for the intensity evaluation were performed in the Palaeomagnetic Laboratory of the Geophysical Institute in Sofia (Bulgaria).

The ancient geomagnetic field elements were determined by the Thellier double successive heating method (Thellier and Thellier, 1959). 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.

The estimation of the ancient intensity F^A is determined from the relationship: $F^A = b.F^{LAB}$ and is thus dependent on the slope (b) of the line formed by plotting experimentally obtained decreasing values of NRM against increasing values of laboratory induced TRM (Kovacheva and Toshkov, 1994).

12 samples were studied for palaeointensity. Among these 9 gave successful results according to the stringent acceptance criteria (Kovacheva and Kanarchev, 1986; Kovacheva and Toshkov, 1994). These criteria include the following requirements: 1) the stability of the NRM direction; 2) not less than 6 experimental points on the Area diagram used for determination of the ancient palaeointensity value; 3) pTRM checks showing less than 10% changes in TRM capacity; 4) less than 10% changes in the room temperature volume magnetic susceptibility K into the temperature interval used for obtaining palaeointensity value.

The paleofield value was derived from the slope on the ARAI diagram. The appropriate range of temperatures was selected by considering the linearity of the Arai diagram (Nagata *et al.*, 1963).

RESULTS

Anisotropy of magnetic susceptibility is potentially a large source of error in archaeointensity measurements. The degree of anisotropy P' is less than 1.06 (that is 6%) for our samples. The parameter - χ_{FD} % - is used for the concentration of superparamagnetic (SP) grains. (Maher, 1988). In Table 1, all obtained K, P' χ_{FD} % values for the studied samples are listed.

Table 1. Results for magnetic susceptibility (K), degree of anisotropy (P') and parameter χ_{FD} %

No sample	K(x 10^{-5} SI)	P'	χ_{FD} %
AMF 1a	440.54	1.031	4.47
AMF 1b	512.55	1.030	4.54
AMF 1c	367.53	1.030	4.23
AMF 2a	567.68	1.042	11.27
AMF 2b	764.36	1.043	12.38
AMF 2c	566.69	1.048	11.34
AMF 3a	967.49	1.044	10.11
AMF 3b	924.28	1.050	8.24
AMF 3c	1335.52	1.059	11
AMF 4a	984.38	1.038	12.9
AMF 4b	433.09	1.044	13.81
AMF 5a	998.29	1.031	5.03
AMF 6a	1295.29	1.057	10.33
AMF 6b	611.88	1.057	11.21
AMF 7a	995.8	1.022	4.46
AMF 8a	2364.1	1.010	9.94
AMF 8b	1742.78	1.062	13.41
AMF 8c	1799.4	1.063	12.98

The acquisition curves of isothermal remanent magnetization (IRM) of 3 specimens (AMF 1c, AMF 3b, AMF 4a) are shown in Fig 3. All specimens are characterized by soft magnetic minerals that saturate in a field of about ~ 250 μT (for magnetite this field is typically 200-300 μT).

Table 2. Magnetic properties of the studied archaeomagnetic samples.

No sample	MDF (μT)	Thermomagnetic analysis (T_B)	L-F test
AMF 1c	12	575	SD
AMF 2c	15	560	BM
AMF 3b	17		
AMF 4a	22		BM
AMF 6b	24	570	MD
AMF 8c	17	570	

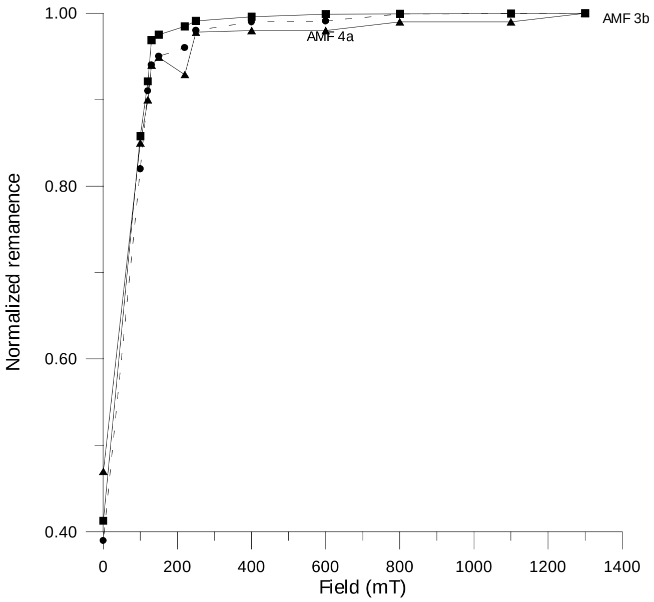

FIG. 3. Acquisition curves of isothermal remanent magnetization (IRM).

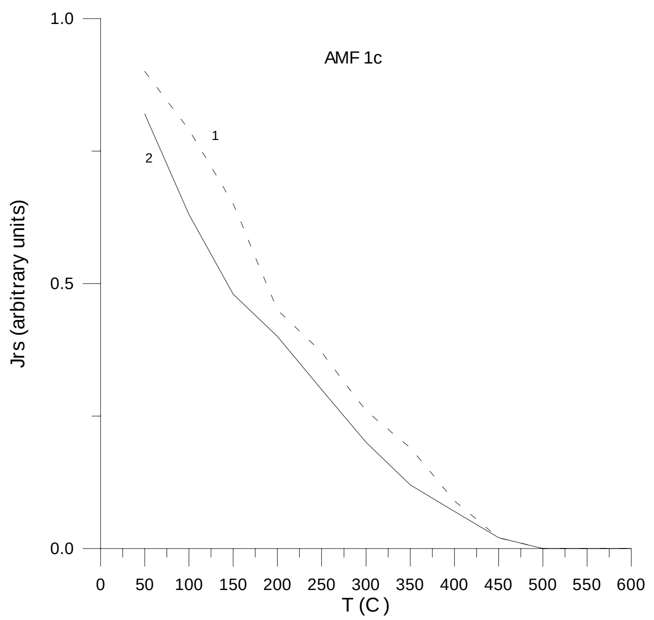

FIG. 4. Thermomagnetic analysis of sample AMF 1b

Six pilot specimens were demagnetized by alternating field up to 100 μT. The curve of demagnetization shows that the main carrier of remanence is magnetically soft. The coercivity spectrum from 10 to 40 μT is usually connected with titanomagnetites.

Four specimens were submitted to thermomagnetic analysis of the remanent magnetization of saturation. The specimens were saturated twice up to 2 T and the two corresponding curves of demagnetization with the subsequently augmented temperature were registered. For specimens AMF 1c, AMF 2c, AMF 6b, AMF 8c unblocking temperatures of ~500° C are displayed which indicates the presence of (titano)magnetite (Fig. 4 -AMF 1c).

The mineral magnetic properties of these samples are summarized in Table 2. The results of Lowrie-Fuller test (Lowrie and Fuller, 1971) (3rd column) suggest in 2 cases (AMF 2c, AMF 4a) grains of bimodal type (BM). In the specimen AMF 1c the grains are of single domain type (SD) and for AMF 6b of multidomain type (MD).

In Table 3, we report the results for all the samples, with the exception of 3 samples which are rejected. In figure 5 (accepted result) and 6 (rejected result) we show two examples of archaeointensity measurements as NRM versus TRM plots.

Table 3. **T_{min} -T_{max} is the temperature interval used for archaeointensity determination; n is the number of points defining segment on the NRM-TRM plots; MDT is median destructive field; $F_a \pm \sigma$ is the individual archaeointensity estimate and associated standard error.**

No sample	T_{min} -T_{max}	n	MDT	$F_a \pm \sigma$ (μT)
AMF 1a	20°-320°	7	390°	62.04±2.97
AMF 1b	20°-380°	8	390°	63.05±2.30
AMF 2a	20°-280°	6	280°	53.52±2.30
AMF 2b	20°-320°	7	320°	57.72±2.53
AMF 3a	20°-420°	9	400°	73.54±3.94
AMF 3c	100°-420°	8	320°	75.51±2.34
AMF 4b	100°-320°	6	150°	90.18±2.60
AMF 5a	rejected		230°	rejected
AMF 6a	150°-420°	7	400°	73.62±1.78
AMF 7a	rejected		420°	rejected
AMF 8a	20°-420°	9	370°	74.29±2.90
AMF 8b	rejected		350°	rejected

Table 4. **Archaeointensity values from each kiln.**

Accepted samples	F_a(μT)	σ
AMF 1a, 1b (second kiln)	62.34	2.63
AMF 2a, 2b (piece from brick from second kiln)	55.45	2.41
AMF 3a, 3c, 4b, 6a, 8a (first kiln)	74.12	3.94

For specimen AMF 4b the temperature interval 100°-320° is used for the slope evaluation of the best fitted line between the six experimental points (left-hand diagram), pTRM checks is positive and mineralogical changes are not observed (right diagram).

Figure 6 gives one example of a rejected Thellier experiment. A strong change in susceptibility was observed and the pTRM check at 180° C shows also a strong change.

In Figure 7 the smoothed Bulgarian archaeointensity curve is shown (Kovacheva *et al.*, 1998). The territory of Bulgaria is located in the same longitudinal band, north of Greece, for this reason, a comparison of our results with Bulgarian data is possible.

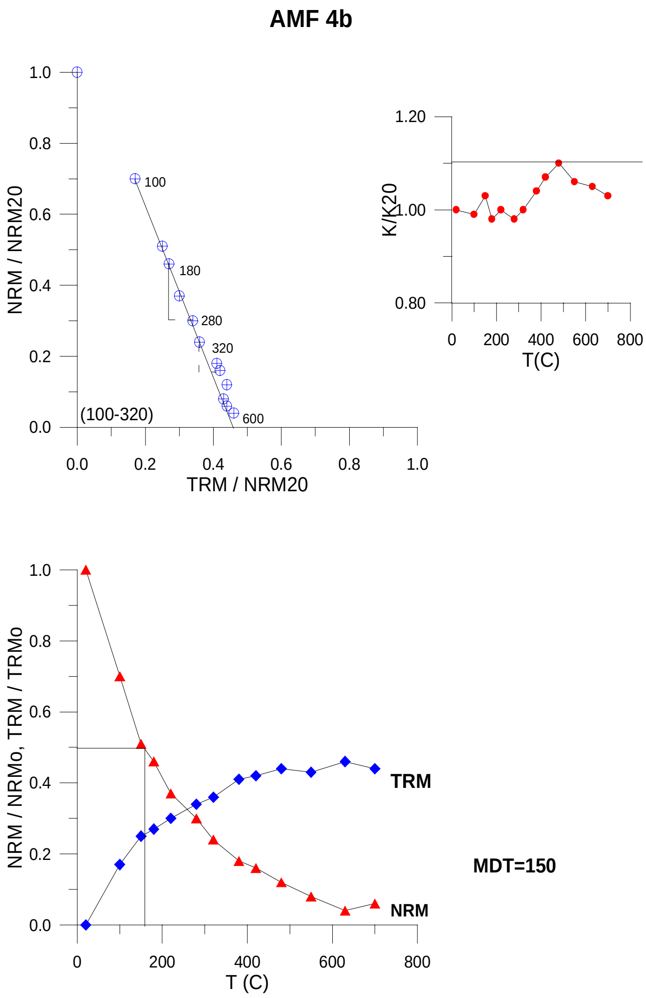

FIG. 5. Example of an accepted result for sample AMF 4b.

ARCHAEOMAGNETIC RESULTS

Three values for the arhaeointensity are obtained from the above results (Table 4). For the North Wall and the Gymnasium (74.12 μT and 62.34 μT respectively) these are considered as characteristic of the last firing of the kiln and are consistent with the Bulgarian reference curve for the time span 500 BC-100 AD. Nevertheless the two different archaeointensity values indicate different ages for the two kilns. The third value (55.45 μT) confirms that the brick, found close to the kiln, did not belong to it but to another construction.

ARCHAEOMAGNETIC DATING

In addition to the archaeointensity results directional data have been obtained from the north wall kiln both in Edmonton (Evans, oral communication, 1999) and in Thessaloniki. The two data sets display a satisfactory grouping, therefore we consider their mean value as reliable. This value (N=7, D= 352.6, I= 60.1, a_{95}=3.9) is used here in order to restrain the tentative dating from the intensity data. For the NW kiln a possible age is 620 to 480 BC. The Gymnasium kiln is certainly younger, between 100 and 600 AD.

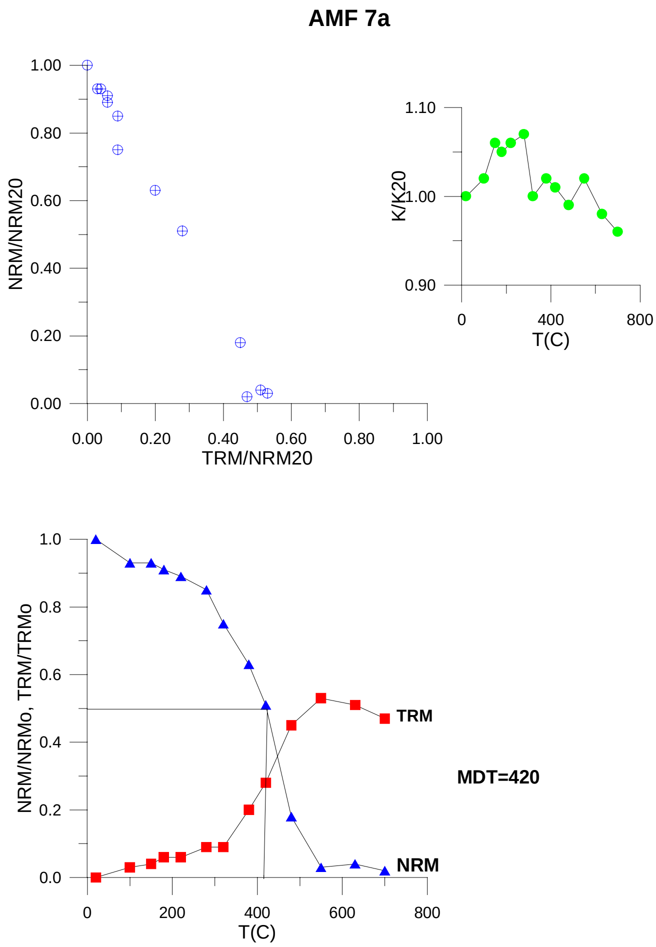

FIG. 6. Example of a rejected result for sample AMF 7a

CONCLUSION

The archaeomagnetic investigations of the geomagnetic field variations are of great interest in both geophysics and archaeology. With the present results we have been able to obtain 3 new accurate archaeointensity results from one Classic and one Hellenistic kiln in Northern Greece. We hope that these results will help to solve some of the problems in geophysics connected with the characteristics of the geomagnetic field elements in the past, and will contribute to the construction of a reference archaeomagnetic curve for Greece.

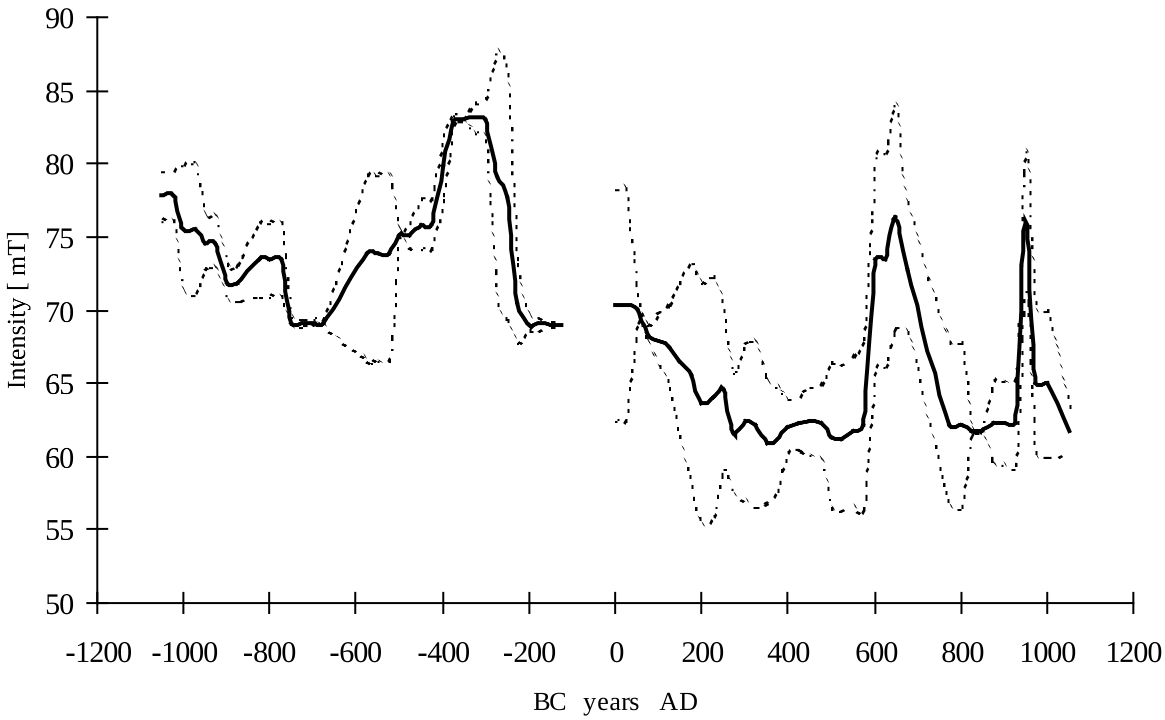

FIG. 7. The Bulgarian reference archaeomagnetic curve.

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