

ADVANTAGES AND DISADVANTAGES OF BRICKS AS A MATERIAL FOR ARCHAEOMAGNETIC STUDY

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ABSTRACT

Three collections of bricks were archaeomagnetically studied – Roman bricks (taken from the Diocletianopolis city wall, present Hissarya), Turkish bricks (coming from a mosque excavated on the territory of „40 Saint Martyrs” church, Veliko Tarnovo) and bricks with inscription (found also on the territory of „40 Saint Martyrs” church). The bricks differ significantly according to their shape and size. The main aims of the study were: 1) to determine the geomagnetic field elements (inclination and intensity); 2) to evaluate the magnetic anisotropy effect; 3) to verify the reliability of previously obtained archaeomagnetic determinations for Hissarya bricks (involved in the Bulgarian archaeomagnetic database); 4) to demonstrate the reliability and capabilities of archaeomagnetic dating method using bricks with well-known manufacturing date.

The rock-magnetic experiments performed indicate that the magnetic properties of all bricks are suitable for archaeomagnetic study. This is a consequence of the fact that bricks are usually baked at high temperatures (above 700°C) so they always carry a stable full TRM.

The inclinational data obtained show unacceptable scatter for the Turkish bricks and mean inclinational value was calculated only for the Roman bricks and the bricks with inscription. The magnetic anisotropy corrections applied do not improve the dispersion observed for none of the collection studied. Therefore, it can be concluded that these bricks were not strictly arranged along their long narrow sides during their production and obviously, this dominates the magnetic anisotropy influence. It is suggested that the Turkish bricks were situated in the furnace much more randomly compared to the other ones. There is a good internal consistency among the archaeointensity results obtained for the different collections and the magnetic anisotropy does not affect significantly the final mean results. The repeated archaeomagnetic study of the referent site Hissarya confirms its old inclinational determination but changes the old intensity result. Based on all the archaeointensity data received for the Roman bricks it can be suggested that some of the bricks in the construction of Hissarya fortress were reused (they were baked at least in two different periods).

Archaeomagnetic dating was performed only by one geomagnetic field element (intensity) for the studied Turkish bricks and by two geomagnetic field elements (inclination and intensity) – for the bricks with inscription. The dating intervals obtained on 95 percent probability level (2σ) are: 1817 – 1894 AD (Turkish bricks) and 1833 – 1894 AD (bricks with inscription) as they ended with the last year of the Bulgarian archaeomagnetic dataset. The archaeomagnetic dating interval obtained for the Turkish bricks indicate that they were produced rather in the end of the Ottoman ruling than in the end of XVII – beginning of XVIII century. This does not contradict the archaeological data. The maximum of probability density distribution for the bricks with inscription is around 1880 AD and agree quite well with the year of their production – 1888 AD. It should be considered that dating by all geomagnetic field elements (impossible for bricks materials) in the most cases produces narrower and more precise archaeomagnetic dating intervals compared to dating by one or two geomagnetic field elements.

The Turkish bricks and the bricks with inscription are included as new referent points with their archaeological dates in the Bulgarian archaeomagnetic database. With the new study of the Roman bricks an important correction for the referent site Hissarya was done. This demonstrates the importance and requirement of regular revision of the available archaeomagnetic dataset especially with regard to the old results.

Key words: archaeomagnetism, bricks, magnetic anisotropy, Diocletianopolis, Veliko Tarnovo

ПРЕДИМСТВА И НЕДОСТАТЪЦИ НА ТУХЛИТЕ КАТО МАТЕРИАЛ ЗА АРХЕОМАГНИТНО ИЗСЛЕДВАНЕ

Мария Костадинова-Аврамова

РЕЗЮМЕ

Обект на настоящото изследване са три колекции тухли, различаващи се съществено по форма и размери – римски тухли (от крепостната стена на Диоклецианопол, гр. Хисаря), турски тухли (от турска джамия, разкрита на територията на църквата „Св. 40 мъченици“, гр. Велико Търново) и тухли, върху които е шампирана точната дата на тяхното производство (от територията на църквата „Св. 40 мъченици“). Основните цели на изследването са: 1) да се определят елементите на земното магнитно поле (инклинация и интензитет); 2) да се оцени ефектът на магнитната анизотропия върху получените резултати; 3) да се провери достоверността на включените в археомагнитната база данни стари резултати за обекта в Хисаря (получени по много по-малобройна колекция и чрез прилагане на много по-малко лабораторни експерименти); 4) да се демонстрират възможностите на археомагнитния метод чрез датиране на тухли с известна дата на производство.

Според резултатите от направените магнитно-диагностични лабораторни експерименти и трите вида тухли имат подходящи за археомагнитно изследване магнитни свойства. Това до голяма степен е свързано с факта, че при изпичането тухлите винаги се нагряват до много високи температури, което е основна предпоставка за придобиването на стабилна пълна термоостатъчна намагнитеност.

Данните за инклинацията на древното геомагнитно поле показват неприемливо „разхвърляне“ за турските тухли, поради което среден резултат за тази характеристика е определен само за римските и шампираните тухли. След въвеждането на поправка за влиянието на магнитната анизотропия, наблюдаваното „разхвърляне“ не се подобрява за нито една от колекциите. Следователно то най-вероятно е следствие от не достатъчно прецизно подреждане на тухлите в пещта по време на изпичането, а не толкова ефект от магнитна анизотропия. Може да се предполага, че най-внимателно в пещите са били редени шампираните тухли, а най-хаотично – турските. Стойностите, определени за археоинтензитета като цяло имат много добра вътрешна съгласуваност и за трите колекции като отчитането на магнитната анизотропия не ги променя съществено. Повторното изследване на римски тухли от крепостта Хисаря показва, че вследствие на малкия брой образци, при първото изследване, е получена много по-висока и очевидно нереална стойност за палеоинтензитета (резултатът за инклинацията се потвърждава). От всички данни за археоинтензитета би могло да се допусне, че при строежа на крепостта Хисаря са били използвани тухли, изпечени в различни моменти от време.

Археомагнитно датиране е направено по един геомагнитен елемент (интензитет) за турските тухли и по два (инклинация и интензитет), за шампираните. Дефинирани са следните датируеми интервали: 1817 – 1894 г. (турски тухли) и 1833 – 1894 г. (шампирани тухли). И в двата случая края на интервалите съвпада с края на археомагнитния ред от данни. Полученият за турските тухли времеви интервал предполага, че е по-вероятно те да са били произведени в края на Османския период, отколкото в края на XVII – началото на XVIII. Това не е в противоречие с археологическите данни. Полученият за шампираните тухли времеви интервал е в много добро съответствие с годината на тяхното производство – 1888 (максимумът на разпределението на плътността на вероятността на получения археомагнитен датируем интервал е около 1880 година). Важно е да се отбележи, че датирането по трите геомагнитни характеристики (неприложимо в случай на тухли), в повечето случаи стеснява получаваните археомагнитни датируеми интервали.

Изследваните три колекции тухли са включени в Българската археомагнитна база данни като реперни точки с археологическите им дати. Повторното изследване на тухлите от крепостта при Хисаря даде основание да се направи една много важна корекция в базата данни, което показва колко важно може да се окаже в някои случаи преразглеждането на старите резултати.

INTRODUCTION

Archaeomagnetism is an interdisciplinary geophysical approach, which can be used as a reliable dating tool in archaeology (Kovacheva et al. 2004, 1563-1479; Kostadinova, Kovacheva 2008, 511-522; Ben-Yosef et al. 2010, 7-9; Aidona, Kondopoulou 2012, 839-842; Herve et al. 2011, 153-154;

Prevosti et al. 2013, 2696-2700; Casas et al. 2014, 861-864; Kostadinova-Avramova et al. 2014, 44-47; Tema et al. 2015, 501-504; Ech-Chakrouni et al. 2015, 578-593). The physical background of archaeomagnetic methodology is based on baked clay capability to acquire a thermoremanent magnetization (TRM) during its cooling in a weak magnetic field from temperatures above 400°C. This TRM contains information about the direction (I – inclination and D – declination) and the intensity (F) of the inducing magnetic field (Earth's magnetic field existing during the final cooling). The accumulation of sufficient amount faithful archaeomagnetic determinations, coming from well dated (with other methods) archaeological sites, enable local secular variation curves (SVCs) to be built and used for dating purposes. The basic feature of Bulgarian archaeomagnetic database is the intention of simultaneous determination of the three geomagnetic field elements from the same materials and the fact that it covers almost the entire prehistoric and historic periods (Kovacheva et al. 2014, 79 – 94).

The preferable materials for archaeomagnetic studies are different baked clay remains found *in situ* because they allow all the geomagnetic field elements (inclination, declination and intensity) to be restored. From displaced materials, only the geomagnetic field intensity can be determined. More specific and complicated is the situation with bricks. When the bricks are used in a kiln construction, they can be oriented and studied as *in situ* materials. In this case, it should be considered the sample's position and spatial distribution of firing temperatures inside the kiln. If in some parts of the kiln, relatively lower (less than 500-600°C) firing temperatures were achieved, the bricks will retain information for two firing moments – the moment of their production and the last usage of the kiln. The latter could complicate the undertaken archaeomagnetic investigation without making it impossible. When the bricks are collected from some building constructions (not burned), their archaeomagnetic study will fix only the time of brick's manufacturing. Two geomagnetic field elements could be defined for such samples – inclination and intensity. The result for the ancient inclination, however, can be obtained only if the bricks were arranged precisely in the furnace along their long narrow side during their baking.

Regardless of whether the bricks were secondary baked or not, there are two important factors, which can affect the carried TRM – magnetic anisotropy and cooling rate effect. The magnetic anisotropy in bricks is due to mechanical alignment of magnetic grains during the treatment of clay in the moulding process. Many studies (Aitken et al. 1981, 53-64; Lanos 1987, 985-1012; Garcia et al. 1997, 89; Chauvin et al. 2000, 117-129; Hus et al. 2002, 1319-1331) show that sometimes the magnetic anisotropy effect is quite important. It could be responsible for significant deviations between the TRM vector and the vector of the ancient geomagnetic field and thereby, to distort the archaeomagnetic determinations. It is proven that magnetic anisotropy affects the archaeointensity results of bricks in less extend compared to pottery (Jordanova et al. 1995, 49-58; Kovacheva et al. 2009, 730-731). Although, it seems that quite often the application of magnetic anisotropy corrections improves the inter-sample consistency and gives more precise archaeomagnetic evaluations (Chauvin et al. 2000, 134; Hill et al. 2007, 476-478; Kovacheva et al. 2009, 731; Tema 2009, 213-223).

Three brick collections were archaeomagnetically studied with the following aims: 1) to determine the geomagnetic field elements (inclination and intensity); 2) to evaluate the magnetic anisotropy effect; 3) to verify the reliability of previously obtained archaeomagnetic determinations for a referent site Hissarya; 4) to demonstrate the reliability and capabilities of archaeomagnetic dating method using bricks with well-known manufacturing date.

MATERIALS AND METHODS

1. Description of the collections studied

The first collection consists of 13 Roman bricks taken from the Diocletianopolis city wall (present Hissarya), from which 71 standard (8 cm³) cubic specimens (subsamples) were cut. A small brick collection coming from the same archaeological site was archaeomagnetically studied many years ago

(in 1969) when archaeomagnetism started to develop in Bulgaria. Having in mind the small number of samples and the fact that archaeomagnetic methodology was considerably improved thereafter, the verification of these old results (involved already in the Bulgarian archaeomagnetic database) is quite important. The second collection includes 26 Turkish bricks from a mosque excavated on the territory of „40 Saint Martyrs” church, Veliko Tarnovo and 214 standard cubic specimens. According to the archaeologists, the Roman bricks were more probable produced during III-IV century AD or earlier, while the Turkish bricks were baked at the earliest in the end of XVII – beginning of XVIII century AD and no later than the Turkish slavery Liberation (1878). The third collection, containing only 2 bricks (found also on the territory of „40 Saint Martyrs” church) and 12 cubic specimens, is quite small, but each brick has an inscription of its manufacturing year – 1888 AD. Consequently, the study of this small collection can serve as a good example of the reliability and capabilities of archaeomagnetic dating method.

The bricks included differ considerably according to their shape and size. The Roman bricks are larger and better formed than the Turkish ones. The bricks with inscription have dimensions similar to these of the Turkish bricks but they are significantly thicker in comparison to the Roman and Turkish bricks.

2. Laboratory procedures

The success of an archaeomagnetic study strongly depends on fulfilment of several conditions: 1) the materials have to carry a stable thermoremanent magnetization; 2) the mineralogical changes during laboratory heating experiments have to be negligible (less than 10 percent); 3) the prevailing magnetic particles have to be in appropriate domain sizes (single or close to). That is why in the last years rock-magnetic experiments are obligatory part of each archaeomagnetic investigation. A regular set of laboratory analysis (Kovacheva, Jordanova 2001, 685-696; Kostadinova-Avramova et al. 2014, 37-42) were done for selected specimens:

- **viscous cleaning** – all subsamples;
- **demagnetization with alternating field (AF demagnetization)** – five Roman, four Turkish and one brick with inscription;
- **thermal demagnetization of isothermal remanence induced along three orthogonal directions in a sample (3IRM test)** (Lowrie 1990, 159-162) – five Roman, five Turkish and one brick with inscription;
- **thermal demagnetization of isothermal remanence with subsequent magnetization at room temperature after each heating step (SIRM test)** (Van Velzen, Zijdeveld 1992, 79-90; Jordanova et al. 2003, 146-158) – five Roman, five Turkish and one brick with inscription;
- **Thermomagnetic analysis** – five Roman, four Turkish and one brick with inscription;
- **Lowrie and Fuller test** (Lowrie, Fuller 1971) – six Roman, four Turkish and one brick with inscription.

ROCK MAGNETIC RESULTS

The results of the rock-magnetic experiments carried out, lead to the conclusion that the investigated materials are appropriate for archaeomagnetic study. The calculated viscosity coefficient values (S_v) are highest for the bricks with inscription (the most S_v values are above 9 percent) and lowest for the Roman bricks (S_v values vary from 2 to 10 percent with a maximum of 6 percent) – Fig. 1. The obtained S_v values for the Turkish bricks are between 6 and 10 percent with a maximum of 8 percent. Generally, the observed high S_v values are explained by insufficient firing of the materials in the past or/and the presence of high quantities fine unstable magnetic particles of superparamagnetic (nano) sizes. Obviously only the second explanation should be considered for bricks. The available secondary viscous remanence was easily removed with applying of low (5-10 mT) alternating fields – Fig. 2 (the quick alignment of the experimental points is obvious on the left upper plot). From 3IRM test and thermomagnetic analyses can be concluded that the magnetic mineralogy of Turkish bricks and

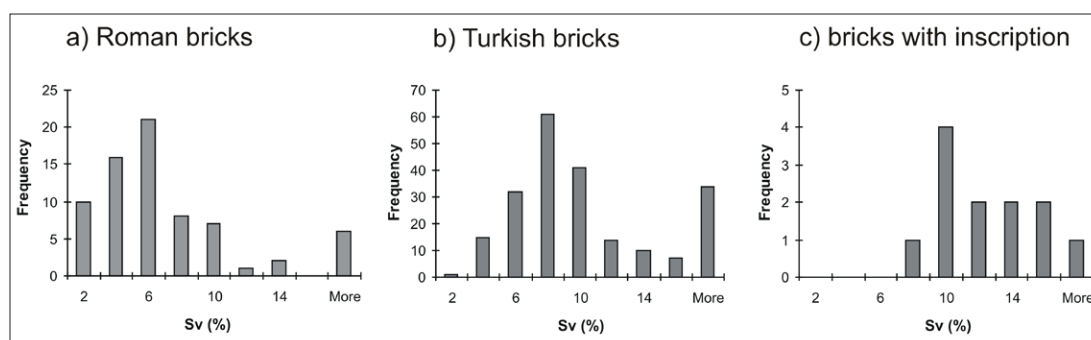


Fig. 1. Frequency distribution of the viscosity coefficient S_v : a) Roman bricks b) Turkish bricks and c) bricks with inscription

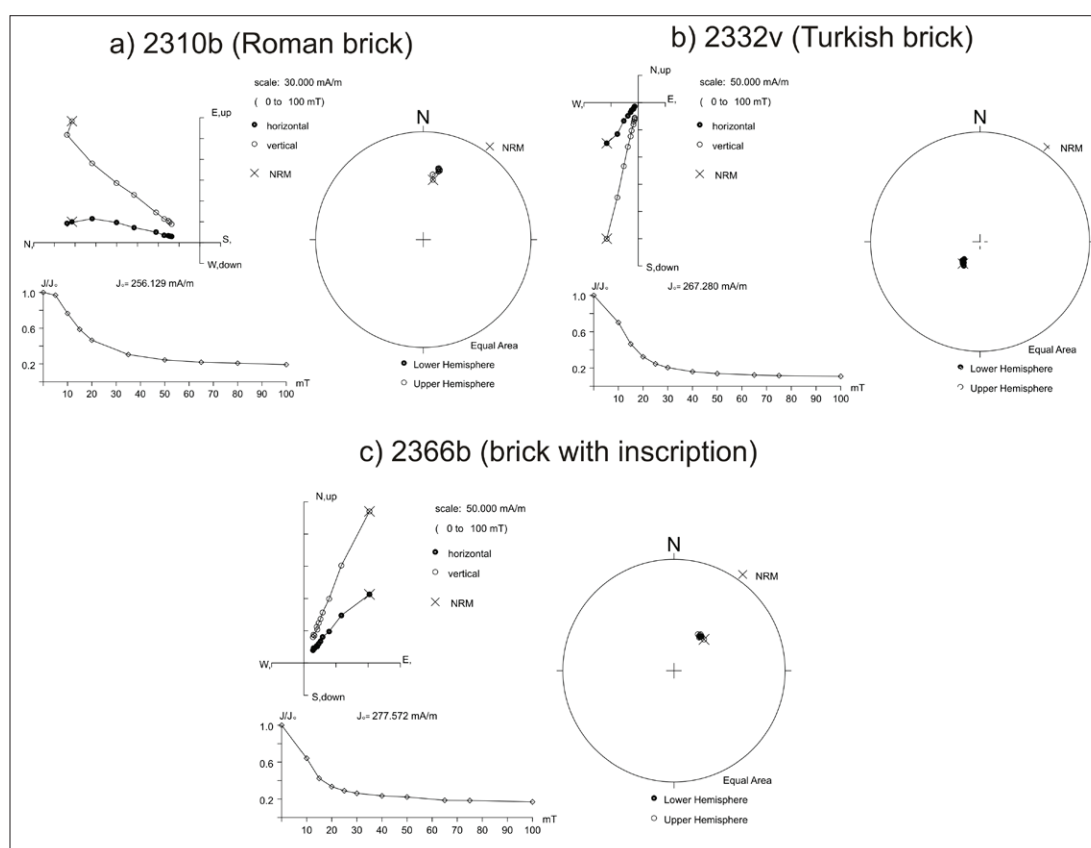


Fig. 2. Typical examples of AF demagnetization: a) Roman brick b) Turkish brick and c) brick with inscriptions. In all graphs, a cross marks the initial values of the measured remanence.

the bricks with inscription is quite similar and magnetically soft minerals prevail – *titanomagnetite*/*magnetite* and *maghemite* (Fig. 3b, c and Fig. 4b, c). This similarity suggests a common origin of the clay used for their production. In contrast, in the Roman bricks a significant amount of high coercivity minerals (*goethite*, *hematite* and *epsilon iron oxide*) are detected (Fig. 3a; Fig. 4a; Lopez-Sanches et al. 2017). The thermomagnetic analyses and SIRM tests carried out indicate that overall there are no strongly expressed magnetic mineralogical transformations during laboratory heating (Fig. 4, b, c; Fig. 5). The magnetic susceptibility (K) monitored during 3IRM and SIRM tests confirms the stability of magnetic mineralogy (Fig. 3; Fig. 5). Lowrie and Fuller tests failed for the Roman bricks because of the significant presence of high coercivity magnetic minerals (the test is applicable only for magnetite type minerals). For the other two brick collections, bimodal (Fig. 6a) and single (Fig. 6b) domain sizes of magnetic carriers are supposed (Dunlop 1983).

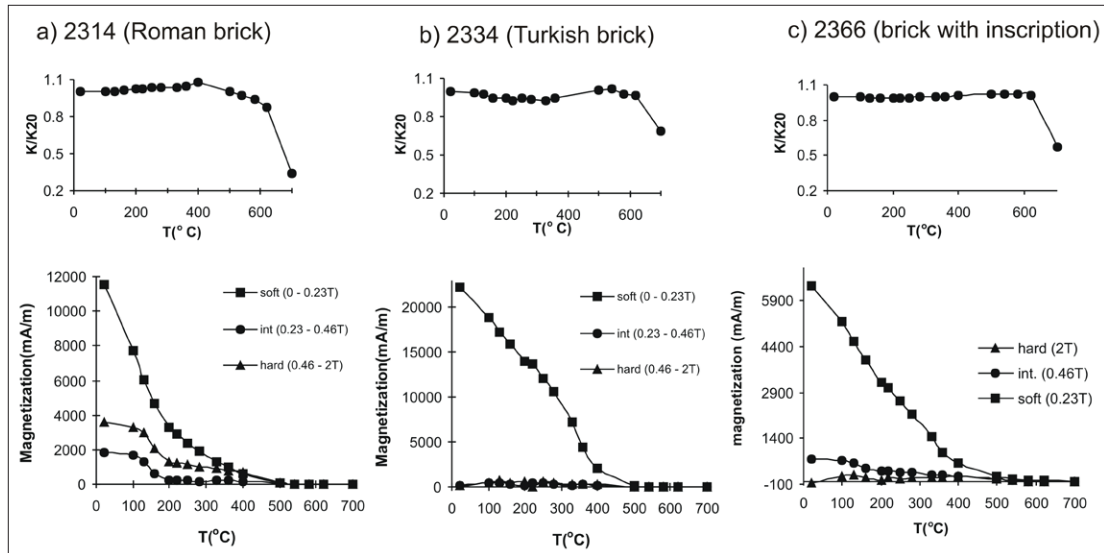


Fig. 3. Typical examples of 3IRM test: a) Roman brick b) Turkish brick and c) brick with inscription. The upper graphs show the behaviour of magnetic susceptibility (K) during the thermal demagnetization. K was measured at room temperature after each heating step.

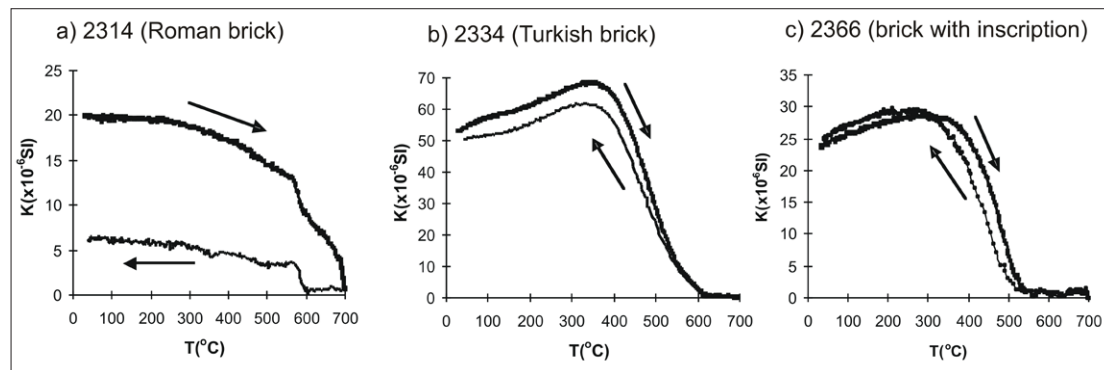


Fig. 4. Typical examples of thermomagnetic analyses: a) Roman brick b) Turkish brick and c) brick with inscription. The magnetic susceptibility behaviour was constantly monitored during the heating and cooling cycles.

According to the rock-magnetic results, 40 specimens were carefully selected for archaeointensity (F) determination – 18 Roman, 20 Turkish and 2 bricks with inscription. The classical Thellier method (Thellier, Thellier 1959) was applied (Fig. 7). During the experiment, the magnetic susceptibility at room temperature was measured at each heating step to monitor if any mineralogical changes occur. With few exceptions, the variations in this parameter are acceptable (less than 10 percent). Three additional archaeointensity determination experiments were done by Dr. Fabio Donadini for the old previously investigated collection from Hissarya (Roman bricks) using Coe protocol (Coe, 1967).

MAGNETIC ANISOTROPY AND ARCHAEOMAGNETIC DETERMINATIONS

The influence of magnetic anisotropy on archaeomagnetic determinations was evaluated using **anhysteretic remanence anisotropy tensor method** (Kostadinova-Avramova 2009, Chapter III. 2). Owing to the similarity of AARM and ATRM tensors, anisotropy of anhysteretic remanence (AARM) can be used as a substitute of thermoremanent (TRM) anisotropy. Thereby, the thermally induced mineralogical alterations are avoided.

The obtained results show that, for samples with a higher degree of remanence anisotropy, expectedly, higher anisotropy corrections are observed. The Roman bricks are more anisotropic

than the Turkish ones and the bricks with inscription (Kostadinova-Avramova 2009, Chapter III. 2). The magnetic anisotropy affects archaeointensity in less degree than inclination, which agrees well with Kovacheva et al. (2009, 730-731).

All archaeomagnetic results obtained are summarized in Table 1. In the first column the numbers of accepted/all measured specimens are given. The mean inclination for each independently oriented sample is calculated as an average of the values measured for the relevant subsamples after the corresponding cleaning. For the Roman and Turkish bricks the scatter between the inclinational data obtained for the different samples is significant (Table 1a and b). The comparison between uncorrected and corrected for the magnetic anisotropy effect I values is given in columns 2 and 3 of Table 1. Although, the individual determinations for the inclination shift significantly in few cases as a result of this effect, the average I value per collection does not change considerably. Hence, the applied corrections for the magnetic anisotropy effect (third column in Table 1 – I_{corr}) do not improve the inclinational dispersion. Therefore, the most probable explanation for the

observed scatter is the assumption that Roman and Turkish bricks were not arranged exactly along their long narrow sides during their baking. Nevertheless, after the rejection of two results (2310 – the lowest and 2314 – the highest I value – Table 1a), an acceptable final value for the Roman bricks is determined (after magnetic anisotropy correction): $I_{\text{corr}} = 53.0^\circ \pm 4.1^\circ$ (given in bold at the end of Table 1a). For the Turkish bricks, however, the scatter between the results is so high that it is impossible to determine any mean inclination (Table 1b). The two bricks with inscription have quite similar inclinational values and gives averaged result: $I_{\text{corr}} = 55.1^\circ \pm 1.6^\circ$ (after magnetic anisotropy correction).

The studied Turkish bricks are much more numerous in comparison to the other two brick collections but nevertheless, only for them the inclinational results are unacceptable. Therefore, it can be concluded that Turkish bricks were arranged in the furnace more randomly and imprecisely during their production compared to the other ones.

The obtained archaeointensity (F) values are also given in Table 1 before and after magnetic anisotropy corrections (column 5 and 7) with the corresponding errors (column 6 and 8). The temperature intervals used for the intensity determination are shown in column 4. The final F value (given in bold in Table 1) for the Roman bricks is calculated from 10 accepted results corrected

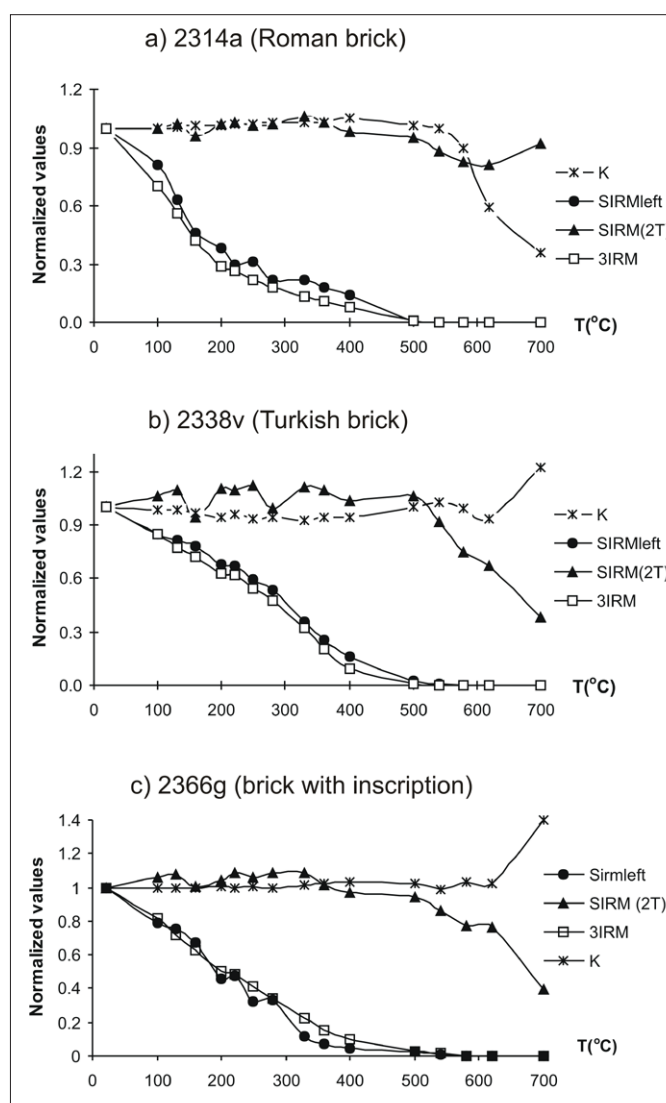


Fig. 5. Typical examples of SIRM test: a) Roman brick b) Turkish brick and c) brick with inscription

Table 1. Summary of the archaeomagnetic determinations obtained: a) Roman bricks, b) Turkish bricks and c) bricks with inscription. № – sample`s number; I (I_{corr}) – magnetic inclination (in degree) before (after) magnetic anisotropy correction; $T_{min} - T_{max}$ – temperature interval used for F determination; F and σ (F_{corr} and σ_{corr}) – the obtained archaeointensity value and its corresponding error (in microtesla) before (after) magnetic anisotropy corrections.

a) Roman bricks							
№	I°	I°_{corr}	$T_{min} - T_{max}$ (°C)	F (μT)	σ (μT)	F_{corr} (μT)	σ_{corr} (μT)
2305 (7/6)	47.9	48.6					
2306 (8/8)	51.8	53.7		rejected			
				rejected			
2307 (6/6)	61.2	58.2	20 – 430	64.20	1.33	59.71	0.93
			20 – 320	64.01	5.60	54.47	0.85
2308 (3/3)	53.5	53.9	20 – 370	64.01	2.86	61.58	0.96
2309 (4/4)	55.8	58.5		rejected			
				rejected			
2310 (5/5)	43.4*	-	100 – 320	60.50	1.49	57.23	0.94
			20 – 320	62.79	2.59	59.27	0.94
2311 (5/5)	47.5	48.3					
2312 (3/3)	64.0	58.7					
2313 (5/5)	47.0	49.0	20 – 430	63.40	2.10	61.50	0.97
			20 – 430	62.30	1.87	62.92	1.01
2314 (5/5)	64.6*	63.5*		rejected			
2315 (6/6)	61.4	60.4	130 – 460	57.61	2.90	58.30	1.01
			130 – 460	57.04	3.05	58.18	1.00
2316 (7/7)	49.8	48.8	100 – 620	61.34	2.44	63.12	1.03
				rejected			
2317 (7/7)	56.7	56.8	100 – 320	74.53*	1.14	76.99*	1.03
			100 – 320	74.56*	2.82	78.66*	1.06
Average	54.2	53.0		62.10	2.11	59.42	2.66
St. dev.	6.1	4.1					

b) Turkish bricks							
№	I°	I_{corr}	$T_{min} - T_{max}$ (°C)	F (μT)	s (μT)	F_{corr} (μT)	σ_{corr} (μT)
2329 (6/6)	55.2	56.2	100 – 370	39.47	0.46	39.23	0.46
2330 (6/6)	44.9	44.1					
2331 (6/6)	47.4	48.1					
2332 (7/7)	70.5	69.9	130 – 460	45.38	0.84	44.70	0.83
2333 (6/6)	47.5	47.4	100 – 430	45.87	1.33	45.55	1.32
2334 (6/6)	57.6	58.8					
2335 (6/6)	43.2	40.7	100 – 430	42.41	0.80	43.39	0.82
2336 (6/6)	41.4	40.5	100 – 370	39.28	0.99	39.59	1.00
2337 (6/6)	40.1	40.5	100 – 460	45.84	1.26	45.89	1.26
2338 (6/6)	51.0	50.9	100 – 370	48.73	1.71	47.85	1.68
2339 (6/6)	53.3	56.6		rejected			
2340 (6/6)	40.8	38.5	130 – 430	52.74*	2.42	53.69*	2.46
2341 (6/6)	40.8	40.0					
2342 (6/6)	53.7	53.6	100 – 370	42.98	0.84	43.50	0.85

2343 (7/7)	42.3	43.3					
2344 (6/6)	63.5	63.6	20 – 370	41.91	1.60	41.11	1.57
2345 (5/5)	44.1	41.5					
2346 (6/6)	47.3	48.4					
2347 (6/6)	35.7	36.7	20 – 460	41.99	0.88	42.03	0.88
2348 (6/6)	43.4	42.7	20 – 370	39.93	1.91	40.53	1.94
2349 (6/6)	43.4	42.6					
2350 (6/6)	51.8	-	200 – 370	48.01	1.45	46.91	1.42
2351 (6/6)	40.3	39.7		rejected			
2352 (7/7)	41.9	41.3	100 – 370	40.88	0.69	42.60	0.72
2353 (6/6)	51.9	51.7					
2354 (5/5)	36.8	37.3					
2355 (6/6)	39.4	39.2					
2356 (6/6)	57.0	55.3					
2357 (6/6)	49.8	47.2					
2358 (6/6)	48.9	48.3		rejected			
2359 (6/4)	53.5	55.1					
2360 (6/6)	49.8	49.2					
2361 (6/6)	60.8	61.4	100 – 280	39.74	1.30	39.90	1.30
2362 (6/6)	70.7	70.6					
2363 (6/6)	42.1	41.6	100 – 320	46.67	2.59	47.04	2.61
2364 (6/6)	52.8	52.2	100 – 370	42.67	0.91	42.71	0.91
Average	48.7	48.4		41.95	2.53	42.13	2.45
St. dev.	8.6	9.0					

c) bricks with inscription							
Nº	I°	I _{corr}	T _{min} – T _{max} (°C)	F (μT)	σ (μT)	F _{corr} (μT)	σ _{corr} (μT)
2365 (6/6)	55.5	53.5	100 – 460	44.58	1.41	44.60	1.41
2366 (6/6)	57.7	56.7	100 – 460	44.01	2.10	44.40	2.12
Average	56.6	55.1		44.40	0.26	44.54	0.06
St. dev.	1.6	1.6					

for magnetic anisotropy $F_{\text{corr}} = 59.42 \pm 2.66 \mu\text{T}$ (Table 1a). For 6 subsamples the experiment failed (Table 1a, Fig. 7a). For two sister specimens the determined F values are too high (sample 2317, Table 1a, with italic and asterisk) and they were not taken into account in the final mean intensity calculation.

The old archaeomagnetic determinations for the Roman bricks (obtained in 1969 and included in the Bulgarian archaeomagnetic database) are $I = 52.1^\circ \pm 4.4^\circ$ and $F = 71.88 \pm 9.72 \mu\text{T}$. It is obvious that the old I value is very close to the newest one but the old F value, determined with an objectionable error (9.72 μT), is too high. The later is not surprising considering that the old archaeointensity mean value were calculated using only 4 results varying from 57.08 to 82.74 (difference of more than 20 μT – Table 2, column 3, samples 596, 597, 604, 608). It was mentioned above that additional archaeointensity experiments were performed for three specimens taken from 1969 collection in 2008. The results are very close to the newest F determinations (Table 2, column 3, values given in bold). It is interesting that the old Roman brick collection also gives two very high intensity values (samples 596, 608 – Table 2) which are comparable with the excluded from the present collection F values (sample 2317, Table 1a). In this context, it can be supposed that some of the bricks in the construction of Hissarya fortress are reused (they were baked in different time). Taking into account the accepted inclinational and intensity values for both Roman brick collections

(Table 1a, Table 2) the final archaeomagnetic determinations for the referent site Hissarya were obtained: $I = 53.27^\circ \pm 3.88^\circ$ and $F = 59.91 \pm 2.29 \mu\text{T}$ and an important correction was done in the Bulgarian archaeomagnetic database (Kovacheva et al. 2014, 83).

For the Turkish bricks three archaeointensity determination experiments were unsuccessful (sample 2339, 2351, 2358) and one F value is substantially higher (sample 2340) – Table 1b. The other 16 intensity determinations are in very good agreement and the final (magnetic anisotropy corrected) F value is $F_{\text{corr}} = 42.13 \pm 2.45 \mu\text{T}$.

Table 2. Summary of the old (1969) archaeomagnetic determinations of Hissarya bricks. The three new archaeointensity evaluations (the same collection) obtained in 2008 are given in bold.

No	I°	F (μT)	σ (μT)
596	68*	79.76*	5.00*
597	58.0	57.08	3.00
	58.0	65.15	2.82
598	46.5		
599	rejected	59.11	2.54
600	54.6		
601	45.0	62.02	1.84
602	55.3		
603	53.7		
604	53.0	60.90	3.00
605	57.0	rejected	
606	55.0		
607	48.5		
608	47.0	82.74*	5.00*
609	52.0		
Average	52.6	61.09	2.43
St. dev.	4.5		

ARCHAEOMAGNETIC DATING

Archaeomagnetic dating for the studied Turkish bricks was performed by one geomagnetic field element (intensity) and for the bricks with inscription – by two geomagnetic field elements (inclination and intensity) using RenDate software (Lanos 2004, 43-82). The final archaeomagnetic determinations (intensity value for the Turkish bricks; inclination and intensity values for the bricks with inscriptions) are compared to the corresponding reference curves (updated in 2002 year) for the time interval 1500 – 1900 AD (Fig. 8a and b). The calculated dating intervals on 95 percent probability level (2σ) are: 1817 – 1894 AD for the Turkish bricks and 1833 – 1894 AD – for the bricks with inscription (Fig. 8). The archaeomagnetic dating interval obtained for the Turkish bricks (Fig. 8a) suggests that these bricks were produced rather in the end of the Ottoman

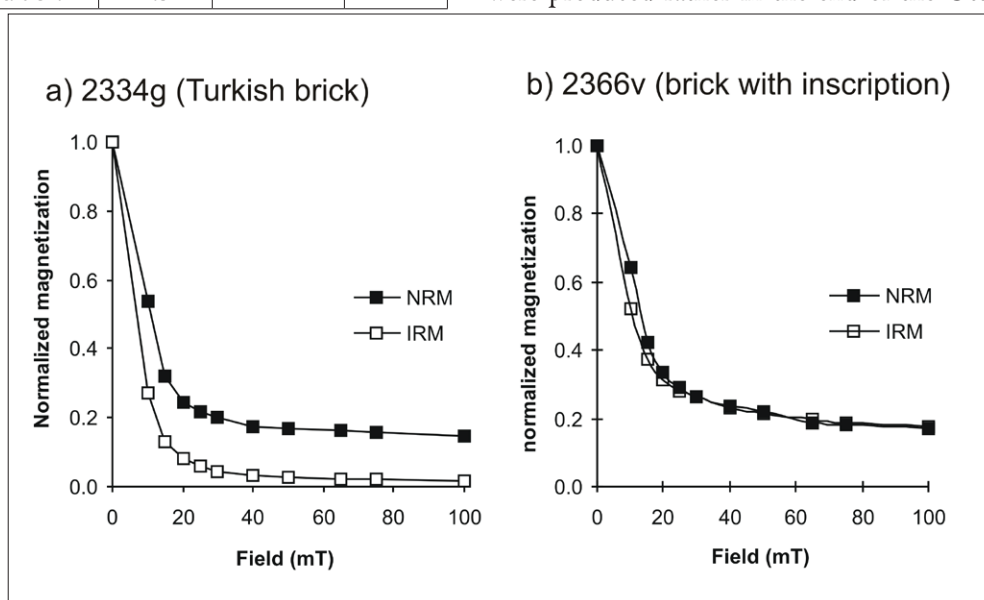


Fig. 6. Typical examples of Lowrie and Filler test: a) Turkish brick and b) the brick with inscription

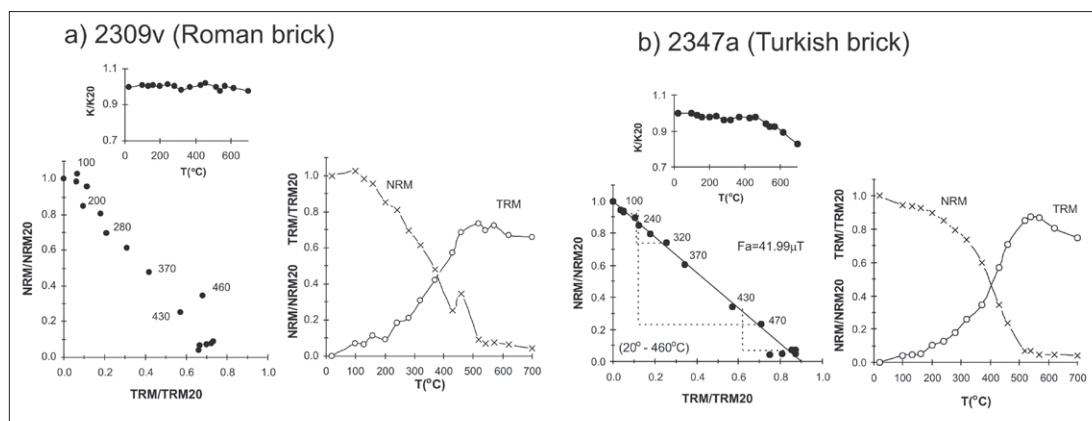


Fig. 7. Examples of Thellier experiment: a) Roman brick (failed) and b) Turkish brick (successful)

ruling (1878) than in the end of XVII – beginning of XVIII century. The maximum of probability density distribution for the bricks with inscription is around 1880 AD (Fig. 8b) and agrees quite well with the year of their production – 1888 AD. It should be noted that 1894 (the end of the archaeomagnetic dating intervals obtained for both brick collections) is the last year in the Bulgarian dataset used for the reference curves calculations. If direct geomagnetic field measurements were taken into account, in both cases wider dating intervals would be obtained. It is worth remarking that dating by all geomagnetic field elements (impossible for bricks materials) in the most cases produces narrower and more precise archaeomagnetic dating intervals compared to dating by one or two geomagnetic field elements. Archaeomagnetic dating for the Hissarya bricks cannot be done because the old determinations of this referent site participate in the Bulgarian secular variation curves. It is important to underline that archaeomagnetic dating of any site could be performed only before its involvement in the database.

The precision of each archaeomagnetic dating depends not only on the accuracy of the experimental archaeomagnetic results but also from the accuracy of the reference curves used. In turn, the accuracy of the reference curves depend on the number of the included reference points and on the accuracy of their input dates. That is why each local database requires a constant updating and improvement. With the new study of the Roman bricks an important clarification for the referent

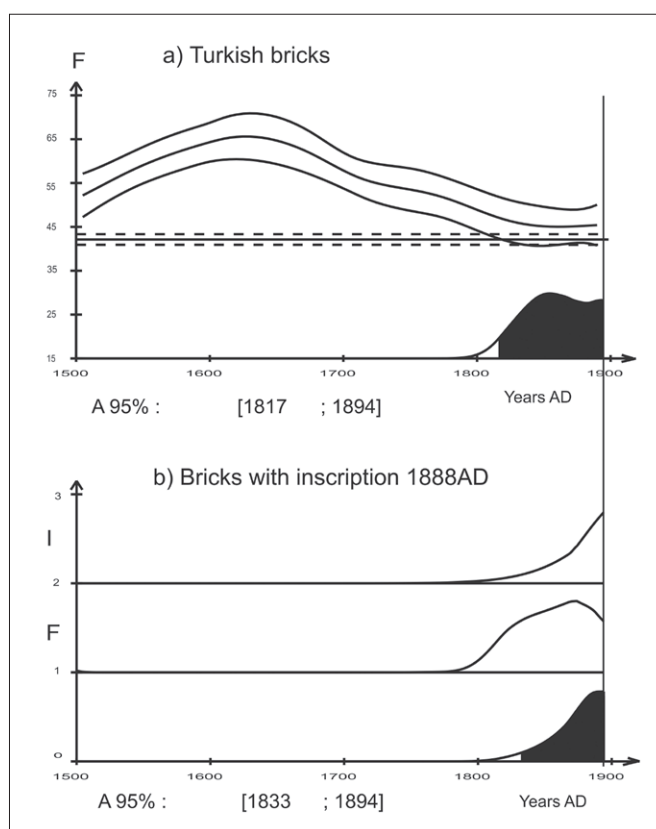


Fig. 8. Archaeomagnetic dating: a) Turkish bricks (only by intensity determination) and b) bricks with inscription (by inclination and intensity).

site Hissarya is done (the old intensity determination is revised and the old inclination is confirmed). The Turkish bricks and the bricks with inscription are included as new referent points with their archaeological dates in the Bulgarian archaeomagnetic database.

The cooling rate effect that was mentioned above as another important factor for archaeointensity determination is a subject of another investigation (Kostadinova-Avramova and Jordanova, 2019). Having in mind that the Bulgarian database consists of archaeointensity data uncorrected for this effect, the dating procedure is properly carried out.

CONCLUSIONS

1. The magnetic properties of the studied brick collections are suitable for archaeomagnetic study. The bricks are usually baked at high temperatures (above 700°C) so they should carry a stable full TRM. Additional advantage of bricks is that they are always well consolidated. That is why it is quite easy to be cut at subsamples without any water glass impregnation (the latter is obligatory procedure before cutting of fragile baked clay materials).

2. Great disadvantage of bricks is the fact that if they are not found *in situ* (after their final cooling) it is very difficult to obtain a reliable result for the ancient inclination and it is impossible to determine the declination of the past geomagnetic field. The establishment of the directional geomagnetic field elements is not easy even when the bricks can be oriented. The magnetic anisotropy and cooling rate factors could be combined with the possible presence of multi-component TRM.

3. The applied magnetic anisotropy correction on the archaeomagnetic determinations (inclination and intensity) obtained do not change significantly the final mean results and do not improve the inter-sample consistency for none of the studied brick collection. The individual corrections over the palaeointensity results are less in comparison to these for the inclination.

4. The repeated much more detailed archaeomagnetic study of the referent site Hissarya confirms its old inclinational value but changes the old intensity result. This illustrates the importance and requirement of regular revision of the available database especially with regard to the old results.

5. The reliability of archaeomagnetic dating is proved by the investigation of bricks with inscription.

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