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NEW ARCHEOINTENSITY RESULTS ON A BAKED-CLAY TILE COLLECTION FROM THE NEW JERUSALEM MONASTERY (MOSCOW REGION, RUSSIA)

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Abstract. We report on new archeointensity results from two groups of baked-clay tiles sampled in the New Jerusalem Monastery, Moscow region (Russia). These groups of fragments are precisely dated from 1680-1690 AD (NJ01) and 1710-1720 AD (NJ02). All archeointensity measurements were carried out using the experimental protocol developed for the Triaxe magnetometer, which allows magnetization measurements directly at high temperatures. Mean intensity values derived at the group level are obtained from five (NJ01) and four (NJ02) different fragments. We analyzed four to seven specimens per fragment using two cooling rates (25°C/minute and 2°C/minute) for laboratory thermoremanent magnetization acquisition. We show that the cooling rate effect is statistically insignificant in our intensity determinations. Implications of these data are twofold. First, they do not argue for a regular decrease of the dipole field moment over the past four centuries. Second, they appear in relatively good agreement with the field intensity variations observed in Western Europe, suggesting the absence of a significant non-dipole field effect over Europe. However, further development of archeomagnetic study in the European part of Russia is necessary to confirm these preliminary conclusions.

Keywords: archeomagnetism, archeointensity, secular variation, dipole, Europe.

Introduction

In recent years, interest in secular variation of the geomagnetic field over the past millennia has increased. This has led to improvements in the completeness and quality of the existing archeomagnetic databases, such as GEOMAGIA or ArcheoInt [*Brown et al.*, 2015; *Genevey et al.*, 2008]. Constraining the geomagnetic field intensity variations during the 17th and 18th centuries is particularly important for testing the reliability and accuracy of the historical geomagnetic field models [*Jackson et al.*, 2000; *Gubbins et al.*, 2006; *Finlay et al.*, 2008; *Genevey et al.*, 2009; *Korte et al.*, 2011]. Their reliability is indeed crucial for deciphering the geodynamo processes at the origin of the observed variations, and to forecasting geomagnetic fluctuations in the near future. The latter aspect would, for instance, allow better understanding of the issue of the occurrence of the next polarity reversal [*Constable and Korte*, 2006; *Korte et al.*, 2011].

For certain areas and at different periods, the existing geomagnetic field models predict intensity and/or directional values that are different from the data obtained. Such discrepancies are due, at least partly, to the fact that the models are constructed using a compilation of data with uneven spatial and temporal distributions. It is thus necessary to obtain new archeomagnetic data, in particular archeointensity results, and to focus archeomagnetic investigations on the regions with presently poor data coverage. Among these regions, North-Western and Central Russia are good examples. There, archeointensity data were previously obtained for the time interval between the 15th and 18th century. However, most of these data were acquired in the 1970s/1980s [*Burlatskaya,* 1970; *Burlatskaya et al.*, 1986; *Nachasova,* 1972] using the classic *Thellier and Thellier* [1959] method, and they often do not fulfill modern quality criteria (such as the criterion concerning the correction for the TRM anisotropy effect [*Biggin and Peterson,* 2014]). This study is hence part of a project aiming to obtain new archeointensity determinations in North-Western and Central Russia that satisfy modern quality standards.

Sampling and Methodology

In the course of archeological excavations conducted in 2014-2015 in the New Jerusalem monastery (Moscow region, Russia 55.92°N; 36.84°E), we collected 37 fragments of baked-clay decor wall tiles, which were produced in two ovens that were precisely dated thanks to historical and stratigraphic arguments. The last use of the first oven is dated to between 1680 and 1690 AD, whereas the second oven was in activity between 1710 and 1720 AD (O.N. Glazunova, unpublished data). Two groups of fragments were thus assembled: NJ01 comprising 22 fragments produced in the first oven and NJ02 with 15 collected fragments produced in the second oven.

Analyses of the magnetic properties were carried out at the Institute of Physics of the Earth - Russian Academy of Sciences (IPE RAS) in Moscow (Laboratory of Archeomagnetism and Evolution of the Earth's Magnetic Field) and in Borok (Geophysical observatory; Yaroslavl region). All archeointensity experiments were conducted in the Paleomagnetic laboratory of the Institut de Physique du Globe de Paris (France).

The fragments were first subjected to laboratory tests in order to determine their suitability for archeointensity assays. The behavior of susceptibility (K) vs temperature curves and/or of the thermal evolution of the saturation magnetization (J_s) was used as a first selection criterion. The measurements were carried out using respectively a Kappabridge MFK1-FA coupled with a CS4 furnace (Agico, Czech Republic) and a magnetometer MM VFTB (Peterson Instruments, Germany). The latter instrument was also used to investigate the progressive acquisition of isothermal remanent magnetization. Fragments for which the magnetic mineralogy was observed stable upon heating were retained for further intensity experiments.

Intensity data were obtained using the experimental protocol developed for the 3-axis Triaxe magnetometer, which allows magnetization measurements on a specimen at high temperatures [*Le Goff and Gallet,* 2004]. This protocol derives from the classic Thellier-Thellier [1959] method. It involves several series of continuous magnetization measurements performed during heating and cooling in zero field or in a chosen laboratory field. The intensity determinations rely on the demagnetization curves over the very same temperature range of both the natural (ancient) remanent magnetization and of the laboratory thermoremanent magnetization acquired during the treatment. The protocol takes into account the thermal variations of the spontaneous magnetization. Moreover, the laboratory thermoremanent magnetization is acquired in such a way that its direction is the same as that of the natural remanent magnetization. As a consequence, a correction for the thermoremanent magnetization anisotropy effect is not required. An important asset of the Triaxe procedure lies in its rapidness: an archeointensity determination for one specimen is achieved in about 2.5 h when the laboratory thermoremanent magnetization is acquired using a cooling rate of 25°C/minute [*Le Goff and Gallet,* 2004]. Note that comparisons between intensity results obtained from the same fragments using the Triaxe protocol and other more classic protocols derived from the original Thellier and Thellier method such as the Thellier-Coe procedure [*Thellier and Thellier*, 1959; *Coe*, 1967] showed a good agreement between the different datasets [e.g. *Genevey et al*., 2009; *Hartmann et. al*, 2010].

Archeointensity results and discussion

Magnetic properties. For all fragments, thermomagnetic measurements of $K(T)$ and $J_s(T)$ revealed the presence of a magnetic mineral with Curie temperatures (T_K) between 540°C and 580°C, which likely belongs to the (titano)magnetite family. For several fragments, higher T_K up to 680-700°C also indicates the presence of hematite (Fig. 1 *a*, b*). We note that the presence of the latter mineral has no significant effect on the archeointensity determinations, because a large fraction of the magnetization is carried by (titano)magnetite.

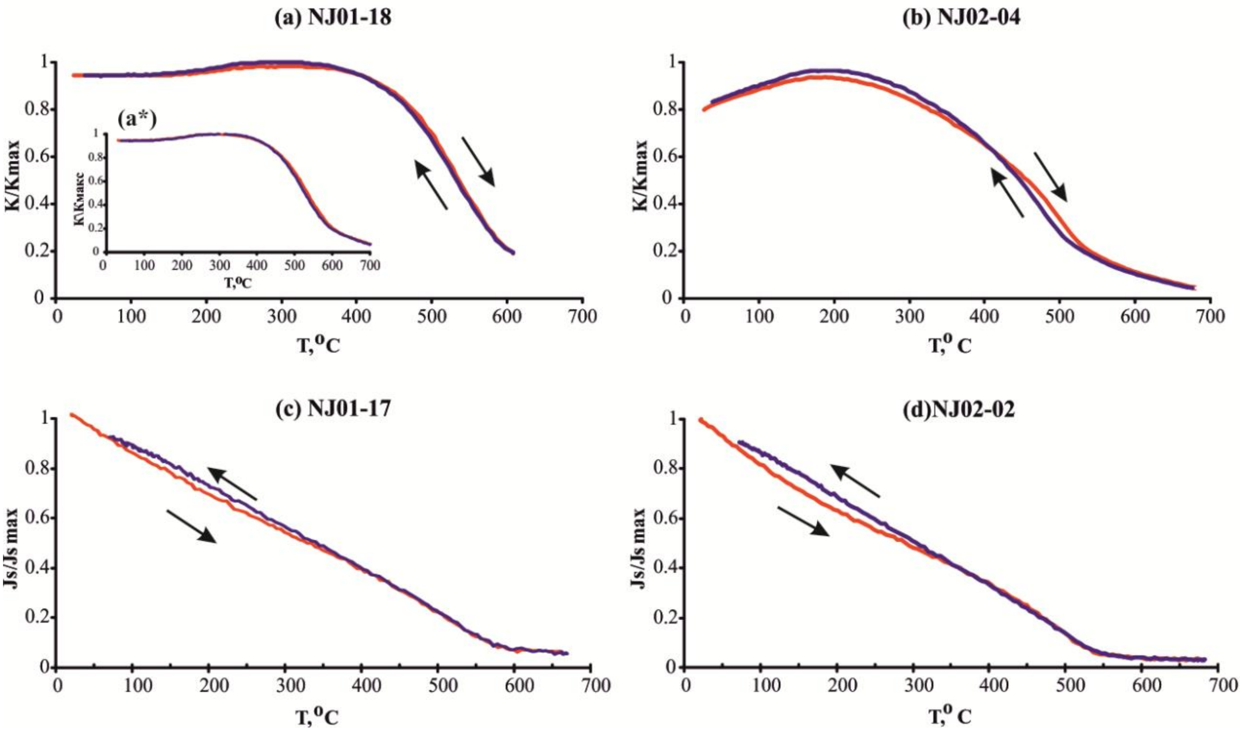

Fig. 1. Normalized $K(T)$ and $J_s(T)$ heating and cooling curves obtained for two fragments from group NJ01 (*a*, *c*) and two fragments from NJ02 (*b*, *d*). The inset in (*a*) shows the curve obtained from a fresh powder heated up to 700°C.

Thermomagnetic analyses of $K(T)$ and $J_S(T)$ showed a satisfactory reversibility between the heating and cooling curves (Fig.1) and at this stage, all fragments were retained for performing intensity experiments.

The isothermal remanent magnetization acquisition curves often show a weak inflexion around 0.3 T (Fig. 2), which further indicates the presence of minerals with low ((titano)magnetite) and high coercivities.

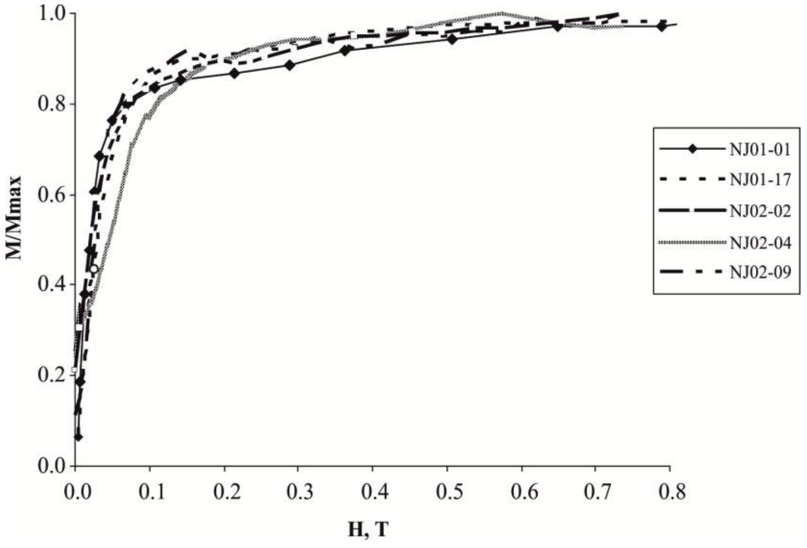

Fig. 2. Examples of progressive acquisition of isothermal remanent magnetization up to 0.9 T for several fragments from NJ01 and NJ02.

Archeointensity experiments. The laboratory thermoremanent magnetization was acquired in a field of 50 µT or 55 µT (that is a value close to the expected intensity) using a cooling rate of 25°C/min or 2°C/min. The Triaxe data were retained according to a set of selection criteria [e.g. *Gallet and Le Goff*, 2006; *Genevey et al.*, 2013]. Following are two of them:

1. The curves depicting the ratios between the demagnetized fractions of natural remanent and laboratory thermoremanent magnetizations across the selected temperature interval must be fairly horizontal. This is evaluated both qualitatively and quantitatively using parameter S, which gives the difference (in %) between the intensities obtained at low and high temperatures, assuming a linear evolution across the entire temperature interval. The S value must be of less than 10%. For our retained specimens, S ranges from 0% to 8%;
2. The intensity data must rely on a significant fraction (>50%) of the magnetization carried by the fragments above the minimum temperature considered for the intensity determinations (referred to as T1 or T1'; e.g. *Genevey et al.*, [2013]). For our collection, the proportions vary from 65% to 98%.

The fragments successfully analyzed generally possess an univectorial magnetization component isolated from low to high temperatures. The intensity values were therefore determined over a large temperature range from 175-205°C (T1') to 505-520^{o}C (T2). Among the retained fragments, only one fragment (NJ01-22) displayed a rather large secondary magnetization component, which is likely due to a second heating of the corresponding tile. In this case, it is worth mentioning that the temperature interval of analysis was reduced to between 325-335°C and 510-520^{o}C (Table 1).

Results satisfying the quality criteria were obtained for five fragments (30 specimens) from group NJ01 and four fragments (21 specimens) from group NJ02. For the other fragments, data could not be obtained either because of the presence of a large secondary magnetization component or because their magnetization was too weak to be measured with the Triaxe magnetometer. Four to seven specimens were successfully analyzed for each retained fragment (Table 1, Fig. 3). At the fragment level, the standard deviation of the means varies from 0.4 μT to 2.1 μT (i.e. from 0.8% to 4.4% of the corresponding mean).

The results indicate that there is no statistical difference between the intensity determinations obtained using a cooling rate of 25°C/minute and of 2°C/minute for the laboratory thermoremanent magnetization acquisition (difference of 2% and 1.9% for group NJ01 and NJ02, respectively). The original cooling rate experienced by the tile fragments (that is obviously lower than 25°C/minute) is unknown. However, the absence of statistical difference between the intensity values obtained using the two cooling rates strengthens the argument that the Triaxe protocol gives the ability to overcome this uncertainty.

Table 1. Archeointensity results obtained from the New Jerusalem monastery

Fragment	***Specimen***	***Cooling rate, (°C/mn)***	***H_{lab} (μT)***	***Tmin - Tmax (° C)***	***NRM T1 (T1') (%)***	***S (%)***	***$F_{spec.}$ (μT)***	***F_{mean} at the fragment level ±σF (μT)***
New Jerusalem monastery, site NJ01 (1680–1690 AD)								
NJ01-01	a	25	50	195–520	93	–3	49.6	49.4±1.4
	b	25	50	195–520	94	1	51.2	
	c	25	50	200–520	95	–4	50.0	
	a-v2	2	50	360–520	92	2	49.9	
	e-v2	2	50	190–515	96	2	48.0	
	f-v2	2	50	195–515	90	5	47.5	
NJ01-02	a	25	50	195–510	97	–1	49.4	48.4±0.8
	b	25	50	200–510	98	–1	48.1	
	c	25	50	200–515	96	2	49.3	
	d-v2	2	50	200–510	96	0	48.4	
	e-v2	2	50	195–520	97	–3	47.6	
	f-v2	2	50	205–510	98	–2	47.7	
NJ01-17	a	25	55	240–520	67	4	53.0	52.3±0.4
	b	25	55	255–530	72	4	52.2	
	c	25	55	220–530	73	3	52.5	
	d-v2	2	50	270–515	69	–2	52.3	
	e-v2	2	50	260–515	67	–1	51.9	
	f-v2	2	50	245–520	71	1	51.8	
NJ01-18	a	25	55	175–520	85	3	53.5	52.3±1.1
	b	25	55	175–520	85	4	52.8	
	c	25	55	175–520	84	3	53.1	
	g	25	50	175–520	84	3	52.0	
	a-v2	2	50	175–520	85	1	51.8	
	e-v2	2	50	175–505	82	–3	52.4	
	f-v2	2	50	175–515	82	–6	50.3	
NJ01-22	a	25	55	325–525	96	4	48.5	48.6±0.7
	b	25	55	335–520	95	1	48.5	
	c	25	55	335–525	96	5	48.8	
	e-v2	2	50	325–515	96	–6	49.5	
	f-v2	2	50	335–515	96	2	47.6	

New Jerusalem monastery, site NJ02 (1710–1720 AD)								
NJ02-02	a	25	50	180–520	78	6	49.4	47.2±1.6
	b	25	50	180–520	96	2	47.3	
	d-v2	2	50	175–510	96	3	46.2	
	e-v2	2	50	175–510	96	–2	47.9	
	f-v2	2	50	175–515	94	8	45.3	
NJ02-04	a	25	50	180–520	93	–2	46.1	45.8±1.8
	b	25	50	180–520	92	–2	47.6	
	c	25	50	180–520	94	–2	47.1	
	d-v2	2	50	200–520	93	–6	46.9	
	e-v2	2	50	175–520	94	0	43.2	
	a-v2	2	50	175–520	95	–3	44.1	
NJ02-09	a	25	50	180–520	80	4	50.3	47.4±2.1
	b	25	50	225–520	75	–2	45.7	
	c	25	50	190–520	93	0	48.3	
	b-v2	2	50	175–515	86	–4	44.6	
	e-v2	2	50	175–510	79	–4	46.8	
	f-v2	2	50	175–510	65	2	48.6	
NJ02-14	a	25	50	175–515	80	1	48.4	50.2±1.3
	b	25	50	175–510	85	–2	49.9	
	c-v2	2	50	185–510	83	–5	51.2	
	d-v2	2	50	175–510	80	–1	51.2	

Notes: First and second columns: name of the fragments and associated specimens. Third and fourth columns: cooling rate and laboratory field used for laboratory thermoremanent magnetization acquisition. Fifth column: temperature interval used for archeointensity determinations. Sixth column: fraction (in %) of NRM involved in intensity determination (from T1 or T1'). Seventh column: slope (in %) of the intensity data obtained for each specimen within the temperature interval of analysis. Eighth column: intensity value in μT derived for each specimen. Ninth column: mean intensity in μT computed at the fragment level with its standard deviation.

Fig. 4 shows a comparison between our new data and the results spanning the past 600 years previously obtained in Central Russia and adjacent regions (i.e. within a 500 km-radius circle around Borovichi, thus including Moscow and St. Petersburg areas). The horizontal and vertical lines associated with each mean intensity value represent the uncertainties with respect to dating and mean determinations, respectively. All intensity values were transferred to the latitude of Moscow using the VADM (Virtual Axial Dipole Moment) approximation [e.g. *Merrill et al.*, 1996].

At this stage of our study, the conclusions are the following:

1. The mean archeointensity values obtained from the New Jerusalem monastery are 50.2±2.0μT for group NJ01 (1680-1690 AD) and 47.7±1.8μT for group NJ02 (1710-1720 AD).
2. The data from groups NJ01 and NJ02 lie within the distribution of the archeointensity results previously obtained by *Burlatskaya* [1970], *Burlatskaya et al.* [1986], *Nachasova* [1972], *Donadini et al.* [2007] and *Pesonen et al.* [1995]. However, the latter results are very scattered, which may either indicate the fact that at least some data are not accurate or that large and rapid field intensity variations occurred during this time interval. We note that the data obtained in Bulgaria [*Kovacheva et. al*, 2009] for the same time interval raise a very similar issue.

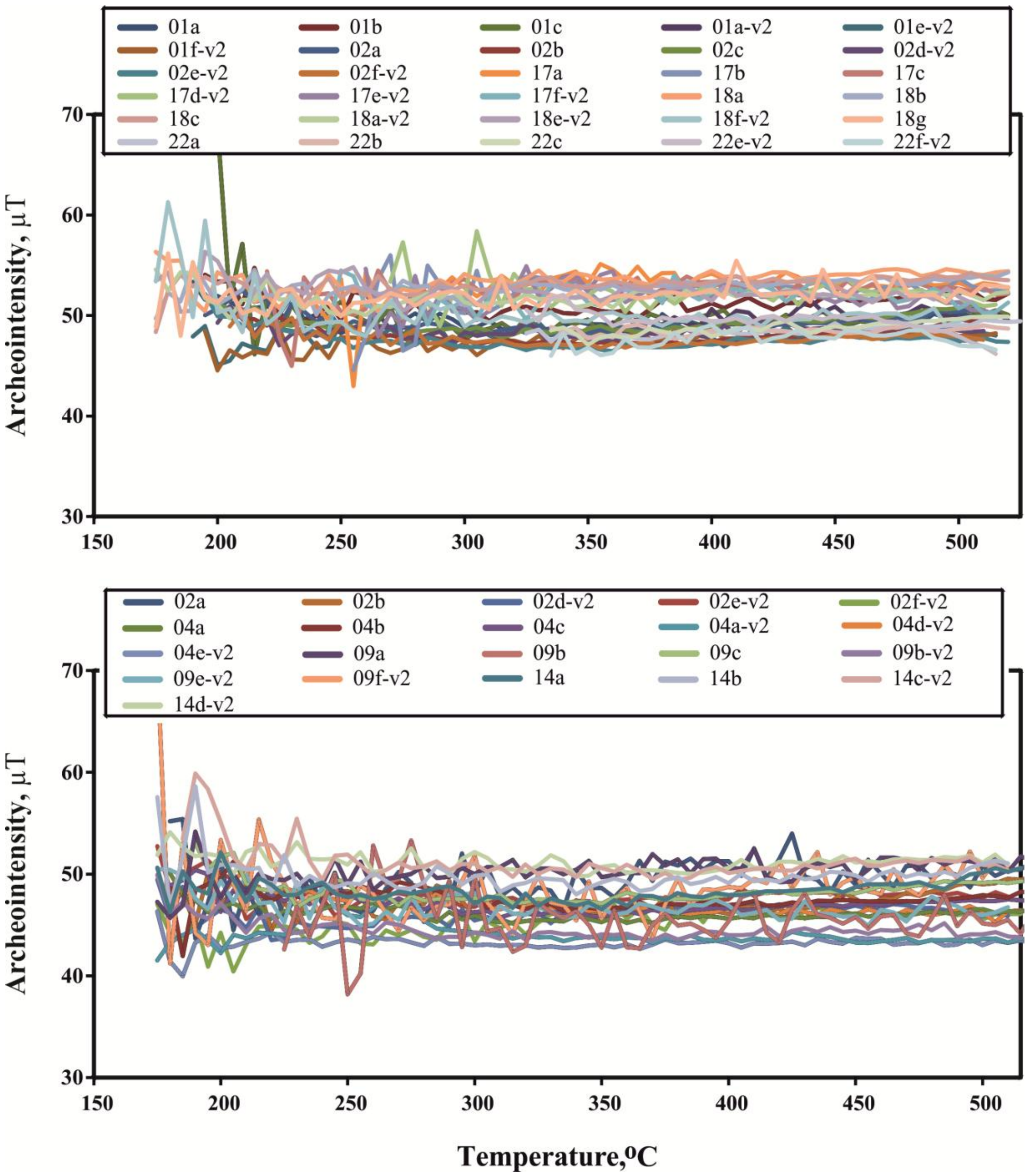

Fig. 3. Archeointensity data obtained for groups NJ01 (upper panel) and NJ02 (lower panel). Each individual curve exhibits the intensity data obtained for one specimen across the selected temperature interval.

3. Our new results appear in good agreement with the archeointensity variation curve obtained for Western Europe [*Genevey et al.*, 2009; 2013] after its transfer to the latitude of Moscow using the VADM approximation. This argues for the probable absence of a significant non-dipole field effect between Western and Eastern Europe during the time interval of concern. However, we recognize that at this step, constraining the homogeneity of the intensity variations at the European scale still requires the acquisition of new archeointensity data.

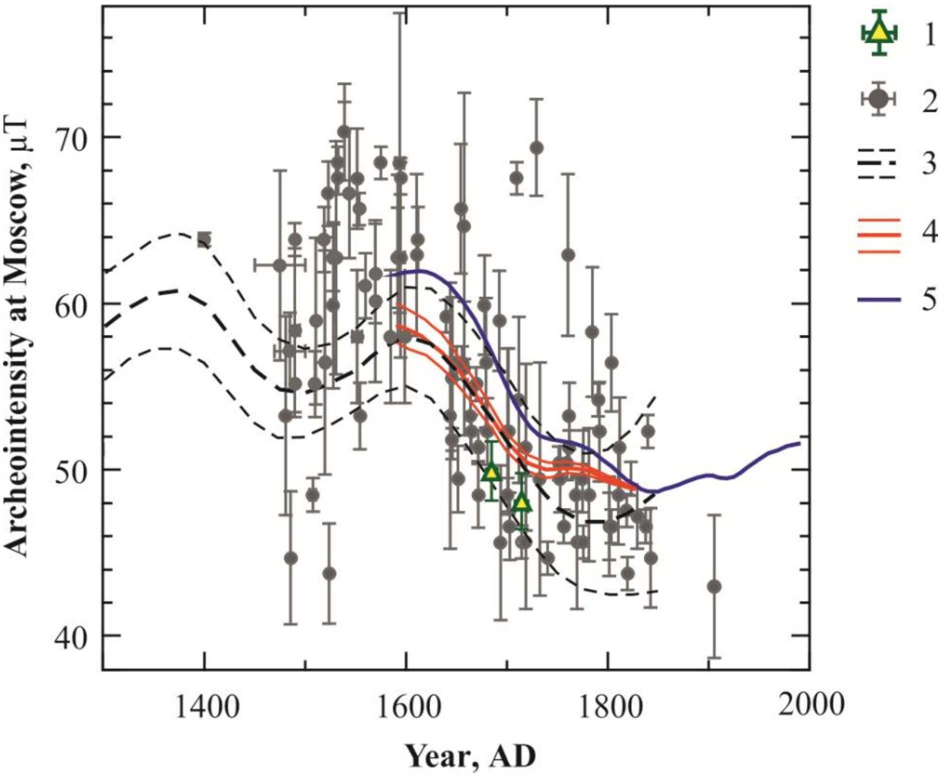

Fig. 4. Comparison of the New Jerusalem data with previous archeointensity results obtained in the same region (grey symbols), from Western Europe (dashed lines) and with the field intensity values derived from available historical geomagnetic field models. 1: New results reported in the present study. 2: Previous results obtained by *Burlatskaya* [1970], *Burlatskaya et al.* [1986], *Nachasova* [1972], *Donadini et al.* [2007] and *Pesonen et al.* [1995]. 4, 5: Intensity values expected from two versions of historical geomagnetic field models (4, red curve: *Gubbins et al.* [2006]; 5, blue curve: *Jackson et al.* [2000]).

4. The New Jerusalem data are slightly lower than the intensity values expected from the historical geomagnetic field model that assumes a rather flat evolution of the geocentric axial dipole moment between 1600 and 1840 AD [*Gubbins et al.*, 2006]. In Jackson et al. [2000], the latter evolution is marked by higher axial dipole moments with a significant decreasing trend, yielding expected intensity values that are much higher (by ~5 µT) than our new data (Fig. 4).

It is worth mentioning that the implications of our data are still preliminary, and their strengthening requires continuing archeomagnetic investigations in the European part of Russia.

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