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A Method and Results of Studying the Geomagnetic Field of Khiva from the Middle of the Sixteenth Century

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The collection gathered at Khiva is represented by 250 bricks from 32 dated architectural monuments [1]. For the purpose of obtaining information about the old geomagnetic field in this region, the collection was treated by two methods—Tellier's method [2] and the method of thermal curves. The method of thermal curves, proposed earlier [3], was tested in this study on an extensive collection.

From the bricks we sawed off cubic samples oriented along the faces of the brick—with an edge of 24 mm for work according to Tellier's method and with an edge of 10 mm for work by the method of thermal curves. Before the measurement the samples were carefully washed under a stream of water, in order to remove from the faces and from the pores of the sample the clay remaining after sawing and polishing the sample. During work by the method of thermal curves the experiments were carried out on a thermomagnetometer, the design of which is described in [4]. In determining the magnetization of a sample along its axes, use is made of the property of the device's phase detector to carry out an operation of multiplication of the signal from the sample which is proportional to the projection of the magnetization vector onto the horizontal plane, onto the cosine of the reference voltage angle—this angle is read off from the limb of the reference voltage generator. Therefore, by setting the limb of the generator on 0 or 180°, we can measure the magnetization component along the sample holder; at 270 or 90° the component perpendicular to the axis of the sample holder is measured. With three methods of fastening the sample in the holder each magnetization component will be measured twice; from the results obtained we can calculate the mean value of the components and the error:

$$I_x \pm \Delta I_x, \quad I_y \pm \Delta I_y, \quad I_z \pm \Delta I_z.$$

We took as the z-axis of the sample the axis along which the magnetization is maximum, assuming that during the firing of the brick one of its sides was horizontal (but from early works [5] it is known that the field inclination in adjacent regions (Samarkand, Bukhara) during the investigated time interval was greater than 50°); we took as the y-axis the direction with minimum magnetization.

From the data obtained we calculated the modulus of the remanent magnetization vector M, the old inclination J, and the coefficient C with a relative error $\Delta C/C$:

$$M = \sqrt{I_x^2 + I_y^2 + I_z^2},$$

$$J = \arcsin \frac{I_z}{M},$$

$$C = \frac{M}{\sqrt{I_x^2 + I_z^2}},$$

$$\frac{\Delta C}{C} = \frac{1}{M^2}\left[I_y \Delta I_y + \frac{(I_x \Delta I_x + I_z \Delta I_z) I_y^2}{I_x^2 + I_y^2} \right].$$

In measuring the magnetization of a sample during heating, the sample is mounted in a holder with its y-axis downward, i.e., only the projection of the I_{xz} magnetization vector on the xz plane is measured, and the coefficient C shows how many times greater the total moment is than its projection on this plane.

If there is a secondary magnetization in the sample, arising from the time of the laying of the brick in the building and, as a rule, not parallel to the primary magnetization, then the vector in the xz plane will rotate during heating. The heating of such samples was carried out until the rotation of the vector stopped. After this, the sample was cooled to room temperature without a field, and the components of the magnetization, which was taken to be the primary one, were measured again. The values of M, J, C, and C/C in this case were determined over again. Further heating of the sample was carried out from the temperature at which cleaning of the sample was terminated.

A typical temperature dependence of the rotation of the magnetization vector φ_{xz} in the xz plane is shown in Fig. 1. The bulk of the samples are cleaned to temperatures of 100-120°C. The small values of $\Delta\varphi_{xz}$ (0-5°) and the low cleaning temperatures enable us to assume the presence of an isothermal viscous magnetization in these samples. Only isolated samples with a secondary firing at high temperatures are encountered in the collection.

The magnetization of the sample was measured at 20° intervals from 40 to 700°C. In order to create an artificial thermal magnetization in the sample, it was cooled from 700°C to room temperature in the field of the magnetizing coils of the device. The field strength was determined from the current i in the coils, the constant of which $\varepsilon = 17.55$ Oe/amp, and usually amounted to about 0.5 Oe. The field direction—horizontal, was usually given from the direction of the projection of the natural magnetization. After cooling the sample to room temperature, the sample was heated and a measurement of the remanent magnetization I_r was carried out at the same temperatures as in the case of I_n. The values of $(I_{xz})_j$ and $(I_{rt})_j$ obtained at each j-th temperature were plotted on a graph in the coordinates I_{xz}, I_{rt}. A straight line $I_{xz} = KI_{rt}$ was drawn by the method of least squares through the points obtained (Fig. 1).

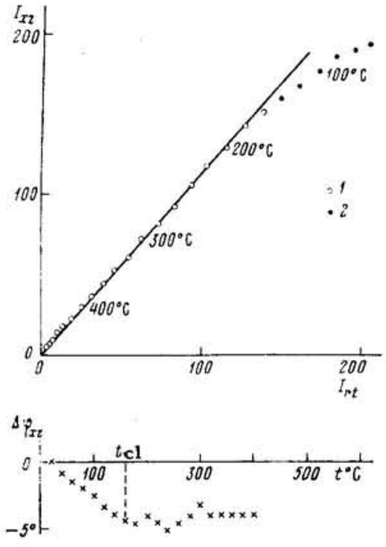

Fig. 1. Graph for determining the coefficient K.

The line is drawn through the origin and the significant points 1; points 2 are discarded during cleaning. Below—rotation of the I_n vector in the xz plane as a function of temperature; t_{cl} is the cleaning temperature.

In the calculation of the value of K we incorporated all the significant points, except the ones discarded during cleaning. Assuming that the weight of a point is proportional to the magnetization, we determine K as:

$$K = \frac{\sum_j^n (I_{xz})_j (I_{rt})_j}{\sum_j^n (I_{rt})_j^2},$$

$$\sigma_K = \sqrt{\frac{\sum_j^n [K(I_{rt})_j - (I_{xz})_j]^2}{(n-1)\sum_j^n (I_{rt})_j^2}}.$$

The strength of the old field is determined as F = = KCiε, while the variance σ_F^2 is estimated from the expression:

$$\sigma_F = \sqrt{\sigma_K^2 + \left(\frac{\Delta C}{C}\right)^2 + \left[\left(\frac{\Delta i}{i}\right)^2 + \left(\frac{\Delta b}{b}\right)^2\right]}.$$

The term in brackets, which takes into account the error in determining the magnetization current i and the instability (slow drift) of the amplification factor b of the thermomagnetometer, was taken to be the same for all the samples, equal to ~0.55%, since $\Delta i/i$ amounts to ~0.2-0.3%, while $\Delta b/b$ during the time required to measure a single sample amounts to 0.3-0.5%. It should be noted that if no changes occur in the sample during heating, all the experimental points lie on a straight line passing through the origin. The variance σ_K^2 in this case characterizes the accuracy of the measurements. If, on the other hand, changes have occurred in the sample, and the typical sign of such changes is a shift of the blocking temperatures (as a rule, into the low-temperature range), then the points will lie either on a curved line or (and this often happens) on a straight line which does not pass through the origin. If there are two or more types of ferromagnetics in the sample, differing in their heat resistance, the points will again not lie on a single straight line. In such cases σ_K^2 is no longer actually a mathematical quantity—the variance, but is a quantity reflecting the degree of changes which have occurred in the sample both during heating and during the time of existence of the sample (the loss of primary magnetization). Naturally, the greater these changes, the greater σ_K will be. Therefore, in averaging the data over an object, $\bar{F}$ is calculated as a weighted mean:

$$\bar{F} = \frac{\sum^m F_i P_i}{\sum^m P_i},$$

$$\Delta\bar{F} = \sqrt{\frac{\sum^m (\bar{F}-F_i)^2 P_i}{\sum^m P_i}},$$

$$\sigma_{\bar{F}} = \frac{\Delta\bar{F}}{\sqrt{m-1}},$$

where $P_i = 10^{-4}/(\sigma_F)_i^2$ and m is the number of determinations for the given object.

From the obtained values of $\bar{F}$, $\Delta\bar{F}$ we determined the confidence interval corresponding to $3\Delta\bar{F}$; determinations lying outside of this interval were discarded, and the values of $\bar{F}$ and $\Delta\bar{F}$ were calculated over again without the discarded determinations.

The quantity ΣP_i is an important parameter, reflecting the quantity and quality of the measurements. We considered the measurements to be reliable if $\Sigma P_i > 10$; if this value was not reached, the collection was supplemented with new samples from the given object, and on these additional measurements were carried out.

A characteristic feature of the Khiva collection is the fact that it is represented by two types of bricks—red and white. These bricks also differ with respect to a number of other properties. For example, red bricks contain a larger quantity of soluble salts than white ones, which obviously causes them to disintegrate faster in structures. Red bricks are also more

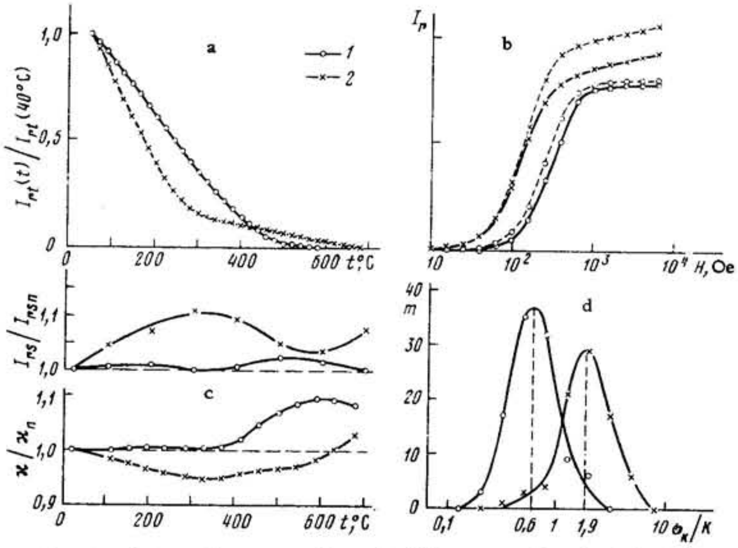

Fig. 2. Magnetic properties of white (1) and red (2) bricks: a) curves of thermal demagnetization of total thermal magnetization, b) curves of normal magnetization of the samples before heating (solid line) and after heating to 700°C (broken line), c) change in the saturation magnetization and initial magnetic susceptibility after heating the sample to a temperature of t°C, d) histograms of the distribution of the relative errors of the determination of K by the method of thermal curves, σ_K/K is expressed in percents.

hygroscopic and lose more weight during heating. They also differ magnetically (Fig. 2). Red bricks are characterized by the presence of two ferromagnetic phases with Curie points of 240-260°C and 675°C (hematite), while in white bricks basically only one phase with a Curie point ~ 420°C is present (Fig. 2a). The natural remanent magnetization of white bricks is 3 to 10 times greater than that of red bricks. The magnetization of white bricks is distinguished by greater resistance to a field (Fig. 2b). After heating to 700°C, a characteristic change in the case of white bricks is a displacement of the coercive spectrum (a parallel shift of the magnetization curve) into the weak-field range without any significant change in the remanent saturation magnetization (broken curve). Typical of red bricks is a deformation of the magnetization curve, which manifests itself, on the one hand, in an increase in the saturation magnetization after heating (broken curve), and, on the other, in the fact that the initial section of the magnetization curve (the Rayleigh range) lies somewhat below the primary curve. The changes in the saturation magnetization and the initial magnetic susceptibility after heating the samples to a temperature of t°C are shown in Fig. 2c, where it may be seen that in the case of white samples these parameters remain constant to 400°C, while in the case of red ones they vary continuously, starting from 100°C.

The determinations of field strength on red bricks do not introduce any significant contribution to the determination of the weighted mean value of the field for the object, since the error σ_K/K for them is significantly greater than for white bricks (Fig. 2c).

Taking the above-said into account, we carried out the field strength determination by Tellier's method of double heatings mainly on white bricks, and we used the magnetic susceptibility determination as a control of the mineralogical changes. We took into account determinations of I_n and I_{rt} to the temperature at which the susceptibility changed by more than 5%. For certain objects we also carried out determinations on red bricks; in this case we used the temperature range from 250 to 500°C.

From the values of I_n and I_{rt} obtained for each temperature we calculated the strength of the old field F_{old}, the rms error σ_F, and the extrapolated value of the natural magnetization I_{n0}:

$$K=\frac{n\sum_i^n (I_n)_i (I_{rt})_i-\sum_i^n (I_{rt})_i \sum_i^n (I_n)_i}{n\sum_i^n (I_{rt})_i^2-\left[\sum_i^n (I_{rt})_i\right]^2},$$

$$I_{n0}=\frac{\sum_i^n (I_n)_i-K\sum_i^n (I_{rt})_i}{n},$$

Date	Object	$\bar{F}$, oe	$\sigma_{\bar{F}}$, oe	m	$\bar{J}°$	$\sigma_{\bar{J}}°$	m
1549	Uch-Ovliya mausoleum	0,501	0,022	11	57,1	3,4	8
		0,502	0,013	8	57,7	3,2	8
1616	Arab-Muhammed-khana	0,466	0,007	9	58,6	4,6	7
	medrese	0,451	0,008	6	61,6	4,5	6
1657	Ak-mosque and Anusha-	0,452	0,016	6	56,3	4,7	4
	khana baths	0,444	0,013	3	60,9	5,3	3
1718–1719	Shirgazi-khana medrese	0,465	0,010	10	54,6	3,4	8
		0,462	0,015	4	47,0	0,4	4
1726–1728	Shirgazi-khana tomb	0,490	0,017	14	63,6	3,6	8
		0,470	0,010	6	63,9	4,0	7
1765	Muhammed-Amin-	0,462	0,012	19	52,6	1,5	10
	inaka medrese	0,427	0,006	7	52,2	1,7	7
1785–1805	Ermagomed-Divan	0,450	0,007	8	54,0	2,8	6
	mosque	0,450	0,004	3	51,0	4,5	3
1804–1806	Palvan-Darvaza gate	0,461	0,008	5	62,1	3.0	4
		0.467	0,019	4	54,8	5.2	4
1804–1812	Kutlug-Murad-inaka	0,473	0,013	6	58,4	2,5	6
	medrese	0,449	0,009	4	56,7	5,3	4
1810	Palvan-Baba mausoleum	0,446	0,018	7	53,0	3.5	3
		0,456	0,007	3	53,7	7,4	3
1820–1830	Dash-Darvaza gate	0,446	0,009	6	53,9	3,7	5
		0,453	0,016	3	51,2	7,3	3
1833	Tim Alla-Kuli-khana	0,494	0,010	5	66,1	1,4	4
	caravansary	0,457	0,024	2	70,7	2,9	2
1834	Alla-Kuli-khana	0,469	0,011	6	49,7	2,6	4
	medrese	0,458	0,026	5	49,2	3,2	5
1830–1838	Alla-Kuli-khana	0,462	0,008	8	57,0	3,8	8
	Tash-khauli palace	0,451	0,010	3	62,4	0,7	3
1832–1841	Kunya-Ark	0,490	0,011	7	54,8	2,7	6
		0,461	0,002	2	61,1	2,5	2
1839	Khodzhmi-Melorima	0,481	0,016	4	59,6	3,0	3
		0,473	0,002	1	54.9		1
1841	Musa-Tyure medrese	0,457	0,004	11	57,5	1,9	10
		0,427	0,001	7	59,3	3,2	7
1842	Sent-baya mosque	0,462	0.009	5	65.0	0,9	2
		0,412	0,016	2	66.5	0,6	2
1842	Koy-Darvaza gate	0.463	0,015	10	53,9	4,5	7
		0,467	0,016	4	49,8	5,3	4
1851–1852	Muhammed-Amin-	0,478	0,003	4	62,8	2,9	3
	khana medrese	0,465	0.011	3	63,5	2.2	3
1854–1855	Abdullah (Bolo-khana)	0,471	0,011	11	56,1	3.8	9
	medrese	0,441	0,007	5	54,4	5,0	5
1864	Korikhona	0,481	0,007	7	59,4	3,6	6
		0.471	0,008	4	64,2	2,4	4
1870	Amir-Tyure medrese	0.480	0,011	4	63,6	1,6	4
		0,439	0,007	4	64,3	1.3	4
1871	Mat'yaz-Divan-Begi	0,475	0,008	23	50,4	2.1	15
	medrese	0,433	0.006	8	49,9	3,0	8
1871	Muhammed-Rakhim-	0,484	0,011	10	51.5	2,9	9
	khana medrese	0,439	0,003	2	44,2	2,7	2
1882	Dost-Alyam medrese	0,471	0,015	10	57.9	2,6	9
		0,466	0,006	4	59,9	2.1	4
1882–1884	Atadzhan-bay medrese,	0,467	0,015	8	56,6	2,8	8
	Mazari-sherif	0,471	0.008	3	57,1	1,7	3
1885	Tort-Shabbaz	0,465	0.004	6	56,0	4,1	6
		—	—	—	—	—	—
1905	Matpana-baya medrese	0,482	0,008	6	59,7	2,1	4
		0.459	0,010	4	59,3	3.0	4
1905	Kazi-Kalyan-Akhun	0.468	0,006	7	56.4	5,3	6
	medrese	0.455	0,006	5	59,3	5,9	5
1905	Ulbay-Khorezmi-ogly	0,468	0,008	1	51,8	10,0	2
	medrese	0,475	0,001	2	49.4	10,0	2
1906	Yusup-Yasaul-bashi	0,475	0,014	5	59,7	4.2	4
	medrese	0,437	0,007	4	56,5	5,0	4

$$\sigma_K = \sqrt{\frac{n\left[\sum_i^n (I_n)_i^2 - I_{n0}\sum_i^n (I_n)_i - K\sum_i^n (I_n)_i (I_{rt})_i\right]}{(n-2)\left\{n\sum_i^n (I_{rt})_i^2 - \left[\sum_i^n (I_{rt})_i\right]^2\right\}}},$$

$$F_{old} = K\cdot F_{lab}, \qquad \sigma_F = \sigma_K \cdot F_{lab},$$

where F_{lab} is the strength of the laboratory field, and n is the number of temperature ranges.

For certain samples the value of σ_F was found to be very small, less than 200 gamma; in calculating the weighted mean values of the field of an object, too large a weight would be given to these samples. We estimated the real value of the field variance σ_0 from a number of objects for which there were a sufficient number of determinations with $\sigma_F < 0.005$ Oe. It turned out to be equal to 0.012 Oe. In determining the weighted mean value of the field for an object, the weight of each determination was taken to be

$$P_i = \frac{10^{-4}}{\sigma_F^2 + \sigma_0^2}.$$

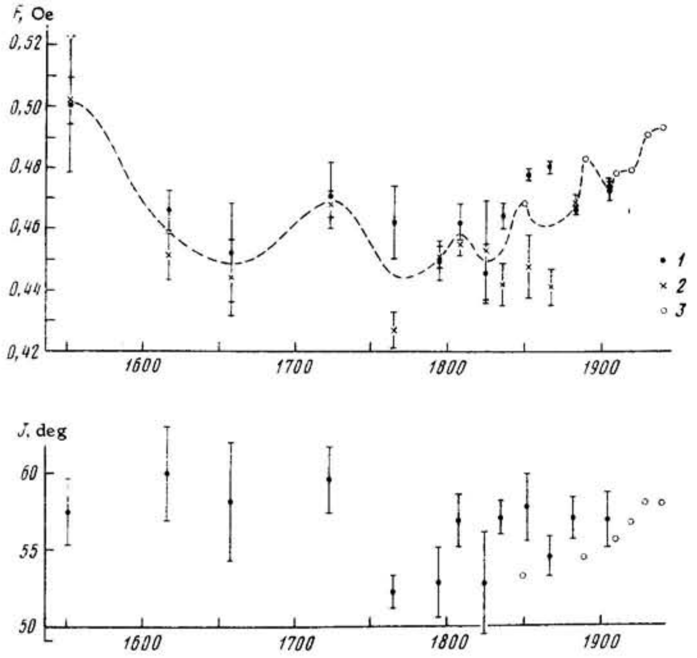

Fig. 3. Mean values of the geomagnetic field strength.

Obtained: 1) by the method of thermal curves, 2) by Tellier's method, 3) results of direct determinations [6]. Below—mean values of the inclination, obtained by both methods; the white dots are the results of direct determinations [6].

The results of the determinations of the field strength and inclination from the objects are presented in the table. The upper lines are the results obtained in work by the method of thermal curves, while the lower lines are the results obtained by Tellier's method; m is the number of investigated samples; σ_F and σ_J are the rms errors of the determination.

The discrepancies in the determinations of the geomagnetic field strength F in most cases lie within the limits of the determination errors. Shown in Fig. 3 are values of F which are average for objects the dating of which differs within a range of several years (no more than 10 years). The difference in the values of F exceeds the limits of the determination errors in four out of thirteen cases, which is natural, since the rms error corresponds to the 67% probability level. Two-thirds of the values of F determined by Tellier's method lie below the determinations of F obtained by the method of thermal curves. The discrepancies in cases where the former lie above are very small (several times less than the errors), i.e., they are of random nature. The understated values obtained by Tellier's method are apparently attributable to the fact that, when this method is used and we assume invariability of the composition and magnetic properties of the ferromagnetic fraction, we are limiting ourselves to a comparatively low-temperature range, the upper limit of which usually does not exceed 450°C. On the other hand, ferromagnetics with low blocking temperatures can lose a part of their initial magnetization. The method of thermal curves encompasses a higher-temperature range and includes stabler ferromagnetics.

A comparison of the data obtained with the results of direct observations [6] showed that the results of direct observations [6] shows that the results of direct observations lie between the values obtained by us by the different methods. The data obtained by the method of thermal curves lie somewhat closer to them.

The results of the determination of the inclination J are of tentative nature, owing to the low accuracy of the determinations. This is obviously due to the deviation of the axes of the brick form the vertical during firing, which amounts, on the average, to 9°. With field inclinations of less than 54° cases can occur where the inclination of the magnetization relative to the faces of the brick amounts to less than 45°. The artificial choice of the axis with the maximum magnetization as the z-axis of the brick leads to a displacement of the distribution function of the values of the individual determinations of J relative to the real value of the field inclination. Samples the inclinations of which were in reality less than 450° were reoriented in such a way that the inclination was increased. As a result, this led to a certain overstating of the mean value of the field inclination (Fig. 3).

The Khiva region is characterized by a field strength variation amplitude which is small in comparison, for example, with that of the Moscow region. In the geomagnetic field strength variation we can see the presence of a long wave and also short periods lasting several decades. The minimum of the long-period wave occurs in the second half of the eighteenth century, while in the case of the Moscow region it occurs in the middle of the nineteenth century, which once again confirms the presence of a westerly drift of the long-period part of the geomagnetic field at a rate of approximately 0.3° per year.

Thus on an extensive collection (383 samples) a comparison has been made of data obtained by the method of thermal curves and Tellier's method. The results coincide within the limits of the determination errors. The presence of short-period (~60 years) geomagnetic field variations has been confirmed once again.

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