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Calibration of geomagnetic paleointensity data based on redeposition of sedimentary rocks

A.Yu. Kurazhkovskii *, N.A. Kurazhkovskaya, B.I. Klain

Geophysical Observatory Borok, Institute of Physics of the Earth, Russian Academy of Sciences, Borok, Yaroslavl Region 152742, Russian Federation

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ABSTRACT

A new express-method for redeposition of sedimentary rocks is proposed. The method may be used for calibration of the ancient geomagnetic field intensity data obtained using sedimentary rocks. The results of testing of the method for assessment of the intensity of ancient geomagnetic field (using redeposition) on the modern sediments formed in different climatic zones are presented. It is shown that the error of a single determination of the magnetic field intensity on the contemporary marine sediments does not exceed 20%. The results of determination of the ancient geomagnetic field intensity from sedimentary rocks available to date are summarized. The average values of the paleointensity in the Late Cretaceous, Early Jurassic, Late Jurassic, Triassic, Permian, Late and Early Carboniferous obtained from sedimentary and thermomagnetized rocks has been compared. It is revealed that sedimentary and thermomagnetized rocks have similar potentials for the assessment of the dynamics of the Late Paleozoic–Mesozoic paleointensity.

1. Introduction

Perspectives of the use of sedimentary rocks for the study of the intensity of ancient geomagnetic field are quite obvious. Detailed continuous series of the data obtained by studying the sedimentary rocks can be used further to complement the scale of magnetostratigraphic polarity by the scale of paleointensity behavior. The main obstacle in construction of paleointensity scale is a short (usually no more than several millions years) duration of the formation of homogeneous layers of sediments. This is why examinations of sedimentary layers allow only for gaining the fragmentary knowledge on paleointensity behavior. The transformation of the fragments of the paleointensity behavior into a generalized uniform pattern necessitates obtaining the calibrated values. The calibration of the data on sedimentary rocks can be achieved by various methods. For example, for calibration of the Pleistocene paleointensity Valet et al. (2005) used earlier obtained results on thermomagnetized rocks. However this method of calibration is not acceptable yet for the remote intervals of geological time, since as a rule, the data obtained on thermomagnetized rocks are insufficient. There is a method for calibration (determination of absolute or numerical values of paleointensity) which is based on the redeposition (Khramov and Sholpo, 1967). By this method the paleointensity was determined using nonlithified and weakly lithified deposits of the Late Paleozoic and Early Mesozoic (Khramov, 1982). For a long time the comparison of the results of paleointensity determinations obtained on sedimentary and thermomagnetized rocks was difficult because of the lack of the suitable material. For example, according to Bol'shakov and Solodovnikov (1981), for the studies of changes in paleointensity occurred for the past 400 million years both sedimentary and thermomagnetized rocks were used. The age of sedimentary and thermomagnetized rocks differed. In this relation the data on magmatic and sedimentary rocks could supplement each other but were not suitable for intercomparison.

The method of the paleointensity determinations using sediments proposed by Khramov and Sholpo (1967) was rather laborious that did not allow for receiving a large volume of paleomagnetic data. We have sufficiently modified this method (Kurazhkovskii and Kurazhkovskaya, 2001). In a new method the procedure of a laboratory redeposition has been simplified and accelerated. In addition, new testing of petromagnetic properties of deposits for their suitability for paleointensity measurements was applied. Application of this technique made it possible to receive a large volume of information on the magnetic field intensity of the Late Jurassic – Cretaceous (Kurazhkovskii et al., 2010). By the present the amount of paleointensity data on thermomagnetized rocks has also essentially increased (Thomas et al., 2000; Heller et al., 2003; Biggin and Thomas, 2003; Valet, 2003; Tauxe and Yamazaki, 2007). It afforded an opportunity to start the comparison of the results of the paleointensity determinations conducted on sedimentary and thermomagnetized rocks and to discuss the problem of their reasonableness and the possibility of the combined application.

* Corresponding author.
E-mail address: ksasha@borok.yar.ru (A.Yu. Kurazhkovskii).

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In paleomagnetology opinion about the correctness of methods for determination of the ancient magnetic field intensity is based on two tests: (1) Verification of methods on the contemporary geological objects formed in a known magnetic field. (2) The comparison of the paleointensity data obtained on ancient rocks of the same age.

The present study describes the method for calibration of the data on ancient geomagnetic field intensity obtained from sedimentary rocks. The results of testing of correctness of the proposed technique are discussed.

2. Method for determination of geomagnetic field paleointensity

Methods of paleointensity determination (with the use of a redeposition) are based on the relationship between the intensity of detrital remanent magnetization (DRM) of sediments and intensity of the magnetic field in which their accumulation took place (Nagata, 1961). Adequacy of the obtained data depends equally on accuracy of paleointensity value and dating of sedimentary layers. This is why the study of paleointensity should be regarded as continuation of magnetostratigraphic investigations. Samples for the determination of paleointensity should be selected from those same pieces of ores and layers, which were used to magnetostratigraphic studies (in the stratigraphy this is called as "a sample in a sample"). It makes possible to gain the most accurate information about a stratigraphic age of sedimentary layers and the on correspondence of the paleointensity to chrons of magnetic polarity. In addition, the data on magnetomineralogical composition and properties of the natural remanent magnetization obtained during magnetostratigraphic studies can be used in studies of the ancient geomagnetic field intensity. The process of the paleointensity determination is conventionally divided into testing of samples validity and the procedure of determination of its numerical values. Testing of samples validity and their grading is carried out in two stages: before the procedure of a redeposition, and after it.

2.1. Testing of the samples validity before redeposition

The natural remanent magnetization (NRMt) of the samples used for paleointensity determinations should have the orientational nature and should become the single-component at temperatures of cleaning (200–350 °C). Heating to higher temperatures is undesirable because it increases the probability of magnetomineralogical changes of samples. There are no strong evidences for an orientational nature of the magnetization. Nevertheless, there is the set of tests aiding to justify the suggestions on the nature of the remanent magnetization. The paper by Guzhikov et al. (2003) presents the following series of tests testifying to an orientational nature of the magnetization: (1) low inter-layer paleomagnetic concentration (up to several tens) and an inverse dependence of intra-layer paleomagnetic concentration on the sizes of the sediment particles, (2) low values of Königsberger factor (Q) (it is less than 0.1), (3) presence of clastic grains of minerals – carriers of remanent magnetization. These tests can be supplemented. For example, the allothigenic nature of minerals particles – carriers of magnetization is the argument in favour of an orientational nature of magnetization of sediments. According to the monograph by Strakhov (2008), the allothigenic nature of particles – carriers of magnetization is testified by their uniform distribution in the fractions separated during a grain-size analysis. In practice the test consists of the comparison of the weight of fractions separated as a result of a grain-size analysis with the magnitude of saturation isothermal remanent magnetization (SIRM) of these fractions. On the basis of results of the above-mentioned tests the conclusion on the nature of magnetization and suitability of sediments collections for determination of the geomagnetic field intensity can be drawn.

2.2. Procedure of the redeposition

After primary grading and measuring of NRMt values the redeposition of the samples is carried out according to the following rules.

(1) Semi-fluid suspension of the sediment is redeposited. Its initial water content should exceed the water content relevant to the beginning of fluidity but should not be higher than values at which the differentiating of particles by the size and density begins. To eliminate losses of substance it is necessary to prepare suspension in the same vessel in which the redeposition will take place. Redeposition at low water content was conducted for the following reasons.
(2) Redepositional marine aleurite grey-colored sediments acquire the magnetization at low water content. An increase in the initial water content does not lead to the magnetization growth (Kurazhkovskii, 1990). The redeposition at low water content allows for reducing the time of this procedure and reduces probability of magnetomineralogical changes. As the magnetization of redepositioned samples can depend on an ionic composition of the fluid (Bol'shakov and Kurazhkovskii, 1989; van Vreumingen, 1993a,b; Tauxe et al., 2006) marine sediments should be redeposited in a solution of marine salt with concentration of 5–10‰.
(3) In one vessel only one sample is redeposited. It allows for controlling precisely the modification of petromagnetic parameters before and after the redeposition.
(4) The vessel for the redeposition is selected in such way that samples of the natural and redeposited sediment have an equal size and the shape.
(5) Prior to the procedure of an exsiccation the suspension of the sediment should be subjected to transient vibration (for acceleration of formation of the steady texture and stabilization of a remanent magnetization magnitude).
(6) Each sample should be redeposited several times. It allows for detecting the modifications of the magnetomineralogical composition. Fig. 1 presents examples of DRM behavior during several redepositions. The samples in which DRM does not change in the course of several redepositions, are used for paleointensity determinations (Fig. 1, curve a). The monotonic growth or the decrease in the magnetization in the course of reiterated redepositions indicates the magnetomineralogical modifications (Fig. 1, curve b) and such samples should be discarded. It is known that in some cases changes in magnetic susceptibility (K) can indicate magnetomineralogical modifications. However, the use of K measurements for checking the magnetomineralogical modifications is rough and less reliable (Kurazhkovskii, 1990).

According to the proposed technique the redeposition of minimal amount of matter (one sample) is carried out at low initial water content. The procedure from preparation of suspension till the drying the sample takes 1–4 days, i.e. is significantly shorter than in the redeposition method by Khramov and Sholpo (1967). Thus, our method can be regarded as an express-method of redeposition.

2.3. Estimation of numerical values of the paleointensity

The calculation of an ancient geomagnetic field intensity is based on a well-known relationship between the magnitude of

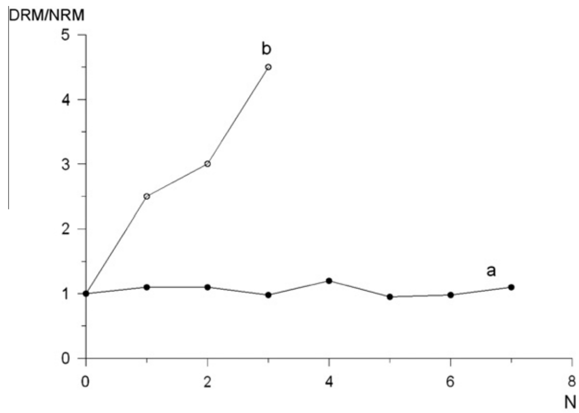

Fig. 1. Examples of changes in the magnetization of the samples DRM/NRM, depending on the number of redepositions (N): (a) the sample collected near the Kirovskii, Astrakhan Oblast, Russia (Table); (b) the sample collected in the central part of the Sea of Azov ($\varphi = 46°$, $\lambda = 36.5°$).

remanent magnetization of sediments and the magnetic field intensity in which their sedimentation took place $H = H_0 * \text{NRMt}/\text{DRMt}$, where H_0 is a magnetic field intensity in laboratory. The ratio $P = \text{NRMt}/\text{DRMt}$ is known as the coefficient of the redeposition using which the behavior of the paleointensity is identified (Khramov and Sholpo, 1967). Our experience shows that if paleointensity is studied according to visually homogeneous sedimentary layers, there is no necessity in redeposition of all samples. Reconstruction of the paleointensity behavior is divided into two phases. First, the relative paleointensity is determined by all samples which is identified based upon the behavior of the parameter $\text{Rnst} = \text{NRMt}/\text{SIRMt}$, where SIRMt is the value of SIRM after the same thermal cleaning that was applied at determination of NRMt. Then, the redeposition of the replicate samples from several (10 is sufficient) layers distributed in the sedimentary column is carried out. According to the results of redeposition the average value of the parameter $\text{Rdst} = \text{DRMt}/\text{SIRMt}$ is determined. Numerical values of the paleointensity are calculated using the equation: $H = H_0 * \text{Rnst}/\text{Rdst}$.

2.4. Testing of the samples validity after redeposition

At determination of the paleointensity the samples in which the magnetization varies during several redepositions (Fig. 1b) should not be considered. Such changes in DRM often take place during redeposition of marine grey-colored sediments. In this regard some of the collections of ancient sediments can not be used for the determination of H.

In addition, samples were rejected, if their DRM is related to H nonlinearly. In marine aleurite grey-colored deposits nonlinear relationship between DRM and H is seldom. However, such relation may take place (Kurazhkovskii and Kurazhkovskaya, 2001; Tauxe et al., 2006) resulting in errors in the determination of H. Usually, the conclusion about the form of relation between DRM and H is drawn on the basis of results of the redeposition of sedimentary rocks in the magnetic fields of varying intensity (Kent, 1973; Tucker, 1980). This is a direct method of determination of the pattern of dependence of DRM on H. Earlier studies have shown (Kurazhkovskii, 2003) that there is an indirect way to detect samples having nonlinear relationship between DRM and H. For instance, if the direction of magnetization of the redeposited samples had differed from the direction of the magnetic field in laboratory by more than 45°, DRM these samples has been related to H nonlinearly.

The examples of the behavior of the declination (D) (Kurazhkovskii and Kurazhkovskaya, 2001) and DRM of the samples that are unsuitable for the determination of H are shown in Fig. 2a and b. These deposits were formed during a Pleistocene transgression of the Black Sea (Kurazhkovskii and Kurazhkovskaya, 2001). In the redeposited samples D is the angle between the horizontal component of magnetization and the horizontal component of the magnetic field. In the average D should be 0° and its permissible changes should not exceed 45°. As seen from Fig. 2a, the declinations of the magnetization of samples from layers 4 to 6 are significantly higher than 45°. These samples are not suitable for the determination of paleointensity. The dependence of the DRM (sample from the layer 4) on the field in which the redeposition took place is shown in Fig. 2b: the magnetization of such samples is nonlinearly related to the intensity of magnetic field.

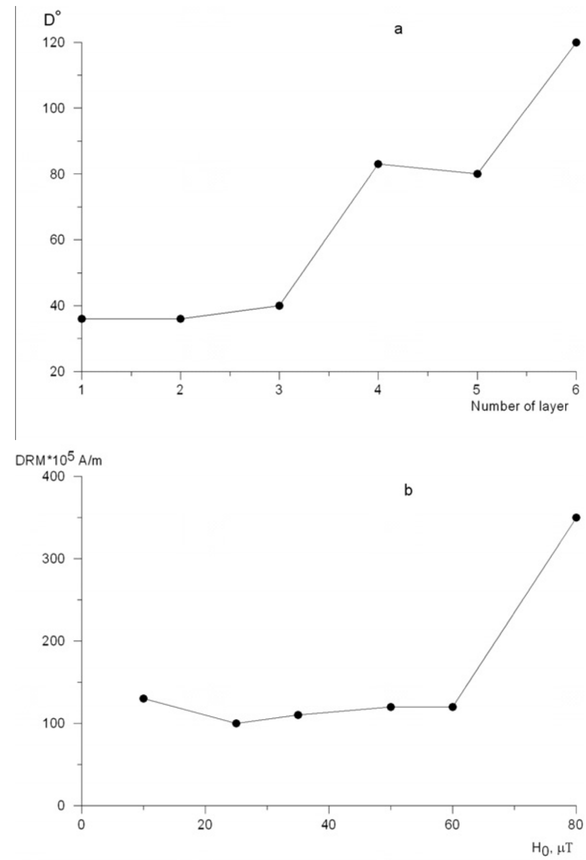

Fig. 2. Examples of behavior of the direction and magnetization of the samples unsuitable for paleointensity determination: (a) change in the declination D of samples redeposited from different layers of one sedimentary thickness, (b) the dependence of DRM on the intensity H_0 of magnetic field, in which the redeposition was carried out.

3. Redeposition of contemporary deposits

The technique for determination of the magnetic field intensity testing was tested on the contemporary marine and freshwater deposits formed in various climatic zones. The samplings of sites of deposits are presented on Fig. 3 and in the Table 1. In addition, in the Table 1 shows the intensity of the geomagnetic field at place of core sampling, number and magnetic parameters of the samples of natural and redepositional sediments. The suggested aim of this testing was to estimate the accuracy to which the magnitude of the remanent magnetization of natural contemporary deposits may be reconstructed using the laboratory redeposition. Values of the contemporary magnetic field intensity at sampling sites varied from

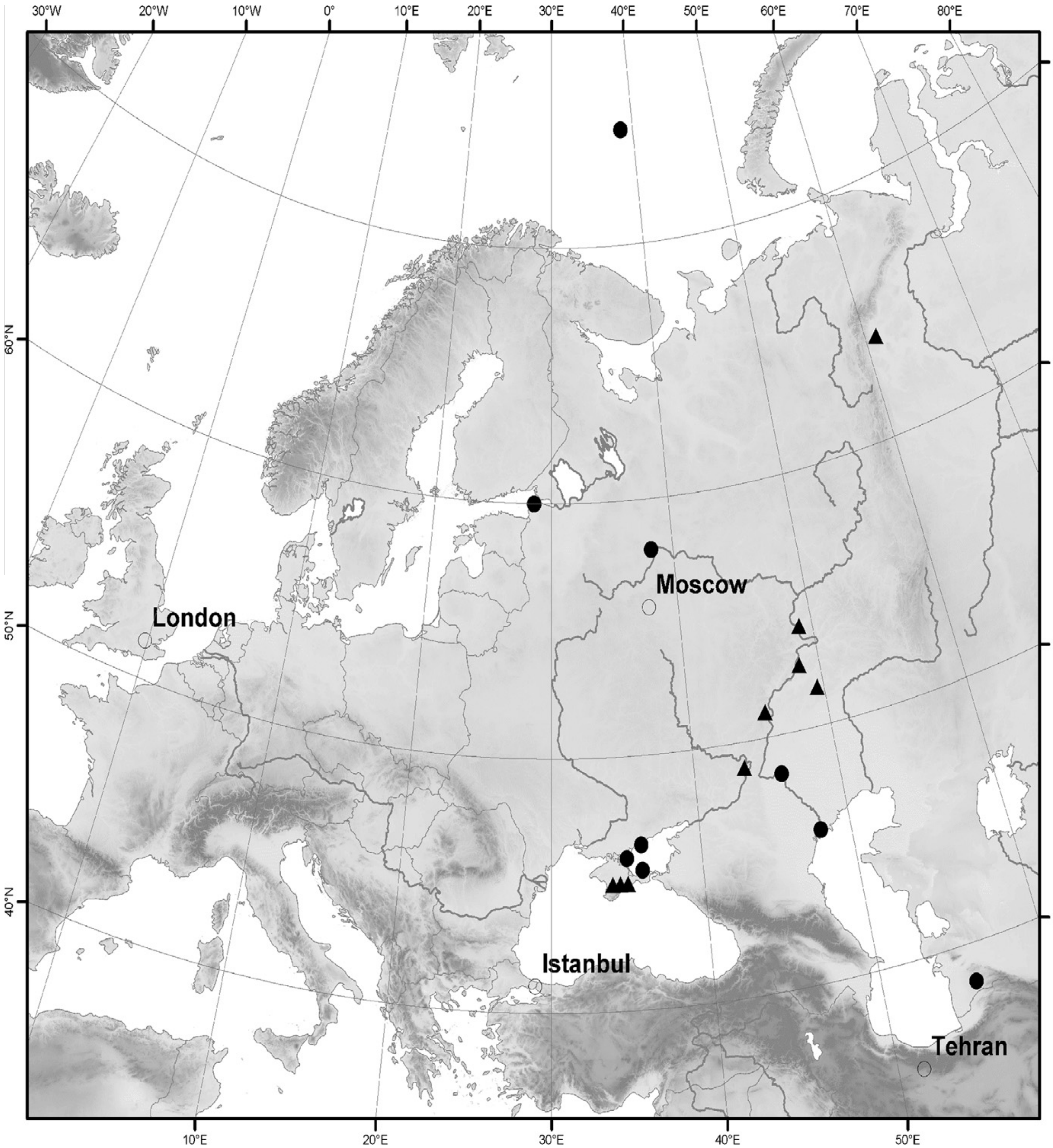

Fig. 3. Sampling sites of the contemporary (circles) and ancient (triangles) sediments.

54 μT (northern part of the Barents Sea) to 46 μT (a southern part of the Sea of Azov). The magnetic field intensity in laboratory in which the redeposition was made amounted to 50 μT. The Table 1 shows that the difference between the magnitude of the magnetic field in laboratory and at sampling sites did not exceed 10%. Little differences in the values of the geomagnetic field intensity had no pronounced effect on the value of the redeposition coefficient P. The used method does not allow for confident detection of 10% changes in the geomagnetic field intensity. The correlation coefficient between P and H/H_0 is 0.2.

The samples were collected by a percussion tube from the horizon 2 to 10 cm lying lower than the water – sediment boundary. The main mass of deposits was formed in reduced chemical conditions as indicated by their grey color. At the same time, some samples were collected from the deposits accumulated in weakly – oxidative conditions (the deposits of the western part of the Sea of Azov, former riverbed lake in the Astrakhan Oblast and Turkmenian takyrs). The color of the deposits had brown tints. The modal size of particles of sediments varied within 8–60 μm. Grain-size analysis of sediments was carried out following the

Table 1
The sampling of sites and results of redeposition of the contemporary sediments.

The sampling of sites	H/H_0	h (m)	n	Q	NRMt∗10^5 (A/m)	DRMt∗10^5 (A/m)	SIRMt∗10^2 (A/m)	P	Rnst∗10^3	Rdst∗10^3
The Sea of Azov, southern part (φ = 45.5°, λ = 36°)	0.92	8	4	0.085	160 ± 12	163 ± 15	48	1.0 ± 0.08	3.4	3.4
		10	4	0.085	160 ± 10	181 ± 17	46	0.87 ± 0.07	3.5	3.9
		12	4	0.070	160 ± 13	168 ± 5	42	0.95 ± 0.08	3.8	4.0
The Sea of Azov, western part (φ = 46°, λ = 35°).	0.93	5	4	0.065	80 ± 8	83 ± 12	40	1.0 ± 0.01	2.0	2.1
		7	4	0.060	90 ± 12	86 ± 4	46	1.05 ± 0.01	2.0	1.9
The Sea of Azov, northern part (φ = 46.5°, λ = 36°).	0.94	5	4	0.075	120 ± 12	132 ± 20	33	0.9 ± 0.11	3.6	4.0
		6	4	0.080	150 ± 12	137 ± 3	38	1.1 ± 0.07	4.0	3.6
		8	4	0.075	160 ± 9	177 ± 18	42	0.9 ± 0.11	3.8	4.2
		11	4	0.070	80 ± 10	94 ± 12	21	0.85 ± 0.10	4.0	4.5
Delta of the Volga River (Kirovskii, Astrakhan Oblast) (φ = 46°, λ = 48°).	0.94	0.2	5	0.060	50 ± 4	55 ± 5	16	0.9 ± 0.08	3.0	3.4
		1.0	5	0.050	40 ± 3	44 ± 4	16	0.9 ± 0.10	2.5	2.8
Delta of the Volga River (lake, Cherny	0.95	0.5	1	0.040	35	35	16	1.0	2.2	2.2
Yar, Astrakhan Oblast) (φ = 48.5°, λ = 46°).		1.0	1	0.040	32	34	15	0.95	2.2	2.3
Rybinsk reservoir (sublitoral) (φ = 58°, λ = 38.2°).	1	1.0	1	0.025	20	17	8	1.2	2.5	2.1
The Gulf of Finland (φ = 60°, λ = 28.5°).	0.98	42	1	0.030	45	44	23	1.03	2.0	1.9
The Barents Sea, southern part (φ = 74.5°, λ = 38.5°).	1.06	80	3	0.040	20 ± 3	19 ± 3	8	1.05 ± 0.10	2.5	2.4
The Barents Sea, (φ = 80.5°, λ = 44.5°)	1.1	143	4	0.092	196 ± 17	206 ± 20	75	0.95 ± 0.08	2.6	2.7
Northern part (φ = 81°, λ = 46°)		205	4	0.098	325 ± 19	295 ± 11	90	1.1 ± 0.07	3.6	3.3
(φ = 79.5°, λ = 42°)		290	4	0.095	90 ± 11	82 ± 15	30	1.1 ± 0.01	3.0	2.7
(φ = 80°, λ = 42°).		325	4	0.080	286 ± 10	317 ± 21	116	0.9 ± 0.09	2.4	2.7
Western Turkmenistan (takyr) (φ = 38.5°, λ = 55.5°).	0.94		5	0.060	60 ± 5	61 ± 5	31	1.0 ± 0.10	2.0	2.0
Average values of parameters	0.98				112 ± 84	116 ± 85		0.99 ± 0.09	2.9 ± 0.73	3.0 ± 0.8

φ and λ are geographic latitude and longitude; H/H_0 is geomagnetic field intensity in the place of core sampling, where H_0 = 50 μT; h is depth of waterbody in the place of core sampling; n is number of samples; Q is Königsberger factor; NRMt is natural remanent magnetization; DRMt is the detrital remanent magnetization; SIRMt is saturation isothermal remanent magnetization; P is coefficient of the redeposition; Rdst = DRMt/SIRMt. All magnetic parameters are obtained after 200° t – cleaning. SIRMt is obtained after redeposition and measurement of the DRMt.

methods (the "sieving and pipette" technique) described in (Leeder, 1986). Such deposits are often subject to paleomagnetic investigations.

For testing of the method the deposits with the natural remanent magnetization of the presumably orientational nature were used. Three tests were used to reveal the orientation nature of the sediments magnetization: low values of Königsberger factor, presence of clastic grains of magnetic minerals and proportional correspondence between weight and SIRMt values of the fractions obtained during a grain-size analysis. The values of magnetic parameters of samples shown in Table 1 were obtained after 200° t – cleaning. The values of standard deviation of the means of the NRMt, DRMt and P are also shown in Table 1. In all cases the redeposition was made according to the method mentioned above.

The values of H derived from the equation $H = H_0{*}$NRMt/DRMt show that the accuracy of determination of the magnetic field intensity in the first turn is determined by an accuracy of coincidence of NRMt and DRMt values. As shown in Table 1, NRMt and DRMt values differ by no more than 20%. The maximum deviation of the P values from 1 (or the difference between NRMt and DRMt) was found in sediments of the Rybinsk Reservoir (0.2) and the northern part of the Sea of Azov (0.15). Thus, the error of determination of the modern magnetic field does not exceed 20%. Earlier, the similar result has been reported by Tucker (1981). According to Tucker (1981), it is possible to determine the magnetic field intensity using turbidite deposits within accuracy to 16%. The study revealed that the P values depended neither on the depth of a waterbody nor on the climatic zone in which the sediment was accumulated. Therefore, paleoclimatic changes should not exert a significant influence on the accuracy of determination of the ancient magnetic field intensity.

The values of Rdst coefficient varied from 2×10^{-3} to 4×10^{-3}. The studied materials do not allow yet for the precise determining the relation of this coefficient to conditions of deposits accumulation. However, it is worth noting that Rdst of brown deposits is in average slightly lower than of grey-colored sediments.

The Table 1 shows (bottom line) that the average values of the H/H_0 and P, DRM and NRM, Rdst and Rnst are almost identical. According to the studied materials (Table 1) and the study by Kurazhkovskii and Kurazhkovskaya (2001), the error of a single determination of H using the sedimentary rocks usually does not exceed 20%. At testing of the heating methods (by Thellier, and Wilson) applied for studies of the contemporary Hawaiian lavas the errors of the H determination (Valet, 2003) were also close to 20%. Therefore, sedimentary and termomagnetized rocks allow for determining the paleointensity with the same accuracy.

4. Comparison of the paleointensity data obtained for sedimentary and termomagnetized rocks

The coincidence of the paleointensity data obtained by different methods is the strongest argument at discussion on the problem on their correctness. A direct comparison of same-age values of the paleointensity obtained on sedimentary and termomagnetized rocks is extremely difficult since as rule the errors of dating of ancient geological objects exceed considerably the characteristic times of secular variations. In addition, the places of formation of thermomagnetized and sedimentary rocks are usually spatially remote. The reviews (e.g., Valet, 2003; Tauxe and Yamazaki, 2007), and the world database PINT08 (Perrin and Schnepp, 2004) represented on a site (http://www.geo.uu.nl/~forth/Software/PINT08/PINT08.htm) show that paleointensity varies over a wide range. The "same-aged" values of the paleointensity can differ more than by a factor of 20. The database does not allow for drawing a conclusion on the reasons for such a large scatter in the paleointensity values. If the paleointensity was determined by cores of deposits, the data on its behavior can differ depending on a sampling site (Tauxe and Yamazaki, 2007). At the same time, Petrova (1998) has shown that regional differences in the paleointensity behavior do not influence the estimations of its average values for long-term (about 100 thousand years) time intervals. Thus, if the intervals of averaging are long enough the regional differences at estimations of mean values of the paleointensity may be insignificant. This is why, we will limit the discussion on the problem of coincidence of results of the determination of the ancient magnetic field intensity by sedimentary and termomagnetized rocks to the comparison of its average values obtained for long time intervals (geological epochs and periods).

We used the results of the paleointensity determinations on termomagnetized rocks provided by the world database PINT08. The paleointensity data obtained by the Mesozoic and Paleozoic sedimentary rocks are taken from papers (Kurazhkovskii et al., 2008, 2010; Khramov et al., 1982).

All ancient deposits were collected on the territory of Russian Plate and its edges. The sampling sites of the Mesozoic deposits used in the works (Kurazhkovskii et al., 2008, 2010) are shown in Fig. 3. Since in most cases the exposures of crystalline (magmatic) rocks were located at a large distance from sites of formation of the studied sedimentary layers the sedimentary layers formed earlier served a main source of the material for their formation. This was the likely reason why the studied deposits had the complex magnetomineralogical composition. According to the preliminary estimations obtained on the basis of the thermomagnetic analysis, magnetite was the main carrier of the remanent magnetization in grey-colored deposits; haematite, of brown deposits. However, the analysis using of electron-probe analyzer "Tescan Vega II" revealed that a broad spectrum of minerals of ilmenite and titanomagnetite lines present in all studied deposits. In addition, the particles of iron and nickel were detected in some samples of Mesozoic deposits. The amount of such particles in analyzed samples varied depending on the location and age of sedimentary layers. Thus, irrespective of conditions of sedimentation the assortment of magnetic minerals in all studied deposits was rather diverse. As the main requirement for magnetomineralogical composition of deposits, was the compliance with the results of the tests indicating the orientational nature of their magnetization and the stability of magnetomineralogical composition during the redeposition.

In order to maximally increase the volume of the analyzed data obtained on sedimentary and termomagnetized rocks we did not recalculated the values of paleointensity into values of the virtual dipole magnetic moment. As it was noted above, at sufficient data availability, the "same-aged" (with accuracy to errors of dating) values of the paleointensity usually differ not less than by a factor of 20. The values of the virtual dipole magnetic moment have the same scatters. Such scatters of values of the paleointensity and of the virtual dipole magnetic moment considerably exceed the errors related to the methods of determinations of these parameters and ways of their calculations. Therefore, the amount of the data used for estimations of average values of the paleointensity for intervals of the geological time is the main factor determining the correctness of estimations. The criteria of determining the necessary volume of the data have not been formulated yet. We intended to make this volume as much as possible. At the present time the amount of paleointensity determinations considerably exceeds the amount of the virtual dipole moment (V) determinations. In addition, the analysis of PINT08 data has shown that when comparing the mean H/H_0 and V/V_0 (V_0 is modern dipole magnetic moment of the Earth) ratios for geological epochs of the Mesozoic and Early Paleozoic, their values coincided to a good accuracy (Ho was taken 40 μT, $V_0 = 8 \times 10^{22}$ A m^2). For determination of the Mesozoic paleointensity (Kurazhkovskii et al., 2010) the deposits formed in "middle latitudes" (30–60°) of epicontinental seas of the Russian Plate and adjacent territories were used. As the laboratory in which the redeposition was made is also located in the midlatitude zone, the recalculation of values H/H_0 into values V/V_0 inconsiderably changes the pattern of the ancient magnetic field behavior and its numerical values.

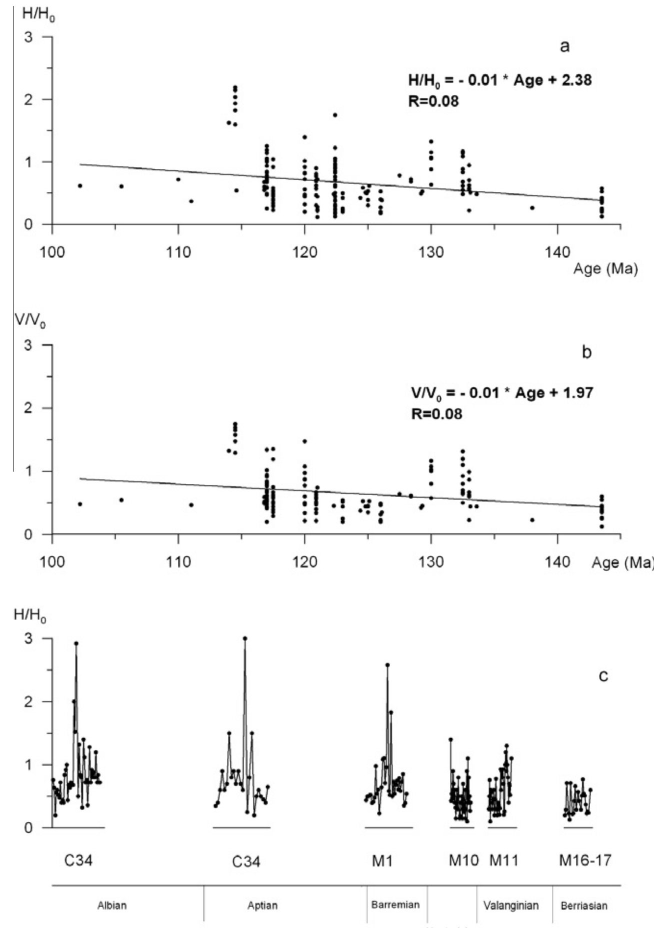

Fig. 4. (a) Paleointensity H/H_0 and (b) the virtual dipole magnetic moment V/V_0 data of the Early Cretaceous according to PINT08 database. The straight line shows approximation of these data. Regression equations and correlation coefficients are presented. (c) Fragments of the Early Cretaceous paleointensity obtained on sedimentary rocks are taken from (Kurazhkovskii et al., 2010), of the paleointensity fragments are attributed to polarity chrons according to (Guzhikov et al., 2007).

The paleointensity data of Early Cretaceous obtained on sedimentary and termomagnetized rocks were shown in Fig. 4a and b for the illustration of the above mentioned discussion. The straight line shows the linear approximation of H/H_0 and V/V_0. Fragments of the paleointensity obtained on sedimentary rocks are presented in Fig. 4c. This temporal interval has been selected as it is the most completely provided with the paleomagnetic material. The Fig. 4 shows that the transition from H to V changes neither numerical values nor concepts on general tendencies of the paleointensity modification. The values of the coefficients in the regression equations and the same (low) values of the coefficients of correlation between the used data and the approximating straight lines confirm the above statement. Consequently, the data on both H/H_0 and V/V_0 lead to the similar concept on the behavior of the ancient geomagnetic field. The data from sedimentary rocks allow for receiving of considerably more complete and clear view of modifications of the paleointensity than termomagnetized rocks.

The average values of paleointensity obtained on sedimentary and termomagnetized rocks for an interval Early Carboniferous – Late Cretaceous are shown in Fig. 5. Points of the graph are obtained by the averaging of the paleointensity data of the Early and Late Carboniferous, Permian, Triassic, Late Jurassic, Early and Late Cretaceous. The uneven distribution of duration of time intervals relate to the uneven distribution (insufficient quantity) of

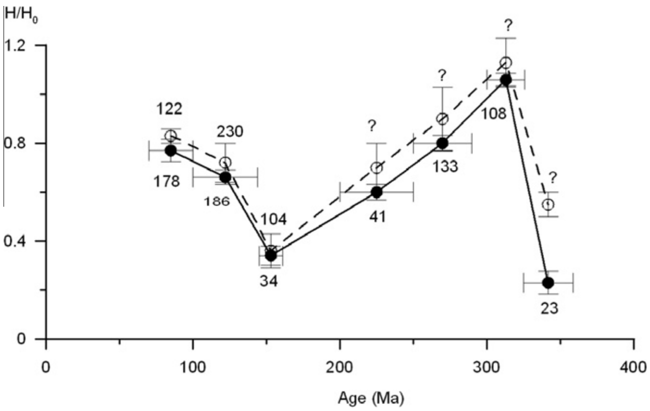

Fig. 5. Modifications of paleointensity H/H_0 in the Early Carboniferous – Late Cretaceous interval. Points are obtained by a data averaging using sedimentary (light circles) and termomagnetized rocks (dark circles) for Early Carboniferous, Late Carboniferous, Permian, Triassic, Late Jurassic, Early Cretaceous and Late Cretaceous. Horizontal bars show the age intervals of the averaging of paleointensity data. Vertical bars show 95% confidence intervals of estimates of the average values of the paleointensity. The number of data for each of the studied time interval is shown for sedimentary and thermomagnetic rocks above and below the light and dark circles, respectively.

paleointensity data. The 95% confidence interval for the mean paleointensity did not exceed 0.1 H_0. The data taken from (Khramov et al., 1982) present the average values and standard deviations of the paleointensity. When calculating confidence intervals we assumed that only four samples were used. This is certainly much less than was used by Khramov et al. (1982). This is why the confidence intervals of estimates of mean values of Paleozoic paleointensity are obviously overestimated.

The data in Fig. 5 show that the behaviors of the paleointensity obtained on sedimentary and termomagnetized rocks are practically identical. For example, relatively high values of the paleointensity are characteristic of the end of Paleozoic (300–250 Ma). The values of the paleointensity in the Triassic – Jurassic (250–150 Ma) are lower, and increase again in the Cretaceous (after 150 Ma). Thus, the dynamics of paleointensity obtained on sedimentary and termomagnetized rocks are similar to each other.

The values of the paleointensity obtained on sedimentary rocks are slightly higher than the values obtained on termomagnetized rocks. However, the differences in estimations of average values of paleointensity are much lesser than the amplitude of its modifications. Therefore, the data obtained both on sedimentary and on termomagnetized rocks can be used jointly for investigation of paleointensity behavior.

5. Discussion

The analyzed materials have shown that results of calibration of the paleointensity data obtained on sedimentary rocks do not depend on conditions of sediments accumulation (depths of a waterbody, climatic zone). The coefficients of redeposition close to 1 have been obtained at the redeposition of all available contemporary sediments. According to the mentioned above testing, the remanent magnetization of these sediments had the orientational nature.

Methods of paleointensity determination (for example, Thellier, Wilson and method proposed in the present paper) are based on the comparison of a primary magnetization with the magnetization obtained in the contemporary magnetic field. During the time since the moment of the rock formation the magnitude of their magnetization may have changed. The modern research methods do not always allow for estimating and detecting these modifications of magnetization. Therefore, the above mentioned methods can yield not quite adequate concept on the magnitude of the ancient geomagnetic field. The effect of possible magnetomineralogical changes on results of paleointensity determinations was discussed earlier in the paper by Heller et al. (2003). In the present investigation we tried to replace the common term "absolute values of the paleointensity" by the term "numerical values of paleointensity" or "calibrated data on paleointensity". In our opinion, such terms characterize the available data on paleointensity more exactly. The analyzed materials show (Fig. 5) that the paleointensity dynamics of sedimentary and termomagnetized rocks coincides. Numerical values of the paleointensity of sedimentary and termomagnetized rocks on average are rather close to each other. This indicates that the data on sedimentary and termomagnetized rocks do really reflect changes in the geomagnetic field intensity.

It is unclear to which degree the paleointensity data correspond to the true values of the ancient geomagnetic field intensity. The attention should be paid to the difference in average values of the Cretaceous paleointensity depending on mineralogical peculiarities of thermomagnetized rocks used for its determination (Heller et al., 2003; Tarduno et al., 2006). If the paleointensity measurements are based only on a single class of rocks and a single method it will be impossible to detect errors related to preservation of the primary magnetization. The comparison of the paleointensity data obtained on sedimentary and thermomagnetized rocks gives a factual material for object discussion of adequacy of available estimations of absolute values of paleointensity. Differences in average values of the paleointensity of Late Paleozoic – Mesozoic geological epochs are not always statistically significant. However, it is worth noting that estimations of average values of the paleointensity obtained on sedimentary rocks in all cases are higher than values obtained using thermomagnetized rocks. It is unlikely that such systematic difference is occasional. Therefore, the problem of adequacy of determinations of the paleointensity absolute values is still disputable.

In our opinion, the accumulation of information on peculiarities of Rdst parameter modification would allow us to abandon the use of a redeposition at calibration of the paleointensity data. At present time the application of the redeposition is caused by insufficiency of the knowledge about the dependence of Rdst parameter values on peculiarities of sediment accumulation conditions. According to preliminary estimations basing on the limited material for ancient marine grey-colored sediments, Rdst = $(3.5–4.0) \times 10^{-3}$ (Kurazhkovskii and Kurazhkovskaya, 2001). In our practice the higher values of this coefficient were the characteristic of those marine deposits which underwent magnetomineralogical modifications during laboratory redeposition and were discarded owing to that. In brown deposits formed under oxidizing conditions Rdst varied in the range $(1.8–4.0) \times 10^{-3}$ (Kurazhkovskii and Kurazhkovskaya, 2001). The deposits of the northeastern equatorial part of the Pacific Ocean (12°N, 122°W) had Rdst = 8×10^{-3} (Kurazhkovskii et al., 2005). We hope that the further accumulation of data on the dependence of Rdst parameter on conditions of sediment accumulation will allow for calculating the numerical values of a magnetic field on the basis of measurements of two parameters, NRMt and SIRMt.

The Rdst parameter can be used as the coefficient of proportionality in the empirical equation linking the magnitude of an orientational magnetization of sediments with the magnitude of a magnetic field in which its formation took place NRMt = Rdst∗SIRMt∗H/H_0. As it has been shown above, for marine natural and redeposited (in a 50 μT intensity field) deposits the values of this coefficient vary in rather narrow range $(2–4) \times 10^{-3}$. The low variability of this parameter indicates that the degree of the particles orientation in natural and redeposited marine deposits (by the above mentioned method) inconsiderably depends on grain-size and mineralogical composition, as well as on the depth of the waterbody and the climatic zone in which it is located.

6. Conclusion

The present paper proposes the method for estimation of numerical values of the ancient geomagnetic field intensity on sedimentary rocks. The results of it testing on the contemporary and ancient deposits are given. Testing of the method on the contemporary sediments has shown that errors of determination of the magnetic field intensity do not exceed 20%. The application of the method on ancient sediments has allowed us for obtaining new data on the behavior of the geomagnetic field intensity in the Late Jurassic and Cretaceous. It made also possible to compare the paleointensity values using sedimentary and termomagnetized rocks. It has been found that sedimentary and termomagnetized rocks lead to similar view of the paleointensity dynamics. On the average, the numerical values of the paleointensity obtained using sedimentary and termomagnetized rocks are similar to each other.

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