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The Influence of the Chemical Magnetization of Oceanic Basalts on Determining the Geomagnetic Field Paleointensity by the Thellier Method

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Abstract—Dredged samples of basalts from the Mid-Atlantic Ridge (MAR) and the Red Sea Rift that are 0.2 to 1 Ma in age are used to show the possibility of separating the thermoremanent and chemical remanent magnetization components in oceanic basalts by the conventional Thellier–Coe method. It is found that the decay rate of chemical remanent magnetization during exposure of basalt samples with Curie temperatures of $T_c = 145$ and 240°C at temperatures of 340 – 380°C in the air was less than the formation of partial thermoremanent magnetization during the experiments using the Thellier–Coe method by a factor of 4.5 – 5 ; in contrast, for thermoremanent magnetization these rates almost coincide. Using this fact, we estimated the contributions from chemical remanent and thermoremanent magnetization components into the natural magnetization of basalts and, based on the thermoremanent magnetization component, defined the paleointensity of the geomagnetic field for the epoch when these basalts formed. In basalts from the southern MAR that are 1 Ma in age, the contribution of chemical remanent magnetization to the natural remanent magnetization is 60% to 80% ; in those of 0.35 Ma it was less than 50% ; in those of 0.2 Ma it was less than 10% . The calculated values of the virtual magnetic dipole moment of the Earth were close to those that have been published in the literature.

Keywords: paleomagnetism, rock magnetism, basalts, chemical remanent magnetization, Thellier–Coe method.

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INTRODUCTION

Titanomagnetites are carriers of natural remanent magnetization (NRM) in oceanic basalts. As a result of low-temperature oxidation under ocean-floor conditions, these minerals can be altered during the geological evolution of rocks. As a result, secondary chemical magnetization may form to complicate the determination of the characteristics of the ancient geomagnetic field from NRM of these basalts.

The most widespread primary magnetic mineral in basalts of the upper layer of the oceanic crust is titanomagnetite $\text{Fe}_{3-x}\text{Ti}_x\text{O}_4$ ($x \approx 0.6$), which usually contains Al and Mg as admixtures [1]. It was found that at low temperatures (below 250°C) titanomagnetite could undergo oxidation to form titanomaghemite [2–5].

The primary thermoremanent magnetization (TRM) is replaced by chemical remanent magnetization (CRM). The direction of chemical magnetization that is obtained by decay and oxidation of cation-deficient titanomagnetite one-domain and pseudo-one-domain (OD-PSD) grains may not fit the direction of

the magnetic field that acted during the formation of this chemical magnetization [6]. Some researchers also believe that the data on the paleointensity of the geomagnetic field from ferromagnetic minerals that are prone to transformation into secondary minerals should be considered with caution [7]. Due to magnetization, determination of the geomagnetic field paleointensity of submarine basalts by the Thellier method without analysis of the chemical magnetization contribution to the NRM (I_{rn}) can yield underestimated values, because CRM (I_{rc}) is usually lower than TRM (I_{rt}) that was obtained in the same field [8–10]. As an example, the ratio between the chemical magnetization of the phase that is obtained from the oxidation of titanomagnetite with $T_c = 100^\circ\text{C}$ at a bake (exposure) temperature of $T_{bake} = 400^\circ\text{C}$ and the thermoremanent magnetization was 0.36 [7]; this ratio grew as the temperature of I_{rc} formation increased. In the same publication, the authors stated that basalts that contain weakly oxidized titanomagnetite $z \approx 0.2$ could yield satisfactory results regarding the paleointensity definition.

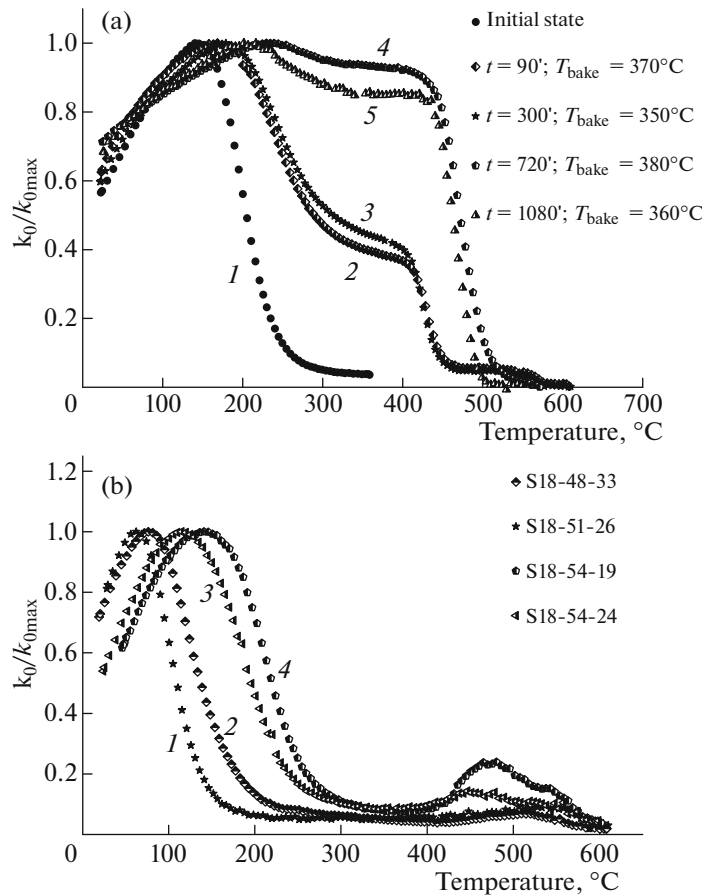


Fig. 1. The dependence of the magnetic susceptibility on temperature for the basalt samples from the Red Sea (a) and the southern MAR (b) upon heating in an argon atmosphere.

It was believed earlier [11, 12] that CRM and TRM had similar stabilities relative at the effect of a variable demagnetizing field and at thermal demagnetization; therefore, they could be easily distinguished from each other. However, it has been noted in [13] that information about the similarity between CRM and TRM is contradictory. The theoretical studies in [14] concluded that for noninteracting one-domain grains CRM and TRM can be separated on the basis of Thellier experiments. Experiments in [15, 16] also provided evidence for possible separation of the chemical remanent and thermoremanent magnetizations using the Thellier method. As an example, experiments on lepidocrocite–magnetite–hematite transformations in [15] have shown the complete absence of similarities between the spectra of the blocking temperatures of CRM and TRM.

It is known [2] that the Curie point of basalts grows with an increase in the degree of oxidation of titanomagnetite in these basalts; hence, the spectra of the blocking temperatures for the initial titanomagnetite TRM and the transformed titanomagnetite CRM will also differ from each other. It also should be noted that the value TRM is, as shown above, larger than CRM.

All these facts indicate that application of the Thellier method can separate the TRM and CRM of titanomagnetite in basalts (with the latter being formed from low-temperature oxidation of the mineral).

In the present work, we will study the possibility of separating the TRM and CRM components in oceanic basalts and that of an increase in the reliability of defining the geomagnetic field paleointensity from remanent magnetization of these basalts using the Thellier–Coe method [17].

1. SAMPLES AND METHODS

For our study we used dredged samples of basalt (nos. S18-18, S18-51, and S18-54) from the southern Mid-Atlantic Ridge (MAR) and the basalt sample no. P72-8 from the Red Sea Rift. The ages of basalts from the southern MAR is, according to [18], from 0.2 to 1 Ma (see table); the age of basalt from the Red Sea Rift is no more than 0.5 Ma [19, 20].

To estimate the initial phase state of ferrimagnetic grains, we performed thermomagnetic analysis of the magnetic susceptibility dependence on temperature, $k_o(T)$ (Fig. 1), using an MFK1-A instrument (manu-

The phase, structural, and paleomagnetic characteristics of the studied basalts from the southern MAR and the Red Sea

Sample no.	M_r/M_s	H_{cr}/H_c	T_C (°C)	Age (Ma)	$b \pm \Delta b$	q	$H_{pl} \pm \Delta H$ (A/m)	VDM $\times 10^{22}$ (A m ²)
S18-51/26 (MAR)	0.22	1.45	145	0.2	0.62 ± 0.03	9.76	24.7 ± 1.2	4.5
S18-48/33 (MAR)	0.22	1.48	185	0.35	1.06 ± 0.01	25.9	42.5 ± 0.4	8.0
S18-54/24 (MAR)	0.35	1.39	245	1	0.44 ± 0.04	2.07	17.5 ± 1.6	3.3
S18-54/19 (MAR)	0.47	1.34	265	1	0.61 ± 0.04	3.81	24.5 ± 1.6	4.5
P72-8 ($H = 40$ A/m)					0.18 ± 0.01	7.51		
P72-8 ($H = 120$ A/m)	0.19	1.45	240	≤ 0.5	1.17 ± 0.07	11.4	46.8 ± 2.8	
(Red Sea)					0.38 ± 0.03	11.0	45.9 ± 3.6	13.3

factured by the AGICO company). To prevent oxidation during the laboratory experiments, the samples were heated in an atmosphere that contains 99.98% argon. The dependence of the magnetic susceptibility on temperature was measured on powdered specimens.

To estimate the domain structure of ferrimagnetic grains, we measured hysteresis magnetic characteristics such as saturation magnetization (M_s), remanent saturation magnetization (M_r), coercive field strength (H_c), and the remanent coercive field strength (H_{cr}) using a VMA-1 vibration magnetometer [21]. To define the M_s of ferrimagnetic grains, we measured the dependence of sample magnetization on the value of magnetic field $I(H)$ in the interval $H = 0-1$ T using a vibration magnetometer. When calculating the saturation magnetization of ferrimagnetic grains, we also took the paramagnetic contribution into account; M_s was defined by extrapolation to the zero field of linear approximation of the data from the dependence $I(H)$ in strong fields of more than 0.4 T. It is seen in the table that in the studied samples $M_r/M_s > 0.19$, $H_{cr}/H_c < 1.5$. In terms of the Day criterion [22], ferrimagnetic grains of the examined basalts are under a small- or one-domain state.

The NRM of the studied basalts and TRM and CRM that were simulated in the laboratory were studied using the Thellier–Coe method [17]. The data were represented as Arai–Nagata plots, from which the value of the geomagnetic field paleointensity that acted during the formation of the basalts was calculated by the formula $H_{pl} = b_1 \times H_{lab}$. Here, b_1 is the coefficient of linear approximation of the dependence NRM = f (PTRM) (this coefficient was defined from the magnetization component of supposedly thermoremanent nature); H_{lab} is the value of the laboratory field acted when partial thermoremanent magne-

tization (PTRM) formation in the Thellier cycles. The coefficient of the quality of paleointensity definition was calculated by the formula from [17]

$$q = |b_1| fg / \sigma_b,$$

where g is the factor of uniformity of the point distribution in the Arai–Nagata plot along the coordinate axis, i.e., along the axis on which NRM was plotted in the temperature interval T_1, T_2 ; f is the NRM fraction that falls within the interval T_1, T_2 ; b_1 is the coefficient of linear approximation in the Arai–Nagata plot in the interval T_1, T_2 ; σ_b is the mean square error of b_1 .

In the Thellier experiments, heating was performed in a noninductive AC-line electric oven that was placed in a four-layered permalloy screen. To avoid oxidation, heating was made in an argon atmosphere.

To control the phase transitions during the Thellier experiments under laboratory conditions, partial thermoremanent magnetization from the lower (checkpoint) temperatures was made during cooling after heating to a certain temperature; the data were compared to those on PTRM(I_{rPT}) in the previous heating cycles.

Remanent magnetization at room temperature was measured with a JR-6a spinner magnetometer (AGICO company); that at higher temperatures was measured with a vibration magnetometer. Hysteresis characteristics were defined and the experiments to measure NRM, TRM, and CRM were performed on cubic (1 cm³ in volume) samples that were cut from the main rock samples.

2. RESULTS AND DISCUSSION

To assess the applicability of basalts for paleomagnetic studies, it is necessary to know the state of titanomagnetite, and, first of all, the degree of its low-temperature oxidation. We showed earlier [23, 24] that

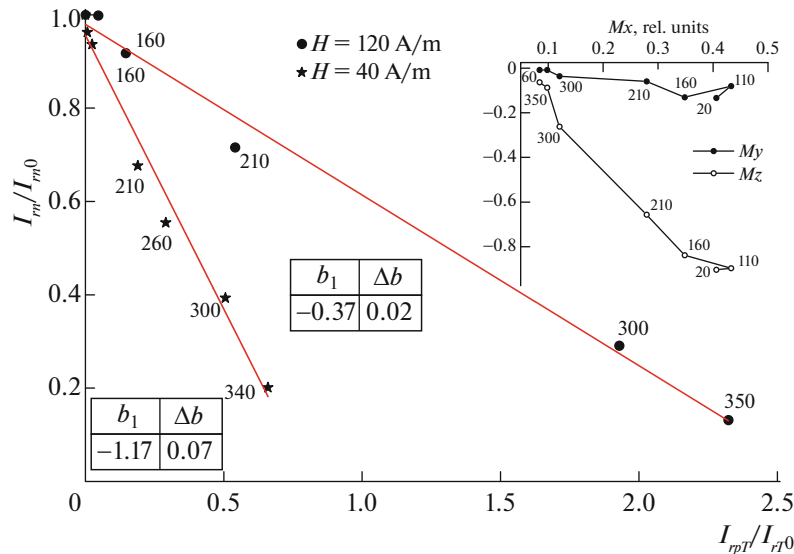


Fig. 2. The Arai–Nagata and Zijdeveld (inset) plots for the NRM studies of the basalt sample no. P72-8 from the Red Sea using the Thellier–Coe method. (H is the value of laboratory field that occurred during the formation of the partial thermoremanent magnetization I_{rpT}). The digits near the points indicate the maximum temperatures of sample heating during the Thellier cycle.

the ferrimagnetic grains of the basalt sample no. P72-8 consist of titanomagnetite with an ulvospinel content of approximately 50%. The thermomagnetic analysis showed that basalt sample no. P72-8 from the Red Sea floor under its natural state contains ferrimagnetic grains with a Curie temperature $T_C = 240^\circ\text{C}$ (Fig. 1, curve I ; table). The closeness of the measured Curie temperature to the calculated one ($T_{C_{calc}} = 220^\circ\text{C}$; defined from the ulvospinel content [2]) indicates the low degree of single-phase oxidation of titanomagnetite in the studied basalt.

The Curie temperatures of the basalt samples from the southern MAR (Fig. 1b, table) ranged from 145 to 265°C. According to the dependences $k_o(T)$, these specimens also appeared to have small amount of ferrimagnetic material with a Curie temperature close to T_C of magnetite. It is known [2] that as the degree of single-phase oxidation of titanomagnetite grows the Curie temperature increases as well, hence, it can be supposed that titanomagnetite in the basalt sample no. S18-51/26 ($T_C = 145^\circ\text{C}$) has the lowest degree of oxidation among all of the basalts from the southern MAR that were studied in the present work, while in sample no. S18-54/19 ($T_C = 265^\circ\text{C}$) titanomagnetite has the highest degree of oxidation. The value of the Curie temperature correlates to the age of rocks and may also argue for the performed estimation of the degree of titanomagnetite oxidation in the studied basalts (see table).

Investigation of the NRM for the Red Sea basalt (P72-8) using the Thellier–Coe method showed that

the dependences $\text{NRM} = f(\text{PTRM})$ in the Arai–Nagata plot, which were obtained on double samples at different values of the laboratory field ($H_{lab} = 40$ and 120 A/m), are described well by linear functions (Fig. 2). It is seen in the Zijdeveld diagram (inset in Fig. 2) that the less stable component NRM is demagnetized at heating to 110°C and, most probably, has a viscous origin [25] and its contribution to NRM is small. The larger part of NRM in the basalt sample no. P72-8 is of a thermoremanent nature. The values of the geomagnetic field paleointensity that are defined by the formula $H_{pl} = b \times H_{lab}$ at two values of the laboratory field (table) appeared to be equal within the error limits. The quality factor was 11.4 and 11.0, respectively. According to [17], the determined value of the geomagnetic field paleointensity is considered to be valid if the quality factor is $q > 5$.

The results of studying NRM in basalts from the southern MAR using the Thellier–Coe method are presented in Figs. 3a, 3b, 4a, and 4b. It is seen that the dependence $\text{NRM} = f(\text{PTRM})$ in the Arai–Nagata plot cannot be approximated by one linear function. It was believed that the NRM consists of several components of different origins. The component that demagnetizes after heating to approximately 80–120°C is probably of a viscous nature (VRM), analogous to basalt sample no. P72-8 from the Red Sea floor. In fact, after heating of the specimens to these temperatures the turning of the NRM vector nearly stopped (Figs. 3a, 3b, 4a, and 4b). The contribution of the viscous component in the value of NRM ranged from 10% to 40%.

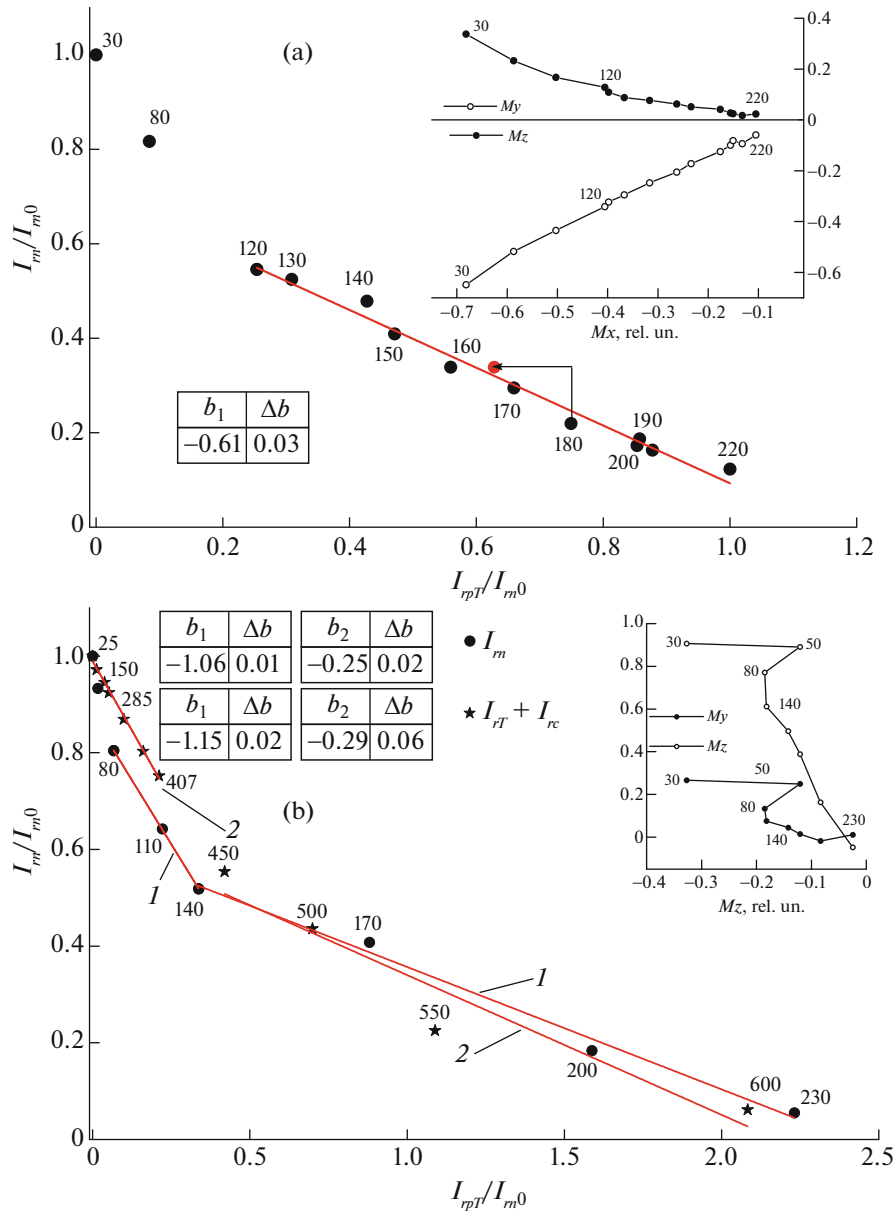


Fig. 3. The Arai–Nagata and Zijderveld (inset) plots for the NRM studies of the basalt samples from the southern MAR using the Thellier–Coe method. Samples nos.: (a) S18-51/26; (b) S18-48/33. The value of the laboratory field that occurred during the formation of the partial thermoremanent magnetization is $H = 40$ A/m. The digits near the points indicate the maximal temperatures of sample heating during the Thellier cycle.

Perhaps some part of the remanent magnetization in the basalt sample no. S18-51/26 with a blocking temperature of $T_b > 120^\circ\text{C}$ is primary and of a thermoremanent nature, because this basalt specimen had the lowest Curie temperature ($T_C = 145^\circ\text{C}$) among the measured ones and its age did not exceed 0.2 Ma. The dependence $\text{NRM} = f(\text{PTRM})$ at $T > 120^\circ\text{C}$ of this basalt (Fig. 3a) was well described by a linear function with the approximation coefficient $b_1 = 0.62 \pm 0.03$ and quality factor $q = 9.76$. The value of the geomagnetic field paleointensity that was calculated from this

part of magnetization was $H_{pl} = 24.7 \pm 1.2$ A/m. It is seen from Fig. 5 that approximately 40% of the NRM was still preserved after heating of sample no. S18-51/26 to $T = T_C = 145^\circ\text{C}$, i.e., the blocking temperatures of the NRM part appeared to be higher than the T_C that was defined by the dependence $k_o(T)$. The same pattern was observed in all of the basalts that we studied in the present work (see Figs. 1b and 5), i.e., blocking temperatures of the NRM part appeared to be higher than the T_C that is defined by the dependence $k_o(T)$. Based on this, we can conclude that the

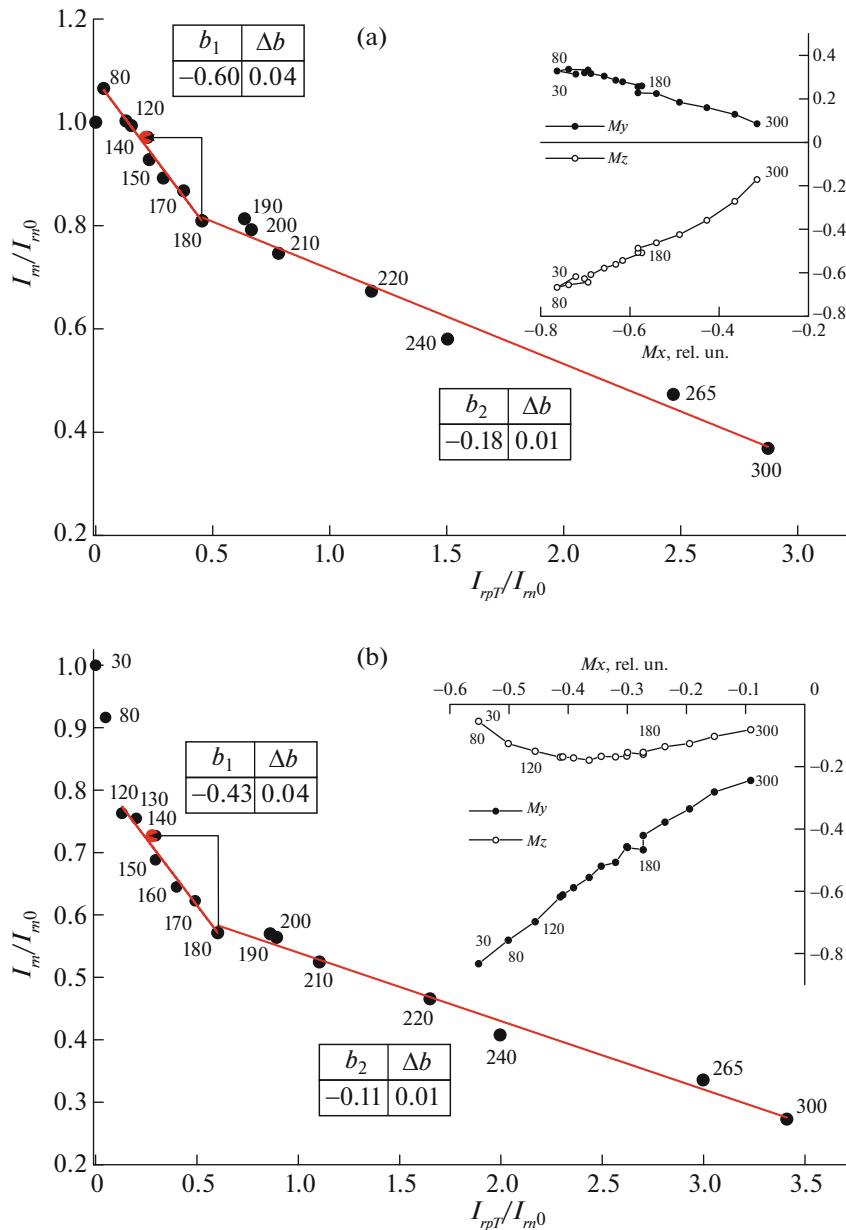


Fig. 4. The Arai–Nagata and Zijdeveld (inset) plots for the NRM studies of the basalt samples from the southern MAR using the Thellier–Coe method. Samples nos.: (a) S18-54/19; (b) S18-54/24. The value of the laboratory field that occurred during the formation of the partial thermoremanent magnetization is $H = 40$ A/m. The digits near the points indicate the maximum temperatures of sample heating during the Thellier cycle.

ferrimagnetic grains of the studied basalt samples are characterized by the spectrum of Curie temperatures and that the T_C that is defined by the dependence $k_o(T)$ should be considered as the most probable value.

The Thellier experiments on samples nos. S18-48/33, S18-54/19, and S18-54/24, (Figs. 3b, 4a, and 4b) showed slightly different results compared to samples nos. P72-8 and S18-51/26 (Figs. 2 and 3a). The Zijdeveld diagrams (insets in Figs. 3b, 4a, and 4b) show that after heating of the samples to

$T = (80–100)^\circ\text{C}$ the less stable viscous magnetization component demagnetizes, analogous to the samples that are considered above. However, at $T > 80–120^\circ\text{C}$, the dependence $\text{NRM} = f(\text{PTRM})$ also appeared to be nonlinear: it could be described by two linear functions with the approximation coefficients $b_1 = 0.43–1.06$ and $b_2 = 0.11–0.25$. The part of the magnetization of the samples with the blocking temperatures $T_b = (80–140)^\circ\text{C}$ for sample no. S18-48/33 (Fig. 3b), $T_b = (80–180)^\circ\text{C}$ for sample

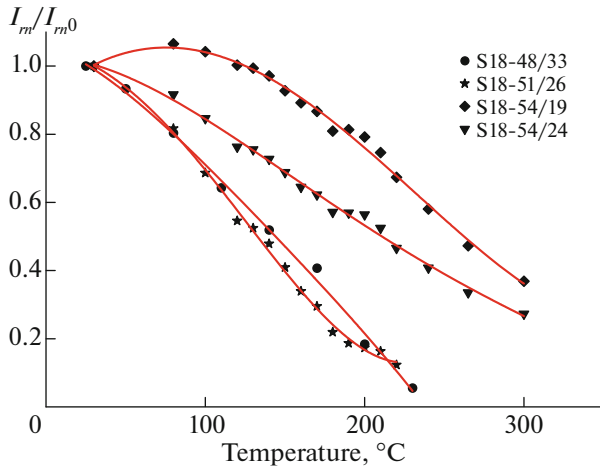


Fig. 5. NRM destruction curves for the basalt samples from the southern MAR during heating during Thellier cycles.

no. S18-54/19 (Fig. 4a), and $T_b = (120-180)^\circ\text{C}$ for sample no. S18-54/24 (Fig. 4b), which is characterized by the linear approximation coefficient b_1 , is probably of a thermoremanent origin and carries the information about the ancient magnetic field. Figures 3b, 4a, and 4b also show that there is still quite a large part of the NRM (from 50% to 80%) at the point of inflection of the dependence $\text{NRM} = f(\text{PTRM})$. It can be supposed that this part of the NRM with high blocking temperatures is secondary and was formed as a result of low-temperature oxidation of titanomagnetite, i.e., that of a chemical origin. One-phase oxidized

titanomagnetite is likely the carrier of this part of the NRM. This is indicated, in particular, by the higher Curie temperatures of these samples compared, for example, to sample no. S18-51/26 (see Fig. 1, table).

The characteristic feature of the results that were obtained by Thellier experiments at $T > 140$ and $> 180^\circ\text{C}$ is the considerable exceedence of the yielded value of PTRM above that of thermal decay NRM. Here, the linear approximation coefficient b_2 was 3–4 times smaller than b_1 (see the table and Figs. 3b, 4a, and 4b). In order to determine whether the part of the magnetization in the basalt samples from the southern MAR is of chemical origin, the chemical (CRM) and thermochemical (CRM + TRM) magnetizations were examined on basalt samples with a low degree of titanomagnetite oxidation (P72-8 from the Red Sea floor and S18-51/26 from the southern MAR). The duplicates of the basalt sample no. P72-8 showed that CRM was formed as a result of sample exposure at temperatures from 340 to 380°C during 12–18 h in a magnetic field of 80 A/m . Thermomagnetic analysis (Fig. 1a) has shown that the magnetic phases with Curie temperatures of $T_{C2} = (450-510)^\circ\text{C}$ formed after high-temperature annealing. In the first series of experiments, after sample exposure in a field of $H_{lab} = 80 \text{ A/m}$ at higher temperature ($T = T_{bake}$), the sample itself was cooled to room temperature in the absence of a magnetic field. The chemical magnetization that was obtained this way was studied using the Thellier–Coe method. The value of the magnetic field during the production of the partial thermoremanent magnetization in the Thellier experiments was also 80 A/m . The

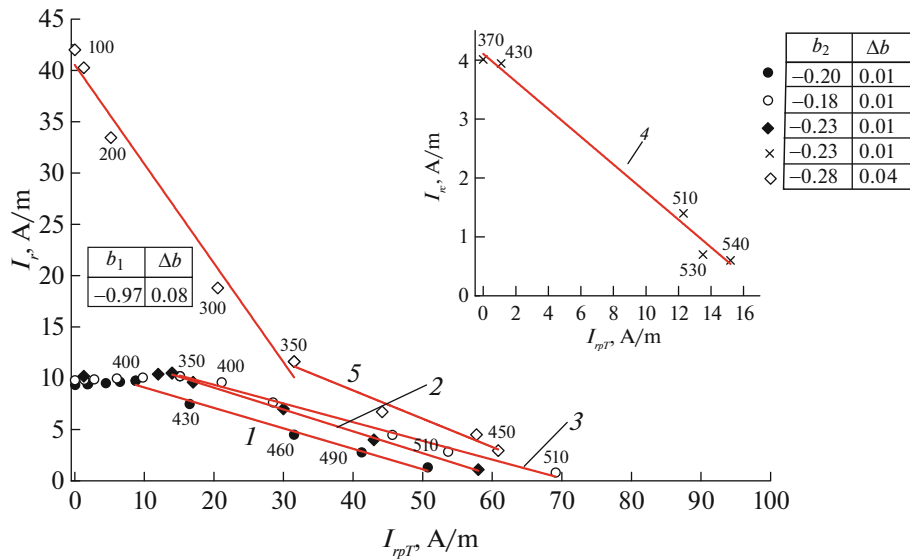


Fig. 6. The Arai–Nagata plot for the study of laboratory-obtained remanent magnetizations in samples P72-8: chemical remanent I_{rc} (1–4) and chemical remanent + thermoremanent $I_{rc} + I_{rT}$ (5) at a different temperature T_{bake} and exposure time t : (1) $T_{bake} = 360^\circ\text{C}$, $t = 18 \text{ h}$; (2) $T_{bake} = 360^\circ\text{C}$, $t = 17.5 \text{ h}$; (3) $T_{bake} = 380^\circ\text{C}$, $t = 18 \text{ h}$; (4) $T_{bake} = 350^\circ\text{C}$, $t = 5 \text{ h}$.

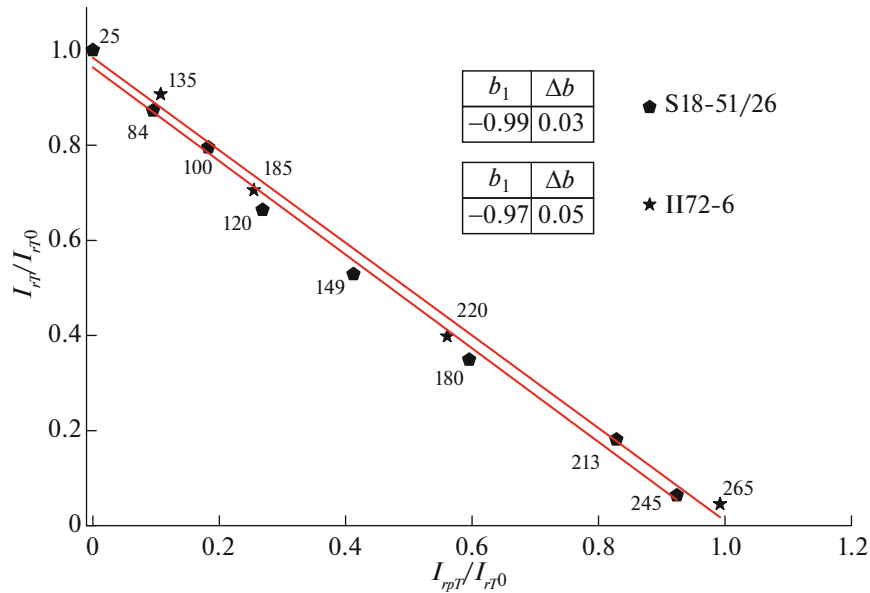


Fig. 7. The Arai–Nagata plot for the study of the laboratory-obtained thermoremanent magnetization in the basalt samples from the Red Sea (P72-6) and the southern MAR (S18-51-26). The TRM formation field was equal the PTRM formation field in the Thellier–Coe experiments.

results are shown in Fig. 6. As was expected, after heating to $T < T_{bake}$ within the Thellier cycles, the value of the remanent magnetization as measured at room temperature almost does not change (Fig. 6, curves 1–3). When heating to $T > T_{bake}$, the chemical remanent magnetization begins to decay. The dependence $CRM = f(PTRM)$ in the Arai–Nagata plot at $T > T_{bake}$ could be described by a linear function. The linear approximation coefficients were much less than 1: $b_2(CRM) = 0.18–0.23$.

In the second series of experiments, after exposure at $T_{bake} = 370$ during 16 h in a magnetic field of 80 A/m, the sample was not cooled to room temperature and the chemical and partial thermoremanent magnetizations were measured at the temperature of exposure ($T_{bake} = 370^\circ\text{C}$). These experiments were carried out on a VMA-1 vibration magnetometer [21]. The results are shown in Fig. 6. The dependence $CRM = f(PTRM)$ for the chemical magnetization as measured at T_{bake} was also described well by a linear function with the approximation coefficient $b_{2T} = 0.23 \pm 0.01$. Based on the results of remanent magnetization measurements, the linear approximation coefficients that are defined from the Arai–Nagata plots were similar at both the room (b_2) and exposure (b_{2T}) temperatures. The small value of the coefficient $b_2 = 0.18–0.23$ that was obtained when studying the chemical remanent magnetization using the Thellier–Coe method indicates a considerable difference of the value and the spectrum of the blocking temperatures between the CRM and TRM. The b_2/b_1

ratio was 0.2–0.24, i.e., the value of chemical remanent magnetization in our experiments was less than that of the thermoremanent magnetization by a factor of 4.5–5. This result qualitatively agrees with the data from [7] where $CRM/TRM = 0.36$ was obtained.

The Thellier–Coe method was also applied to study magnetization that formed via the annealing of samples at higher temperatures in a magnetic field during a certain time interval and further cooling to room temperature in the same magnetic field. The dependence of the magnetic susceptibility on temperature for the sample no. P72-8 after its 5-h exposure at $T_{bake} = 350^\circ\text{C}$ in the air demonstrates the presence of two ferrimagnetic phases with Curie temperatures T_{C1} , which is close to the T_C of the initial state, and $T_{C2} = 450^\circ\text{C}$ (Fig. 1, curve 3). Since the minimal blocking temperature of the chemical remanent magnetization, according to these results, is always more or equal to the exposure temperature (Fig. 6, curves 1–3) we can believe that, in the given case, the obtained remanent magnetization is the sum of two components of chemical remanent and thermoremanent origins ($CRM + TRM$). Since $T_{C1} < T_{bake} < T_{C2}$, the additional magnetization of the thermoremanent origin in this case consists of the thermoremanent magnetization of the source phase remains with a low Curie temperature that is close to $T_{C1} = 240^\circ\text{C}$ and partial TRM of the product phase with a Curie temperature of $T_{C2} = 450^\circ\text{C}$.

As is seen in the Arai–Nagata plot, in the temperature interval from room temperature T_0 to $T \approx T_{bake}$ the dependence ($CRM + TRM = f(PTRM)$) is

described well by a linear function with an approximation coefficient that is close to 1: $b_1 = 0.97 \pm 0.08$ for sample no. P72-8 (Fig. 6, curve 5) and $b_1 = 1.15 \pm 0.03$ for sample no. S18-48/33 (Fig. 3b, curve 2). According to the Thellier principles for thermoremanent magnetization, the linear approximation coefficient of the dependence $\text{TRM} = f(\text{PTRM})$ in the Arai–Nagata plot should be of unit value if the forming field, I_{rpT} , in the Thellier cycles was equal to the forming field I_{rT} . In fact, thermal demagnetization of the laboratory-obtained thermoremanent magnetization using the Thellier–Coe method yielded a value of b that is close to 1 (Fig. 7), which indicates that the definition of the magnetizing field that produces thermoremanent magnetization using the Thellier–Coe method in the studied basalts is valid.

At temperatures above T_{bake} , the dependence $(\text{CRM} + \text{TRM}) = f(\text{PTRM})$ was less satisfactorily described by a linear function (Fig. 3b, curve 2; Fig. 6, curve 5). The linear approximation coefficient $b_2 = 0.28 \pm 0.04$ and $b_2 = 0.29 \pm 0.06$ was much less than 1, while it was slightly more than the coefficients $b_2 = 0.18–0.23$ that were obtained when studying purely chemical remanent magnetization using the Thellier–Coe method. The ratio between the slope b_1 that was calculated from the destruction of the thermoremanent part of the magnetization and the slope that corresponds to the destruction of the chemical part of the magnetization b_2 for the basalt samples nos. P72-8 and S18-51/26 yielded $C = b_2/b_1 \approx 0.29$ and $C \approx 0.25$, respectively.

The comparison between the results of the study of NRM in oceanic basalts by the Thellier method and the results of the model magnetization study show that the character of NRM demagnetization by the Thellier method that was obtained on the basalt samples from the southern MAR (S18-48/33, S18-54/24, and S18-54/19) (Fig. 3b, curve 1; Figs. 4a and 4b) was very similar to the character of remagnetization for the laboratory-modeled magnetization that consisted of chemical remanent and thermoremanent components (Fig. 6, curve 5; Fig. 3b, curve 2). This verifies the assumption that was made above that some part of the magnetization in the basalts from the southern MAR of $t \geq 0.35$ Ma in age (table) is of a chemical nature. Thus, if the dependence $\text{NRM} = f(\text{PTRM})$ in the Arai–Nagata plot, when the studied NRM using the Thellier–Coe method at temperatures of more than 100 °C, can be described by two linear functions with linear approximation coefficients that differ by a factor of approximately 3.5, we can state that higher-temperature NRM part is of chemical nature.

The Thellier experiments enable one to estimate the contributions from the thermoremanent and chemical remanent magnetizations to NRM based on the value of NRM destruction at the point of inflec-

tion of the Arai–Nagata plot. In the basalts from the southern MAR that are 1 Ma in age (samples nos. S18-54/19 and S18-54/24), the contribution from CRM to NRM is from approximately 60% to 80%; in the MAR basalts that are 0.35 Ma in age, (sample no. S18-48/33), the CRM is less than 50% of NRM.

CONCLUSIONS

Based on the study of CRM and TRM that were simulated in the laboratory in oceanic basalts, we can make the following conclusions. By performing Thellier experiments, the component of a chemical nature that formed in some part of the ferrimagnetic phase due to oxidation under ocean-floor conditions can be separated from the NRM of the oceanic basalts. This allows the contribution of the primary TRM to the NRM to be estimated and the reliability of defining the value of the geomagnetic field paleointensity from the remanent magnetization of the oceanic basalts to be increased. As was shown by our experiments, the thermoremanent component can be separated even if its contribution to NRM is less than 20%. The coefficient of paleointensity definition quality decreases with the growth of the degree of oxidation and the contribution of chemical magnetization to NRM. The basalt samples have higher Curie temperatures and, hence, are characterized by the presence of titanomagnetite grains with a high degree of oxidation, the coefficient of H_{pl} definition quality was quite low ($q = 3.1–3.9$), i.e., smaller than 5, whereas in the samples with a low degree of titanomagnetite oxidation for the H_{pl} coefficient the definition quality was 10–11.

Our results on titanomagnetites from the submarine basalts verify the conclusions that were made in [14, 15] that the CRM and TRM could be separated using Thellier experiments. This increases the reliability of the H_{pl} definition from the NRM of the oceanic basalts.

It is known that the geomagnetic field intensity changes with time [26]. When the primary thermoremanent magnetization was formed in a field of intensity that was smaller than the mean value of the field intensity during the formation of the chemical part of the NRM, the value of CRM may approach that of TRM. If the contribution from the primary TRM to NRM is less than 20%, the estimation of the nature of the magnetization becomes complicated. However, as was noted above [15], CRM and TRM differ in both the values and spectra of the blocking temperatures. This supports the possibility of separating the chemical remanent and thermoremanent magnetization components in the oceanic basalts using the Thellier method, although this requires additional studies, in particular, the spectrum of blocking temperatures should be defined for CRM and TRM that formed in one phase within the oceanic basalts.

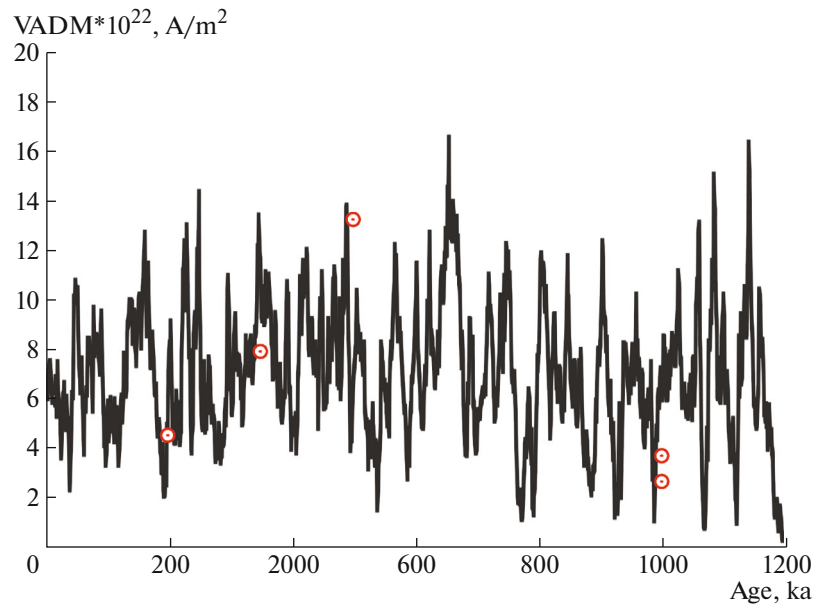


Fig. 8. The dipole magnetic moment of the Earth as calculated for the last 1.2 Ma, the PISO-1500 model [26] (solid curve) and our data calculated from remanent magnetization of the basalt samples from the southern MAR and the Red Sea (circles with dots).

Based on the geomagnetic field paleointensity data we found, the virtual dipole magnetic moment (VDM) of the Earth was calculated (see table). The calculated $VDM = (3.3\text{--}8.0) \times 10^{22}$ A m² was quite close to the values of the virtual dipole magnetic moment of the Earth that were obtained in [26] (see Fig. 8). In fact, according to [26], the terrestrial magnetic field in the periods of 0.2 and 1 Ma ago was characterized by lower intensity, while around 0.35 Ma ago it was higher or close to the present-day value, which is consistent with our results (see Fig. 8).

This increases the reliability of the geomagnetic field paleointensity we defined from the remanent magnetization of the oceanic basalts. The virtual dipole magnetic moment that was calculated from the Red Sea basalts ($VDM = 13.3 \times 10^{22}$ A m²) was higher than the present-day value by a factor of almost two, while still being close to the values of VDM that we defined earlier [27]. Although the age of the studied basalt from sample no. P72-8 is not precisely known (the estimated age is approximately 500 ka [19, 20]), this result can also be considered reliable, because such a strong terrestrial magnetic field could occur 350–500 ka and approximately 640–660 ka ago [26] (see Fig. 8).

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