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MARINE GEOLOGY

Virtual Dipole Moment Variations through the Proterozoic–Phanerozoic Eons

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Abstract—The international bank of virtual dipole moment (VDM) data, combined with materials from recent publications (3384 values in total), served as a basis for the analysis of the VDM's distribution through the Proterozoic and Phanerozoic eons (0–2.6 Ga). The VDM distribution obtained by the method of a moving average exhibits a positive linear trend from 3.7×10^{22} Am^2 2.6 Ga ago to 5.8×10^{22} Am^2 at present. Against the background of this linear growth, fluctuations with a periodicity of approximately 390 Ma are defined. The obtained data substantially specify the available data on the behavior of the magnetic field during the Proterozoic and Phanerozoic eons and should be taken into consideration for modeling the physical processes in the development of the Earth in the geological past and predicting its ecological and energetic evolution in the future.

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INTRODUCTION

The virtual dipole moment's (VDM) distribution [31] in particular past epochs is one of the most important charcateristics of the temporal variations in the Earth's magnetic field. The VDM values derived from the analysis of the rock's geomagnetism reflect the magnetic geodynamo activity in the geological past.

The Thelliers [2], who proposed a method for determining all three components of the geomagnetic field (the declination, inclination, and intensity) by comparing the behavior of the natural and artificial remanent magnetization under heating and cooling of the same sample, contributed much to the study of the magnetic field variations in the geological past. They developed methods of exact orientation and sampling of rocks in natural conditions; in addition, equipment of the induction type for measuring the remanent magnetization in any samples was also designed in their laboratory.

Using the Thelliers' method [2] and subsequent techniques [15, 30], the researchers obtained data on the temporal behavior of the Earth's magnetic field dipole component, which point to its substantial variations through the Proterozoic and Phanerozoic eons [4–9, 16, 17, 26, 29, 33, 35, 37–45, and others]. The significant scatter of the individual VDM values limited until recently the possibilities of their interpretation allowing only some regularities to be defined at the qualitative level. Previously, we proposed a general methodical approach to the processing of the VDM data for the last 160 Ma [5], the last 400 Ma [6], and the entire Phanerozoic Eon (the last 570 Ma). The application of the quantitative approach formulated in [5] and developed in [6, 7] for the analysis of such regularities in the Proterozoic–Phanerozoic eons (the last 2500 Ma) is the purpose of this work.

MATERIALS

For the analysis of the temporal VDM variations, an international database (the IAGA Paleointensity Data Base) was recently developed; it is available at the website of the Geophysical Data Center in Boulder Colorado in the United States [27]. The database was subsequently updated [11, 12], and, by the beginning of 2011, it numbered >2900 VDM values from over 270 published sources for the Proterozoic–Phanerozoic, the lower boundary of which is defined at 2500 Ma [19]. This international database, combined with additional information stored at the database of the Borok Observatory [14] and data from [10, 13, 18, 22–26, 28, 32, 34, 36], served as the basis for this work. The updated database used in this work includes 3384 VDM values and corresponding geochronological dates. All the ages of the stratigraphic units used in this work are grounded by the most advanced version of the geochronological scale [19].

The qualitative analysis of the data reveals that the values of the earth's magnetic dipole moment were variable through time. At the same time, the quantita-

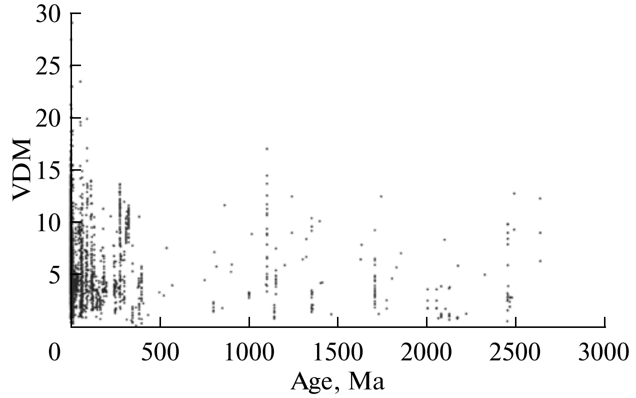


Fig. 1. The temporal distribution of the VDM values (10^{22} Am^2) derived from the updated data base used in this work.

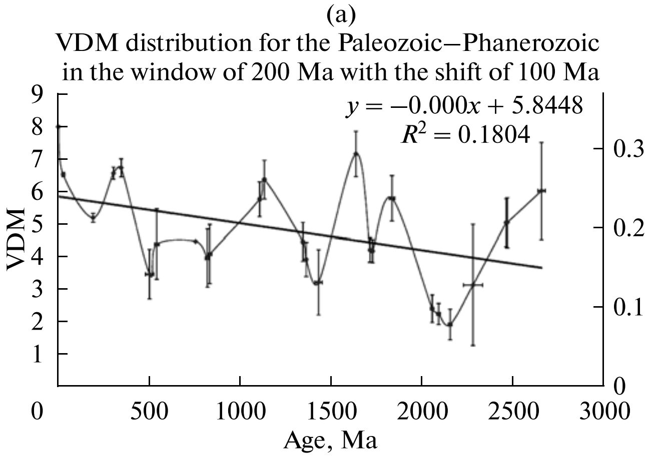
tive analysis of the qualitative regularities was hampered by the significant scatter of the real individual VDM values (Fig. 1).

Among other interpretation approaches, the method of a moving average makes it possible to smooth the spontaneous fluctuations of the data used. This method was selected as being the main one. Many estimates [5–7] demonstrate that the interval of 10 Ma represents the most optimal window for averaging the available data for the last 400 Ma, while the optimal moving step is equal to 5 Ma. This window size is also used for the period of 400 to 580 Ma. Unfortunately, such a window size is unacceptable for the Proterozoic, where the quantity of the calculated points appears to be considerably lower and requires an enlarged averaging window. Our estimates show that the interval of 200 Ma may be accepted as being optimal for the averaging window.

For the Phanerozoic–Proterozoic eons, the maximal number of points used in this analysis is characteristic of the intervals of 0.0–0.2 Ga (2833 points), 0.1–0.3 Ga (474 points), 0.2–0.4 Ga (353 points), 0.3–0.5 Ga (172 points), 1.0–1.2 Ga (51 points), and 1.1–1.3 Ga (45 points). In other intervals, their number never exceeds 40 points. Moreover, the intervals of 0.4–0.8, 1.4–1.7, 1.8–2.0, and 2.2–2.4 Ga are characterized by <10 points.

In all the cases, we used the average VDM values and their standard deviations in the averaging interval. These values were correlated with the average values of the ages determined in the same averaging intervals. The distribution mode of the standard deviations of the ages from the average values corresponds to the interval of ±7–8 Ma. There are three values exceeding ± 15 Ma in the intervals of 0.4–0.6, 1.4–1.6, and 1.8–2.0 Ga. The distribution mode of the standard VDM deviations from the average values corresponds to the interval of $\pm 0.6–0.7 \times 10^{22}$ Am^2 Ma. At the same time, there are three values exceeding $\pm 1 \times 10^{22}$ Am^2 in the intervals of 0.5–0.7, 1.4–1.6, and 2.2–2.4 Ga.

(a)


VDM distribution for the Paleozoic–Phanerozoic in the window of 200 Ma with the shift of 100 Ma

(b)

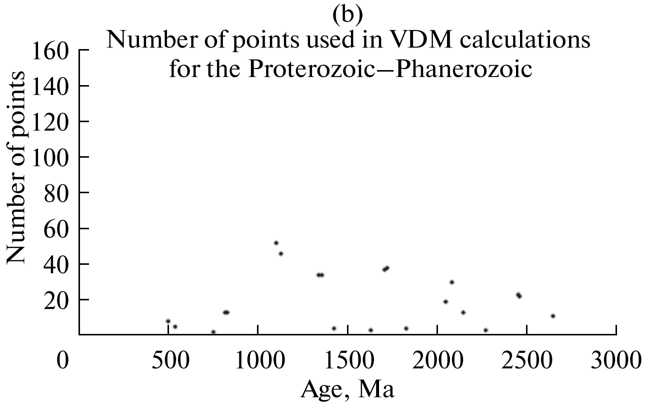

Number of points used in VDM calculations for the Proterozoic–Phanerozoic

Fig. 2. The VDM distribution (10^{22} Am^2) in the period of 0–2500 Ma (a) and the number of calculation points (b). The values are calculated by the method of a moving average in a window of 200 Ma with a step of 100 Ma. The plot shows the linear approximation of the values and reflects the growth of the dipole component value for the earth's magnetic field toward the recent times. The right vertical axis indicates the VDM values recalculated into the equatorial intensity of the paleomagnetic field in erstheds. The vertical and horizontal bars show the representativeness errors, i.e., the standard mean square deviations from the average in each calculation window. The dots indicate the numbers of calculated values in each of the windows except for the windows with the number of points exceeding 100: 0–200 Ma (2833 values), 100–300 (474 values), 200–400 Ma (353 values), and 300–500 Ma (172 values).

RESULTS

Figure 2 illustrates the distribution of the average VDM values for the interval of 0–2.5 Ga in the window of 200 Ma with a shift of 100 Ma. The ages that correspond to their average values in the averaging window are given along the horizontal axis. The vertical and horizontal bars designate the standard deviations, which represent a measure of the scatter of the points used in the calculations relative to their average values.

The plot shows that the virtual dipole moment, the present-day value of which is equal to 8×10^{22} Am^2 [5, 21, 29], varied through time. For the last 2.5 Ga, the averaged VDM values were maximal ($7.16 \pm 0.7 \times 10^{22}$ Am^2) and minimal ($1.9 \pm 0.47 \times 10^{22}$ Am^2) at 1627.5 ± 2.5 and 2142.8 ± 9.7 Ma ago, respectively. As a whole, the VDM distribution is characterized by a positive trend from 3.7×10^{22} Am^2 at 2.6 Ga ago to 5.8×10^{22} Am^2 at the present.

Against this background, there are local maximums with centers in the Paleoproterozoic at 1800 Ma (the Orosirian Period with an absolute value up to 5.8×10^{22} Am^2 and a relative amplitude of approximately 2×10^{22} Am^2) and 1620 Ma (the Staterian Period with an absolute value up to 7.2×10^{22} Am^2 and a relative amplitude of approximately 3×10^{22} Am^2). In the Mesoproterozoic, the maximums correspond to 1120 Ma (the Stenian Period with an absolute value up to 5.7×10^{22} Am^2 and a relative amplitude of approximately 2×10^{22} Am^2); in the Neoproterozoic, they are recorded at 650 Ma (the Cryogenian Period with an absolute value up to 4.4×10^{22} Am^2 and a relative amplitude of approximately 1×10^{22} Am^2) and in the Paleozoic at 340 Ma (the Serpukhovian Age of the Carboniferous Period with an absolute value up to 6.6×10^{22} Am^2 and a relative amplitude of approximately 2×10^{22} Am^2). Since 190 Ma, the VDM value demonstrates an increase from 5.2×10^{22} to 8×10^{22} Am^2 and is continuing to grow now.

The above-mentioned maximums alternate with VDM minimums with centers corresponding to 2150 and 1700 Ma in the Paleoproterozoic (the Ryasanian and Staterian periods with absolute values up to 1.9×10^{22} and 4.2×10^{22} Am^2, respectively), 1400 Ga in the Mesoproterozoic (the Ectasian Period with an absolute value up to 3.2×10^{22} Am^2), 800 Ma in the Neoproterozoic (the Cryogenian Period with an absolute value up to 3.9×10^{22} Am^2), 500 Ma in the Paleozoic (the Ayusockanian Age of the Cambrian Period with an absolute value up to 3.5×10^{22} Am^2), and 190 Ma in the Mesozoic (the Sinemurian Age of the Jurassic Period with an absolute value up to 5.1×10^{22} Am^2). The extreme parts of these maximums and minimums are frequently characterized by complex patterns.

It also follows from Fig. 2 that the fluctuations periods (the intervals between the neighboring (both positive and negative) extremums) range from 198 to 605 Ma and their average value (for nine measurements) is 386 ± 45 Ma.

DISCUSSION

The calculations of the average VDM values by the method of a moving average show that their temporal distribution is regular with the directed linear VDM growth (1.5 times) during the last 2.5 Ga with a decrement of 0.00084×10^{22} Am^2/Ma. Against the background of this linear trend, there are fluctuations with the period estimated at the first approximation to be 390 Ma. This periodicity in the behavior of the main magnetic field of the Earth corresponds by the value's order to the Wilson geological cyclicity [e.g., 3]. The latter describes the cyclic formation and breakup of Pangea in response to changes in the mantle's convection regime. Such large-scale cyclicity is characterized by a period of 400–500 Ma. Inasmuch as Pangea's dispersion was accompanied by the opening of secondary oceans (the Atlantic, Indian, Arctic, Mediterranean, and their predecessors), while the restoration of a single continent stimulated the closure of these oceanic basins and, correspondingly, the growth of a primary ocean with its transformation into the Panthalassa, these megacycles may be identified with transitional periods [3] between two- or multicelled and single-celled structures of mantle convection.

The VDM value and that of the ancient magnetic field intensity H_{anc} for the same age at a particular latitude correlate with each other, which allows the virtual dipole moment to be used for describing the intensity of the main (dipole) part of the ancient magnetic field. We characterize the corresponding values as fractions of the recent magnetic field intensity H_{rec}, the equatorial value of which is as high as 0.33 e (26.3 Am/m) or 33000 nT [1]. The linear tendency for the growth of the intensity of the geomagnetic field dipole component at the equator for the last 2.5 Ga may be estimated as corresponding to 3.46 nT/Ma.

Such fluctuations are reflected in the intensity values lowered to 0.25 of H_{rec} in the period of 2.1–2.2 Ga and to 0.55 of H_{rec} in the period of 1.7–1.73 Ga in the Paleoproterozoic, to 0.4 of H_{rec} in the period of 1.35–1.45 Ga in the Mesoproterozoic, to 0.5 of H_{rec} in the period of 0.8–0.83 Ga in the Neoproterozoic, to 0.4 of H_{rec} in the period of 0.48–0.51 Ga in the Paleozoic, and to 0.63 of H_{rec} in the period of 0.17–0.21 Ga in the Mesozoic.

The significant (from $>7 \times 10^{22}$ to $<2 \times 10^{22}$ Am^2) variations in the averaged intensity of the dipole component of the earth's magnetic field unequivocally indicate that they should be taken into consideration in modeling the physical processes of the earth's evolution in the geological past and predicting them in the future.

The revealed distribution (Fig. 2) considerably specifies the available data from [8, 9, 22, 29, 43, 44, and others] on the VDM variations through the Proterozoic and Phanerozoic eons.

CONCLUSIONS

The analysis of the updated database of digital information on the virtual dipole moment reveals that the VDM distribution is characterized by a positive linear trend from 3.7×10^{22} to 5.8×10^{22} Am^2 during the last 2.6 Ga. Against the background of such a trend, there are fluctuations with periodicity of approximately 390 Ma.

The VDM distribution obtained by the method of a moving average substantially specifies the available data on the behavior of the ancient geomagnetic field through the Proterozoic and Phanerozoic eons and may be taken into consideration in modeling the physical processes in the development of the earth in the geological past and predicting its ecological and energetic evolution in the future.

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