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MARINE GEOLOGY

Variations of the Earth's Magnetic Field in the Phanerozoic

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Abstract—The global VDM database, which was later supplemented by new determinations published in the world literature (a total of 3194 determinations), is used as the basis for addressing the VDM behavior in the Phanerozoic (0–542 Ma) and up to 580 Ma. The results revealed a positive linear trend to higher VDM values from 3.5×10^{22} Am^2 to 5.7×10^{22} Am^2. Against this background, fluctuations of the mean VDMs occur with a periodicity of about 40 Myr. In the Phanerozoic, prominent minima of the intensity are found in the time intervals of 510–520, 420–460, 340–370, 290–300, 240–270, 190–210, 165–140 Ma (chrons M17–M43), 130–120 Ma (chrons M2–M10), 100–110 Ma (chron C34), 75–85 Ma (chrons C33 and the beginning of chron C34), 70–60 Ma (chrons C31–C27), and 40–15 Ma (chrons C18–C5AD). The distribution of the VDMs appears to reflect the paleomagnetic field behavior and may be taken into account in a magnetization model for the reversely magnetized oceanic crust.

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INTRODUCTION

An important source of information concerning the earth's magnetic field and its variation in time is provided by the distribution of the virtual dipole moment (VDM) in time (VDM × 10^{22} Am^2), which is considered to be the equivalent geocentric dipole moment that would have produced the measured intensity and inclination of the ancient dipole field [22] in the past. Knowledge of the variation of the VDM values recovered during the study of the geomagnetism helps us to understand how the geodynamo worked in the geological past.

Pioneering work in this area was undertaken by E. Thellier and O. Thellier, who developed techniques for the determination of the geomagnetic field elements (declination, inclination, and intensity) by comparing the behavior of the natural and induced remnant magnetization acquired by a single sample during its heating and cooling [2]. Thellier and Thellier also set up quality procedures for the sample orientation and selection during core sample recovery in the field and designed an induction magnetometer for laboratory measurements of the remnant magnetization in samples of an arbitrary shape.

The data obtained using the Thellier method [2] and its modifications [10, 21] indicated large variations in the dipole component of the earth's magnetic field in the Phanerozoic [4–6, 11, 17, 20, 24, 26–32, and others]. Until recently, the considerable scatter of the individual VDM values allowed only the qualitative confirmation of any observed trend of the data. A general methodological approach to the VDM data processing was proposed in [4] and applied to an analysis of VDMs for the time intervals of 0–160 Ma [4] and 0–400 Ma [5]. At the same time, all the age determinations are based on the most recent version of the geochronological time scale [13]. The quantitative approach outlined in [4] and subsequently modified in [5] and its application to the analysis of the data trends in the Phanerozoic (0–542 Ma) and up to 580 Ma (the mid-point of the interval used in the calculation is 570 Ma) is the main focus of this study.

MATERIALS USED

Recently, in order to examine the time history of the VDM, an international database (the IAGA Paleointensity Database) was created; it is available at the site of the Geophysical Center in Boulder Colorado (the United States) [18]. At the beginning of 2009, this database contained 2800 VDM values for the Phanerozoic, whose lower boundary is estimated at 542 ± 1 Ma [13], collected from 240 published sources [14]. This database, together with additional information from the database of the Borok Observatory [9] and the data published in [7, 8, 12, 15, 16, 19, and 23–26], was used as the basis for this study. The updated database used

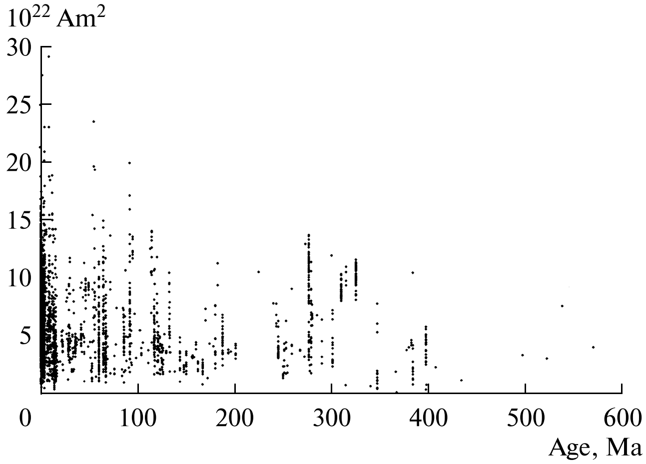

Fig. 1. Distribution of the VDMs (10^{22} Am^2). The data are taken from the updated paleointensity database.

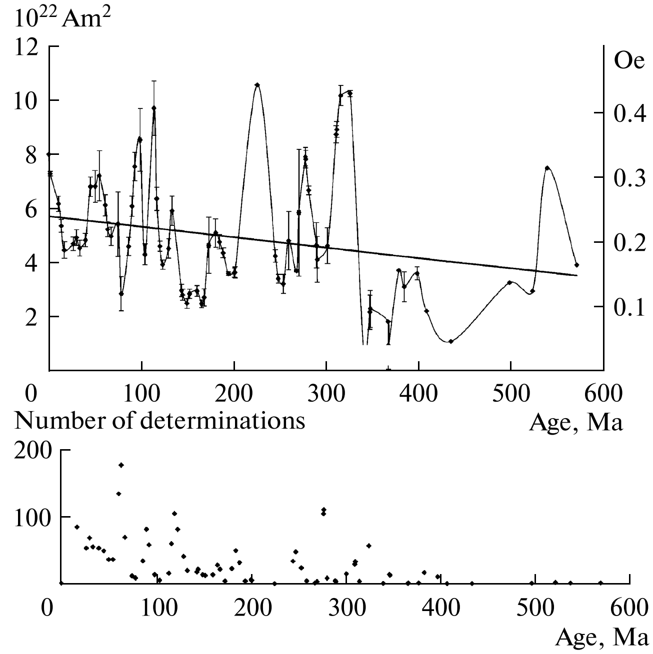

Fig. 2. Variations of the mean VDMs (10^{22} Am^2) in the interval of 0–580 Ma. The VDM values are averaged in a 10 Ma time window in steps of 5 Ma. The right vertical axis indicates the VDM values normalized to the equatorial field values (Oe). The vertical bars show the uncertainties in the age determinations as standard deviations for each window. The points below the age axis indicate the number of determinations in each time window, except for those where the number of determinations exceeds 200: 0–10 Ma (1828 determinations), 5–15 Ma (281 determinations), and 10–20 Ma (239 determinations) and the time windows such as 215–240, 415–430, 440–490, 500–520, and 545–570 Ma (no determinations).

in this study included 3194 VDM values with corresponding absolute age determinations.

The qualitative interpretation of the data shows that the strength of the earth's magnetic dipole did not remain constant in time. At the same time, the large scatter of the individual VDM values precludes the quantification of the qualitative trends in the data (Fig. 1).

Among other methods, we used a sliding window approach, which enabled the considerable smoothing of the random fluctuations in the data. The previous results [3, 4] showed that the best estimates can be obtained when averaged over 10 Ma sliding windows in steps of 5 Ma for the time interval up to 400 Ma. Such a window length was also used for the time interval of 400–542 Ma and then up to 580 Ma. In this study, we used the linear magnetic anomaly time scale and the corresponding polarity subchrons from [3, 13].

The maximum number of VDM values used in this study fall in the intervals of 0–10 Ma (1828 determinations), 10–20 Ma (239 determinations), 60–70 Ma (178 determinations), and 275–285 Ma (110 determinations). The intervals of 220–230, 260–270, 265–275, 285–295, 310–320, 335–345, 360–370, 365–375, 400–410, and up to 570 Ma are covered by less than 7 determinations each; the time intervals of 215–240, 415–430, 440–490, 500–520, and 545–570 Ma seem not to be represented by the data.

In all the cases, the mean VDM values and their standard deviations were used in the averaging. These values were then correlated with the mean age calculated over the same averaging interval. The modal value of the standard deviations of the mean ages falls within the interval of ±0.32…±0.69 Ma. There are six values that exceed the observed values of ±1 Ma to…±1.13 Ma in the interval of 75–85 Ma, ±1.5 Ma in the interval of 170–180 Ma, ±1.05 Ma in the interval of 95–105 Ma, ±1.49 ma in the interval of 160–170 Ma, ±1.43 Ma in the interval of 265–275 Ma, and ±1.01 Ma in the interval of 285–295 Ma.

RESULTS OF THE CALCULATIONS

Figure 2 shows the distribution of the mean VDM values observed for the past 400 Myr in the 10 Ma-window shifting by an interval of 5 Ma. The vertical bars show the standard deviations, which represent the amount of scatter of the individual values about the mean. The horizontal axis is the age determinations averaged over each time interval. The plot shows that the virtual dipole moment, whose present value is 8×10^{22} Am^2 [20], was not constant with time. Over the past 580 Myr, the mean VDMs demonstrate a linear increase from 3.5×10^{22} to 5.7×10^{22} Am^2 towards the present-day dipole moment and reach a maximum near 10.58×10^{22} at about 225 Ma and a minimum near 0.98×10^{22} Am^2 at about 366.5 Ma. Against the background of this linear increase, fluctuations of the mean VDMs occur with a periodicity of 20 Myr and more.

In the Paleozoic, there are several maxima of the dipole moment at 530–560 Ma (the Lower Cambrian: an absolute value of up to 7.5×10^{22} Am^2 with an amplitude of about 3×10^{22} Am^2), 370–420 Ma (the Gorstian–Frammenian: an absolute value of up to 3.7×10^{22} Am^2 with an amplitude of about 2.6×10^{22} Am^2), 360–340 Ma (the Famennian–Tournaisian: absolute values of up to 2.2×10^{22} Am^2 with an amplitude of about 2×10^{22} Am^2), 340–300 Ma (the Visean–Gzelian: an absolute value of up to 10.2×10^{22} Am^2 with an amplitude of about 8×10^{22} Am^2), and 290–270 Ma (the Sakmarian–Kungurian: an absolute value of up to 7.9×10^{22} Am^2 with an amplitude of about 4×10^{22} Am^2).

For the Mesozoic, the maxima were observed at 251–200 Ma (the Indusian–Hettangian: an absolute value of up to 10.6×10^{22} Am^2 with an amplitude of about 6.5×10^{22}), 195–165 Ma (the Sinemurian–Bathonian: an absolute value of up to 5.1×10^{22} Am^2 with an amplitude of about 2×10^{22} Am^2), 150–123 Ma (the Tithonian–Barremian: an absolute value of up to 6×10^{22} Am^2 with an amplitude of about 3×10^{22} Am^2), 123–103 Ma (the Aptian–Albian: an absolute value of up to 9.6×10^{22} Am^2 with an amplitude of about 6×10^{22} Am^2), 103–78 Ma (the Albian–Campanian: an absolute value of up to 8.8×10^{22} Am^2 with an amplitude of about 5×10^{22} Am^2), and 78–67 Ma (the Campanian–Maastrichtian: an absolute value of up to 5.1×10^{22} Am^2 with an amplitude of about 4×10^{22} Am^2).

For the Cenozoic, there is a maximum at about 67–33 Ma (the Danian–Priabonian: an absolute value of up to 7.2×10^{22} Am^2 with an amplitude of about 2.5×10^{22} Am^2). There appears to be a steady increase in the VDM from 4×10^{22} Am^2 at 16.9 Ma to its present value of 8×10^{22} Am^2.

The minima of the dipole moment occur between its maxima. The extreme parts of the minima and maxima plot contain additional local peaks with an amplitude up to 0.5×10^{22} Am^2. This distribution (Fig. 2) enables the more detailed VDM description in this time interval compared to the earlier data presented in [6, 15, 20, 30, 31, and others].

RESULTS AND DISCUSSION

The linear increase in the VDMs obtained using a sliding window is clearly traceable over the past 580 Myr, and the measurements in this interval give a mean VDM about 1.5 times the present dipole moment. Against this linear increase in the dipole moment, fluctuations occur with a period of roughly 40 Myr.

It is supposed that there is a linear relationship between the magnitude of the VDM and the paleointensity value H_{an} for the same time interval and latitude, which allows one to use the VDM to characterize the intensity of the dipole part of the ancient magnetic field. The corresponding values will be expressed as fractions of the present-day field intensity H_{pr}, whose equatorial value is 0.33 Oe (26.3 A/m) or 33000 nT [1]. The linear trend to higher intensity values of the dipole part of the geomagnetic field at the equator during the past 580 Myr is estimated to be 0.015 nT/kyr.

In the Paleozoic, the trend to lower values is representative of the time intervals of 510–520 Ma (0.25 of the H_{pr}), 420–430 Ma and 340–350 Ma (0.15 of the H_{pr}), 300–290 Ma, 270–240, and 210–190 Ma (0.4 of the H_{pr}).

In the Mesozoic, the trend to lower values is representative of the time interval of 165–140 Ma (chrons M43–M17; 0.3 of its present value). Furthermore, relative paleointensity minima of up to 0.5 of its present value are found in the time intervals of 130–120 Ma (chrons M10–M2), 100–110 Ma (chron C34), and down to 0.35 of its present value in the interval of 75–86 Ma (chron C33 and the beginning of chron C34).

In the Cenozoic, prominent minima in the intensity are found at around 70–60 Ma at the Danian–Maastrichtian boundary (chrons C31–C27; 0.7 of its present value) and at 40–14 Ma (chrons C18–C5AD; 0.5 of its present value). Note that, closer to the midpoints of the minima at 370–340, 270–240, 165–144, and 40–14 Ma, there are few intervals where the intensity was high.

Over the past 580 Ma, the intervals of the VDM minima and maxima are of almost equal length. The greatest variations (from 10×10^{22} Am^2 and more to 0.3×10^{22} Am^2 and less) in the dipole field should be taken into account in modeling the paleomagnetic anomalies originating at the spreading axis in the Mesozoic–Cenozoic time, as well as in modeling the reversely magnetized layers of the oldest zones within the oceanic crust, which are assumed to exist in the earth.

CONCLUSIONS

The analysis of the updated paleointensity database showed a tendency for the VDMs to increase in an approximately linear manner from 3.5×10^{22} Am^2 to 5.7×10^{22} Am^2 over the past 580 Ma. Against this background, the VDM values fluctuate with a periodicity of about 40 Myr.

The distribution of the VDMs obtained using a sliding window appears to reflect the paleomagnetic field's behavior and may be taken into account in a magnetization model for the reversely magnetized oceanic crust between chrons C1 and M43. The VDM values obtained for the time intervals older than 162.45 Ma (the oldest part of chron M43) can be used in the magnetic modeling of the reversely magnetized layer of the oldest zones within the oceanic crust, which are assumed to exist in the earth.

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