ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2009, Vol. 45, No. 1, pp. 14–20. © Pleiades Publishing, Ltd., 2009.
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The Geomagnetic Field at the Proterozoic–Paleozoic Boundary and Lower-Mantle Plumes

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Received January 16, 2008; in final form, April 14, 2008

Abstract—Data on the amplitude of variations in the direction of the geomagnetic field and the frequency of reversals in the Vendian–Cambrian are presented. It has been established from these data that (a) distributions of variations in the direction of the geomagnetic field S_p are bimodal (modes 9° and 11°); (b) the maximum of the average amplitude S_p takes place by 5–10 Myr later than the Vendian–Cambrian boundary; (c) S_p tends to increase as plume epicenters are approached; and (d) the plume formation is more often confined to intervals with different frequencies of geomagnetic reversals than to the interval of a stable state of the geomagnetic field without reversals (Vendian hyperchron). The listed features of the geomagnetic field behavior are repeated near all boundaries of geological eras of the Phanerozoic.

PACS numbers: 91.25.Ng

DOI: 10.1134/S1069351309010030

INTRODUCTION

According to current notions, lower–mantle plume magmatism originated at the core–mantle boundary of the Earth. This is reflected in the relationship between the total amplitude of variations in the geomagnetic field direction and the plume magmatic activity, both present-day and near the Mesozoic–Cenozoic and Paleozoic–Mesozoic boundaries, with respect to the plume origination time [Pechersky, 2001, 2006, 2007; Pechersky and Garbuzenko, 2006]. The interval from the time of origination of plumes fixed by the amplitude of field variations and the time when they reach the Earth's surface is 20–50 Myr, which reflects the time it took for a plume to rise from the core–mantle boundary to the Earth's surface and it is related to different paths of the plume's rise, "delays" on the path, etc. The paradox between short-term disturbances in the core responsible for plume formation and the long "lifetime" of each plume is explained by, first, the prolonged existence of the plume and, second, the formation of a series of plumes (superplumes) in the same region of the core–mantle boundary.

The results indicate that the origination of lower-mantle plumes of various times of formation, world magnetic anomalies, and an increase in the amplitude of variations in the geomagnetic field direction are phenomena of a unified nature, i.e., they result from local excitations in the upper part of the liquid core [Pechersky, 2007]. On the other hand, there is no relation between plume generation and the frequency of geomagnetic reversals: periods of plume formation fall on different variants of the frequency of reversals.

Earlier, we considered the geomagnetic field behavior and the relation of plumes to it at the present time [Prchersky, 2001] and near the Mesozoic–Cenozoic [Pecherskii and Garbuzenko, 2005] and Paleozoic–Mesozoic [Pechersky, 2006] boundaries. This paper is devoted to a similar analysis for the Proterozoic–Paleozoic boundary.

VARIATIONS IN THE DIRECTION OF GEOMAGNETIC FIELD

Method of Investigation

The total amplitude of variations in the direction of geomagnetic field can be determined from the standard deviation $S = 81/K^{1/2}$, where K is the precision parameter of individual vectors in the statistics on a sphere [Khramov et al., 1982]. To determine and analyze the behavior of S near the Paleozoic–Proterozoic boundary, we used the GPMDB-2007 database of paleomagnetic data, from which paleomagnetic determinations for the period from 500 to 610 Ma were selected. The chosen time interval includes (a) a series of large plumes related to the lower part of the mantle: the Antrim (Australia, age 509 Ma, epicenter coordinates 15°S, 130°E), Wichita (North America, 530 Ma, epicenter coordinates 34°N, –98°W), Japetus (North America, 550 Ma, epicenter coordinates 40°N, –78°W), and Ouarzazate (East Africa, 560 Ma, epicenter coordinates 30°N, –7°W [Ernst and Buchan, 2002, 2003]; (b) the Cambrian–Vendian boundary (544 Ma); and (c) the entire Vendian, taking into account the expected 20- to 50-Myr difference between the time when the plume

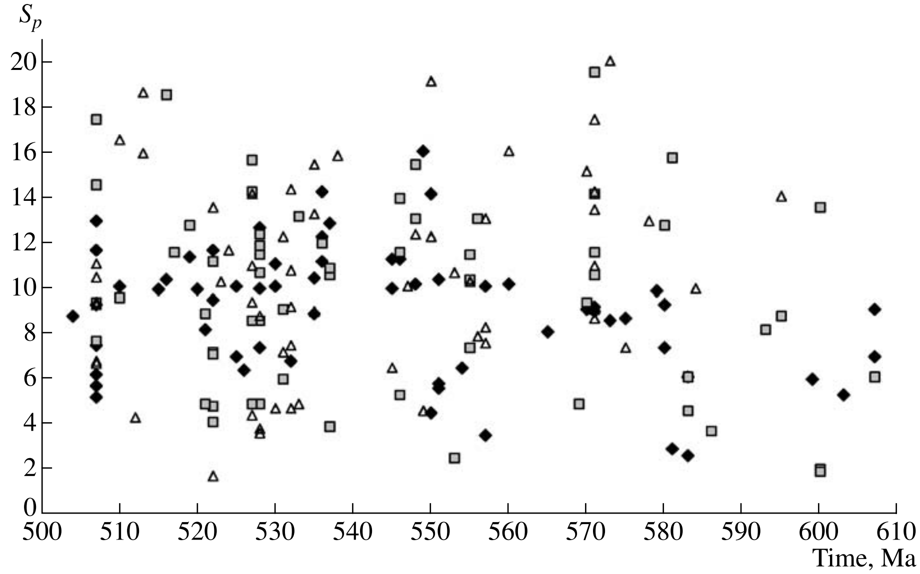

Fig. 1. Time distribution of S_p values in the Vendian–Early Cambrian (500–600 Ma). Determinations of a high, medium, and low reliability are marked by black rhombs, gray squares, and open triangles, respectively.

reaches the surface and the time of activity at the core–mantle boundary, which led to an increase in the amplitude of geomagnetic field variations and plume formation [Pechersky, 2001, 2007].

These paleomagnetic data were classified in accordance with the following four categories. (1) *Unreliable paleomagnetic data.* The number of samples used for a determination is no more than ten, the thermal demagnetization is either absent or heating temperatures do not exceed 200°C, the alternating-field (AF) demagnetization field is not higher than 15 mT, the precision parameter $K < 7$, and the confidence angle $\alpha_{95} > 25°$. Such determinations result from the remagnetization of older rocks and are excluded from further consideration. (2) *Paleomagnetic data of low reliability.* The number of samples is no more than 20, the thermal demagnetization temperature is no higher than 400°C, and the AF demagnetization field is no higher than 30 mT. The index of paleomagnetic reliability of such determinations is 0.1. (3) *Paleomagnetic data of medium reliability.* The number of samples is more than 20, the thermal demagnetization temperature is no lower than 500°C, the AF demagnetization field is no lower than 50 mT, and some field tests, such as the test for the fold, are positive. The index of paleomagnetic reliability of such determinations is 0.5. (4) *Paleomagnetic data of high reliability.* The number of samples is more than 20, and complete thermal and AF demagnetizations are combined with the component analysis and extraction of the characteristic component of the natural remanent magnetization (NRM). At least two field tests (fold, pebble, baking, reversal) must be positive. The index of paleomagnetic reliability of such determinations is 1.0. When average S values are calculated, these reliability indices are used as weights of determinations. The scatter in S values is large, primarily due to technical and methodological factors (incomplete demagnetizations, measurement errors, additional magnetization in the process of demagnetization, a large age interval used for calculating the average paleomagnetic direction, etc.); average and modal values of S are more reliable.

We selected 175 paleomagnetic determinations for the interval 610–500 Ma (Fig. 1). These determinations were distributed over continents in the following way: Australia, 20; Asia, 76; Antarctica, 3; Africa, 16; Europa, 36; India, 3; North America, 23; and South America, 7. The distribution over rocks is as follows: sedimentary rocks, 111; lavas, 33; and intrusions, 35.

Due to the absence of reliable paleotectonic reconstructions for the time interval under investigation, positions of points of paleomagnetic observations with respect to epicenters of the nearest plume were considered only within the continent, on which one of the selected plumes is located, i.e., in Australia, Africa, and North America.

In accordance with the S dependence on the latitude [Pechersky, 1996], all determinations of S are reduced to one paleolatitude, namely, to the pole latitude (S_p).

RESULTS OF INVESTIGATIONS

The selected paleomagnetic determinations (Fig. 1) were used to calculate the weighted average values of S_p in intervals of 5–10 Myr, and the results were in turn smoothed with a window of 20–25 Myr (Fig. 2). The pattern obtained evidently characterizes the behavior of the average amplitude of variations in the direction of the "normal" geomagnetic field. As seen from Fig. 2,

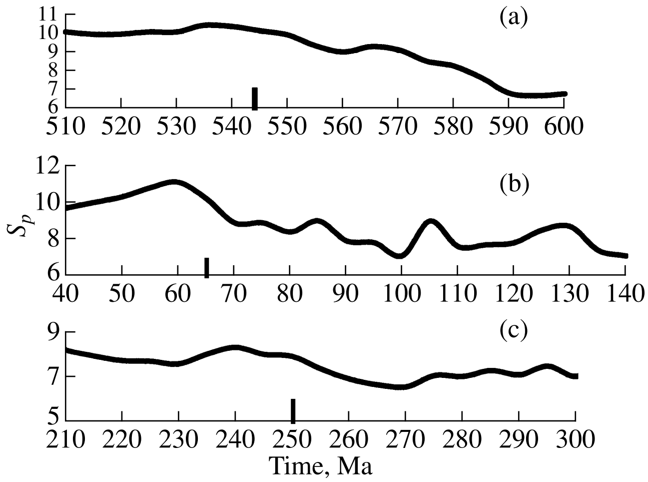

Fig. 2. Averaged over intervals of 5–10 Myr and smoothed S_p values for the time intervals including the (a) Proterozoic–Paleozoic, (b) Mesozoic–Cenozoic, and (c) Paleozoic–Mesozoic boundaries. The thick black vertical bars mark the boundaries of geological eras.

the Proterozoic–Paleozoic boundary, as well as the boundaries of the two other eras, is located on the ascending branch of the amplitude of field variations at a distance of 5–10 Myr from its maximum. If the S_p maximums are brought into coincidence, as it is done in Fig. 2, the positions of era boundaries will diverge by no more than 5 Myr; i.e., significant events at the core–mantle boundary and at the Earth's surface are nearly synchronous. However, such a similarity between the pattern of field variations and the positions of era boundaries does not reflect the opposite tendency in the evolution of biota, because the diversity of biota abruptly increases at the Vendian–Cambrian boundary, but at the two other boundaries, biota abruptly dies off on the Earth; i.e., the synchronism of the processes does not mean that they have a cause-and-effect relationship.

The bimodal S_p distribution clearly pronounced for the time interval, when such large superplumes as Iceland–Greenland, Deccan (Fig. 3b), and Siberian (Fig. 3d) were formed, is not so obvious for the Vendian–Cambrian time: the first (9°) and second (11°) modes (Fig. 3a) are located very close to each other and are insufficiently expressive due, first, to a small amount of determinations that fall on a large time interval and, second, to a high level of the normal field throughout the almost entire period under consideration (Fig. 2a). Previously, it was shown [Pechersky, 2007] that the bimodal distribution of S_p values is caused by two factors, global and local. The global factor indicates that the first (smaller) S_p mode always exists in the time intervals under consideration and does not depend on the distances to plume epicenters; this mode characterizes the normal state of the geomagnetic field, which is lowest during the Mesozoic (Fig. 2b) and Late Paleozoic (Fig. 2c) and is highest in the Early Paleozoic (Fig. 2a). The local factor indicates that the second (higher) mode exists only at small distances from plume epicenters and vanishes as these distances increase; i.e., this mode is caused by disturbances in the normal state of the geomagnetic field and by plumes originating at this time.

Depending on the intensity of disturbances and the distribution of points of geomagnetic observations with respect to plume epicenters, the following variants are possible: (1) a bright second mode that noticeably lags behind the mode of the normal field, when the intensity of disturbances is high and the mode height depends on the relative number of observation points located in regions of disturbances and near them; the histograms for the 140–50 Ma (Fig. 3b) and 290–270 Ma (Fig. 3d) time intervals are examples of such cases; (2) the distance between the second and first modes is not so large, the intensity of disturbances is relatively weak, and, above all, many observation points are located outside the regions of disturbances (Fig. 3c); and (3) the histogram is close to the single-modal one with a large variance (Rayleigh distribution consisting of two independent Gaussian distributions with close mathematical expectations, Fig. 3a).

The explanation of the S_p modes proposed in [Pechersky, 2007] is related to the Vendian–Cambrian time as well.

Notwithstanding the scarcity of paleomagnetic data, we will try to consider the S_p dependence on the distance between the paleomagnetic observation point and the epicenter of the nearest plume. Since distances to plume generation places and datings of many paleomagnetic determinations cannot be determined with certainty, the scatter of S_p values, and the amplitude of variations must increase as the plume epicenter is approached [Pechersky, 2007]. The addition of technical errors will also increase the scatter in individual values of S_p. Therefore, it is better to use average values; however, the amount of data is insufficient for obtaining such values. The statistics is also insufficient for tracing the S_p behavior with increasing distance from the epicenter of a concrete plume. Therefore, we will restrict ourselves to the distributions of the amplitudes of variations with respect to the epicenters of the four plumes mentioned above (Fig. 4). Recall that the distance from the epicenter of the plume to the place of its formation at the core–mantle boundary is ~3000 km, and that the plume rise channel can be inclined [Ernst and Buchan, 2003]. Accordingly, if the distance from the plume epicenter to the observation point is smaller than the distance to the core–mantle boundary, substantial regular S_p changes with increasing distance from the plume epicenter will be improbable. Figure 4 displays very weak tendencies toward a decrease in the S_p value with increasing distance from the plume epicenter. In order to fix these tendencies with greater certainty, we united the weighted average S_p values at 10-degree intervals of

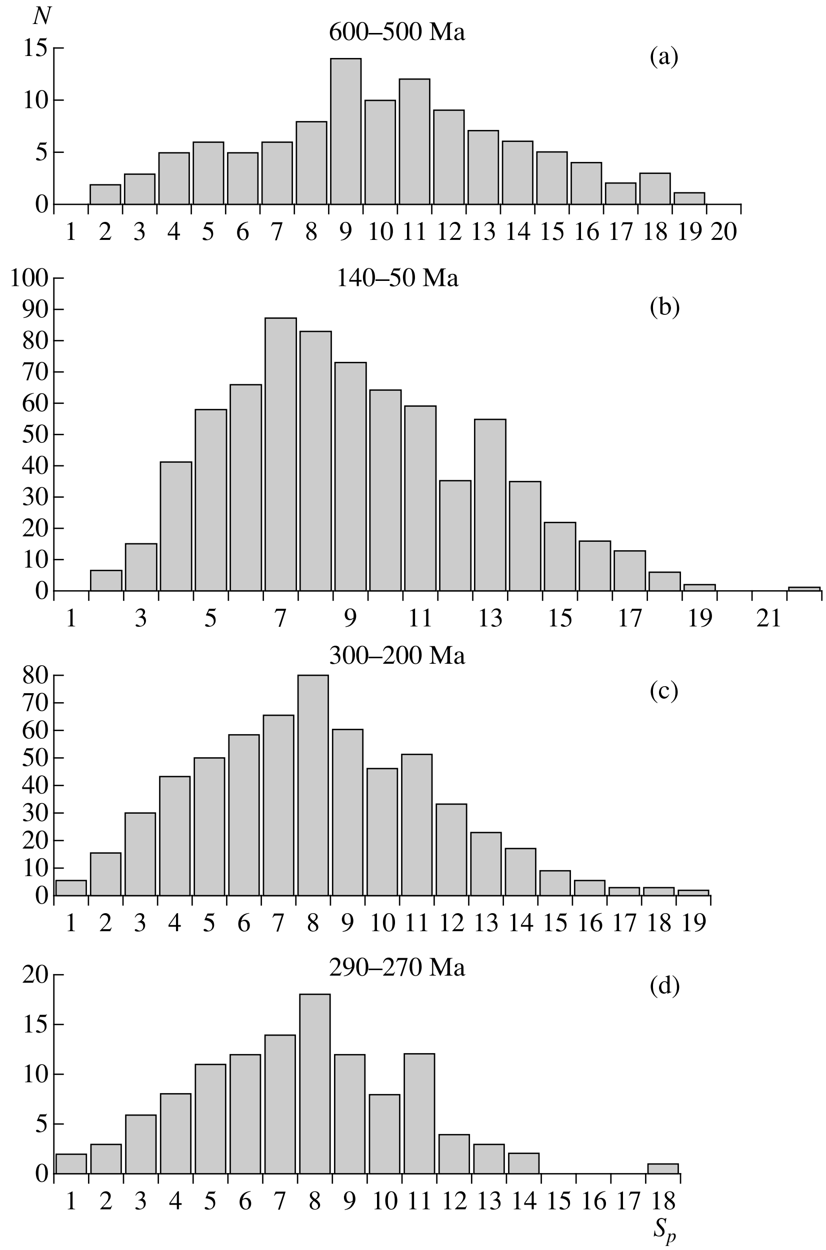

Fig. 3. Histograms of the distributions of amplitudes of variations in the geomagnetic field direction S_p for the time intervals: (a) 600–500 Ma, (b) 140–50 Ma, (c) 300–200 Ma, and (d) 290–270 Ma. The last histogram presents the formation time of the Siberian plume at the core–mantle boundary.

the distances to the plume epicenters presented in Fig. 4. The S_p values for the interval from the time, when a given plume reaches the surface to a possible time of its formation (60 Myr maximum) are included into the calculation. The thus obtained data (table) display a certain tendency toward a decrease in the average values of S_p with increasing distance from the plume epicenter. This difference is insignificant if the distance from the plume epicenter varies from zero to 30°, which corresponds to the aforesaid about the comparability of the distance between the observation point and the plume epicenter with the distance to the plume origination place at the core–mantle boundary. Only if this distance is 30°–40° will a decrease in the average value of S_p become significant (table).

Average weighted values of S_p (± standard error of the average) for different distances to the epicenters of four plumes

distance	0°–10°	10°–20°	20°–30°	30°–40°
S_p	10° ± 1.23°	8.7° ± 0.6°	8.9° ± 0.82°	7.6° ± 0.84°

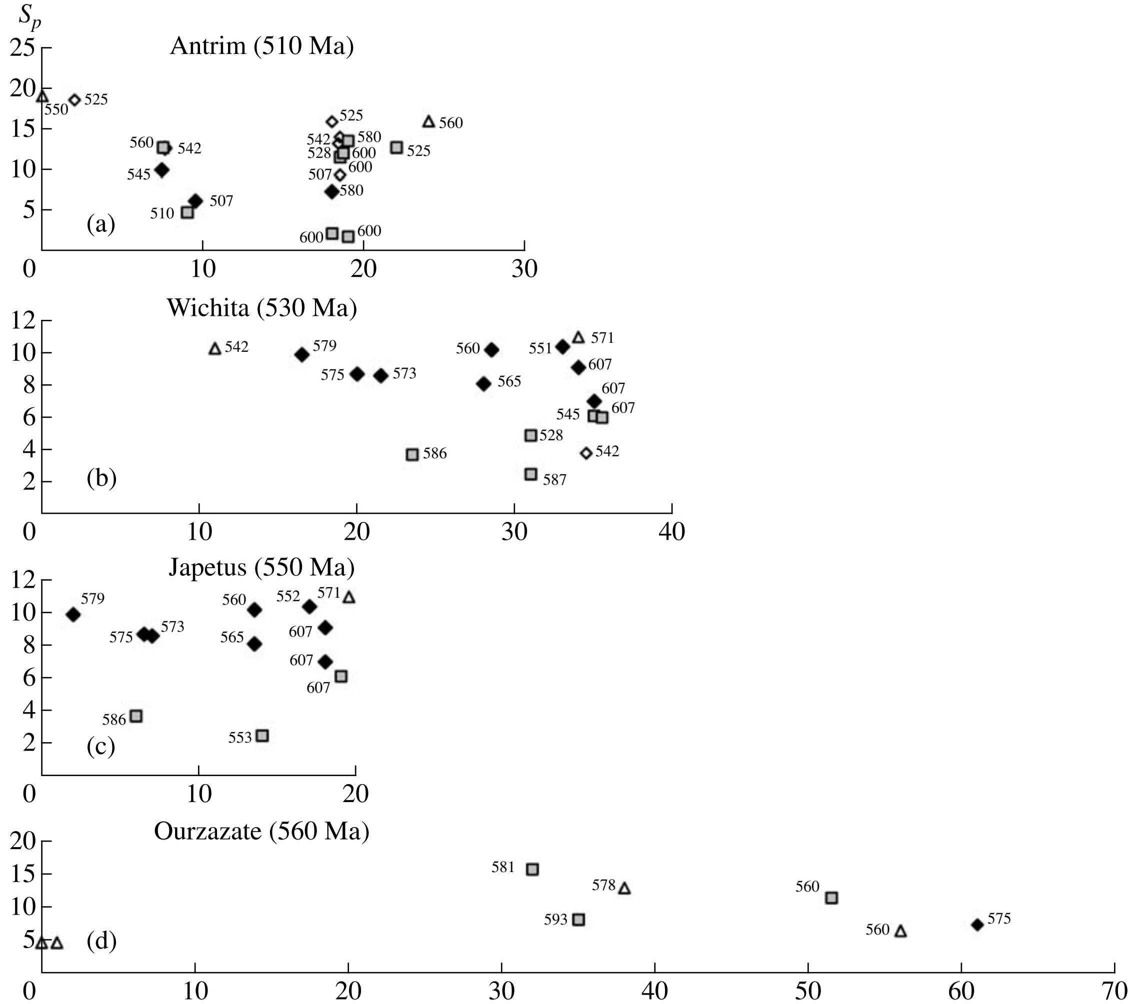

Fig. 4. Examples of the S_p distributions depending on the distances to the epicenters of the (a) Antrim, (b) Wichita, (c) Japetus, and (d) Ourzazate plumes in degrees of the arc of the great circle. Determinations of high, medium, and low reliability are marked by black rhombs, gray squares, and open triangles, respectively. Numerals near symbols indicate the age of paleomagnetic data.

Thus, during the Vendian–Cambrian, the relationship between field variations and plume activity is the same as in later times. This is not so obvious due to the scarcity of data; however, the similarity in the S_p behavior at all time intervals makes it possible to extend the conclusions based on the data for later times to the Vendian–Cambrian time.

The paucity of data and the absence of paleoreconstructions make it impossible to identify compact regions of increased values of S_p, i.e., the regions of plume formation at the core–mantle boundary, as it was done for the Permian–Triassic [Pechersky, 2006, 2007].

PALEOMAGNETIC POLARITY AND THE FREQUENCY OF GEOMAGNETIC REVERSALS

To analyze the polarity and the frequency of field reversals, we used the geomagnetic polarity scale [Pechersky, 1998]. The plot of the frequency of reversals (the number of reversals over 1 Myr) of the geomagnetic field in the Vendian–Cambrian was constructed with the use of this scale (Fig. 5a). It is seen from this figure that the Vendian–Cambrian boundary, as well as the boundaries of other geological eras of the Phanerozoic, i.e., the time of maximum changes in biota, falls on the interval when the frequency of reversal increased. The stable regime devoid of reversals was replaced by the regime of frequent polarity changes in 15–20 Myr before the boundaries of the three eras. The periods of a high plume magmatic activity at the Earth's surface noted in Fig. 5 fall on intervals with different frequencies of reversals. At the core–mantle boundary, plumes were formed 20–50 Myr earlier [Pechersky, 2006, 2007]. Accordingly, if these 20–50 Myr are counted from the periods of plume activity at the Earth's surface, the periods of plume formation will fall on intervals with different frequencies of geomagnetic reversals and more often, on intervals of a stable field

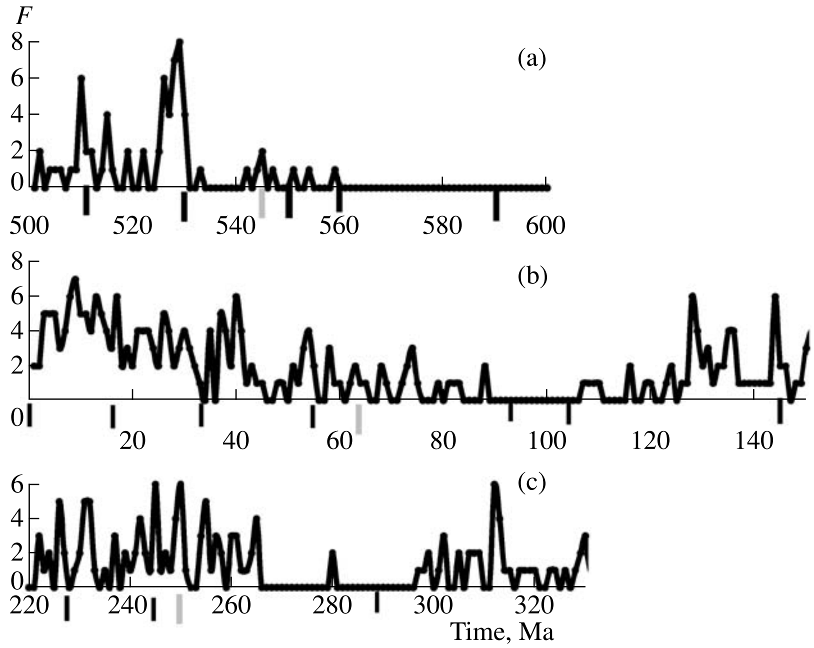

Fig. 5. Frequencies of reversals (the number of geomagnetic field reversals per 1 Myr) in the time intervals including the boundaries of geological eras: (a) Proterozoic–Paleozoic, (b) Mesozoic–Cenozoic, and (c) Paleozoic–Mesozoic. Black vertical bars near the abscissa axis mark periods of magmatic activity of plumes at the Earth's surface [Ernst and Buchan, 2003]. Gray vertical bars mark boundaries of geological eras.

with no reversals, i.e., on the Jalal, Kiama, and Vendian superchrons, which points either to the absence of any relation between the two processes: geomagnetic reversals and the plume formation, or, possibly, to the presence a feedback between them.

CONCLUSIONS

Notwithstanding the paucity of paleomagnetic and paleotectonic data for the Vendian–Cambrian, the following main features of the field behavior in the interval 600–500 Ma are evident: first, the noted bimodality of the distribution of the amplitude of variations in the geomagnetic field direction S_p (modes 9° and 11°); second, the character of temporal changes in the average amplitude S_p with the maximum by 5–10 Myr later than the Vendian–Cambrian boundary; third, a significant S_p increase as plume epicenters are approached; and, fourth, the predominant confinement of the plume formation to intervals of a stable state of the geomagnetic field without reversals. All these features also accompany the geomagnetic field behavior near the two other boundaries of geological eras of the Phanerozoic. Therefore, one can state that unified regularities are present in the geomagnetic field behavior during the Phanerozoic and that the processes of plume formation are related to these regularities.

(1) The bimodality of S_p histograms. The first mode characterizes the behavior of the normal geomagnetic field, whereas the second mode is associated with local disturbances responsible for the plume formation.

(2) The boundaries of geological eras are located near the S_p maximum, being ahead of it by 5–10 Myr. At the same time, the boundaries of eras are in the region of frequent reversals of geomagnetic polarity and are 15–20 Myr later than the hyperchrons of a stable field state (one polarity) preceding them. This means that significant events at the core–mantle boundary and at the Earth's surface are nearly synchronous. However, if the diversity of biota sharply increases at the Vendian–Cambrian boundary, the mass extinction of biota at the Earth's surface takes place at the two other boundaries, i.e., the synchronism of processes does not point to their cause-and-effect relationship [Pechersky, 1998], much less, to their association with the fall of large meteorites.

(3) A similar tendency toward an increase in the amplitude of variations in the field direction as epicenters of lower-mantle plumes are approached is seen against the background of the normal field, which indicates that the generation of lower-mantle plumes of various formation times and an increase in the amplitude of variations in the geomagnetic field direction are phenomena of a unified nature; i.e., they result from local excitations in the upper part of the liquid core.

(4) Periods of plume formation are associated with different variants of the frequency of reversals; they are predominantly confined to hyperchrons of a stable state of the geomagnetic field without reversals. This primarily indicates that the generation of plumes is unrelated to the frequency of geomagnetic reversals; i.e., the sources of field direction variations and plumes, on the

one hand, and field reversals, on the other hand, are different. If the sources of the first group of phenomena are confined the core–mantle boundary, phenomena of the second group are, most probably, generated at the liquid–solid core boundary. This resembles the state of an ocean: storms at its surface do not reach its floor, and events at the ocean floor are felt at the ocean surface only as weak responses.

(5) The interpretation proposed is not the final solution to the problem, but only a hypothesis for guiding further investigations.

ACKNOWLEDGMENTS

I am grateful to A.A. Lyubushin for useful comments and recommendations on the data processing and analysis.

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