Geomagnetic field in the vicinity of the Paleozoic-Mesozoic boundary and the Siberian superplume

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Received 15 January 2006; accepted 1 February 2006; published 17 March 2006.

[1] The aim of this study was to generalize the data available for the paleointensity, polarity, and frequency of reversals, and variations in the direction of the geomagnetic field in the vicinity of the Paleozoic and Mesozoic (P/T) boundary which had been marked by a peak in the magmatic activity of series superplumes, including that of the Siberian traps (251 Ma). However, no specific features have been found for the behavior of the field at that time. Some notable changes in its paleointensity had occurred 30 million years before the P/T boundary: the reversals frequency and polarity of the field changed during a period of 15 million years before the P/T boundary. The global changes of the average magnitude of the field direction variations from the unstable state with variations of 6°–10° to 6°–7° marked the lower and upper boundaries of the Kiama hyperchron (the stable state of the reversed-polarity field). The transition of the Kiama hyperchron to the Illawara hyperchron of frequent polarity changes was marked by the growth of the field variation magnitude from 6° (265 Ma) to 8°–9° (240 Ma). The regular growth of the field variation magnitude is marked with approaching to the center of Sibirian traps from the normal state, averaging 7°–8°, to 11°–12°, which demonstrated a connection between the local disturbance in the Earth core at its boundary with the mantle and the formation of the Siberian superplume. The growth of the field variation magnitude continued during a time period of 20–50 million years befor the P/T boundary and maximum activity of the Siberian trap formation, reflecting the time of the superplume rise from the base of the mantle to the Earth surface. This pattern is similar to the World magnetic anomalies, modern plumes, and the plumes in the vicinity of the Mesozoic-Cenozoic (Mz-Kz) boundary, this proving the same origin of the lower-mantle plumes and world magnetic anomalies. *INDEX TERMS:* 1521 Geomagnetism and Paleomagnetism: Paleointensity; 1535 Geomagnetism and Paleomagnetism: Reversals: process, timescale, magnetostratigraphy; 1540 Geomagnetism and Paleomagnetism: Rock and mineral magnetism; *KEYWORDS:* Geomagnetic field, Paleozoic-Mesozoic boundary, superplume, paleointensity.

Citation: Pechersky, D. M. (2006), Geomagnetic field in the vicinity of the Paleozoic-Mesozoic boundary and the Siberian superplume, *Russ. J. Earth. Sci., 8,* ES1004, doi:10.2205/2006ES000191.

Introduction

[2] The boundary between the Paleozoic and Mesozoic eras was marked by the intensive plume-type magmatism, associated with the activity of the Siberian superplume and other plumes, the origin of which is believed to have been associated with the Earth core and mantle boundary [*Ernst and Buchan,* 2003; *Grachev,* 2000; and others]. In this case, this must have been reflected in the behavior of the geomagnetic field. As follows from the analysis of the geomagnetic field in the Cenozoic and in the vicinity of the Mz-Kz boundary [*Pechersky,* 2001; *Pechersky and Garbuzenko,* 2005], a change in the core conditions, leading to the geomagnetic field reversals and to changes in the paleointensity, is not directly related to this boundary, or to the generation of lower-mantle plumes, or to the generation of the magnetic field direction variations. The magnitude of the field direction variations grows closer to the epicenters of lower-mantle plumes, the vigorous magmatic activity of which being close to the modern one (Afar, the volcanoes of the Khamar-Daban Ridge and of the Bolshoi Anyui R. basin, and the Buve, Hawaii, Iceland, Reunion, and Samoa vol-

ISSN: 1681–1208 (online)

canic islands), or to the Mz-Kz boundary (North-Atlantic volcanic province and Deccan traps). However, the origin of these plumes, which is usually correlated with the growth of the magnetic field variation magnitude, took place 25–50 million years befor present-day or before the Mz-Kz boundary. This "retardation" is usually associated with the time of the plume rising from the core-mantle boundary to the Earth surface. A change in the core condition, which caused the geomagnetic field reversals, also began some 20 million years earlier than the Mz-Kz boundary.

[3] The retardations of the onsets of the geological eras from the minima of the reversal frequencies were reported for the Phanerozoic [*Khramov et al.,* 1982; *Molostovskii et al.,* 1976; *Pechersky and Didenko,* 1995] and for the whole of the Neogaean [*Pechersky,* 1997, 1998]. This retardation from the reversal frequency peaks is typical of the average velocity peaks of the continent motions [*Pechersky,* 1998]. This retardation varies from 20 to 60 million years with the average value being 35±10 million years, which correspond to the velocity of the material rising from the core-mantle boundary to the Earth surface, ranging from 4 cm year^{-1} to 10 cm year^{-1}. This velocity agrees with the average drifting velocities of the main continental plates [*Jurdy et al.,* 1995; *Pechersky,* 1997, 1998; *Zonenshain et al.,* 1987; and others].

[4] The aim of this paper is to analyze the behavior of the geomagnetic field in the time interval of 340 Ma to 200 Ma and the potential association of the Siberian superplume with it. This time interval includes the P/T boundary and the potential time interval prior to, during, and after the formation of the Siberian plume and its manifestations on the Earth surface. According to many data, the time of the igneous activity of the Siberian traps was dated 251±0.2 Ma and coincided with the P/T boundary, where as generally the trap magmatism of Siberia lasted roughly from 260 Ma to 240 Ma [*Ivanov et al.,* 2005]. As follows from the magnetostratigraphic data available [*Gurevich et al.,* 1995, 2004], the major period of the volcanic trap activity in Siberia can be dated 251–249 Ma, generally embracing two magnetozones in the Late Permian (Maimecha-Kotui Province) and five magnetozones in the Early Triassic (West Taimyr Traps).

Paleointensity

[5] The results of determining paleointensity using the Thellier, Wilson-Burakov, van-Zijl, and Shaw methods [*Khramov et al.,* 1982; *Merrill and McElhinny,* 1983] and the dipole magnetic moments calculated on its basis are collected in the database and generalized. The authors of the latest generalization [*Shcherbakov et al.,* 2002] used only the most reliable determinations, performed using the Thellier method and its modifications. These data suggest that in the time interval of 330–280 Ma the paleointensity of the magnetic field was high and then declined abruptly (averagely two times) and remained as such up to the time of 200 Ma. It follows that the P/T boundary, and hence the peak of the igneous activity of the Siberian traps (251 Ma) fell into the interval of low paleointensity values [*Shcherbakov et al.,* 2002], and were not fixed in the paleointensity. Yet, the data available are not sufficient to judge about the fine details of the global paleointensity behavior and, especially, about its local specific features. It should be emphasized that the paleointensity decline and the high growth of paleointensity variations was dated 280 Ma, that is, earlier than the boundary between the Kiama reversed polarity hyperchron (steady-state field) and the hyperchron Illawara of the frequent changes of the polarity (unstable state of the field), which has been dated 265 Ma.

The Geomagnetic Polarity and Frequency of Geomagnetic Reversals

[6] We analyzed the polarity and reversal frequency of the geomagnetic field using the geomagnetic polarity time-scale reported in [*Gradstein et al,* 2004]. Using this scale, we plotted reversal frequency curves, using the number of reversals for the time period of one million years, and the curves of the geomagnetic field polarity in per cent for one million years (Figure 1). This Figure shows that the P/T boundary and the time of the maximum Siberian trap activity fell into the time interval of frequent reversals and, hence, frequent geomagnetic polarity changes, without being reflected in the geomagnetic field characteristics. The coinciding peaks of the biota change and of the Siberian trap magmatism "lag behind" from the boundary between the Kiama and Illawara hyperchrons by 15 million years.

Variations in the Geomagnetic Field Direction

[7] The total magnitude of the geomagnetic field direction variations was determined using the standard angular deviation $S = 81/\mathbf{K}^{1/2}$, where $\mathbf{K}$ is the precision parameter in the sphere statistics [*Khramov et al.,* 1982]. Using the same method, we determined S values for the whole of the Neogaea [*Pechersky,* 1998] and for the vicinity of the Mz-Kz boundary [*Pechersky and Garbuzenko,* 2005].

[8] In contrast to the other geomagnetic field characteristics, briefly reported above, the abundant data available for the magnitude of the field direction variations, both in time and space, are sufficient to analyze not only the global behavior of this field characteristic, but also some local features, relative, in particular, to the center of the Siberian traps.

[9] In order to describe the S behavior in the vicinity of the Paleozoic-Mesozoic (P/T) boundary, I used the Paleomagnetic Database (GPMDB-2005), and chose the paleomagnetic data, ranging roughly from 200 Ma to 340 Ma in age. This choice was based on the following reasons: (a) the basic impulse of the Siberian trap activity can be dated 251 Ma, some less intensive magmatic activity was recorded later, during the Triassic [*Gurevich et al.,* 2004; *Ivanov et al.,* 2005]. In order to reconstruct a more complete pattern of the geo-

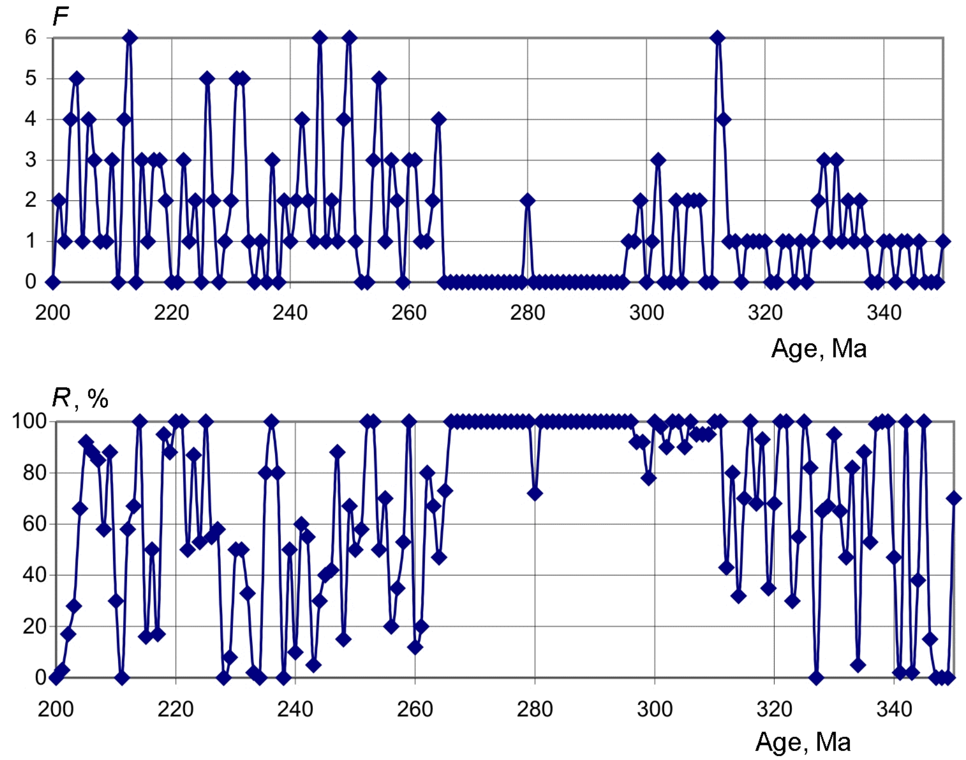

Figure 1. The number of reversals (F) and the contribution of the reversed polarity (R, %) of the geomagnetic field for one million years. This Figure was plotted using the geomagnetic polarity timescale of [*Gradstein et al.,* 2004].

magnetic field variation, I used the time interval after the end of the Siberian trap magmatism, namely, 250 Ma to 200 Ma; (b) earlier, using the examples of the modern igneous activity of the plumes [*Pechersky,* 2001], and of the plumes in the vicinity of the Mz-Kz boundary [*Pechersky and Garbuzenko,* 2005], we found that closer to the plume epicenter the S value and its scatter increase notably, this growth being especially significant during the period of ∼20–50 million years before the beginning of the high magmatic activity of the plume at the Earth surface. In this connection I used the time interval overlapping the potential time of the plume rise, namely, 270–300 Ma. For comparison, I added the time interval of 310–340 Ma, preceding the beginning of the Siberian Plume formation.

[10] The next step was to sort out the data chosen from the paleomagnetic data base into four categories:

[11] (1) the unreliable paleomagnetic data obtained for not more than ten samples, the thermal demagnetization was not higher than 200°C, the AF demagnetization was not higher than 15 mT, the precision parameter $\mathbf{K} < 7$, the confidence angle $\alpha_{95} > 25$, the coordinates of the paleopole were different greatly from the average pole for the given time for the continent in question, the paleomagnetic determinations being considered as the results of the remagnetization of the older rocks. The determinations of this kind were discarded;

[12] (2) the low reliability of the paleomagnetic determinations with the number of the samples not more than 20, the cleaning temperature lower than 400°C, the AF cleaning being lower than 30 mT. The index of the paleomagnetic reliability was 0.1 for this group of samples. This index was used as a weight value in calculating the average S values;

[13] (3) the intermediate reliability of the paleomagnetic determinations with the number of the samples higher than 20, the thermal cleaning was performed at temperatures not lower than 500°C, the AF cleaning was not less than 50 mT. There were examples of positive geophysical tests (fold, pebble, reversal or baking tests). The index of paleomagnetic reliability was 0.5. This index was used as the weight in calculating the average S values.

[14] (4) the high reliability of paleomagnetic determinations with the number of samples larger than 20, the obligatory complete thermal demagnetization and AF demagnetization with the component analysis, the identification of the characteristic NRM component, and the positive fold, pebble, baking, and reversal tests. The index of paleomagnetic reliability, as high as 1.0, was used as the weight in calculating the average S values.

[15] It should be emphasized that the geophysical tests of paleomagnetic reliability, such as the fold, pebble, reversal, and baking tests, are important to prove the identification of the primary NRM component, yet, they cannot be used to prove that the S value corresponds to the variation magnitude of the geomagnetic field direction. As will be demonstrated below, the scatter of the S values is very large, primarily, because of some technical and methodological reasons, such as not complete cleaning, measurement errors,

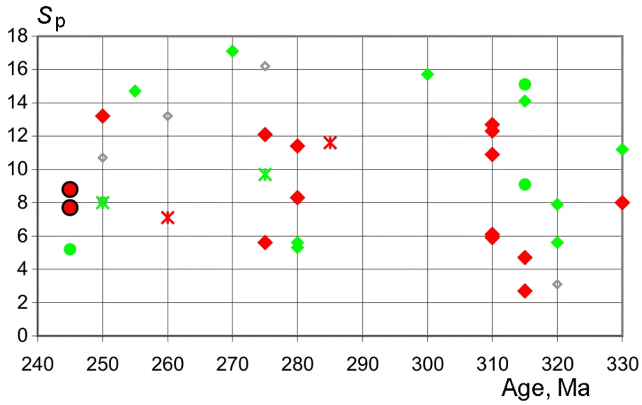

Figure 2. The magnitude of the geomagnetic direction variation (S_p) in the time interval of 240–330 Ma, Australia.

magnetic biasing in the course cleaning, the uncertainty of the age interval during the calculation of the paleomagnetic direction, and the like. For this reason we can be sure only of the average and modal S values.

[16] Based on the types of the rocks we classified our determinations into four groups: sedimentary, redbeds, volcanic, and intrusive rocks. Most of our data belong to the sedimentary rocks. For this reason, the results of this study are combined into groups in terms of their ages and paleomagnetic reliability. A separate group combines the data for Australia, which are characterized, in the age interval discussed, by the elevated S values (Figure 2), which are unrelated to the Siberian plume.

[17] The paleomagnetic determinations, which remained after our data sorting were classified into the following age groups: 340–315, 310–290, 285–270, 265–245, and 240–200 Ma. Each of these intervals was characterized by the respective maps of paleotectonic reconstructions and APW paths for all continents, mainly after [*Torsvik and Van der Voo,* 2002] with the additions for China and other regions after [*Bretstein and Klimova,* 2005; *Didenko et al.,* 1994; *McElhinny and McFadden,* 2000; *Pechersky and Didenko,* 1995; *Scotese and McKerrow,* 1990; *Smethurst et al.,* 1998]. The paleomagnetic data points available were plotted on these maps, and after that were determined their ancient coordinates. There are two models of paleotectonic reconstructions: the GAD model, where the geomagnetic field is assumed to be a dipole one and the G3 model which takes into account a nondipole, octupolar component [*Torsvik and Van der Voo,* 2002]. Without dwelling on the substantiation of these models, I determined the ancient coordinates of the paleomagnetic observation sites for both models. The coordinates of the Siberian traps center, reconstructed for the time of 250 Ma, were found to be 57°N, 30°E, using the GAD model, and 60°N, 45°E, using the G3 model. In both cases we determined the distances, along the great-circle arc, from each of the paleomagnetic determination site to the center of the Siberian traps. I assumed that during the igneous activity of the Siberian plume the position of its epicenter had not changed notably. In terms of clarifying the dependence of the total field direction variation on the distance of the observation site from the trap center, the difference between these two models was insignificant (Figure 3): it was usually not higher than 10°. It was only in the case of the distances to the center of the Siberian traps amounting to more than 80°, it was sometimes as large as 20° and more, in the region where the association of the Siberian plume and the field direction variation was hardly probable. Therefore it is enough to consider only one model, in this paper we will dwell on the G3 model.

[18] In determining the coordinates of the paleomagnetic observation site, we used two factors: the paleolatitude, calculated from the paleomagnetic inclination of the given site, and the position of the site in the map of the "suitable" age reconstruction. The fact is that in many cases the Database offers a fairly broad range of rock and paleomagnetic determinations ages. For this reason, I selected a map where the position of the point in question corresponded best of all to its paleolatitude determined using the paleomagnetic inclination. Also, we took into account the agreement of the polarity of the given paleomagnetic determination with the time-scale of geomagnetic polarity [*Gradstein et al.,* 2004], within a five-million year averaging.

[19] The S value is known to vary with the latitude: it diminishes roughly by two times slowly from the equator to the pole. This is valid for the intervals of the steady-state geomagnetic field throughout the Neogaea [*Pechersky,* 1996]. According to the dependence of the S values with the latitude, all of the S determinations were reduced to one paleolatitude, namely, to the latitude of the pole (S_p). Figure 4a clearly shows the S dependence on the paleolatitude of the observation site, which vanishes after its reduction to the latitude of the pole (Figure 4b).

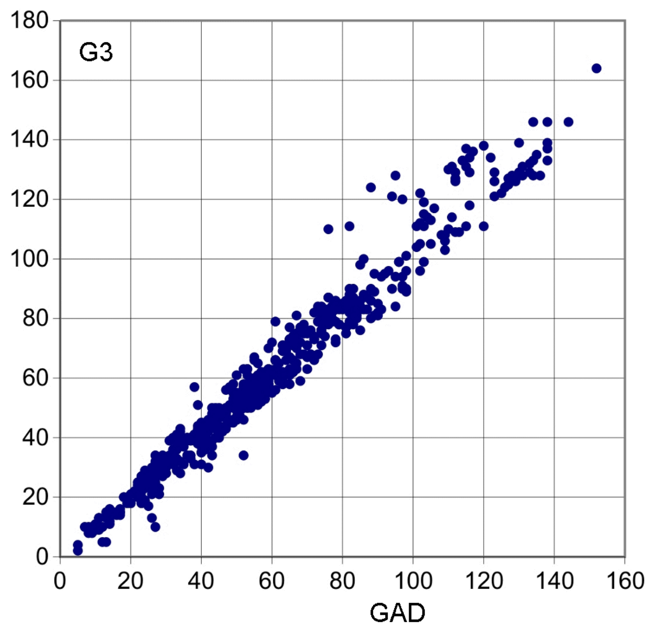

Figure 3. Comparison of the distances from the observation site to the Siberian trap center for the GAD and G3 models [*Torsvik and Van der Voo,* 2002].

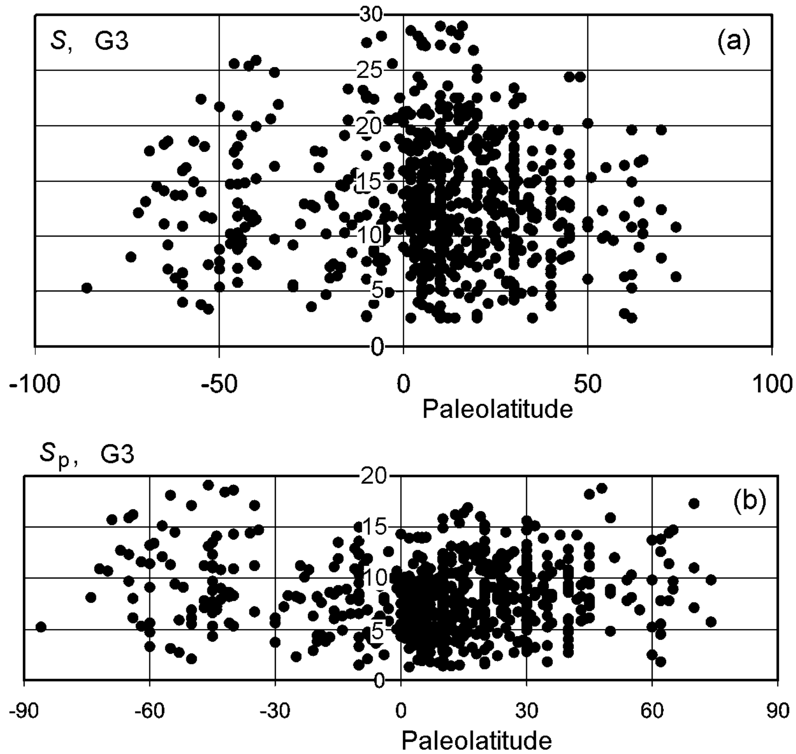

Figure 4. The magnitude of the geomagnetic field direction variations as a function of the paleomagnetic observation site paleolatitude: (a) before reducing the data to one latitude and (b) after this procedure, using the whole data collection.

[20] Depending on the model used (GAD or G3), the paleolatitudes of the observation points were found to be somewhat different and, hence, the S_p values were found to be different, too. This difference is illustrated in Figure 5, which shows that in most cases the difference between the S_p values of both models is not higher than 1–2°.

[21] All of our paleomagnetic determinations were distributed, with some or other accuracy, over five-million year intervals (Figure 6a). For each of the five-million year interval I calculated its average value and performed a smoothing operation for the time intervals of 10 million years, the smoothing step being 5 million years (Figure 6b). The resulting pattern (Figure 6b) shows the behavior of the variation direction magnitude of the "normal" geomagnetic field, where the scatters of different origin are smoothed off. This Figure shows that the direction of the "normal" field varies insignificantly, even without smoothing from 6° to 10°, the changes being minimal in the Kiama hyperchron during the stable state of the geomagnetic field, and more notable in the time interval of 320–300 Ma, which preceded the Kiama hyperchron (Figures 1, 6b). The P/T boundary is not expressed in the S_p behavior, being restricted to the region of some S_p value growth which began at the time of 260 Ma (Figure 6b). Against a background of the "normal" field there is some tendency toward the S_p growth in the direction closer to the center of the Siberian traps by a distance less than 40° (Figure 7). This trend was also recorded in the summarized S_p distribution histogram (Figure 8). This Figure clearly shows the main distribution with the 8° mode, against the background of which clearly shows up the second group of the higher S_p values (10–13°) with a mode of $\sim 11°$, related mainly to the sites located closer than 40° to the center of the Siberian traps.

[22] Discussed below in more detail is the behavior of the variation of the geomagnetic field direction during the main time intervals relative to the P/T boundary and to the center of the Siberian trap, which is believed to have been the epicenter of the plume. It should be emphasized that the distance from the plume epicenter to the region of its origin at the core-mantle boundary was about 3000 km, and its rising path being often inclined [*Ernst and Buchan,* 2003]. Combined with the insufficient accuracy of the paleomagnetic direction determinations and reconstructions, this fact might have caused the significant scatter of the S_p values. It is pertinent to remind that each of these time intervals embraces 15 to 40 million years. Consequently, with the above mentioned uncertainty of the distance to the source of the plume and the long period of time compared to the time of the unstable state at the core-mantle boundary and, hence, the unstable state of the geomagnetic field, the conditions closer to the plume epicenter must be reflected, first, in the growth of the variation magnitude, that is, in the S_p value and, secondly, in the growth of the S_p value scatter. Moreover, the S_p distribution relative to the Siberian plume epicenter could be disturbed notably by the other plumes of different ages, which might have been active during the time

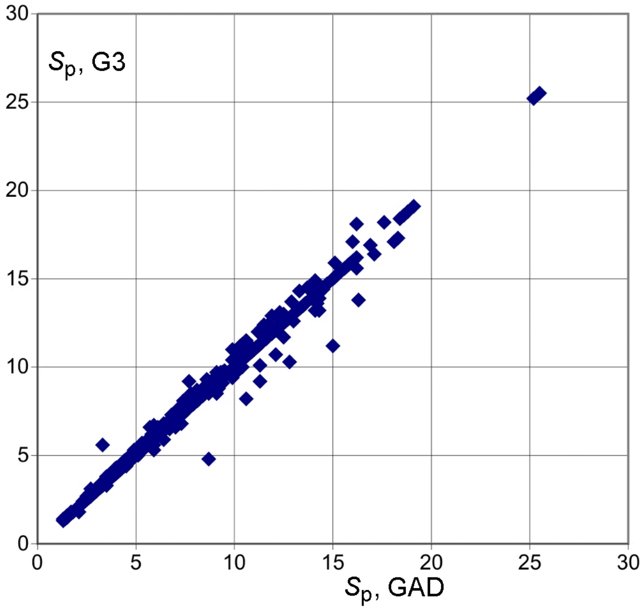

Figure 5. Comparison of the magnitudes of the geomagnetic field direction variation reduced to one paleolatitude (S_p), using the GAD and G3 models [*Torsvik and Van der Voo,* 2002].

period discussed. Apart from the reasons mentioned above, one should not forget technical errors, the inaccuracies of the measurements, the "purity" of identifying the primary NRM components (the presence of stable secondary components), and the like. All of them augmenting the scatter of the S_p unit values, the mean and modal values being more objective quantitative characteristics.

[23] (A) 340–315 Ma. The distribution of the S_p is characterized by the predominance of low values ranging from 4° to 8° with a distinct mode of 8° (Figure 9e), corresponding to the "normal" field in this time interval (Figure 6b). The distribution of the S_p values is not controlled by the distance to the center of the Siberian traps (Figure 10).

[24] (B) 310–290 Ma. The S_p values show a bimodal distribution (Figure 9d). The first 7° mode corresponds to the "normal" field in this time interval (Figure 6b). The second 10° mode depend on the distance to the center of the Siberian traps, which is indicated clearly by the average S_p values (Figure 11). The largest S_p values were found for the time of 290–300 Ma.

[25] (C) 285–270 Ma. The S_p values show a bimodal distribution, including one distinct mode of 8° and a less distinct mode of 11° (Figure 9c). The first mode corresponds to the "normal" field, the second mode being associated with the S_p growth closer to the center of the Siberian traps, as

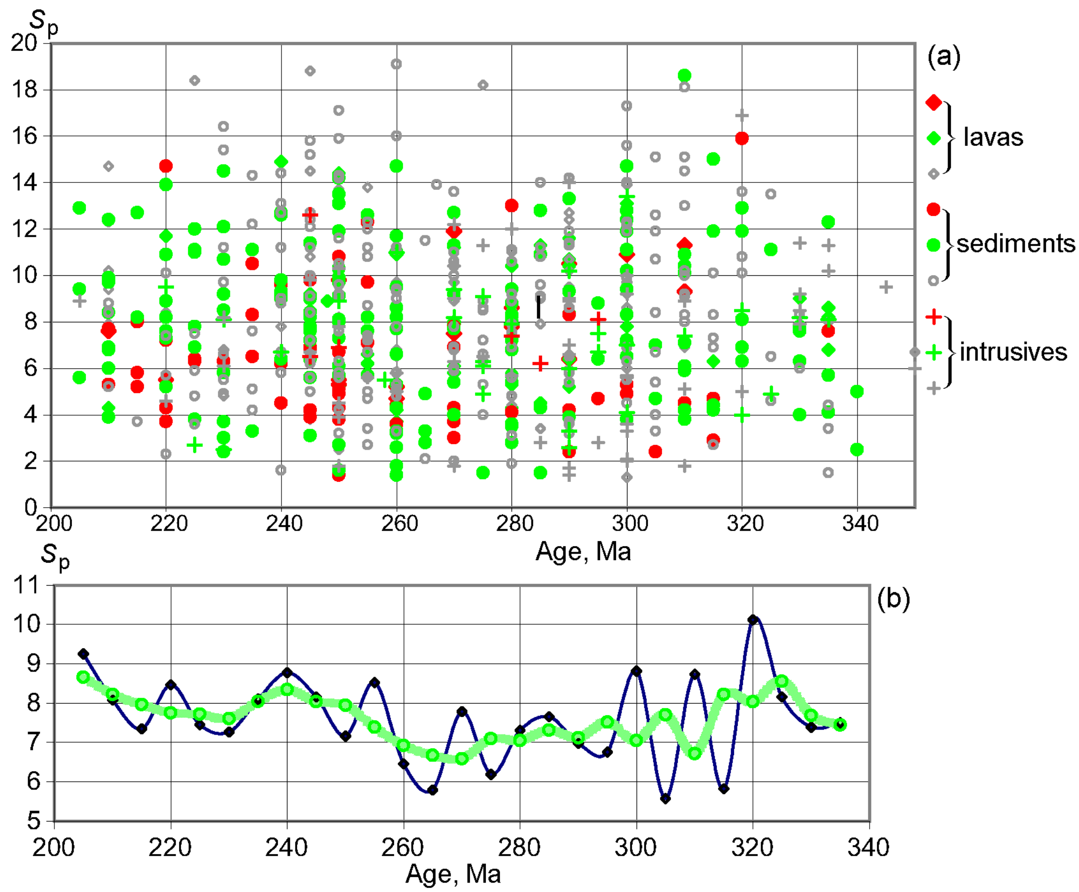

Figure 6. The distribution of the magnitudes of the geomagnetic field direction variations (S_p) over five-million year intervals (a), the black line showing the averaged values, the colored line, their smoothed values (b), the smoothing interval being 10 million years, the smoothing step being 5 million years.

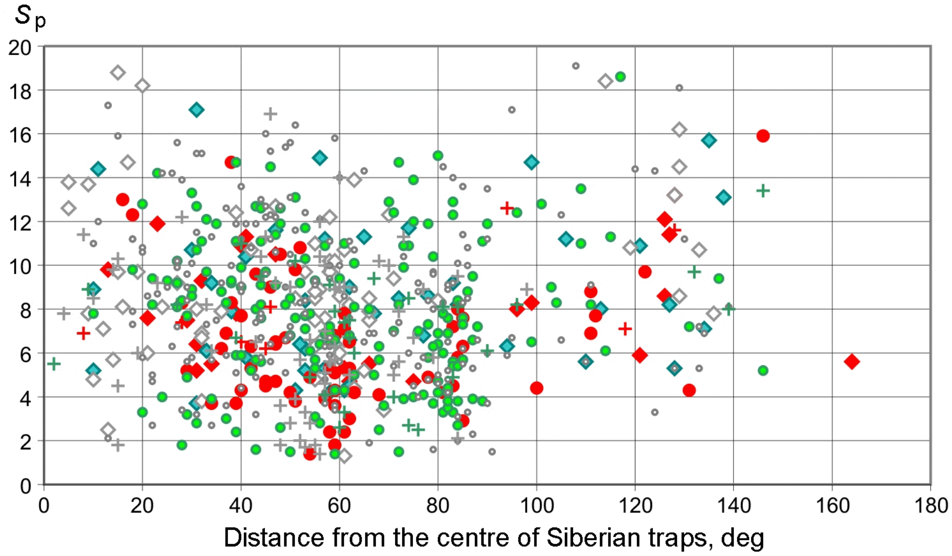

Figure 7. The distribution of the magnitudes of the geomagnetic field direction variations (S_p) as a function of the distance to the center of the Siberian traps, based on the whole collection of the data. The rhombs show the lavas, the circles show the sediments, the + symbols, the intrusive rocks, the red symbols showing the data of high paleomagnetic reliability, the green ones, the intermediate reliability, and the black ones, the low reliability.

seen from the behavior of the average S_p values (Figure 12). The highest S_p values were recorded for the time interval of 270–280 Ma.

[26] (D) 265–245 Ma. The S_p values showed a unimodal distribution with a mode of 8°, which corresponds to the "normal" field, the mode associated with the Siberian Plume is absent (Figure 9b). This was confirmed by the histograms of the unit S_p data selection obtained for the data points residing not far than 30° from the center of the Siberian traps (Figure 13a) and by the selection of the Siberian traps alone (Figure 13b). Some S_p raise at the distance of less than 20° (Figure 14) is proved by a mere couple of reliable data points and averagely does not exceed the "normal" field (Figure 6b).

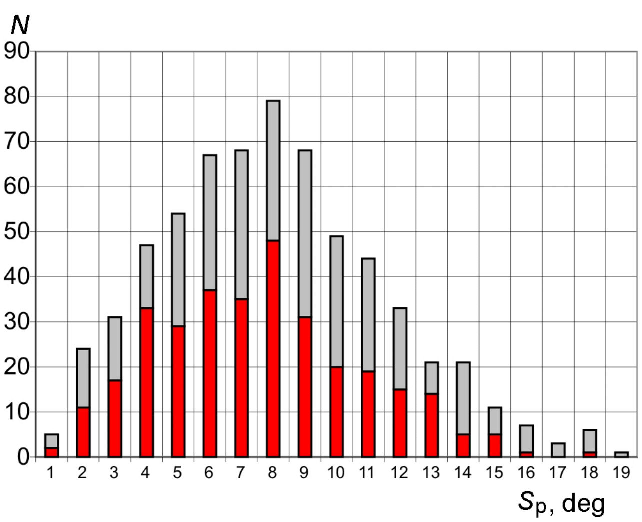

Figure 8. The distribution of the magnitudes of the field direction variations (S_p) for the whole data collection. Shown in red color are the results of medium and high reliability, those shown in gray are of low reliability.

[27] (E) 240–200 Ma. This time interval is characterized by the S_p unimodal distribution (Figure 9a) with a mode of 8°, which corresponds to the "normal" field, its somewhat unstable distribution being obviously associated with the variation of the "normal" field at that time (Figure 6b). As could be expected, the S_p does not show any connection with the distance to the Siberian traps (Figure 15).

Discussion of the Results

[28] The bimodal distribution of the S_p values was caused by two factors: (1) the global first S_p mode exists throughout the time interval of 340–200 Ma, irrespective of the distance to the Siberian traps (Figures 8 and 9); (2) the local second, higher S_p mode appears only in the time interval of 300–270 Ma (Figure 9) and at relatively small distances from the center of the Siberian traps and disappears away from it (Figures 11 and 12). Consequently, during the time period discussed, the variation magnitude of the geomagnetic field direction was averagely 7°–8° (Figure 6b), this being a global effect characterizing the normal state of the geomagnetic field predominantly of reversed polarity. Moreover the transition from the Kiama reversed polarity hyperchron to the Illawara hyperchron of frequent polarity changes had a

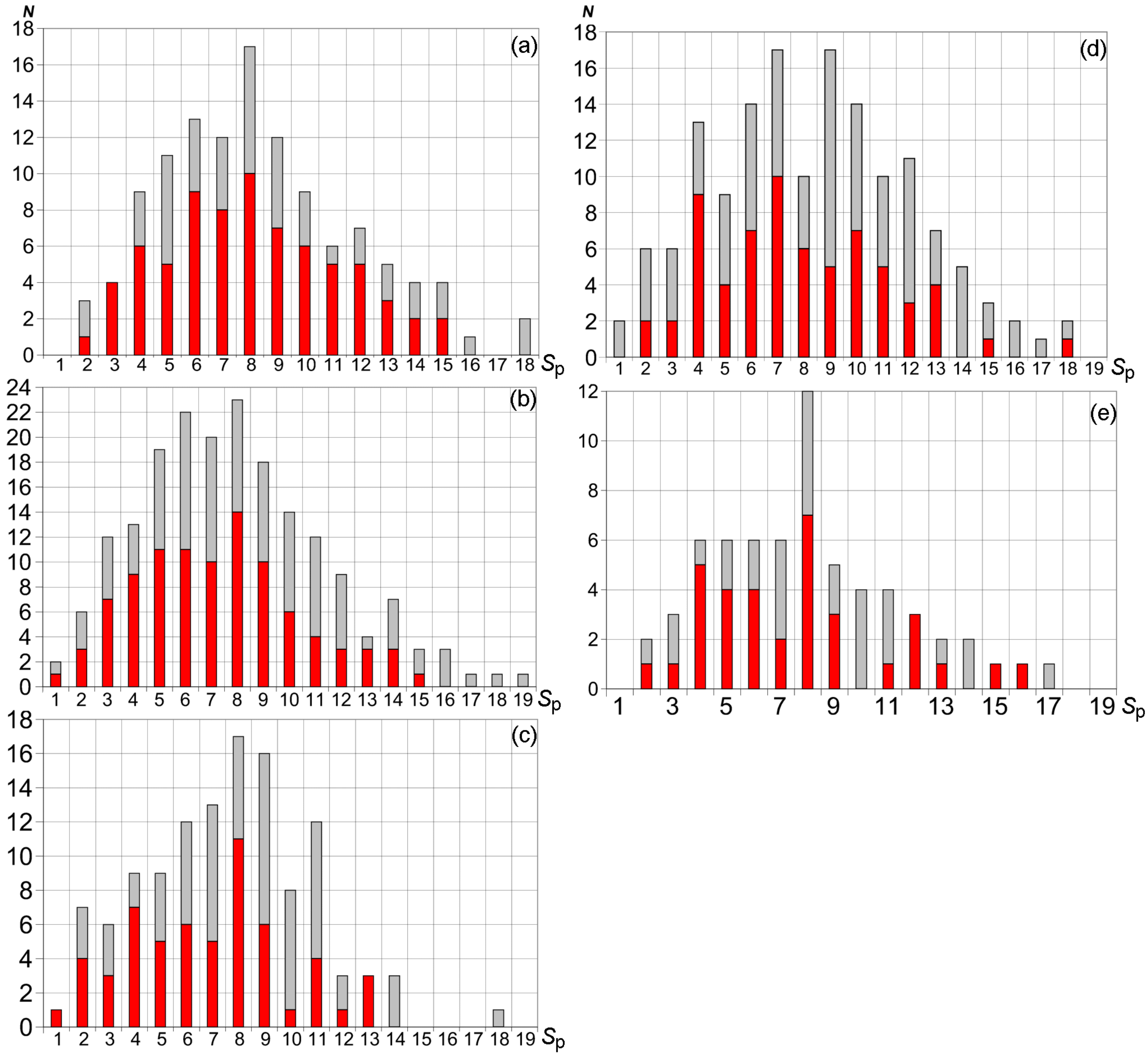

Figure 9. The distribution of the magnitudes of the field direction variations (S_p) for the time intervals of 240–200 Ma (a), 265–245 Ma (b), and 285–270 Ma (c), 310–290 Ma (d), and 335–315 Ma (e). The legend is the same as in Figure 8.

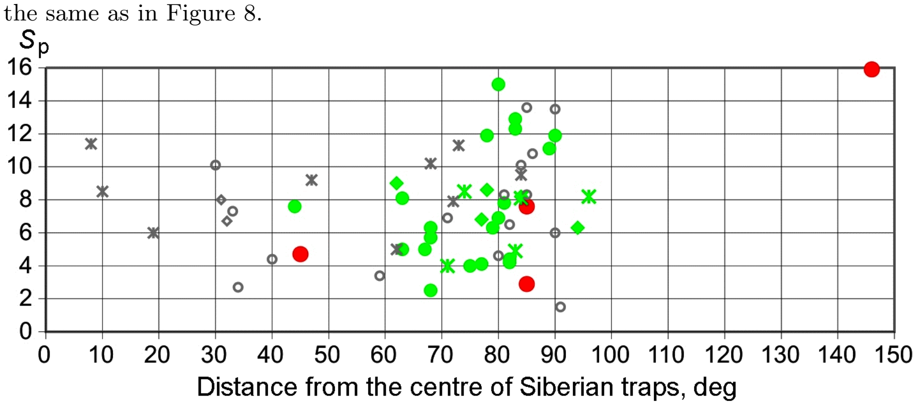

Figure 10. The magnitudes of the geomagnetic field direction variations (S_p) as a function of the distance to the center of the Siberian traps for the time interval of 340–315 Ma. The legend is the same as in Figure 7.

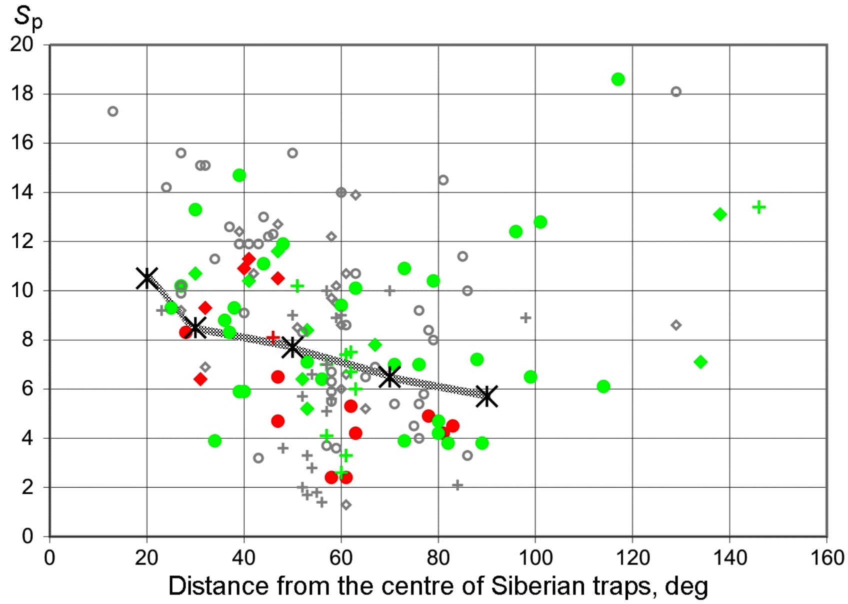

Figure 11. The magnitudes of geomagnetic field direction variations (S_p) as a function of the distance to the center of the Siberian traps for the time interval of 310–290 Ma. The black stars connected by a line are the S_p values averaged over the intervals of 10–20°. See Figure 7 for the other explanations.

poor effect on the average variation magnitude (Figure 6b): it grew 1°–2° larger. This background was overlapped by the anomalous state of the geomagnetic field, which was of local character. Obviously, this was caused by the high disturbance of the "normal" state of the geomagnetic field in the area where the Siberian plume was being generated.

[29] The large scatter of the S_p values in the vicinity of the Siberian trap center suggests the relatively short existence of any large-magnitude variations. It is known that the S_p values get into each of the time intervals concerned during the time period of 15–40 million years. The short-time existence of the anomalous magnitudes of the field variations and plume existence is proved by the following fact. Approaching to the centers of modern world magnetic anomalies, we observe the similar pattern of the growing magnitudes of the geomagnetic field direction variations, the

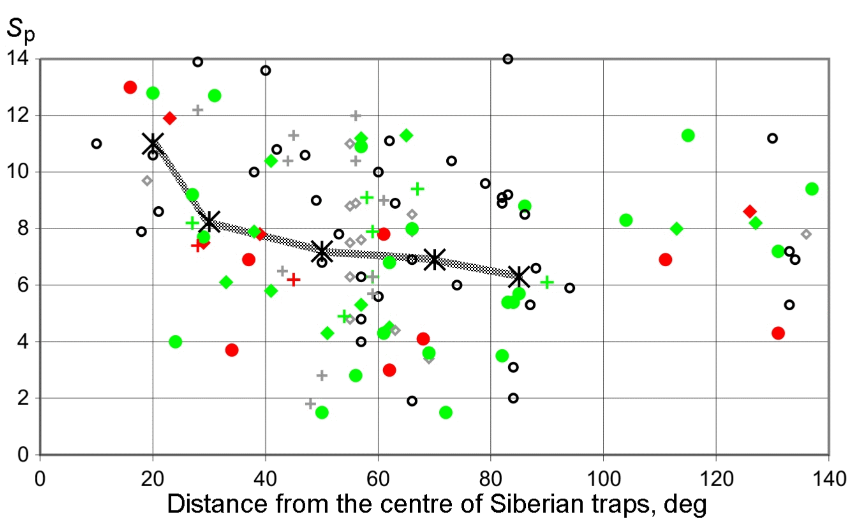

Figure 12. The magnitudes of geomagnetic field direction variations (S_p) as a function of the distance to the center of the Siberian traps for the time interval of 285–270 Ma. The black stars connected by a line are the S_p values averaged over the intervals of 10–20°. See Figure 7 for the other explanations.

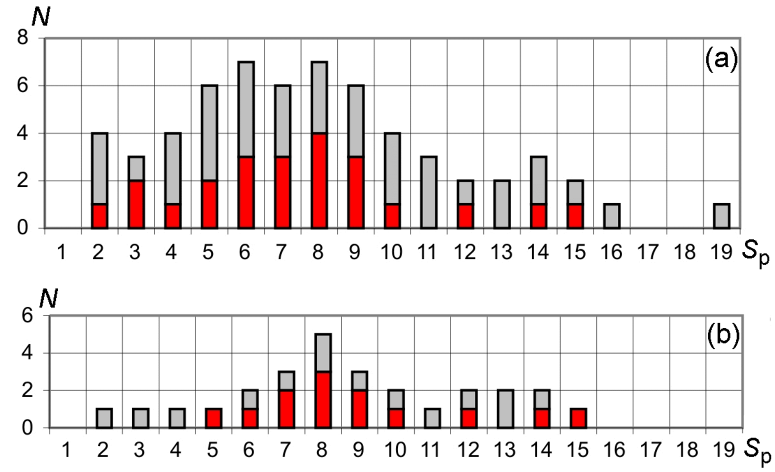

Figure 13. The histograms showing the distribution of the magnitudes of the geomagnetic field direction variations (S_p) for the data points residing not farther than 30° from the center of the Siberian traps (a) and a data sample for the Siberian traps alone (b). See Figure 8 for more explanations.

lifetime of the world anomalies being shorter than 20 thousand years [*Pechersky,* 2001]. We can suggests a close relationship between the sources of the world magnetic anomalies and plume formation, this being emphasized by the short existence of the world magnetic anomalies and the flows of most of the Siberian traps. However, apart from the short-term intensive trap formation, there are some long-lived hot spots, such as, the Hawaii, Galapagos, Iceland, and others, the sources of which had been lower-mantle plumes [*Courtillot et al.,* 2003; *Ernst and Buchan,* 2003]. There is no contradiction here. The impulses causing the generation of the geomagnetic field variations and plumes are very short, yet, the plume chambers produced at the base of the mantle can exist longer than a hundred million years and they are not associated with the core events.

[30] The S_p dependence on the distance to the center of the Siberian traps is obvious in the time interval of 300–270 Ma (Figures 11 and 12). Accordingly, the "retardation"

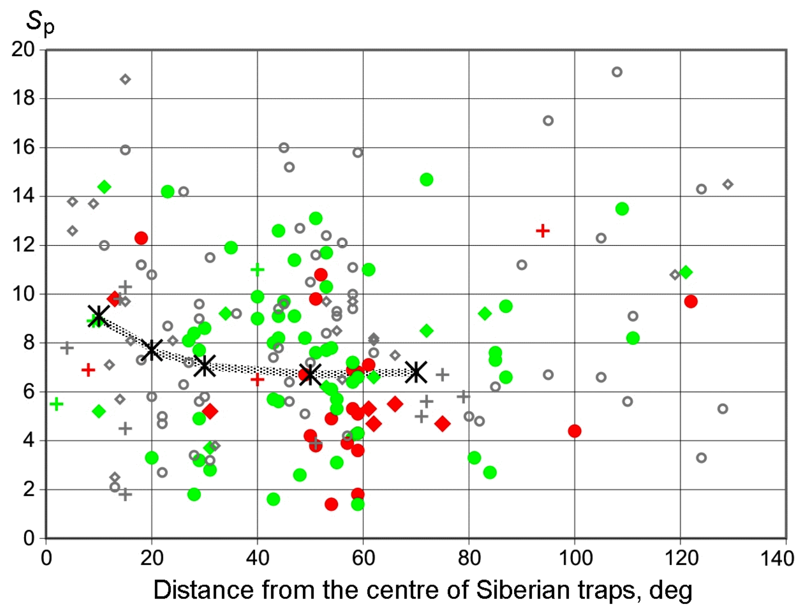

Figure 14. The magnitudes of the geomagnetic field directions variations (S_p) as a function of the distance to the center of the Siberian traps for the time interval of 265–245 Ma. The black stars, connected by a line, are the S_p values average for the intervals of 10–20°. See Figure 7 for the other symbols.

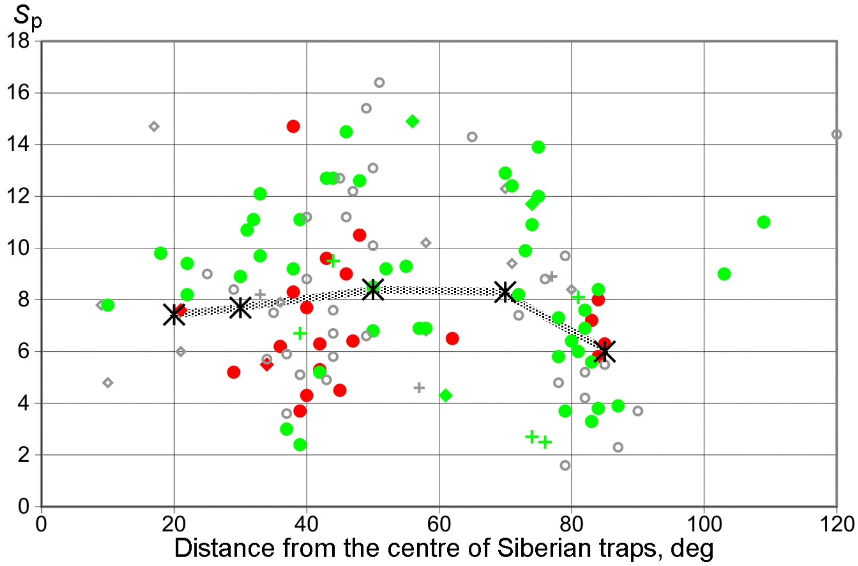

Figure 15. Variation of the geomagnetic field directions (S_p) as a function of the distance to the center of the Siberian traps for the time interval of 240–200 Ma. The black stars, connected by a line, are the S_p values average for the intervals of 10–20°. See Figure 7 for the other symbols.

of the magmatism from the exited state of the core, which caused the higher variation of the geomagnetic field was 20–50 million years. These estimates agree with those obtained earlier for the magmatic activities of the modern plumes and for the plumes refer to the Mz-Kz boundary [*Pechersky,* 2001; *Pechersky and Garbuzenko,* 2005]. This long interval can be explained by the following two alternatives:

[31] The first trivial cause is associated with the uncertainty of dating the rocks and paleomagnetic determinations. The highest S_p values are referred, as mentioned above, to the time interval of 300–270 Ma, the average time of "retardation" being 35 million years.

[32] The second nontrivial cause allows us to suggest that this significant event was caused by the repeated "bursts" of the core reactivation which caused the formation of the series of plumes, all of them representing the Siberian superplume. It appears that not all of the rising plumes, which had originated in the time interval of 300–270 Ma in the vicinity of the core-mantle boundary and reached the surface of the Earth, except for the largest and most powerful "burst" which reached the Earth surface in the form of the main stage of the Siberian trap magmatism.

[33] Apart from the S_p growth recorded in the time interval of 300–270 Ma, some the other time intervals discussed show some elevated S_p values in the areas remote from the center of the Siberian traps (Figures 7, 10, 11, 12, 14, and 15). First, these are randomly scattered sites, possibly, associated with various errors of estimating the precision parameter of the paleomagnetic directions, and, secondly, the compact groups of elevated S_p values (Figure 16). Some of these groups, located not far than 30° from the Siberian superplume can be associated with its halo. Yet, this version is not confirmed by the "compact patterns" of these groups of points, these points not covering the center itself. Moreover, the S_p values of the Siberian traps proper and of the study objects, located not farther than 30° from the center of traps, show a normal, unimodal distribution (Figure 13). In my opinion, these compact groups denote the regions of the excited states of the Earth core near its boundary with the mantle, the regions of the generation of the global magnetic anomalies and the lower-mantle plumes, the rising of the latter to the Earth surface being "expected" at the time 20–40 million years later than the origin of these compact groups. The fact that the rise of a plume, and, moreover, of the group of plumes (a superplume), is not necessarily vertical, may suggest that the elevated S_p clusters, recorded for the time intervals of 300–290 Ma and 285–270 Ma, are the regions of the Siberian superplume generation.

Conclusion

[34] The aim of this study was to generalize the data available for the paleointensity, reversal frequency, and the variation of the direction of the geomagnetic field in the vicinity of the Paleozoic-Mesozoic boundary, which was marked by the peak of the igneous activity of the Siberian traps (251 Ma). For this purpose I used the data, available in the Data Base and the geomagnetic polarity time-scale. However, I did not find any specific features in the behavior of the geomagnetic field for that period of time.

[35] 1. The paleointensity of the field was found to be elevated in the time interval of 330–280 Ma and then declined abruptly (averagely twice as much), remaining the same up

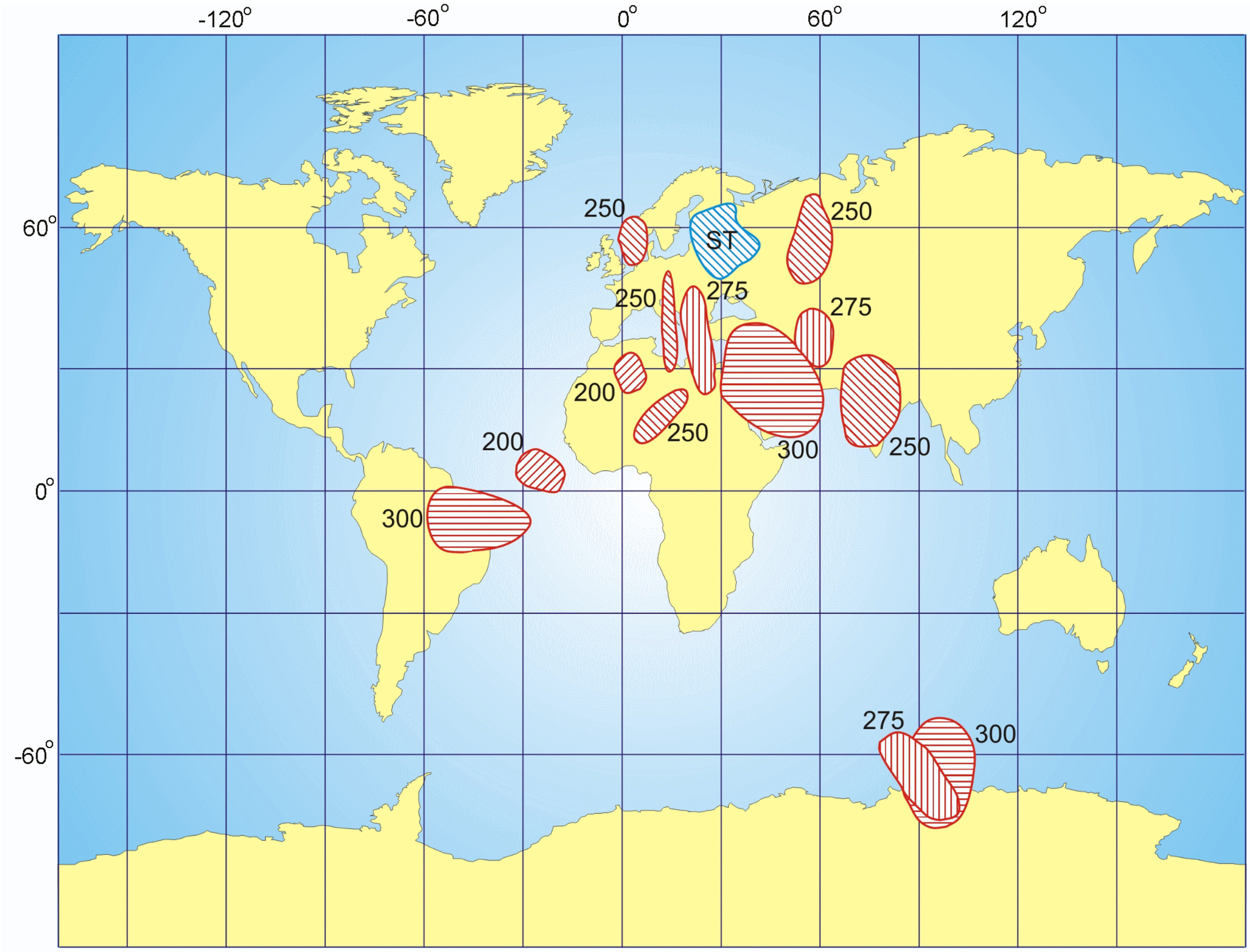

Figure 16. The map showing the distribution of the compact groups of the elevated magnitudes of the geomagnetic field direction variation of different ages, $S_p \geq 9°$ (shown in red shading and contoured by a red line).The age is shown by figures near corresponding areas. The position of the Siberian traps for the time of 250 million years ago is shown in blue shading and countered by blue line.

to 200 Ma. The time interval of the igneous activity of the Siberian traps was situated within the time interval of low paleointensity values and "lagged" 30 million years behind the abrupt changes in the paleointensity.

[36] 2. The Paleozoic-Mesozoic boundary and the time of the maximum trap activity coincided with the period of frequent reversals and, hence, with the frequent changes of the geomagnetic polarity, without being recorded in the specific features of the geomagnetic field. The peak of the biota change, coinciding with the peak of the highest Siberian trap activity, lagged 15 million years behind the boundary between the Kiama hyperchron of the stable reversed polarity field and the Illawara hyperchron of frequent polarity changes.

[37] 3. The global changes of the average magnitude variations of the field direction from its unstable state with oscillations of 6°–10° to 6°–7° fell on the lower and upper boundaries of the Kiama hyperchron. As the Kiama hyperchron was superseded by the Illawara hyperchron, the variation magnitude began to grow from 6° (265 Ma) to 8°–9° (240 Ma). The P/T boundary proper did not show any specific features in the field variation magnitude. Therefore, the Paleozoic-Mesozoic boundary is not recorded in the paleomagnetic data.

[38] 4. With approaching to the center of the Siberian traps, the field variation magnitude showed a regular growth of the field direction variation magnitude from its normal state (7°–8°) to the average value of 11°–12°. This can be explained by a connection between the local excitation in the outer core of the Earth and the formation of the Siberian superplume. This growth of the variation magnitude occurred during the period of 20–50 million years

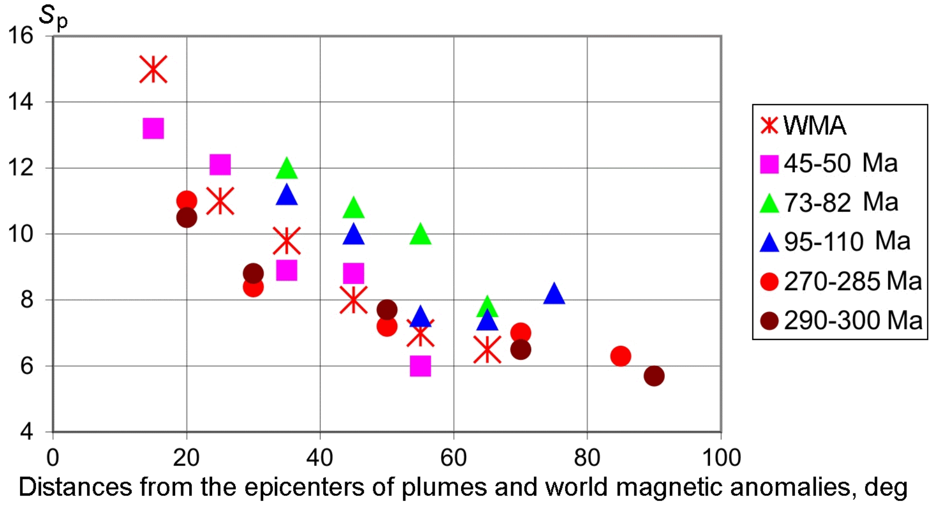

Figure 17. The magnitudes of the geomagnetic field direction variations (S_p) as a function of the distances to the centers of the world magnetic anomalies (WMA) [*Pechersky,* 2001], shown by red stars; same to the epicenters of the modern active plumes (45–50 Ma) [*Pechersky,* 2001], shown by violet squares; same to the epicenter of the Greenland plume (73–82 Ma) [*Pechersky and Garbuzenko,* 2005] shown by green triangles; same to the epicenter of the Deccan plume (95–110 Ma) [*Pechersky and Garbuzenko,* 2005], shown by blue triangles; same to the epicenter of the Siberian plume (270–285 Ma and 290–300 Ma) [this paper], shown by red and brown circles. These data were averaged over the interval ranging from 10° to 20°.

before the Paleozoic-Mesozoic boundary and the maximum activity of the Siberian traps. This "retardation" seems to have been the time of the Siberian superplume rise from the core-mantle boundary to the Earth surface. This long time lagging can be explained by the inexact dating of the objects of the paleomagnetic studies and/or by the NRM age, yet, the most probable explanation is the formation of a series of plumes at that time, in the same region of the core and mantle boundary. This interpretation is validated by the existence of the compact concentrations of the high-magnitude magnetic field directions, as the potential regions of the formation of world magnetic anomalies and plumes in the time interval between 300 Ma and 200 Ma. Main part of such groups concentrated relatively close to one another, between the longitudes of 0°E and 80°E and between the latitudes of 10°N and 60°N. It is possible that the region of the exited state of the upper part of the Earth core (270–300 Ma), which was situated south of the region underlain by the Siberian traps, was the region of the Siberian superplume generation.

[39] 5. The comparison of the results obtained for the behavior of the geomagnetic field in the vicinity of the Paleozoic-Mesozoic boundary with the data reported earlier [*Pechersky,* 2001; *Pechersky and Garbuzenko,* 2005], suggested the following regularity: the boundaries of the geological eras are not recorded in any specific features of the paleointensity, polarity, reversal frequency, and in the variations of the geomagnetic field direction. The boundaries between the eras reside in the region of frequent geomagnetic field polarity changes which occurred 15–20 million years later than the preceding hyperchrons of the steady state (single-polarity) of the magnetic field. Against the background of the "normal" field it is seen an almost similar trend toward the growth of the magnetic field variation magnitude closer to the epicenters of the modern, Greenland, Deccan, and Siberian lower mantle plumes, as well as of the world magnetic anomalies (Figure 17), this suggesting the same origin of the lower mantle plumes, differing in the time of their formation, of the world magnetic anomalies, and of the growing magnitudes of the geomagnetic field direction variations, i.e. all of them being the results of the local disturbances at the top of the liquid core. This unity is proved by the brief existence of both, the world magnetic anomalies and the activity of the Siberian and Deccan traps. At the same time the Siberian and Deccan superplumes originated during the time intervals devoid of geomagnetic field reversals. This fact suggests the different sources of the global magnetic anomalies, local geomagnetic field variations and plumes, on the one hand, and of the field reversals, on the other. The "retardation" of the magmatic activity of the plumes at the Earth surface from the time of their origin at the core-mantle boundary, is the time of the plume rise. In all cases it fits in the time periods of 20–50 million years. Differences in their rise time seem to be associated with the differences in plume rising routes, various obstacles delaying their rising, and the like.

[40] **Acknowledgments.** I thank A. Shatsillo and V. Pavlov for their help in collecting magnetotectonic information, in the preparation of the paleomagnetic data base, and in the computer plotting of the figures. This work was supported by Program no. 5 of the Earth Science Subdivision of the Russian Academy of Sciences and the Russian Basic Research Foundation, grant No 06-05-65324.

References

Bretshtein, Yu. S., and A. V. Klimova (2005), The paleomagnetism of Phanerozoic Terranes, Far-East Russia: Comparison with the North China Plate Data (Review), *Russian J. Earth Sci.* (in Russian), *7*(1), 1.

Courtillot, V., A. Davaille, J. Besse, and J. Stock (2003), Three distinct types of hot spots in the Earth mantle, *Earth Planet. Sci. Lett., 205,* 295.

Didenko, A. N., A. A. Mossakovskii, D. M. Pechersky, S. Ruzhentsev, S. Samygin, and T. N. Kheraskova (1994), The geodynamics of Paleozoic oceans in Central Asia, *Geol. Geofiz.* (in Russian), *35*(7), 59.

Ernst, R. E, and K. L. Buchan (2003), Recognizing mantle plumes in the geological record, *Annu. Rev. Earth Planet. Sci., 31,* 469.

Gradstein, F. M., (Ed.) (2004), *A Geological Time Scale,* 589 pp., Univ. Press, Cambridge.

Grachev, A. F. (2000), Mantle plumes and geodynamic problems, *Phys. Solid Earth* (in Russian), *36*(4), 3.

Gurevich, E. L., M. Westphal, J. Daragan-Suchov, H. Feinberg, J. P. Pozzi, and A. N. Khramov (1995), Paleomagnetism and magnetostratigraphy of the traps from Western Taimyr, North Siberia, and the Permian-Triassic crisis, *Earth Planet. Sci. Lett., 136*(3–4), 461.

Gurevich, E. L., C. Heunemann, V. Radko, M. Westphal, V. Bachtadse, and H. Feinberg (2004), Paleomagnetism and magnetostratigraphy of the Permian-Triassic northwest central Siberian trap basalts, *Tectonophysics, 379,* 211.

Ivanov, A. V., S. V. Rasskazov, G. D. Feoktistov, H. He, and A. Boven (2005), The ^{40}Ar/^{39}Ar dating of the Usolie Sill in the SE Siberian trap large igneous province: Evidence for long-lived magmatism, *Terra Nova, 17,* 1.

Jurdy, D. M., M. Stefanick, and C. R. Scotese (1995), Paleozoic plate dynamics, *J. Geophys. Res., 100,* 17,965.

Khramov, A. N., G. I. Goncharov, and R. A. Komissarova (1982), *Paleomagnetology,* 312 pp., Nedra, Leningrad.

McElhinny, M. W., and P. L. McFadden (2000), *Paleomagnetism: Continents and Oceans,* 386 pp., Academic Press, San Diego.

Merrill, R. T., and M. W. McElhinny (1983), *The Earth Magnetic Field,* 401 pp., Academic Press, London.

Molostovskii, E., M. Pevzner, D. Pechersky, V. Rodionov, and A. Khramov (1976), The Phanerozoic magnetostratigraphic scale and geomagnetic field reversals, in *Thermomagnetic Research,* no. 17, p. 45, Nauka, Moscow.

Pechersky, D. M. (1996), Variations of the total magnitude of the Neogene geomagnetic field direction as a function of the latitude, *Geomagn. Aeron., 36*(5), 130.

Pechersky, D. M. (1997), Some characteristics of the geomagnetic field for the period of 1700 Ma, *Phys. Solid Earth* (in Russian), *33*(5), 3.

Pechersky, D. M. (1998), Neogaean paleomagnetism: Constraints on the processes in the core and at the surface of the Earth, *Russian J. Earth Sci.* (in Russian), *1*(2), 105.

Pechersky, D. M. (2001), The total magnitude of secular variations, the world magnetic anomalies and plumes, *Phys. Solid Earth* (in Russian), *37*(5), 85.

Pechersky, D. M., and A. N. Didenko (1995), *The Paleoasian Ocean: Petromagnetic and Paleomagnetic Information about Its Lithosphere,* 296 pp., Institute of Physics of the Earth, RAS, Moscow.

Pechersky, D. M., and A. V. Garbuzenko (2005), The Mz-Kz boundary: Paleomagnetic characteristics, *Russian J. Earth Sci.* (in Russian), *7*(2), 1.

Scotese, C. R., and W. S. McKerrow (1990), Revised World maps and introduction, in *Paleozoic, Paleogeography and Biogeography,* edited by W. S. McKerrow and C. R. Scotese, p. 1, Geological Society, Memoir 12, London.

Shcherbakov, V. P., G. M. Solodovnikov, and N. K. Sycheva (2002), A change in the magnetic dipole value for the last 400 million years (volcanic rocks), *Phys. Solid Earth* (in Russian), *38*(2), 26.

Smethurst, M. A., A. N. Khramov, and T. H. Torsvik (1998), The Neoproterozoic and Paleozoic paleomagnetic data for the Siberian Platform: from Rodinia to Pangea, *Earth Sci. Rev., 43,* 1.

Torsvik, T. H., and R. Van der Voo (2002), Refining Gondwana and Pangea palaeogeography: Estimates of the Phanerozoic non-dipole (octupole) fields, *Geophys. J. Int., 151,* 771.

Zonenshain, L. P., M. I. Kuzmin, and M. V. Kononov (1987), Reconstruction of the Paleozoic and Mesozoic positions of the continents, *Geotectonics* (in Russian), *21*(3), 16.

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