New paleomagnetic data for the Permian-Triassic Trap rocks of Siberia and the problem of a non-dipole geomagnetic field at the Paleozoic-Mesozoic boundary

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[1] The thorough analysis of the available Permian-Triassic paleomagnetic data for the Siberian Platform and "Stable" Europe was carried out. Paleomagnetic poles, meeting to modern reliability criteria, were used to calculate the mean Permian-Triassic paleomagnetic poles of Siberia and Europe. The comparison of the resulting poles showed significant differences between them. Discussed in this paper are four potential factors that had caused the observed differences between the paleomagnetic poles of Siberia and Europe: (1) the large-scale relative movements of these cratons in post-Paleozoic time, (2) the different ages of the compared paleomagnetic poles, (3) the substantial contribution of non-dipole components to the geomagnetic field at the Paleozoic-Mesozoic boundary, and (4) the shallowing of the magnetic inclination in the European sedimentary rocks. Also discussed is the adequacy of the data selection. Arguments are advanced to prove that the possibility of the post-Paleozoic large-scale relative displacements of the cratonic blocks discussed as well as considerable age difference of their mean poles is unlikely. Also estimated were the input quadrupolar and octupolar sources in the total time-average geomagnetic field and also values of the inclination shallowing factor, which might have explained the observed discordance of the Siberian and European poles. The best agreement of the European and Siberian paleomagnetic data was achieved for the octupolar coefficient $g_3 = -10\%$ or for the inclination shallowing factor $f = 0.62$. Our calculations showed that the statistically significant difference between the Siberian and European average poles can be removed assuming a very small value of the inclination shallowing corresponding to the f values of 0.9 to 0.95, potentially associated with some compaction of the studied sedimentary rocks. This gives grounds for interpreting the low inclinations in the European objects as the most probable source of the observed disagreement between the European and Siberian paleomagnetic data. *INDEX TERMS:* 1520 Geomagnetism and Paleomagnetism: Magnetostratigraphy; 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics: regional, global; 3040 Marine Geology and Geophysics: Plate tectonics; *KEYWORDS:* paleomagnetism, Siberian traps, Stable Europe, non-dipole field, inclination shallowing.

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The Modern State and Formulation of the Problem

[2] In spite of the fact that the hypothesis of a Geocentric Axial Dipole (GAD) is widely used in the paleotectonic interpretation of paleomagnetic data, being the "key stone" of the latter, it cannot be stated that the magnetic field of the Earth (averaged over a time period of about 10^4–10^5 years) existed over the greatest period of its geologic history as the field of a dipole placed in the center of the Earth and oriented along the axis of its rotation. It is obvious that this hypothesis need be verified for all intervals of geological time concerned. This is especially important for the time periods as old as Paleozoic or Precambrian, in the case of which the use of the actualistic approach seems to be fairly problematic.

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[3] *Hospers* [1954] was the first to prove that the virtual pole, averaged over the last several hundred years, coincides with a high accuracy with the geographic pole. This result, as well as those obtained by many other researchers [*Irving,* 1964; *Opdyke and Henry,* 1969, to name but a few], served as a basis for advancing a GAD hypothesis which was later tested repeatedly.

[4] Many researchers [*McElhinny,* 1973; *Merrill and McElhinny,* 1977, 1983; *Quidelleur et al.,* 1994], the first of them being *Wilson* [1970], proved that in addition to its dipole component the magnetic field of the Earth, averaged over the last several million years, might include also some non-dipole members of the second order, whose total contribution, however, was not higher than 5% of the dipole component of the field. *McElhinny et al.* [1996] investigated in detail which of the second-order members of the harmonic expansion of the geomagnetic field could be recorded confidently using the paleomagnetic data availably for the last 5 Ma. Their analysis proved, first, that there were no confident indications that the time averaged field (TAF) included any unzoned (sectorial, tesseral) components and, secondly, that only some geocentric axial quadrupolar member might be established more or less reliably. This result was confirmed independently by *Quidelleur and Courtillot* [1996].

[5] It is important to remind in this connection that *Khramov et al.* [1982] and *Yanovskii* [1978] assumed the potential asymmetry of the paleomagnetic field from the Carboniferous to the Triassic, which had been associated, in their opinion, with the displacement of the dipole, oriented along the axis of the Earth rotation, toward the western segment of the Pacific Ocean. A comprehensive discussion of this point is offered below.

[6] *Khramov et al.* [1982] suggested the possibility of some displacement of the dipole relative to the Earth's center (which is equivalent to the presence of some unzoned members in the spherical harmonic decomposition of the paleomagnetic field (TAF)), proceeding from the papers of *Adam et al.* [1975] and *Benkova et al.* [1973]. In their papers these authors used the nonspherical harmonic representation of the averaged field, assuming obviously that the model they used, although being highly idealized, had a greater physical content than any spherical model. However, as mentioned by *Merrill et al.* [1996], none of the models, stipulating nonspherical decomposition, is satisfactory for describing the physical geometry of the internal sources of the geomagnetic field. Moreover, the modern dynamometric theory infers that the "real" sources of the field must be much more complex and numerous, compared to any physical models based on nonspherical expansion. For this reason, proceeding from the convenience of mathematical description, most of the present-day researchers prefer to describe the field in terms of spherical harmonic expansion. In this case the above-mentioned displacement of the dipole center means that some unzoned members were involved in spherical harmonic expansion. Apart from the authors mentioned above, the existence of unzoned members was proved by *Creer et al.* [1973] and *Geordi* [1974], who inferred that the values of unzoned constituents might be comparable with those of the zoned expansion members. However, *Wells* [1973] proved rigorously that only zonal members were really significant, some unzoned constituents being produced by the irregular distribution of the analyzed data in space. Later, proceeding form the analysis of the larger data base, *McElhinny et al.* [1996] proved that the explanation of the observed data does not require the use of any unzonal coefficients.

[7] All of the above considerations are pertinent to the time interval corresponding to the Quaternary and, partly, to the Neogene, when the movements of the lithospheric plates can be neglected during the analysis of paleomagnetic data. It is obvious that the assumption of the significant contribution of unzoned components to the paleomagnetic field of the older periods of time become even less proved in connection with the uncertainties of paleogeographic reconstructions and the space and time heterogeneity of the data distribution.

[8] Some models based on the analysis of the data available for the Pliocene, Pleistocene, and Holocene periods suggest the presence of an octupolar zonal member in addition to the dipole and quadrupole ones. The axial octupole of these models is always lower than 3% (between 1% and 1.6% [*Carlut and Courtillot,* 1998; *Johnson and Constable,* 1997]; and 2.9% in the model of *Kelly and Gubbins* [1997]. *McElhinny et al.* [1996] estimated the value of the octupolar member to be between 1% and 3%, noting that the accuracy of the data available does not allow them to rank these results as statistically significant.

[9] *Gubbins and Kelly* [1993], *Johnson and Constable* [1995, 1997], and *Kelly and Gubbins* [1997] interpreted the results of their complete spherical harmonic analyses of the geomagnetic field, averaged for the last 5 Ma, as the existence of low, yet statistically significant unzoned members. This conclusion was discussed in detail by *Carlut and Courtillot* [1998] and also by *McElhinny and McFadden* [2000], who proved that because of the low values of the inferred nondipole members the very fact of their discovery depends on the potential minor inaccuracies of the paleomagnetic record and also on the use of the data that did not meet the modern requirements to laboratory processing.

[10] To sum up, at the present time we can be more or less sure that the geomagnetic field of the last 5 Ma can be described fairly well by the field of an axial geocentric dipole with some low contribution of an axial geocentric quadrupole. *Merrill et al.* [1996] estimated this contribution as the g_2^0/g_1^0 ratio equal to 0.038 ± 0.012. The presence of a quadrupolar member may cause the error of computing the paleomagnetic pole as high as 3–4° compared to a purely dipole model. Considering that this value is lower than the typical error of locating the paleomagnetic pole, found using a 95% confidence circle, we can state that the GAD model describes the geometry of the geomagnetic field for the last 5 Ma [*Merrill and McFadden,* 2003].

[11] The data available for the geomagnetic field intensity during the last 10 Ma also show a good agreement with the model of a geocentric axial dipole [*Tanaka et al.,* 1995].

[12] The analysis of the planetary geometry of the geomagnetic field for the older epochs is aggravated by the fact that one has to be sure concerning the fact that large movements of lithospheric plates might or might not take place. In the cases where these movements did occur (the

view shared presently by the overwhelming majority of geologists and geophysicists), we must first reconstruct the plate tectonic pattern for the time of interest, using some independent data (for instance, marine anomalies and bathymetry), and then study the distribution of the paleomagnetic trends in the "old system of the coordinates". In the case of the Cretaceous and younger epochs this analysis suggests it to be unlikely that the non-dipole members had ever been higher than a few percents of the geocentric axial dipole [*Coupland and Van der Voo,* 1980; *Livermore et al.,* 1983, 1984]. Recently, *Besse and Courtillot* [2002, 2003] analyzed in detail the paleomagnetic data for the time of 0–200 Ma, available in one of the latest versions of the Global Paleomagnetic Database (GPMDB). Using the modern kinematic models [*Müller et al.,* 1993; *Nürnberg and Müller,* 1991; *Royer and Sandwell,* 1989; *Royer et al,* 1992], all data were recalculated for one (African) plate and then, using the time-average paleomagnetic field over the past 25 million years [*Wilson,* 1971], they calculated the paleomagnetic poles for each time window of 20 Ma. These poles were found to be confined to the hemisphere opposite, in terms of the reference point, to some hemisphere at an angular distance usually not higher than 2° from the geographic pole. Moreover, the geographic pole always resides inside a 95-percent confidence interval corresponding to each of the calculated paleomagnetic poles. It is only when the whole time interval (200 Ma) is taken into consideration the deviation of the average paleomagnetic pole from the geographical one to the opposite hemisphere (relative to the reference point) becomes statistically significant. This can be taken as the real indication of some "far-side" effect which can be produced by the fact that the geomagnetic field contained a quadrupole component with the value of 3±2% of the dipole. This value has no practical significance for any paleotectonic reconstructions based on paleomagnetic data. In this sense the results obtained by *Besse and Courtillot* [2002, 2003] validate the GAD hypothesis for the time interval of 0–200 Ma.

[13] In the case of older periods of time the uncertainty of plate tectonic reconstructions grows rapidly calling for the use of other methods for estimating the geometry of the Earth magnetic field.

[14] In 1976 M. E. Evans offered a new method for testing the GAD hypothesis in Precambrian and Phanerozoic rocks [*Evans,* 1976], based on the comparison of the real distribution of paleomagnetic inclinations, identified for a fairly long period of time, with the theoretical ones, calculated proceeding from the assumption of the dipole character of the field and the uniform distribution of "paleomagnetic measurements" over the surface of the Earth. The statistical agreement of the observed and calculated data was treated as the evidence proving the dipole character of the magnetic field; otherwise the hypothesis was discarded. It should be noted, however, that the correct application of this method calls for the use of a great number of reliable paleomagnetic data, this requirement being unsatisfied in the case of Late Proterozoic or Early Paleozoic data.

[15] The Evans method used to process Precambrian and Early Paleozoic data [*Kent and Smethurst,* 1998; *Piper and Grant,* 1989] showed the anomalous distribution of paleoinclinations, which may suggest the substantial contribution of non-dipole sources to the geomagnetic field. Admitting the fact that the observed pattern of the paleoinclination distribution may reflect the irregular (low-latitude) distribution of the continents in the time period discussed, which might have been caused by the fact of their being parts of a supercontinent, *Kent and Smethurst* [1998] offered a view that the contribution of the non-dipole components during the Proterozoic had been significantly higher than that during the subsequent periods of the geological history, and that the intensity of the zonal octupolar field at that time might be as high as 25% of the dipole one.

[16] However, *McFadden* [2004] and *Meert et al.* [2003] proved that the basic hypothesis on the uniform distribution of the paleomagnetic data over the Earth surface, on which the M. E. Evans method had been based, was not reliable, and hence the results of the analyses performed by J. Piper and S. Grant, as well as by D. Kent and M. Smethurst, should be dealt with as preliminary ones.

[17] Meanwhile, the authors of some recent papers [*Si and Van der Voo,* 2001; *Torsvik and Van der Voo,* 2002; *Van der Voo and Torsvik,* 2001, to name but a few], reported the results of their calculations which offer a serious challenge to the central axial dipole hypothesis.

[18] Using the original method, *Van der Voo and Torsvik* [2001] analyzed the European and North American paleomagnetic data base, including the data collected by *Torsvik et al.* [2001] for the time interval of 300–40 Ma. The results of this analysis can be treated as the indication of the fact that during the period of 120–40 Ma and 300–200 Ma the total geomagnetic field included some notable zonal octupolar component, the contribution of which might be as high as 10% of the dipole component. No obvious indications were found for the presence of a quadrupolar component in this time interval. The time interval of 200–120 Ma did not show any significant deviations from the dipole model.

[19] The assumed existence of an octupolar component with g_3^0/g_1^0 roughly equal to 0.1 allows one to solve some problems, such as the well known contradiction between the central Asian and Euroasian paleomagnetic data for the Cretaceous and Paleogene, the direct use of which calls for the significant reduction of the crust between the Central Asian continental blocks and North Eurasia, which is absolutely inadmissible in geological terms. It should be noted, however, that this problem seems to have been solved without using the hypothesis of the substantially non-dipole character of the geomagnetic field. *Bazhenov and Mikolaichuk* [2003] proved that the Tien Shan Paleogene basalts studied by them show primary magnetization, the inclination of which agrees fairly well with the curve of the apparent migration of the North Eurasian pole. This result proves the fact that inclination was underestimated in the previously studied Paleogene sedimentary rocks (primarily continental red beds) of Middle Asia, this precluding their use for paleotectonic reconstructions.

[20] If the time-averaged geomagnetic field (TAF) could be represented for the time of 300–200 Ma as a sum of the dipole and octupole fields, this would remove the substantial contradictions arising between the geological and paleomagnetic data during the reconstruction of Pangea. In order to achieve the better agreement between the paleomagnetic

Table 1. The values of the non-dipole components reported by various authors

Time, Ma	$G2$, %	$G3$, %	Reference
0–5	2.6–5.0	< 3	[*Carlut and Courtillot,* 1998; *Johnson and Constable,* 1997; *Kelly and Gubbins,* 1997; *McElhinny et al.,* 1996]
0–40		~ 6	[*Si and Van der Voo,* 2001]
0–200	1–5		[*Besse and Courtillot,* 2002]
40–95		8	[*Torsvik et al.,* 2001]
40–300		≤ 10	[*Van der Voo and Torsvik,* 2001]
70–350		0–20	[*Torsvik and Van der Voo,* 2002]
250–360	≤ 16		[*Khramov,* 1967]
250–3500	10	25	[*Kent and Smethurst,* 1998]

Note: $G2$ and $G3$ are the quadrupolar and octupolar coefficients ($G2 = g_2^0/g_1^0$; $G3 = g_3^0/g_1^0$), the g values being the Gauss expansion coefficients.

poles of Laurussia and Gondwana, which are brought together in the Pangea-A model, ranked in this paper as the most substantiated model, *Torsvik and Van der Voo* [2002] believe that the contribution of the octupolar source varied in time.

[21] It is important to mention that the assumption of the notable contributions of the zonal components to TAF complicates (though insignificantly) the necessary calculations, yet do not preclude the possibility of using paleomagnetic data in paleogeographic and paleotectonic reconstructions.

[22] The hypothesis advanced by R. Van der Voo and T. H. Torsvik was discussed actively during the last 2–3 years. In March 2003, at the conference held in honor of N. D. Opdyke, this problem was discussed by *McElhinny* [2003] who mentioned that the results obtained by R. Van der Voo and T. H. Torsvik could not be taken as a proof for the existence in the past of some substantial non-dipole component and could be explained reasonably in terms of the GAD hypothesis. *Courtillot and Besse* [2004] devoted a special paper to the problem raised by the authors mentioned above. Having analyzed a broader data base, they proved that during the 200-year period of time discussed the contribution of any octupolar source had not been greater than 3%, the error being greater than this value, which makes the latter to be statistically insignificant. At the same time they emphasized that the results of their analysis showed a weak (3%) but trustworthy quadrupolar signal.

[23] To sum up, the numerous studies carried out by the present time show, with a high probability, that the geological history had been dominated by a dipole filed with some zonal (axially symmetric) sources operating in some individual periods of time.

[24] Most of the authors conclude that that the contribution of non-dipole zonal sources was too low to distort the results obtained for the cases admitting the fulfillment of the GAD hypothesis. At the same time there are data (see Table 1 and Figure 1), that can be treated as the indications of some non-dipole components in some periods of the geologic history, this ranking the testing of the GAD hypothesis as an important task of modern paleomagnetology.

[25] In principle, in addition to the methods mentioned above, paleomagnetic data can be used for testing the dipole nature of the geomagnetic field also by way of comparing the paleomagnetic trends obtained for large undeformed crustal blocks. In particular, these blocks include epi-Hercynean platforms the constituents of which were not usually displaced relative to one another, at least since the time of their formation. As to the epi-Hercynean platforms, the largest and best known is the North Eurasian one. *Khramov et al.* [1982] analyzed the Late Permian data available for this platform and found that the distribution pattern of the paleomagnetic trends were in good agreement with a central dipole field with its pole located in the northwestern part of the Pacific Ocean. A similar work was done using the results of the Mesozoic paleomagnetic determinations available for Africa (described in detail in the book by *McElhinny et al.* [1996]). The results of this work also confirmed the consistency of a dipole hypothesis for the time interval concerned.

[26] A large volume of high-quality data, meeting the modern requirements, was accumulated during the last decade for the Permian-Triassic trap rocks of the Siberian Craton. During the study reported in this paper, an attempt was made to test the GAD hypothesis for the Paleozoic-Mesozoic boundary by way of comparing the respective Siberian paleomagnetic poles with the European poles of the same age.

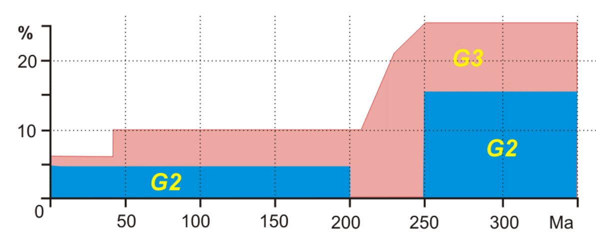

Figure 1. The maximum values of the contribution of the non-dipole components to the geomagnetic field during 350 Ma (see Table 1 for the references).

Also the estimation of the possible non-dipole component contribution to the averaged magnetic field of that time was carried out.

Method of Study

[27] It is believed [*Khain,* 2001] that a new supercontinent, Pangea, had been formed by the end of the Late Paleozoic, which combined all of the major continental blocks, including those composing the basic part of modern North Eurasia. Let us assume (we will return to this point later) that the western part of North Eurasia, including the East European Platform with its pre-Mesozoic foldbelts (we use the term "Stable" Europe for this region in the text that follows) and the Siberian Craton, had not experienced any movements relative to each other during the post-Paleozoic time. In this case we can attempt to verify the dipole type of the geomagnetic field at the boundary between the Paleozoic and Mesozoic by way of comparing the paleomagnetic poles of the Siberian Platform and "Stable" Europe, of the same or closely similar age. The absence of any significant difference between the compared poles (calculated proceeding from the dipole law) was supposed to confirm the dipole character of the Earth's magnetic field in the respective interval of time. In the opposite case the dipole character of the geomagnetic field at the Paleozoic-Mesozoic boundary would be doubtful. The observed differences between the positions of the paleomagnetic poles could be compared with the expected one, proceeding from the assumption of some or other relationships between the zonal non-dipole (quadrupole and/or octupole) and dipole sources. This comparison was supposed to allow us to estimate the potential contribution of the non-dipole components to the geomagnetic field at the Paleozoic-Mesozoic boundary. We believed it most convenient to chose the time interval corresponding to the Permian-Triassic boundary (with an age of about 250 Ma) for the comparison of the Siberian and European paleomagnetic poles. We preferred to use this time interval because, first, there is a significant number of high-quality paleomagnetic data for the rocks of this age and, secondly, this time interval is believed [*Torsvik and Van der Voo,* 2002] to have been marked by the highest non-dipole content of the geomagnetic field (TAF) for the last 300 Ma.

Siberian Permian-Triassic Paleomagnetic Pole

[28] Almost all of the paleomagnetic determinations available for the Siberian Platform for the time period concerned have been obtained for the rocks that participate in the structure of one of the world largest plateau basalt provinces and are usually known as Siberian Permian-Triassic traps. Since the extensive trap flows caused the high-volume remagnetization of the host rocks, the data obtained for the remagnetized rocks can be used to calculate the Permian-Triassic pole of the Siberian Platform.

[29] Only some of the numerous paleomagnetic determinations, available until recently for the Siberian trap rocks, were obtained using the modern methods of laboratory processing. Recently, various authors obtained new data (see Table 2 and Figure 2) which allow one to calculate a new Permian-Triassic paleomagnetic pole of the Siberian Platform, based on the results that satisfy the modern criteria of paleomagnetic reliability [*Van der Voo,* 1993].

[30] Worthy of mention are the data obtained by *Gurevich et al.* [2004] and by *Heunemann et al.* [2003] for trap-type effusive rocks in the area of Norilsk and in the north of the Putorana Plateau, respectively.

[31] In the Norilsk region (Talnakh, Listvyanka, and Kaerkan areas) samples were collected from lava flows and small intrusions at 35 sites. The characteristic magnetization components showed both direct and reversed polarity and were ranked to be substantially antipodal ones, with some virtual poles being fairly widely scattered (the clustering factor of 6.5). *Heunemann et al.* [2003] suggest that the trap rock sequence records a transition from direct to reversed polarity, the stable field being recorded in some stratigraphically lower rocks. We believe that the data available for these 35 sites should be discarded from the calculation of the Siberian magnetic pole.

[32] The 60 lava flows studied in the Abagalakh rock sequence (the northern part of the Putorana Plateau and the valleys of the Abagalakh and Ikon rivers). *Heunemann et al.* [2003] believe that the lower 16 lava flows recorded the latest period of the reversed to normal polarity transition. The magnetization of the remaining 44 lava flows reflect the trend of the stable (unreversed) geomagnetic field and, hence, can be used to calculate the magnetic pole.

[33] *Pavlov et al.* [2001] studied several lava flows and small intrusions at seven sites west of Norilsk City. Their characteristic magnetization showed both direct and reversed polarity, The reversal test gave a positive result. The respective paleomagnetic pole, shown in Table 2, was found to be somewhat different from the pole reported by *Pavlov et al.* [2001]. This was caused by the fact that during the revision of initial data some samples with noise were discarded, and the closely spaced sites were combined.

[34] The results of the paleomagnetic studies of traps and of some rocks remagnetized by them, outcropping in the valleys of the right tributaries the Podkamennaya Tunguska River, known as the Bolshaya Nirunda and Stolbovaya rivers, and also in the valley of the Kotui River (Maimecha-Kotui area), were published in 2003 by *Veselovsky et al.* [2003].

[35] Studied in the Stolbovaya R. Valley were four sites from a large intrusion in the river mouth and three sites in three outcrops of remagnetized Ordovician rocks. Depending on the choice of a method for calculating the mean values, namely, breaking the outcrop of remagnetized rocks into sites (version 1), or considering each of them as one site (version 2); calculating the mean values at the site level (version 1) or at the level of objects, where the object is one remagnetized outcrop, one igneous rock body, etc., (version 2), the respective paleomagnetic poles had somewhat different coordinates (see Table 2).

Table 2. The Permian-Triassic paleomagnetic poles of the Siberian Platform

Region	Pole							
	N	S.Lat	S.Long	P.Lat	P.Long	K	A95	Reference
SIBERIAN PLATFORM								
Abagalakh**	44	70.3	90.1	58.0	149.9	25	4.4	[*Gurevich et al.,* 2004]
West Norilsk	7	69.3	87.9	52.4	159.5	55	8.2	[*Pavlov et al.,* 2001]
Vilyui	3	66.1	111.5	57.5	162.7	19	29.3	[*Kravchinsky et al.,* 2002]
Moyero	22	67.6	104.1	58.4	133.8	66	2.6	(M. L. Bazhenov et al., in press, 2005)
				60.8*	153.5*	42*	7.1*	
Kulyumbe	26	68.0	89.0	51.4	128.9	21	6.4	(M. L. Bazhenov et al., in press, 2005)
				56.4*	141.7*	14*	13.5*	
Bolshaya Nirunda	4	62.0	95.3	55.1	142.5	83	4.8	[*Veselovsky et al.,* 2003]
				54.4*	143.8*	60*	12.0*	
Stolbovaya	7	62.1	91.5	53.3	150.2	56	5.3	[*Veselovsky et al.,* 2003]
				55.3*	148.7*	68*	11.2*	
Kotui	5	73.0	102.4	52.7	148.4	31	13.9	[*Veselovsky et al.,* 2003]
NSP2	8	67	95	55.3	146.9	126	5.0	(M. L. Bazhenov et al., in press, 2005)
VP	8	67	95	56.1	151.0	268	3.4	(this paper).

Note. S.Lat and S.Long are the latitude and longitude of the sampling site; P.Lat and P.Long are the latitude and longitude of the paleomagnetic pole; K is data grouping; A95 is the confidence circle radius; N is the number of the poles used in averaging; * are the alternative poles corresponding to version 2 (see the text); ** are the poles corresponding to the transitional zone (after [*Heunemann et al.,* 2003]), which are not discussed here. The NSP2 pole was obtained by averaging several regional mean poles. The VP pole is a similar pole but calculated using alternative (version 2) poles.

[36] In the Bolshaya Nirunda R. Valley we studied a large igneous rock body and some remagnetized rocks in three outcrops of Ordovician sedimentary rocks. Similar to the Stolbovaya R. objects of study, the mean trends of the Bolshaya Nirunda R. objects of study could be calculated using two methods, one corresponding to Version 1 (see above) and used by (M. L. Bazhenov et al., in press, 2005) the other corresponding to Version 2 used by *Veselovsky et al.* [2003] to their data.

[37] Five sites from 5 lava flows were studied in the Kotui R. Valley. The recorded characteristic magnetization showed both direct and reversed polarity.

[38] *Kravchinsky et al.* [2002] studied several trap lava flows in the Alakit-Markha area of the Vilyui region, in the vicinity of the Sytikan, Aikhal, and Jubilean kimberlite pipes. The data reported by these authors are not discussed here because these pipes are located at a significant distance from the Permian-Triassic trap rocks, and the association of their magnetization with the trap emplacement seems to be insufficiently obvious.

[39] Apart from the data that were published earlier, in this paper we also use the data obtained for the trap rock bodies and the sediments remagnetized by them from the Kulyumbe and Moyero river valleys (M. L. Bazhenov et al., in press, 2005). In the Kulyumbe area samples were collected from 6 lava flows, 7 sills, and 13 outcrops of sedimentary rocks, which appeared to be wholly remagnetized by the traps. In the Moyero R. Valley, results were obtained for 11 intrusions and 11 outcrops of sedimentary rocks, also remagnetized by the traps.

[40] In the case of the Moyero R. area, the data obtained for the sedimentary rocks showed extremely high clustering (K=1327 for the case of 50-percent rectification, K=793 in the geographical system of coordinates, and K=805 in the stratigraphic coordinates) and a significant difference of their mean values from the respective value calculated for the igneous rocks. For this reason, the results obtained for the remagnetized rocks were discarded from the calculation of the mean value for the region as a whole (version 2). This decision was made proceeding from the following two alternative hypotheses. One of the inferred the extremely rapid magnetization of the rocks, during which the secular variations had been averaged. On the contrary, the other hypothesis inferred some fairly long-lasting remagnetization which had been associated with some unknown remagnetization event.

[41] The other method of calculation (version 1) inferred, like in the case of the objects from the Bolshaya Nirunda and Stolbovaya River valleys, the breaking of the remagnetized rock outcrops into sites and the calculation of the average value for the region using the sites where samples were collected both of sedimentary and igneous rocks.

[42] Because of the high clustering of the trends obtained for the sills and remagnetized sedimentary rocks in the lower reaches of the Kulyumbe River, a view was advanced that

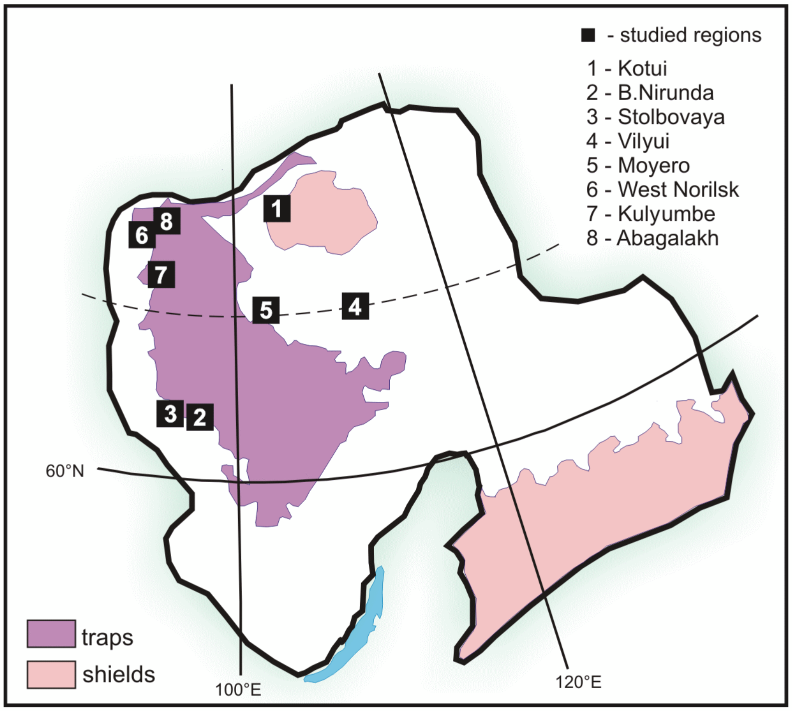

Figure 2. The geographical positions of the study objects whose paleomagnetic poles were used in this paper: (1) Kotui, (2) Bolshaya Nirunda, (3) Stolbovaya, (4) Vilyui, (5) Moyero, (6) the western part of Norilsk, (7) Kulyumbe, (8) Abagalakh.

the former could be interpreted as the single-event apotheses (offshoots) of a large igneous rock body emplaced in the close vicinity, while the latter were remagnetized during the intrusion of these apotheses. Proceeding from this assumption it was suggested to interpret all of the objects studied in the lower reaches of the Kulyumbe River (except for the KV7 sill having a different polarity (see Table 1 in M. L. Bazhenov et al., in press, 2005), this table being available also at the address of http://paleomag.ifz.ru/bazhenov-tab.html) as the products of some short-time event, assigning all of them the same weight, like in the case of the lava flows in the upper reaches of the Kulyumbe River and of the KV7 sill. The average trend calculated using the Devonian remagnetized red rocks, based on the samples collected in different places of the same outcrop, were also recommended to be taken into account, each of them having its own singular weight. This procedure of computing the mean values is also included in the rules recommended for version 2. Like in all other regions, in the case of the Kulyumbe area, this version implies that each isolated outcrop of remagnetized sedimentary rocks can be treated as one site irrespective of the number the samples available.

[43] The paleomagnetic poles calculated using the above procedures for the study areas are listed in Table 2. The location of the regions of the Siberian Platform, whose poles are used in this paper, is shown in Figure 2.

[44] In spite of the fact that the poles were calculated using different methods (version 1 and version 2) the resulting average poles, namely NSP2 (M. L. Bazhenov et al., in press, 2005) and VP (this paper) are located at a distance of merely 2.4° from each other. This distance is notably smaller than the critical angle ($\gamma_c = 5.7°$ [*McFadden and McElhinny,* 1990], which makes it statistically insignificant.

European Permian-Triassic Paleomagnetic Pole

[45] At the present time there is a sufficiently large number of paleomagnetic determinations for "Stable" Europe. However not all of them satisfy the requirements imposed on the quality of paleomagnetic data. Recently *Van der Voo and Torsvik* [2004] carried out a meticulous selection of the paleomagnetic data available for "Stable" Europe and calculated the mean paleomagnetic poles for the time interval of 40–300 Ma, using different criteria, such as, the dating quality and the intensity of magnetic cleaning (DC). In this paper we use the poles of "Stable" Europe with a DC parameter larger than or equal to 3, and were obtained for Late Permian of Early Triassic rocks, the average ages of which correspond to the time interval of 240–260 Ma.

[46] We added 3 poles to the poles suggested by R. Van der Voo and T. H. Torsvik, one of them being published recently [*Szurlies et al.,* 2003]. As follows from the World Database [*Pisarevsky and McElhinny,* 2003], the poles suggested by *Biquand* [1977] and by *Rother* [1971] have DC=3

Table 3. The Permian-Triassic paleomagnetic poles of "Stable" Europe

no.	Object of study	Age, Ma	Average age	S.Lat	S.Long	DC	A95	P.Lat	P.Long	Reference (GPMDB–REFNO)
1	Bunter and Musschelk sandstones, East Germany	241–245 (GPMDB=245–251)	243 (248)	50.8	11	3	15.1	49	146.2	[*Rother*, 1971] (158)
2	Upper Buntsandstein sandstones, France	Olenekian 242–245 (GPMDB=245–251)	243 (248)	48.2	6.7	2 (3)	4.8	43.1	145.7	[*Biquand*, 1977] (1028)
3	Lunner Dikes, Oslo, Norway	Ar-Ar–237–246	243±5	60.3	10.5	4	5.9	52.9	164.4	[*Torsvik et al.*, 1998] (3188)
4	Sudetes Sediments, Poland	Zechstein-Bunts 245–258	251	50.9	16.1	4	4.9	50	163	[*Nawrocki*, 1997] (3161)
5	Dome de Barrot Redbeds, France	Early Thuringian 253–258	255	44	6.8	3	2.7	46.3	147.4	[*Van den Ende*, 1970] (652)
6	Massif des Maures Sediments, France	Thuringian 251–258	255	43.4	6.3	4	4.1	51.1	160.7	[*Merabet and Daly*, 1986] (1408)
7	Lower Buntsandstein Sediments, Central Germany	245–260	252	51.7	11.1	4	3.3	50.6	165.6	[*Szurlies et al.*, 2003] (3525)
8	Esterel extrusives, France	Saxonian 258–270 (GPMDB=245–256)	264 (251)	43.5	6.8	3	6.1	51.5	142	[*Zijderveld*, 1975] (165)

Average poles

Data sample	S.Lat	S.Long	N	K	A95	P.Lat	P.Long
Van der Voo and Torsvik data sample (VT) (Pole nos. 3–6)	49.7	9.6	4	194	6.6	50.3	158.6
Alternative sample (AS) (Pole nos. 1–7)	49.9	9.6	7	138	5.2	49.3	155.7

Note: Lat, Long are the coordinates of the "average" European site, calculated as the averages for the sampling sites used.

Table 4. Comparison of the poles: The data used to calculate them and the results

Initial data						
	Data sample	N	K	A95	P.Lat	P.Long
Europe	VT [*Van der Voo and Torsvik,* 2004]	4	194	6.6	50.3	158.6
	AS (alternative sample) (this paper)	7	139	5.2	49.3	155.7
	[*Iosifidi et al.,* 2005]	9		3	48	163
	[*Gialanella et al.,* 1997]	(193)		3	51	195
Siberia	NSP2 (M. L. Bazhenov et al., in press, 2005)	8	126	5.0	55.3	146.9
	VP (this paper)	8	268	3.4	56.1	151.0
	[*Iosifidi et al.,* 2005]	5	165	20	50	152
	[*Lyons et al.,* 2002]	4		10	53	153

Results of comparison			
no.	Compared poles	γ, °	γ_{cr}, °
1	AS and VP	7.4	5.6
2	VT and VP	7.4	6.0
3	AS and NSP2	8.0	6.7
4	VT and NSP2	8.6	7.8

Note: γ denotes the angular distance, γ_{cr} is the critical angular distance [*McFadden and McElhinny,* 1990].

rather than 2, as suggested by *Van der Voo and Torsvik* [2004]. Moreover, the Rother pole reported by *Van der Voo and Torsvik* [2004] is dated as a Scythian-Ladinian one (227–250 Ma), whereas in the Database its age interval is given as 241–245 Ma.

[47] Also discussed in this paper is the pole obtained for the Esterel igneous, including effusive, rocks [*Zijderveld,* 1975], dated Saxonian by *Van der Voo and Torsvik* [2004]. *Van der Voo and Torsvik* [2004], although in the Global Paleomagnetic Database these rocks are suggested to be 245–256 Ma old. We prefer to date these rocks Saxonian (258–270 Ma) because their host rocks are Saxonian [*Zijderveld,* 1975].

[48] We did not use the Permian-Triassic poles obtained for the eastern part of the East European platform [*Boronin et al.,* 1971; *Burov,* 1979; *Iosifidi et al.,* 2005; *Khramov,* 1963] for the following two reasons. One of them is the fact that the more notable difference between the compared average poles (if any) calls for the use of paleomagnetic data from the areas located at maximum distances from one another in the inferred rigid continental block. Consequently, the poles obtained for the westernmost part of the North Asian craton are more preferable than the poles obtained for the eastern part of the Russian Platform.

[49] The second reason stems from the fact that all of the poles available for the eastern part of the Russian platform show DC values lower than 3 and, hence, do not satisfy the adopted criteria of data selection. The pole recently reported by *Gialanella et al.* [1997] satisfies the quality criteria, yet, being only one pole available, cannot be used in statistical calculations. Moreover, its position differs markedly from the positions of the other Permian-Triassic poles of the Russian Platform [*Iosifidi et al.,* 2005], this point calling for a special discussion which is beyond the scope of this paper.

[50] Table 3 offers two versions of an average European Permian-Triassic pole. One of them was calculated using the data sample offered by *Van der Voo and Torsvik* [2004], the other being based on a larger data sample offered in this paper (see above). Like in the case of Siberia, both of the calculated poles are located in the vicinity of each other and do not show any statistical difference ($\gamma/\gamma_c = 2.1/7.8$).

[51] It is important to note that most of the European paleomagnetic determinations were made using sedimentary rocks.

Comparison of the Poles

[52] The results of comparing four pairs of the averaged Permian-Triassic poles of the Siberian Platform and "Stable" Europe, obtained in this study, are presented in Table 4. One can see that all of the pole pairs differ statistically from one another. It is important to note that both of the Siberian poles (NSP2 and VP) are displaced relative to the European poles (VT and AS) toward Europe almost exactly along the arc of the large circle connecting the center of Europe and its respective pole (see Figure 3).

[53] Since these poles were obtained using different averaging procedures and different data samples, their relationship cannot be treated as a random one and must have its own explanation.

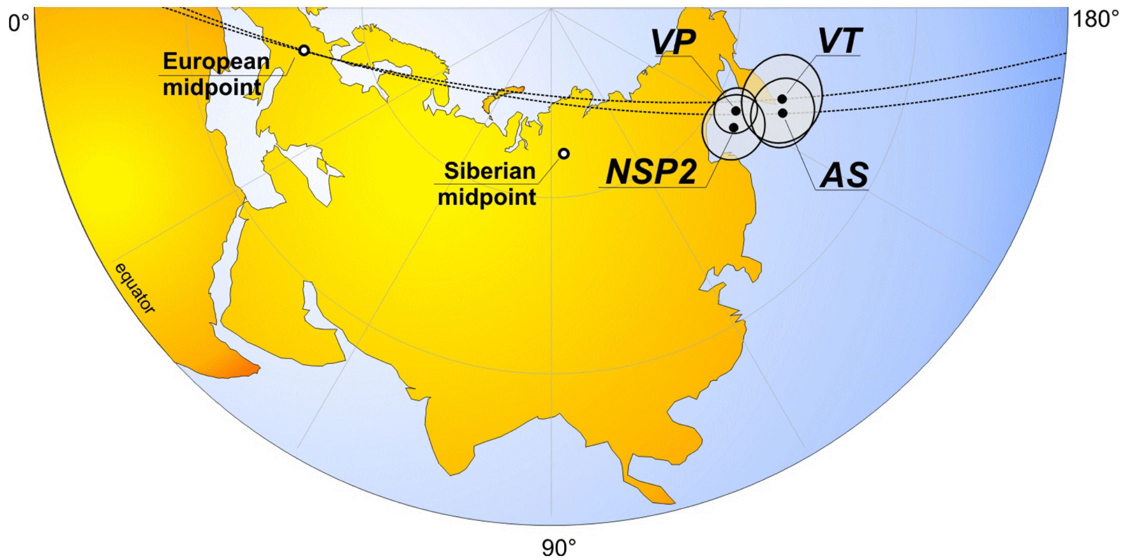

Figure 3. The positions of the average paleomagnetic poles of Siberia and Europe.

Discussion

[54] We believe that the difference observed in the positions of the European and Siberian poles must stem from any of the following causes:

- the relative movements of the Siberian platform and Europe in post-Paleozoic time;
- the different ages of the European and Siberian poles;
- the substantial contribution of non-dipole components to the geomagnetic field at the Paleozoic-Mesozoic boundary;
- the magnetic inclination shallowing in the European data;
- the instability of the solution due to the small and inadequate data sample.

Tectonics

[55] It can be supposed that one of the potential causes responsible for the divergence of the Permian-Triassic poles of Siberia and Europe were the relative displacements of these continental blocks during the Mesozoic and Cenozoic periods of time.

[56] The problem of the relative movements of the Siberian and East European platforms has been discussed repeatedly by many Russian geologists. Using the paleomagnetic data available, *Khramov* [1982] inferred the movement of the northern edge of the Siberian platform away from the East European platform.

[57] Somewhat later, using the criteria of paleomagnetic reliability, *Bazhenov and Mossakovskii* [1986] performed a careful selection of the paleomagnetic data available for Siberia and East Europe, which allowed them to prove a notable difference in the positions of the respective Early Triassic poles. This difference was interpreted by them as the evidence proving the counter-clockwise rotation of the Siberian Precambrian continental block relative to the East European one by the value of about 10°, assuming the rotation pole to be located in the area of North Kazakhstan. The analysis of the specific pattern of the distribution of the Early Mesozoic compression and extension structural features at the periphery of the Siberian Platform carried out by *Bazhenov and Mossakovskii* [1986] seemed to confirm this conclusion. They noted, in particular, that the formation of a system of Triassic grabens in the west of Siberia can be explained by this hypothesis, too.

[58] The formation history of the West Siberian grabens is still a matter of discussion, no unambiguous answer being found so far. A brief review of the work done in this field was offered by *Kremenetsky et al.* [2002, p. 75]. The results of interpreting the numerous studies carried out in this region suggest the West Siberian platform includes a thick (to 15 km) Meso-Cenozoic sedimentary basin resting on the Paleozoic and Proterozoic folded basement of still unknown composition. Associated with the latter are the submeridional linear mostly positive gravity anomalies, ranging between 300 km and 500 km in size and varying greatly in terms of their interpretation [*Kremenetsky et al.,* 2002]. For instance, *Aplonov* [2000], who discussed this problem in many of his papers, assumed the presence of the Ob paleoocean of a submeridional strike, the rifting stage of which had begun (simultaneously with those of the other rifts) about 240–230 Ma ago, and its short-term spreading stage resulted in the 200- to 300-kilometer spreading of the rift sides and was completed about 215 Ma ago. S. V. Aplonov believes that the spreading of the hypothetical Ob paleoocean resulted in the clockwise rotation of Siberia, relative to the East

European Platform, by about 12–14° around the rotation pole situated south of the 60th parallel.

[59] It should be noted, however, that in the case of this rotation the Siberian pole must have been displaced eastward relative to the European pole, that is, the situation must have been opposite to the observed one (Figure 3).

[60] In contrast to the view proposed by *Bazhenov and Mossakovskii* [1986] and *Aplonov* [2000], there are data which suggest the West Siberian rifts degenerated northward, which is imprinted in the lower number and poor expression of their deep-seated geophysical indications. In particular, *Bogdanov et al.* [1998] reported the cross-size of the Koltogor-Urengoi rift is 120–130 km in the area of the Tyumen superdeep hole (TSD-6), the size of the rift valley being about 1.5 km across. In the Arctic region the width of the rift valley is not more than 50–70 km, the depth of the trough diminishing to a few hundred meters. Farther northward the rift attenuates more rapidly and vanishes toward the Kara Sea. Similar data are available for the Khudosey Rift.

[61] It is worth noting that he hypothesis advanced by S. V. Aplonov for the existence of the Ob paleoocean doubted by the results of drilling the Tyumen superdeep hole (TSD-6) which was drilled in the middle of the Koltogor-Urengoi rift graben inferred in the center of the supposed paleoocean. No oceanic crust has been encountered there. On the contrary, in its depth interval of 6424–7502 m (bottom hole) the hole exposed a sequence of volcanic rocks, mostly low-K tholeitic basalt ranging from P_2 to T_1 in age, the detailed study of which proved it to be similar to the tholeite of the trap formation of the Siberian Platform [*Kremenetsky and Gladkikh,* 1997]. *Kazanskii et al.* [1996] believe that the textures and structures of these basalts suggest that they had flowed in land conditions. *Kirichkova et al.* [1999] reported the finds of continental plant remains in this depth interval. The age of the West Siberian trap rocks dated by *Reichow et al.* [2002] using the Ar-Ar method was found to be very close to the age of the trap rocks from the Siberian Platform, which also contradicts the hypothesis offered by *Aplonov* [2000].

[62] The analysis of our mean paleomagnetic poles shows that the explanation of their noncoincidence only by the significant relative movements of the cratons discussed calls for the assumption of the significant convergence of these platforms (over the distance of about 8° of the large circle arc) in Late Paleozoic time. This convergence must have been caused by the rotation of Siberia around the Euler pole which was remote significantly from its geometric pole.

[63] In the case of the rotation of the Siberian platform relative to “Stable” Europe, the Euler pole must have been located at the large circle arc passing across the middle of the arc connecting these poles and perpendicular to it. This pattern shows that the large circle, on which the pole of the Siberian platform rotation must rest, is located significantly far from its geometrical center, this controlling the character of this platform rotation, which could not be a simple strike-slip fault movement at the western margin of the Siberian platform, calling for the significant movement of this platform to the west.

[64] These large-scale movements of the Siberian platform (about 700–800 km) caused the formation of large compression-type structural features in the area of the modern western margin of the platform. Yet, no geological data confirming the formation of any large compression-type structures have been found thus far. As mentioned above, the territory of West Siberia is known for the wide development of Early Mesozoic grabens, the Triassic and Early Jurassic deposits filling them being often folded [*Bochkarev,* 1973]. This proves some compression episode in the Mesozoic history of this area, the scale of which being incomparable with the compression that might have been produced by the above-mentioned convergence of the Siberian and East European platforms.

[65] The only large-scale compression-type structural feature between the East European and Siberian platforms is the Ural fold-mountain belt, which shows the traces of both Mesozoic and Cenozoic tectonic activity including compression and extension. Yet, first, the scale of the compression structural features produced after the Late Hercynian orogeny corresponds to the maximum compression of a few hundred meters which is incomparable with the compression estimate of hundreds of kilometers. Secondly, the Mz-Kz tectonic activity was marked mainly by longitudinal faults [*Bachmanov et al.,* 2001].

[66] Thus, we reject the possibility of explaining the difference between the Permian-Triassic poles of Siberia and Europe by their relative tectonic movements.

Age

[67] By the present time a fairly large number of data have been accumulated [*Bogdanov et al.,* 1998], which prove that the Permian-Triassic igneous activity in the region of the Siberian Platform continued not longer than 10–15 Ma, and that most of the trap rocks were formed in the time interval of 255–253 Ma to 248–244 Ma [*Zolotukhin et al.,* 1996]. Some researchers [*Gurevich et al.,* 1995; *Renne et al.,* 1995] suggest that the most active period of trap volcanism, when huge volumes of basalt lava flowing on the ground surface, might have lasted during a geologically short interval of time causing the death of living organisms and radical changes in the biocenosis at the Paleozoic and Mesozoic boundary some 250 Ma ago. This conclusion was confirmed by the recent U-Pb datings of the rocks from the upper and lower parts of trap rock complexes of the Maimecha-Kotui region reported recently by *Kamo* [2003].

[68] Consequently, the time during which the study rocks had been emplaced (and hence the age of the paleomagnetic poles obtained) can be placed in the interval of 255–244 Ma and, hence, can be taken, with high probability, to be close to the Permian-Triassic boundary which has been dated recently as close to the age value of 251.4±0.3 Ma [*Bowring et al.,* 1998]. On the other hand, since the age of the basalts from the Podkamennaya Tunguska R. Valley was found using the isochronous $^{39}Ar/^{40}Ar$ method to be 238–248 Ma by *Zolotukhin et al.* [1996], it cannot be excluded that the trap magnetism had not been completed after the flow of the bulk of effusive rocks in the north of the Siberian Platform.

[69] In any case, the isotopic and biostratigraphic data available [*Distler and Kunilova,* 1994] suggest that the accumulation of the trap rocks began the very end of the Permian and was completed at the very beginning of the Triassic. In spite of the potentially short time of the trap rock flow, it should be noted that the data obtained in this study might show the fairly good averaging of the secular variations of the magnetic field. The basis for this assumption is the fact that these data were obtained for the rocks which had been magnetized during the epochs of both normal and reversed polarity, that is, during the time of at least several dozens of thousand years.

[70] The bulk of the European data were obtained for sedimentary rocks. In terms of their biostratigraphy these rocks compose the Late Permian (Thuringian) and Early Triassic (Indian-Olenekian) beds which were deposited immediately below and above the Permian-Triassic boundary. *Menning* [1995] believes that these beds accumulated in the time interval of 240–260 Ma. Only one paleomagnetic determination of those used to calculate the average European pole was obtained for igneous rocks, namely, for the Lunner dikes. These dikes were dated using the modern Ar-Ar method and found to be 243±5 Ma. Proceeding from the very short time of the Siberian trap accumulation, it can be expected that they have a more narrow age range than the European objects. However, since the European ages of our data sample are distributed roughly symmetrically relative to age of the Permian-Triassic boundary, it can be expected that the average age of the European objects is close to that of the Siberian Permian-Triassic traps, and that the difference between their ages can be used to explain the difference between the Siberian and European paleomagnetic poles.

The Non-Dipole Pattern of the Geomagnetic Field

[71] Another potential explanation of the difference between the Siberian and European paleomagnetic poles is the potential significant contribution of non-dipole components to the Earth magnetic field during the Late Paleozoic and Early Mesozoic.

[72] To estimate the potential contributions of the quadrupolar and octupolar components to the geomagnetic field at the Paleozoic-Mesozoic boundary, we recalculated the coordinates of the European and Siberian Permian-Triassic poles (that were obtained initially proceeding from the dipole law) using the algorithm similar to the algorithm proposed by *Torsvik and Van der Voo* [2002], which accounted for the non-dipole character of the field (see Appendix A). New average poles were obtained for Europe (AS and VT) and for Siberia (NSP2 and VP) for each pair of the $G2$ and $G3$ values. The values of the quadrupolar ($G2$) and octupolar ($G3$) coefficients ranging from -40% and 40% were recalculated, the values outside of this interval were ranked as improbable.

[73] The results of our calculations are presented in Figure 4, where the $G2$ and $G3$ values expressed in percent of the dipole component are plotted along the coordinate axis. The contour lines show the angular distance (gamma) between the compared Siberian and European poles, calculated in terms of the non-dipole law for the respective values of the non-dipole coefficients.

[74] Shown in Figure 4 is only the region where the gamma angle had a value lower than the critical $\gamma_{\rm cr}$ value for the given $G2$ and $G3$ values [*McFadden and McElhinny,* 1990]. In fact, the $G2$ and $G3$ values corresponding to this region are the required solutions for which the differences between the Siberian and European mean paleomagnetic poles become statistically insignificant. It was also of interest to determine the $G2$ and $G3$ values responsible for the best convergence of the Siberian and European poles.

[75] **The AS and NSP2 poles (Figure 4a)** showed their best convergence (with the gamma angle between them being close or equal to 0°) in the region where the non-dipole coefficients $G2$ and $G3$ showed the values of -10 to 10% and $\sim -10\%$, respectively. Note that the gamma value becomes zero for $G2 = 0$ and $G3 = -10\%$. Therefore the observed difference between the AS and NSP2 poles can be eliminated easily by the assumption of a small (10%) contribution of the octupolar component to the total anomalous Permian-Triassic field.

[76] **The AS and VP poles (Figure 4b).** One can see in this figure that the region of the best agreement between these poles (with the gamma angle between them being close or equal to 1°) extends as a narrow band in the 4th quadrant of the plot in the region where the non-dipole coefficients $G2$ and $G3$ show the values of 25% to 40% and of -20 to -10%, respectively.

[77] It should be noted that although the poles become statistically undistinguishable with the minor displacement of the coefficients from zero, the angle between them becomes close to the minimum value only under the condition of the fairly high contribution of both the octupolar and quadrupolar components. Following *Van der Voo and Torsvik* [2001], it should be noted that the substantial contribution of the quadrupolar component to the geomagnetic field would lead to the notable displacement of the paleoequator position, determined by the paleomagnetic method, from the position based on the study of various paleoclimatic indicators. What actually happens is that this effect is not observed, this fact being confirmed by the results of the study carried out by *Kent and Olsen* [2000] for the purpose of studying the paleolatitudinal position of the Late Triassic sedimentary basin extending along the eastern margin of the North American continent.

[78] **The VT and VP poles (Figure 4c).** These poles show their maximum convergence (with the gamma value close to 0°) for the relatively small $G2$ and $G3$ values equal to 10–12%.

[79] **The VT and NSP2 poles (Figure 4d).** Like in the case of the AS and VP poles, the point of the best convergence of these poles (with the gamma value close to 0°) is displaced significantly into the region of the high values of the quadrupolar coefficient (with the $G2$ value being -30%), whose substantial contribution to the geomagnetic field seems to be very doubtful. The value of the $G3$ coefficient is about -5%.

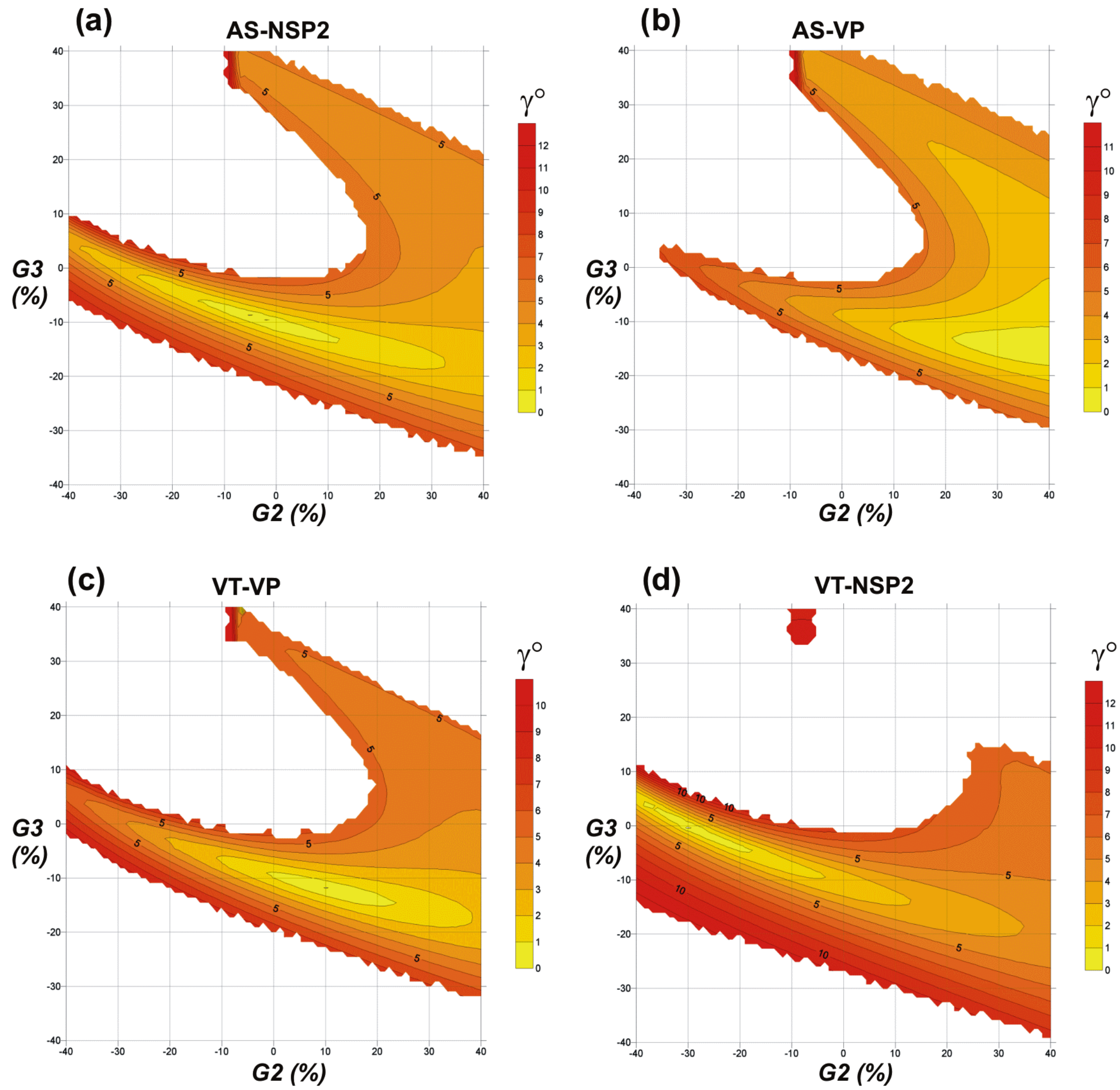

Figure 4. The distances (gamma angles) between the Siberian and European average poles as a function of the values of the non-dipole component contributions. The stepwise pattern of the marginal parts of the curves was controlled by the discrete values of the $G2$ and $G3$ components (1%) used in the calculations.

[80] The inadequate choice of a geomagnetic field model must cause a greater scatter of the paleomagnetic poles obtained for different objects in the same area. Seemingly, the maximum grouping of these poles could be used as a criterion for choosing some optimum model. It is obvious, however, that the great effects of some other factors on the close grouping of the poles, such as, the local tectonics, the errors of determining the dips and strikes, the inadequate averaging of secular variations, to name but a few, preclude the use of the grouping of regional poles for the solution of this problem. This conclusion is illustrated by the series of curves presented in Figure 5, where the maximum crowding is achieved for different regions and different pole combinations in the case extremely improbable values of the $G2$ and $G3$ coefficients.

Inclination Shallowing of the European Data

[81] Do the above statements prove that the non-dipole components played a significant role in the geomagnetic field of the Permian-Triassic boundary? In spite of the fact that our results generally agree with this hypothesis, this conclusion cannot be made definitely, because the disagreement between the European and Siberian poles might have been caused by some other reason. This reason might have been the potential inclination shallowing of the European paleomagnetic directions, since them have been obtained (except one of them) using sedimentary rocks, in which inclination shallowing is often observed.

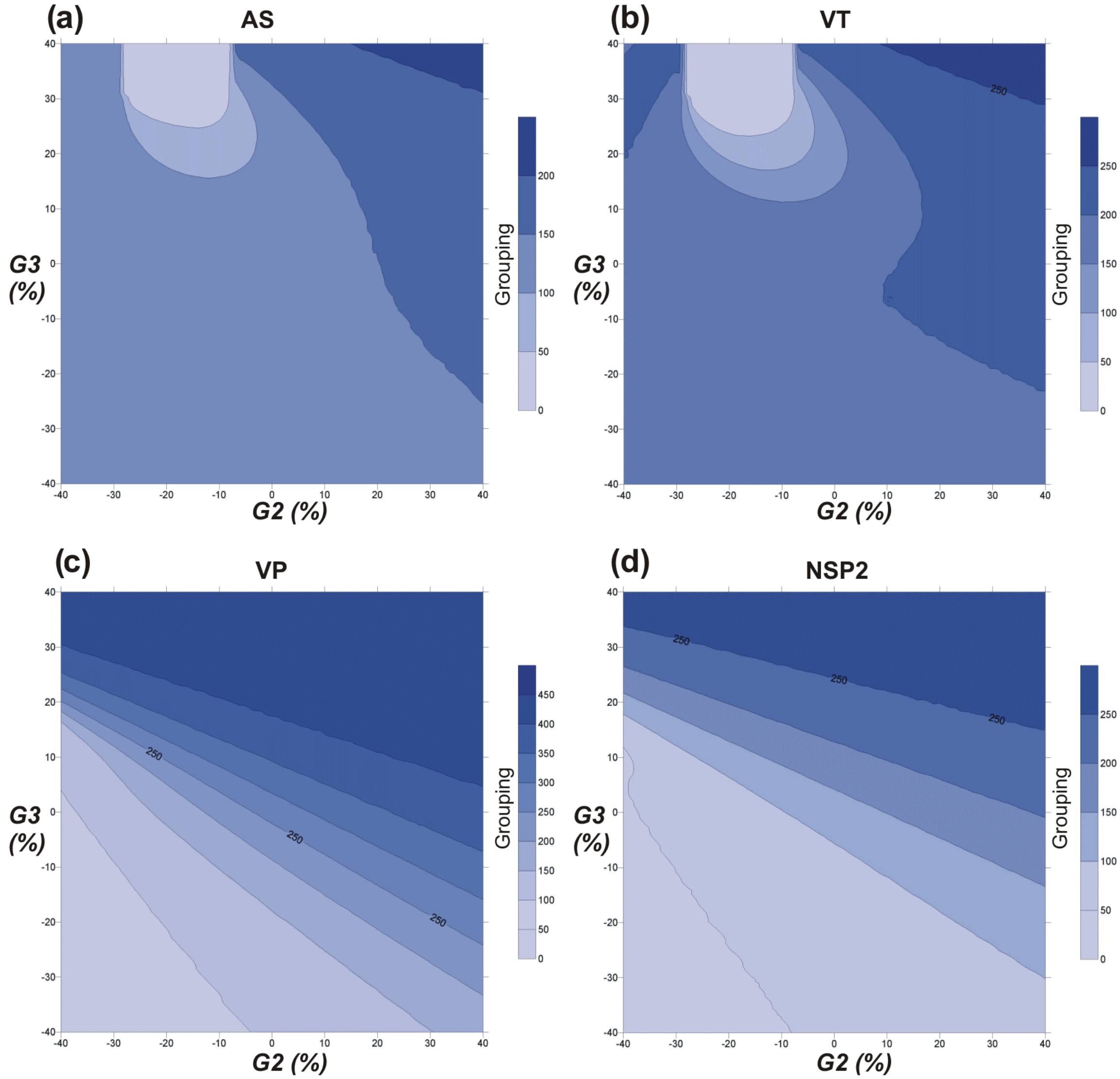

Figure 5. Variation of the Siberian and European poles grouping (Ficherian precision parameter) as a function of the non-dipole coefficient values. In the cases of the non-dipole coefficients, when similar magnetic inclinations corresponded to different paleolatitudes (the use of inclinations gave ambiguous poles), when the values of the non-dipole coefficients were close to the boundary ones, calculations were made using the pole, located most closely to the neighboring exactly located pole, in the case of the close values of $G2$ and $G3$.

[82] Since the coefficient of inclination shallowing must be evaluated for each particular case separately, and we did not have any results of such studies carried out for the European data available, we could estimate some general averaged value (f) of inclination shallowing, for which the compared average poles of the Siberian Platform and "Stable" Europe would not show any statistical difference.

[83] We used the following relationship for the mean European pole recalculation:

$$\tan(I_{\text{observed}}) = f \times \tan(I_{\text{field}})$$

(where I_{observed} is the mean inclination obtained from the mean European pole (which was calculated, using the dipole law) for the average European site, and I_{field} is the inclination of the geomagnetic field during the rocks magnetization), proved empirically and known as the King's Rule [*Barton and McFadden,* 1996; *King,* 1955]. As a result we found the variation of the gamma angle between the pairs of the poles as a function of the ratio of the inclination shallowing factor f (see Figure 6), where plotted along the horizontal axis are the values of the f parameter (over the interval of 0 to 1), those plotted along the vertical axis being the values of the gamma angle between the Siberian Pole and the recalculated European one.

[84] Figure 6a clearly shows that the divergence of the AS

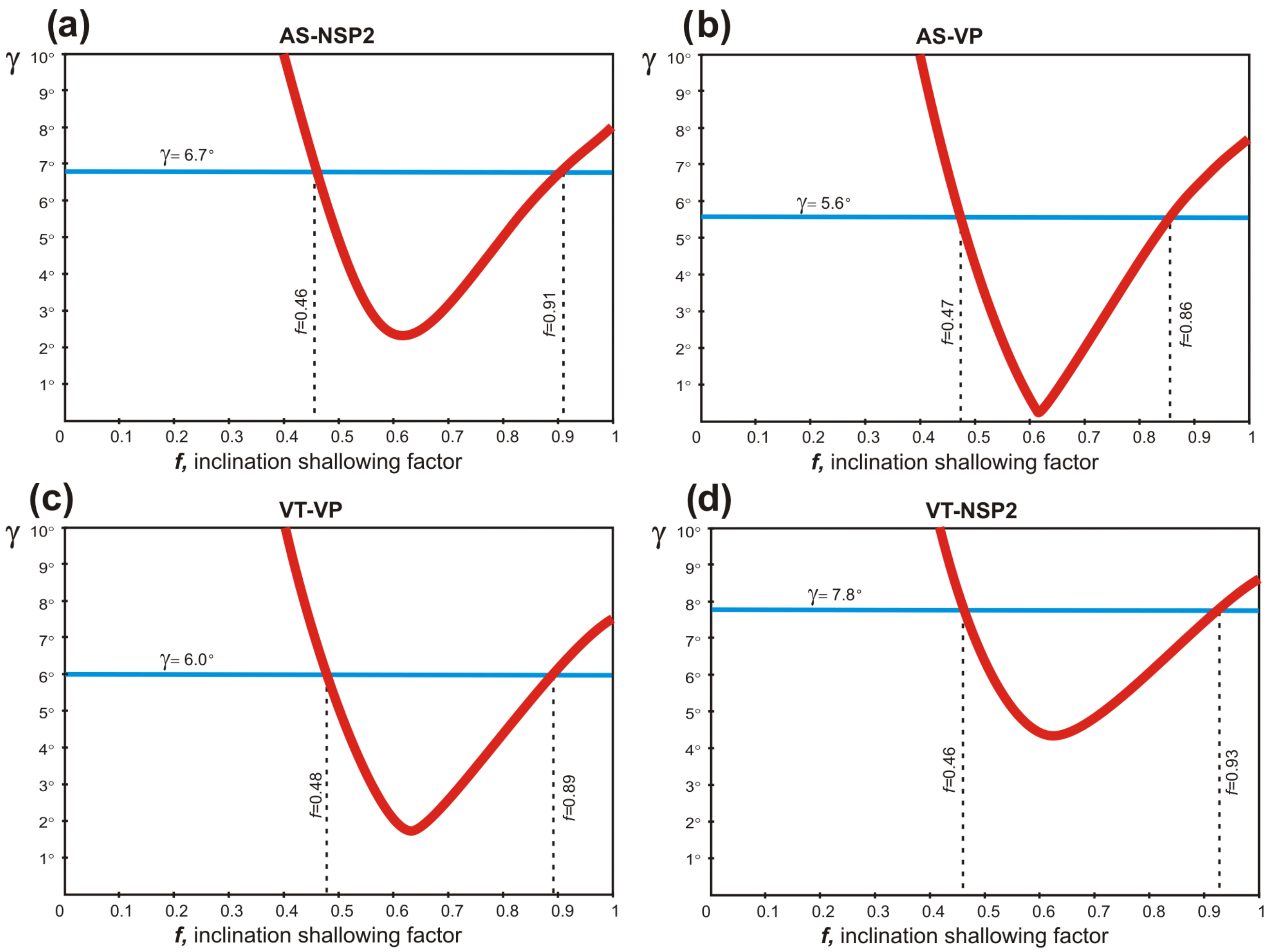

Figure 6. Variation of the distance (gamma angle) between the Siberian and European poles as a function of the inclination shallowing factor supposed for the European data.

and NSP2 poles is minimal for the inclination shallowing factor $f = 0.62$ (with the gamma angle being higher than 2°), the poles being not different statistically for the f values ranging from 0.46 to 0.91.

[85] Figure 6b shows that the divergence of the AS and VP poles might have been caused by the magnetic inclinations shallowing in the European values with an average f value ranging from 0.47 to 0.86. The best convergence of the poles was found for $f = 0.62$.

[86] Figures 6c and 6d show that the divergence of the AS-NSP2 and VT-NSP2 pole pairs can be explained by the inclination shallowing in the European data, the poles showing no statistical differences over the large interval of the f values ranging from 0.45 to 0.95. However, the minimal angle between them (higher than 1.5° and 4°, respectively) differs from zero. This can be explained by the fact that the Siberian NSP2 pole is remote from the large circle connecting the European pole and the center of Europe.

[87] To sum up, the observed difference between the Siberian and European poles can be explained by the inclination shallowing in the European sedimentary rocks. It should be noted that the statistically significant difference between the Siberian and European poles can be removed assuming some small inclination shallowing, namely, f=0.9–0.95, associated potentially with some packing of the studied sedimentary rocks. It should be noted that experiments proved the possibility of even some greater inclination shallowing in sedimentary rocks, the f value of which may be as high as 0.4 [*McFadden and McElhinny,* 1990].

[88] Interesting observation follows from the comparison of the average Siberian poles with the pole having the coordinates Plat=53.0 and Plong=152.9, which was obtained by averaging the data available for the Lunner dikes and the Esterel volcanic rocks (see Table 3). Although the latter were discarded from the data samples used because their age (261 Ma) is formally beyond the age range used in this study (240–260 Ma), this does not preclude the possibility that the pole obtained by the averaging of their pole with the pole of the Lunner dikes may turn out to be close to the true European paleomagnetic pole of the Permian-Triassic boundary. Our comparison shows that the mean pole obtained for the European igneous rocks discussed resides in

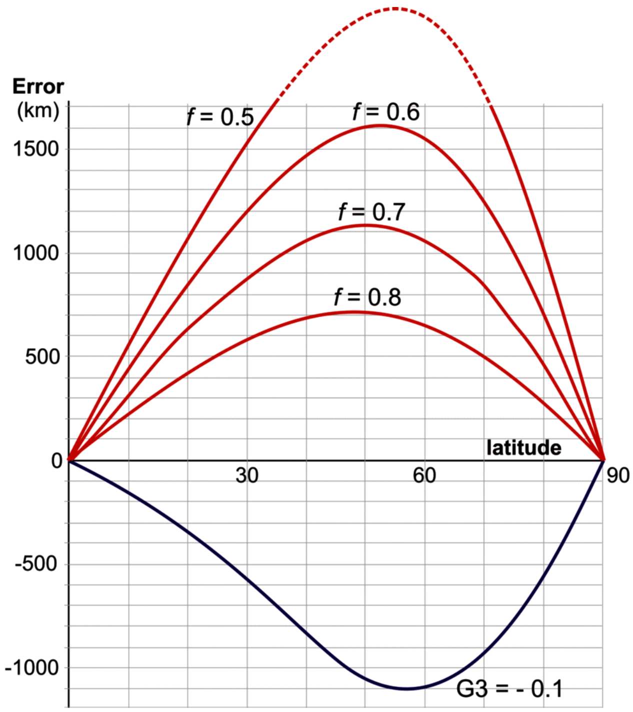

Figure 7. Example of an error in determining the paleolatitude position where the geomagnetic field differed from the dipole one. The red curves show the errors obtained for different inclination shallowing factors. The blue curve shows an error for the contribution of the octupolar component measuring −10% to the magnetic field of the Earth.

the close vicinity of the Siberian poles: VP (with the angular distance of 3.3°) and NSP2 (with the angular distance of 4.2°), inside their confidence circles. This circumstance can be treated as another indication of the potential inclination shallowing in some of the European paleomagnetic directions.

[89] In practical viewpoint, the important parameter is the space error in determining the paleolatitudes without using the non-dipole components of the magnetic field or ignoring the potential effect of inclination shallowing. Figure 7 shows the latitude dependence of errors in determining paleolatitudes when the GAD hypothesis is used to the components of the geomagnetic field differing from the dipole field (Figure 7, blue curve), and also by neglecting of the inclination shallowing phenomenon (Figure 7, red curve).

[90] Seemingly, the choice of the hypothesis which is more suitable for explaining the difference between the European and Siberian Permian-Triassic poles can be made using the recent paleomagnetic determination obtained using the Semeitau rocks of the same age (Kazakhstan) [*Lyons et al.,* 2002]: Plat=56°, Plong=139°, N=15, K=24.6, and A95=7.9°. This pole, obtained for igneous rocks, differs significantly from the European AS pole (γ/γ_{cr} = 12.1°/11.8°) and is not different from the Siberian VP pole (γ/γ_{cr} = 6.7°/10.8°) and from the NSP2 pole (γ/γ_{cr} = 4.5°/11.1°). This situation must have existed in the case of inclination shallowing in the European data. Therefore, the use of the Kazakhstan pole does not help to chose any of these explanations as the most probable one.

The Instability of Solving the Problem Because of the Small and Inadequate Initial Data Sample

[91] The number of the data used for averaging the paleomagnetic poles of the Siberian Platform and "Stable" Europe may appear to be insufficient for getting any stable, statistically correct result. In order to verify the effect of this factor, we compared the average paleomagnetic poles obtained by different authors using different criteria for data collecting. Apart from the average poles obtained in this study, we also used the average poles used by *Gialanella et al.* [1997], *Iosifidi et al.* [2005], and *Lyons et al.* [2002].

[92] The analysis of these data shows that in spite of the different coordinates of the average Permian-Triassic poles of Siberia and Europe, their relative positions remain to be stable: the average pole of Europe is invariably displaced to the southeast relative to the average pole of the Siberian platform, being located at a greater distance from Europe than the Siberian pole (see Table 4).

[93] To sum up, the observed divergence of the poles is of the systematic type, rather than being a consequence of some inadequate data sample.

Conclusion

[94] 1. Reported in this paper is a new average Late Permian-Early Triassic trap-type paleomagnetic pole of the Siberian Platform, obtained using only the paleomagnetic data satisfying the modern criteria of paleomagnetic reliability.

[95] 2. The comparison of the trap-type paleomagnetic pole of the Siberian Platform with the average pole of "Stable" Europe revealed a significant difference between them.

[96] 3. This difference cannot be explained by the movement of the Siberian Platform relative to Europe during the post-Paleozoic time.

[97] 4. The observed difference between the average poles of Europe and Siberia can be explained by the following reasons:

[98] (a) the significant presence of non-dipole components in the geomagnetic field at the boundary between the Paleozoic and Mesozoic. As follows from our estimates the distance between these poles has a minimum value in the case the negative 10% contribution of the octupolar component, and/or

[99] (b) the shallowing of magnetic inclination in the sedimentary rocks, most of which were taken into account during the computation of the average pole of "Stable" Europe. The best convergence of the poles was found using the shallowing factor f equal to 0.62.

[100] 5. The data available are not sufficient to derive a final conclusion, namely, which of the potential explanations of the difference between the poles is correct: the

inclination shallowing of the significant contribution of non-dipole components. However, since our calculations show that the observed difference between the poles becomes statistically insignificant if we assume a very low but quite real value of inclination shallowing ($f = 0.9$–0.95), we believe that currently the hypothesis of inclination shallowing in the European data can be regarded as the most probable one.

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Appendix A

[102] The algorithm of recalculating the paleomagnetic poles (obtained initially using the GAD hypothesis) proceeding from the assumption of the contribution of the non-dipole components $G2$ and $G3$ to the geomagnetic field.

[103] Given: (φ, λ) are the latitude and longitude of the site where paleomagnetic samples were collected; (Φ, Λ) denote the latitude and the longitude of the paleomagnetic pole calculated using the dipole law; $G2$ and $G3$ are the quadrupolar and octupolar coefficients ($G2 = g_2^0/g_1^0$; $G3 = g_3^0/g_1^0$).

[104] Required to find $(\Phi_{32}, \Lambda_{32})$ are the latitude and longitude of the respective paleomagnetic pole accounting for the contribution of the non-dipole components.

[105] Solution: (1) Knowing the coordinates of the sampling site and the coordinates of the pole, we found D and I, which are the declination and inclination of the old geomagnetic field at the sampling site:

$$\varphi_{\mathrm{m}} = \arcsin[\sin(\varphi)\sin(\Phi) + \cos(\varphi)\cos(\Phi)\cos(\Lambda - \lambda)] \ ,$$

φ_{m} being the paleolatitude of the sampling site

$$D = \arccos[(\sin(\Phi) - \sin(\varphi_m)\sin(\varphi))/(\cos(\varphi)\cos(\varphi_{\mathrm{m}})]$$

$$I = \arctan[2 \times \tan(\varphi_{\mathrm{m}})] \ .$$

[106] (2) Using the expression

$$\tan I = \frac{2\cos(\varphi_{\mathrm{m32}}) + 1.5 \times G2(3\cos^2\varphi_{\mathrm{m32}} - 1) + 2 \times G3(5\cos^3\varphi_{\mathrm{m32}} - 3\cos\varphi_{\mathrm{m32}})}{\sin\varphi_{\mathrm{m32}} + G2(3\sin\varphi_{\mathrm{m32}}\cos\varphi_{\mathrm{m32}}) + 1.5 \times G3(5\sin\varphi_{\mathrm{m32}}\cos^2\varphi_{\mathrm{m32}} - \sin\varphi_{\mathrm{m32}})} \ , \qquad \text{(A1)}$$

(where I is the inclination of the magnetic field at the site with paleolatitude φ_{m32}), we found a new paleolatitude of the sampling site φ_{m32} taking into account the contribution of the non-dipole components.

[107] (3) Using the conventional technique, we calculated the new coordinates of the paleomagnetic pole:

$$\Phi_{32} = \arcsin[\sin(\varphi)\sin(\varphi_{\mathrm{m32}}) + cos(\varphi)\cos(\varphi_{\mathrm{m32}})\cos(D)]$$

$$\Lambda_{32} = -b + \lambda + \pi, \text{ if } \sin(\varphi_{\mathrm{m32}}) < \sin(\varphi)\sin(\Phi_{32})$$

or

$$\Lambda_{32} = b + \lambda, \text{ if } \sin(\varphi_{\mathrm{m32}}) \geq \sin(\varphi)\sin(\Phi_{32}) \ ,$$

where

$$b = \arcsin[\cos(\varphi_{\mathrm{m32}})\sin(D)/\cos(\Phi_{32})] \ .$$

[108] (4) As a result, we had the paleomagnetic pole $(\Phi_{32}, \Lambda_{32})$ calculated taking into account the geomagnetic field of the $G2$ and $G3$ non-dipole components.

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