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The Analysis of Meso–Cenozoic Paleomagnetic Poles and the Apparent Polar Wander Path of Siberia

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In blessed memory
of Galina Nikolaevna Petrova
and Aleksei Nikitich Khramov

2 **Abstract**—The Meso-Cenozoic paleomagnetic data for the Siberian Platform and its closest folded framing
are analyzed for compliance with four criteria: structural-tectonic coherency, the accuracy of dating the rocks
2 and the corresponding characteristic component, the quality of the paleomagnetic field and laboratory pro-
cedures, and the degree of grouping of the characteristic components around the mean. It is established that
2 (1) the reliable paleomagnetic data are highly nonuniformly distributed along the time scale. The intervals 0–
60, 80–120, and 180–220 Ma lack any paleomagnetically reliable poles. Three intervals (60–80, 160–180,
and 220–240 Ma) are only characterized by a single reliable pole for each interval. Two intervals (120–
2 140 and 140–160 Ma) have three reliable poles for each of them. The largest number of the reliable paleo-
2 magnetic poles (29) falls in the interval 243–251 Ma. (2) The analysis of the paleomagnetic data for the Mesozoic of the Siberian Platform, the Mesozoic segment of the apparent polar wander path (APWP) constructed from these data, and its comparison with the global APWP curve in the coordinates of stable Europe (Torsvik et al., 2008) discredit the hypothesis of the tectonic incoherence of Siberia to stable Europe since the Late Jurassic (150 Ma). The position of the Triassic poles of Siberia relative to the coeval poles of the global APWP in the coordinates of stable Europe suggests a clockwise rotation of the former relative to the latter by at least 14–15°, which probably took place in the Late Triassic.

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INTRODUCTION

Historically, the development of the geological-geophysical concepts which resulted in the new global tectonics, later named as the lithospheric plate tectonics, was largely focused on the reliability of the continental drift hypothesis. For a long time, the hypotheses of the continental drift have not been popular. Strange as it might appear, these hypotheses were mainly challenged by geophysicists. Their arguments mainly relied on the rigidity of the mantle and the lack of a reasonable mechanism driving the continental motion (Turcotte and Schubert, 1982). The continental drift concept has only received recognition as late as the 1960s after the emergence of the fundamental studies which suggested the explanation of spreading (Dieitz, 1961; Hess, 1962) and subduction of the oceanic crust (Plafker, 1965, Oliver, Isacks, 1967), the existence of a special fault type (transform faults) which not only cut the rifts but also the trenches (subduction zones) into separate segments (Wilson, 1965), the similarity between the rocks of the ophiolite complexes with the rocks of the present-day ocean floor (Peive, 1969), and the linear pattern of magnetic anomalies above the oceans (Vine and Metthews, 1963).

Shortly before the cited works, S. Runcorn (1956) showed that the coeval rocks of North America and
Europe have different paleomagnetic directions and 2
different positions of the corresponding paleomag- 2
netic poles. Runcorn interpreted the significant difference in the positions of the poles as a result of relative drift of two continents, having demonstrated the new possibilities of paleomagnetism. Virtually at the same time, A.N. Khramov has determined one of the tasks of paleomagnetism as “studying the polar wander and continental drift and the related questions of paleogeography and paleoclimatology“ (Khramov, 1958; p. 190).

The first attempts of the Russian paleomagnetologists (*Paleomagnitologiya,* 1962; Khramov and Sholpo, 1967; Petrova and Khramov, 1969; etc.) to relate the
observed differences in the positions of the paleomag- 2
netic poles of the coeval rocks of the different (tecton-

ically incoherent) crustal blocks, including the continental ones, to the continental drift have faced extensive criticism. A particular focus of the criticism laid in 2 the accuracy and datings of the paleomagnetic determinations (Rezanov, 1961; 1968; 1969; Meyerhoff, 1979). The conclusion of these authors was quite certain: 2 ”...the paleomagnetic determinations have been so inaccurate and controversial that they cannot be used as arguments validating or refuting the hypothesis of the relative displacements of continents or their parts“ (Rezanov, 1968, p. 47). Without denying the objective difficulties that were present in the theoretical and methodological aspects of paleomagnetism at that time, Petrova and Khramov in their reply to I.A. Rezanow wrote that “... there is an evident fact to be stressed: the same results cannot be used for solving two problems which are opposite in their sense (*forward and inverse*,—A.D.). For solving the key problem of paleomagnetism—studying the ancient geomagnetic field, as well as for finding the coordinates of 2 the ancient paleomagnetic pole, only the geologically irreproachable data can be used. This means that this data are inferred from the rocks whose exact age is known and that either the absence of crustal displacements and deformations is proven or the sense and magnitude of these deformations is established reliably. Therefore, it is only these measurements that can be used for solving the question of the large horizontal displacements“ (Petrova and Khramov, 1969, p. 67).

The requirements to the reliability and fidelity of the paleomagmnetic data for calculating the ancient 2 paleomagnetic poles and, based on them, the drift parameters of different tectonic blocks, which were suggested by Petrova andf Khramov 45 years ago, have remained topical to date. This is clearly seen from the 2 example of the Meso-Cenozoic paleomagnetic data for the Siberian Platform which, alongside with the East European platform (Baltia), is one of the cornerstones of the tectonic skeleton of Northern Eurasia (Fig. 1, the inset). The time of the consolidation of the latter has been debated since the 1980s. In (Aplonov, 1987; Bazhenov anf Mossakovskii, 1986; *Paleomagnitologiya,* 1982), it was noted that significant relative displacements could have occurred between the Siberian and East European platforms in the Mesozoic.

The analysis of the data for the East European and Siberian plates, conducted more than 20 years ago (Pecherskii and Didenko, 1995; Khramov, 1991; Didenko and Pechersky, 1993) has demonstrated a 2 close but not identical positions of the calculated paleomagnetic poles for the Late Permian and Early Triassic. In (Pecgerskii and Didenko, 1995, p. 8, Fig. 2) it was concluded that ”the APWP of Siberia is generally similar to the APWP of the East Europe, especially from Early Devonian; however, it shifted in time (Fig. 2). The difference of the trajectories 240-320 Ma ago is probably due to the opening of the Ob paleobasin.”

With the emergence of the new data for the Mesozoic of Siberia, whose volume is commensurate with the data that existed in the 1990s, the question concerning the consolidation assembly of the continental blocks of the North Eurasia has again become the focus of discussions (Zemtsov, 2009; Kazansky et al., 2005; Metelkin, 2010; Metelkin et al., 2007; 2008; 2012; Veselovsky et al., 2003; Pavlov, 2012; Cogne et al., 2005).

In fact, considering the same paleomagnetic data, 2 the authors come to alternative conclusions. (1) In the opinion of V.E. Paklov, ”the relative position of the Permian–Triassic poles of the Stable Europe and Siberian Platform contradicts the possibility of relative displacements of these platforms in the post-Paleozoic time“ (Pavlov, 2012, p. 72). (2) D.V. Metelkin et al. believe that ”the strike-slip displacements of the described kinematics within the Eurasian continent continued up to the end of the Mesozoic, which is supported by the systematic divergence of the Mesozoic poles of Siberia and East Europe“ (Metelkin et al., 2012, p. 893).

The question of the reliability of the Mesozoic paleomagnetic poles of Siberia is also extremely 2 important for designing the magnetic-tectonic models for the accretion of the terrains of the Mesozoic orogenic belts in the eastern and southern framing of the platform, which has been the subject of my research recently. For example, the calculated directions from the global APWP in the coordinates of the Stable Europe (Torsvik et al., 2008) and Siberian APWP (Metelkin, 2010; Metelkin et al., 2008; 2012) for the time of 190 Ma and the coordinates of Vladivostok are $Dec = 328°$, $Inc = 75°$, paleolatitude 62°, and $Dec = 305°$, $Inc = 89.7°$, paleolatitude 89.5° respectively. This means that in the calculations of the kinematic parameters of the terrains of the Sikhote-Alin orogenic belt according to the first or second trajectories, the estimate of their latitudinal (along the meridian) drift since the Early Jurassic relative to Stable Eurasia will differ by more than 25° (> 2770 km).

Thus, the present work addresses the following tasks: (1) collecting as far as possible all the original paleomagnetic poles for the Mesozoic and Cenozoic 2 of the Siberian Platform and its nearest folded framing (Supplement 1)[1]; (2) analyzing these data for objective, transparent identification of the most reliable poles (Table 1); (3) answering whether it is possible to judge the tectonic coherency/incoherency of Siberia to stable Europe in the Mesozoic by the most reliable Siberian paleomagnetic poles. 2

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[1] The Supplement in the electronic forms as an .xlsx file is accessible on the website of the Kosygin Institute of Tectonics and Geophysics, Far Eastern Branch, Russian Academy of Sciences at http://itig.as.khb.ru/didenko_a_n/Attachment1_DidenkoPhE2015.xlsx.

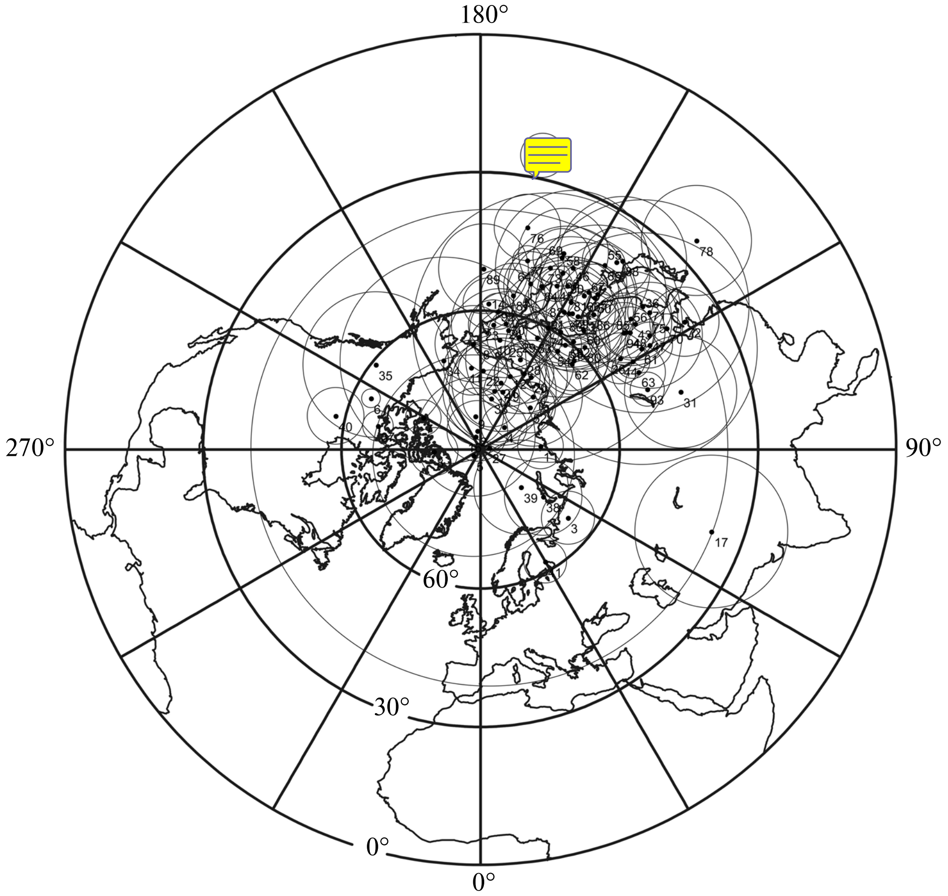


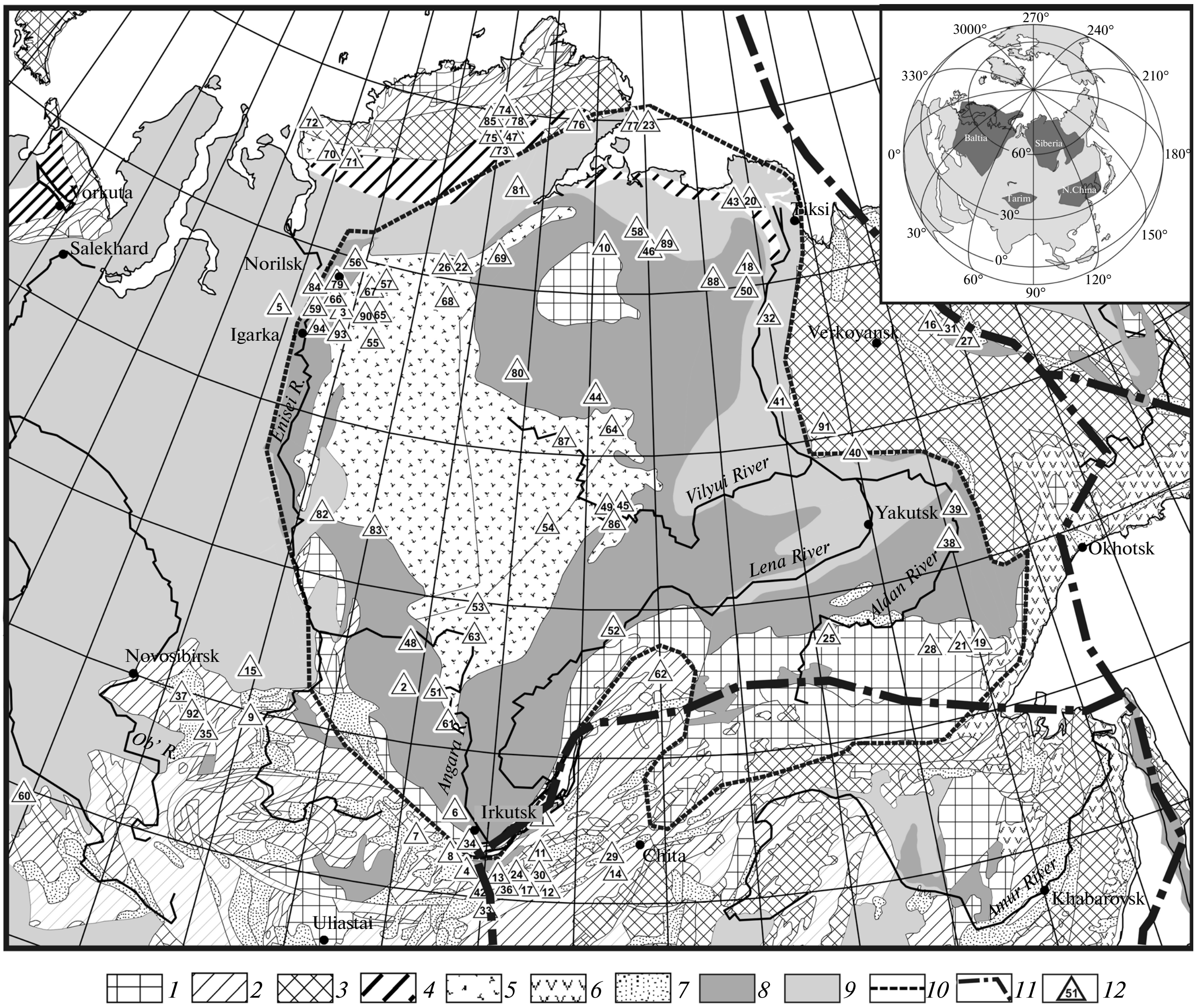
Fig. 1. The tectonic scheme of the Siberian Platform and adjacent regions according to (*Geodinamichskii* ..., 2001, simplified and expanded).

(1) bulges of the Precambrian basement of the platform and Precambrian massifs in its folded framing; (2) Paleozoic folded belts; (3) Mesozoic folded belts; (4) foredeeps of the Mesozoic folded belts: (5) Early Mesozoic regions of intraplate volcanism (traps, alkali basalts); (6) Mesozoic volcanic–plutonic complexes; (7) Cenozoic continental basins (rift zones); (8) pre-Late Cenozoic sedimentary cover; (9) Late Cenozoic sedimentary cover; (10) the boundary of the Siberian Platform; (11) the boundary of the contemporary litho9spheric plates according to (DeMets et al., 2010); (12) the geographic positions of the studied collections, the numbers correspond to Supplement 1 and Table 1; Lambert projection, central meridian 112.5°. The inset shows the position of the Siberian Platform in the structure of the contemporary Eurasian continent.

2 THE METHODOLOGY OF ESTIMATING THE RELIABILITY OF THE PALEOMAGNETIC POLES

The criteria of estimating the reliability of the 2 published paleomagnetic data for the solution of particular tectonic and stratigraphic tasks have been extensively discussed in the literature (Metelkin and Kazanskii, 2014; *Paleomagnetologiya*, 1982; Pecherskii and Didenko, 1995; Shipunov et al., 2007; Briden and Duff, 1981; Ñîå et al, 1985; Didenko and Pechersky, 1993; Harbert, 1990; Hillhouse, 1987; Irving, 1964; McElhinny, 1973; Seguin and Zhai, 1992; Van der Voo, 1990). In the Russian literature, perhaps the most complete analysis of the existing criteria for constructing APWP for tectonic blocks of different area is presented in the books written by (Metelkin and Kazanskii, 2014; Pecherskii and Didenko, 1995). The material of these two publications serves as the basis for the scheme applied in the present paper for assessing the reliability of the paleomagnetic data for the Siberian 2 Platform and its closest folded framing in the Cenozoic–Mesozoic.

For the maximal transparency of the revision of the discussed data, four criteria are applied in the present work. Two criteria are geological and the other two are paleomagnetic. Each criterion has a power of veto. 2 These criteria are the following: (1) the structural control and tectonic coherence (Van der Voo, 1990) of the rocks of each individual collection of the Siberian Platform; (2) the accuracy of the age determinations for the rocks and the corresponding characteristic magnetization; (3) the quality of the paleomagnetic 2 procedures applied when obtaining each particular determination; and (4) the radius of a confidence circle with 95% probability around the mean position of the pole.



2 **Fig. 2.** The positions of all the studied Meso-Cenozoic paleomagnetic poles of the Siberian Platform and the closest folded structures on the sphere. The numbers of the poles in the figure correspond to their numbers in Supplement 1 and Table 1. The circle around the pole is the confidence oval with 95% probability. Polar azimuthal equidistant projection.

The first criterion—the structural control and tectonic coherence of the rocks of each particular studied collection to the body of the Siberian Platform—is fairly clear and perhaps does not need any comment. The boundaries of the platform itself and the contemporary lithospheric plates of Northern Eurasia have been established and, to some extent, accepted. How-
2 ever, the absence of the paleomagnetic data for some time intervals (e.g., for the Jurassic) for the obviously tectonically coherent objects to the platform impels some authors to use the data for the folded framing of this platform instead and to citing some arguments for doing it. Other authors challenge this approach and present their counterarguments.

The second criterion is the accuracy of the age datings for the rocks and the corresponding characteristic magnetization. The threshold value of this criterion assumed in the present work is ±20 Ma, in accordance with (Didenko and Pechersky, 1993; Pecherskii and Didenko, 1995). Metelkin and Kazanskii (2014) criticize this threshold value of ±20 Ma for constructing the Paleozoic APWP of the main continental blocks of Northern Eurasia reasoning that "... a weight of above 0.3 is suggested to only assign to the determinations which have been obtained from the rocks whose age has been determined within an accuracy of ±20Ma. The choice of this particular value is largely based on the fact that the trajectories constructed by the authors are represented by the segments which connect the points (poles) at intervals of 20 Ma. Hence, the introduction of the 20-Ma threshold as one of the highly significant criteria is merely motivated by the desired

2 **Table 1.** The paleomagnetic poles of the Siberian Platform and the nearest folded framing which passed selection

SN	Object	Age, Ma	Dec, °	Inc, °	a_{95}, °	Slat, °	Slon, °	Plat, °	Plon, °	dp, °	dm, °	Source
9	Intrusives, Minusinsk Depression	78 ± 4	12.0	69.5	5.5	54.9	90.3	82.8	188.5	5.7	6.7	Metelkin et al., 2007; Metelkin, 2010
18	Sediments, Verkhoyansk Depression	130 ± 10	70.2	79.2	4.5	70.7	123.9	67.2	183.8	8.1	8.6	Metelkin et al., 2008; Metelkin, 2010
22	Sediments, Khatanga Basin	135 ± 2	46.0	78.0	3.0	70.5	98.0	73.0	178.0	5.3	5.6	GPDB-4.6 (4197)
23	Sediments, Anabar Bay	139 ± 1	83.0	78.0	3.0	75.0	114.0	63.0	174.0	5.3	5.6	GPDB-4.6 (4202)
	Average ($N = 3$)	135						67.8	178.4	8.2	8.2	This work
25	Intrusives of Ryabinovskii massif, Aldan	145 ± 15	39.9	81.6	6.2	58.7	125.9	68.8	156.1	11.7	12.0	Pavlov and Maksimov, 2006
26	Sediments, Khatanga Basin	149 ± 3	138.0	80.0	3.0	70.5	98.0	54.0	123.0	5.5	5.7	GPDB-4.6 (4356)
28	Plutons of KetKap Ridge, Aldan	153 ± 8	22.1	82.2	3.4	57.7	132.1	71.1	150.0	6.4	6.6	Pavlov and Karetnikov, 2008
	Average ($N = 3$)	149						65.4	139.3	18.7	18.7	This work
	Average ($N = 2$)	149						70.0	153.2	6.8	6.8	This work
32	Sediments, Verkhoyansk Depression	165 ± 5	141.4	84.2	2.3	69.1	125.1	59.3	139.2	4.5	4.5	Metelkin et al., 2008; Metelkin, 2010
47	Sills, South Taimyr	228 ± 5	329.9	–74.4	2.9	74.8	100.6	47.1	121.6	4.8	5.3	Walderhaug et al., 2005
50	Tuffs, Lena River	243 ± 2	146.0	78.0	4.0	70.0	123.5	49.0	143.0	7.1	7.5	GPDB-4.6 (4562)
54	Traps, tuffs, Central Siberia	244 ± 1	74.0	82.0	6.0	62.8	107.3	63.0	142.0	11.0	12.0	GPDB-4.6 (4606)
55	Traps, Tungus Syneclise	244 ± 1	108.0	68.0	5.0	67.8	92.1	40.0	144.0	7.0	8.0	GPDB-4.6 (4567)
57	Traps, burnt sediments, Tungus Syneclise	244 ± 1	102.0	72.0	9.0	69.3	91.0	48.0	143.0	14.0	16.0	GPDB-4.6 (4571)
58	Traps, tuffs, Central Siberia	244 ± 1	300.0	–71.0	6.0	72.0	114.0	44.0	157.0	9.1	10.5	GPDB-4.6 (4561)
59	Lavas and tuffs, Norilsk	244 ± 16	88.0	80.0	4.0	69.0	88.0	62.2	133.5	7.3	7.7	GPDB-4.6 (4654)
60	Intrusives, Zaisan, Kazakhstan	248 ± 1	238.1	–69.4	5.4	50.1	79.6	56.0	139.0	7.9	9.2	GPDB-4.6 (8922)
64	Sills, Aikhal, Yakutia	248 ± 3	92.7	74.9	4.0	66.0	111.8	52.6	163.2	6.6	7.3	GPDB-4.6 (7911)
65	Basalts, Tungus Syneclise	248 ± 3	105.0	68.0	3.0	68.5	91.5	42.0	146.0	4.2	5.0	GPDB-4.6 (4506)
67	Basalts, Norilsk	248 ± 3	100.0	72.0	4.0	69.5	91.0	48.8	145.5	6.2	7.1	GPDB-4.6 (7926)
68	Basalts, Tungus Syneclise	248 ± 3	96.0	71.0	1.0	69.5	97.5	48.0	155.0	1.5	1.7	GPDB-4.6 (4511)

Table 1. (Contd.)

SN	Object	Age, Ma	Dec, °	Inc, °	a_{95}, °	Slat, °	Slon, °	Plat, °	Plon, °	dp, °	dm, °	Source
69	Volcanics, Maymecha River	248 ± 3	102.0	69.0	4.0	71.0	101.5	45.0	157.0	5.8	6.8	GPDB-4.6 (4520)
70	Basalts, West Taimyr	248 ± 3	127.0	70.0	2.0	72.8	83.7	42.0	123.0	3.0	3.4	GPDB-4.6 (4625)
71	Basalts, West Taimyr	248 ± 3	122.0	70.0	3.0	72.8	86.0	43.0	129.0	4.4	5.2	GPDB-4.6 (4619)
72	Intrusives, Dikson Island	248 ± 3	310.0	–67.0	5.0	73.5	81.0	38.0	122.0	6.9	8.3	GPDB-4.6 (4618)
73	Basalts, Central Taimyr	248 ± 3	106.0	70.0	2.0	74.7	100.7	48.0	159.0	3.0	3.4	GPDB-4.6 (4632)
74	Basalts, South Taimyr	248 ± 3	288.7	–78.3	7.8	74.9	100.5	59.3	145.8	13.9	14.7	Walderhaug et al., 2005
75	Basalts, Central Taimyr	248 ± 3	330.0	–72.0	7.0	74.9	100.5	46.0	124.0	10.9	12.3	GPDB-4.6 (4627)
77	Volcanics and sediments, East Taimyr	248 ± 3	111.0	71.0	2.0	75.0	114.0	48.0	166.0	3.0	3.5	GPDB-4.6 (4616)
79	Basalts, Norilsk	249 ± 2	93.7	74.7	3.3	70.0	89.0	54.6	146.0	5.5	6.0	GPDB-4.6 (9106)
80	Traps, Moyero River	250 ± 2	109.3	81.7	1.4	67.6	104.1	58.5	134.5	2.6	2.7	GPDB-4.6 (8054); Pavlov et al., 2007
81	Lavas, Kotui River	250 ± 6	111.0	74.7	8.2	73.0	102.4	52.7	148.4	13.6	14.9	Veselovskii et al., 2003; Veselovskii, 2006
82	Intrusives, sediments, metachronic component, Stolbovaya River	250 ± 6	76.7	74.1	6.5	62.1	91.5	55.3	148.7	10.6	11.7	Veselovskii et al., 2003; Veselovskii, 2006
83	Intrusives, sediments, metachronic component, Bol'shaya Nirynda River	250 ± 6	264.6	–76.0	6.9	62.0	95.3	54.4	143.8	11.7	12.7	Veselovskii et al., 2003; Veselovskii, 2006
84	Lavas and intrusives, Norilsk	250 ± 6	80.2	70.0	5.1	69.3	87.9	52.4	159.5	7.6	8.8	Pavlov et al., 2001
85	Metachronic component of Paleozoic rocks, East Taimyr	250 ± 6	138.6	75.0	4.9	75.2	100.0	49.6	128.8	8.2	8.9	Torsvik, Andersen, 2002
90	Basalts, Taimyr	250 ± 16	89.0	71.0	8.0	68.5	91.0	50.0	152.0	12.1	13.9	GPDB-4.6 (4588)
92	Basalts, Kuznetsk Basin	251 ± 1	227.1	–64.3	2.8	54.5	86.9	60.0	172.7	3.6	4.5	Kazanskii et al., 2005
94	Sediments, metachronic component, Kulyumbe River	251 ± 1	112.1	76.0	3.7	68.0	89.0	50.1	129.1	6.3	6.8	Pavlov et al., 2007
	Average ($N = 29$)	248	111.5	78.3	2.0	65.0	110.0	51.1	144.5	3.6	3.6	This work

SN is the individual number of the determinations (identical in the Supplement 1, Fig. 2 and Fig. 4); Dec and Inc are declination and inclination, respectively; a_{95} is the radius of 2 confidence oval around the paleomagnetic direction; Slat and Slong are the latitude and longitude of the sampling site of the collection; Plat and Plong are the latitude and longitude 2 of the paleomagnetic pole; dp and dm are the semiaxes of the confidence oval ariuynd the paleomagnetic pole. In the *Sources* column GPDB-4.6 denotes the Global Paleomagnetic Database version 4.6 (Pisarevsky, 2005). The number in brackets is the original number of the determination (RESULTNO) in the database.

accuracy of the resulting APWP" (Metelkin and Kazanskii, 2014, p. 65).

The threshold of 20 Ma has not been selected by the author's subjective wishes. Quite the contrary, it is the objective state of things both concerning the dating of the geological objects themselves and the datings of their characteristic magnetization. In the classification of the reliability of the paleomagnetic poles of Van der Voo (1990), the age criterion is ranked first among the seven criteria overall. In his opinion, the uncertainty in dating the Phanerozoic rocks should lie within the Late Jurassic to Early Silurian or be established within 4% of the absolute age of the rock. Firstly, 4% of 540 Ma (the lower boundary of the Phanerozoic Eon) is 21.6 Ma; secondly, the durations of 75% of the Phanerozoic epochs (there are 36 of them overall) are shorter than 20 Ma (Gradstein et al., 2008).

The third criterion is the quality of the paleomagnetic procedures applied when determining each particular result. This criterion is based on the DemagCode parameter from the Global Paleomagnetic Database GPDB-4.6 (Pisarevsky, 2005) since most of the paleomagnetic determinations used in this work are the GPDB-4.6 data (Supplement 1) and their analysis has been partly carried out by the founders of GPDB—Khramov (*Paleomagnitnye* ..., 1971; 1973; 1975; 1979; 1982; 1986; 1989] and McElhinny (McElhinny and Lock, 1990]—and by S.A. Pisarevsky (2005). The determinations obtained with the time cleaning alone (DemagCode = 0) and without stepwise demagnetization (DemagCode = 1) are excluded from the analysis. All the new paleomagnetic results (18 overall), which are not included in GPDB-4.6, are assigned DemagCode > 1.

The fourth criterion, the radius of the confidence circle around the mean direction, is, in fact, the integrated value of the main statistical parameters of the analyzed paleomagnetic collection, which is associated with both the number of independently oriented samples/points and the degree of clustering of their characteristic components about the mean. In our analysis, we used the radius of the circular confidence interval recalculated for each original determination:

$$A_{95} = 2\Delta \mathrm{Inc}(1/(1 + 3\cos^2 \mathrm{Inc})),$$
$$\text{where } \Delta \mathrm{Inc} = a_{95} \text{ [Butler, 1992].}$$

If $A_{95} < 15°$, this pole was used in the further analysis as it was assumed in (Didenko and Pechersky, 1993; Pecherskii and Didenko, 1995).

The analysis of the distributions of the sampling sites of the paleomagnetic collections for their structural control by and tectonic coherence to the Siberian Platform, as well as the analysis of the distributions of the paleomagnetic poles themselves on the stereograms and their sorting out, were conducted by a special project in the ArcGis-10.2 environment (http://www.esri.com/), for which various subject layers were used. The interpolation calculations of the different versions of the Mesozoic APWP segment for Siberia were carried out by the moving average methods with a 20-Ma window and 10-Ma interval and by cubic spline interpolation with the smoothing factor λ = 20, implemented in the GMAP-3 program of T. Torsvik (Torsvik, Smethurst, 1999). The selection of the parameters for interpolation by the moving average is likely to not need any special explanation. The smoothing factor in the spline interpolation is specified at 20 due to (1) the limited number of reliable original paleomagnetic poles from which the interpolated trajectories were calculated: in the first case there were 11 such poles and in the second case, 9 poles (Table 2); and (2) the mode of action of the smoothing parameter λ: at λ = 0, the interpolation is reduced to calculating a simple spline; at λ → ∞, the approximation develops into the linear calculation by the least square method. The calculations of the interpolated trajectories in the GMAP2004 program (Torsvik, Smethurst, 1999) with λ = 10–10000 show that at λ = 20 the trend directions and shapes of these trajectories remain close to the original curves.

THE MESOZOIC AND CENOZOIC PALEOMAGNETIC POLES

The initial set of the paleomagnetic poles for the last 251 Ma[2] for the Siberian Platform itself and the encircling folded belts included 94 original determinations (Supplement 1). In the cases when in DPDB-4.6 the mean poles (*combine result*) were calculated from the closely located individual data, only these combine results were used in the analysis.

The particular sampling sites of these determinations are shown in Fig. 1. The positions of the corresponding paleomagnetic poles are depicted in Fig. 2, where pole 1 with an age of 0.5 Ma is the youngest and pole 94 with an age of 251 Ma is the most ancient. The areal distribution of the original determinations is quite satisfactory (the determinations rather uniformly cover the whole platform). In contrast, the time distribution is extremely heterogeneous. The age of half of the poles (47 of 94) is confined to a very narrow interval (the Early Triassic to the first half of the Middle Triassic, 240–251 Ma), whereas the ages of the other 47 poles are scattered in the interval from 0 to 240 Ma (Supplement 1, Fig. 3a).

As seen in Fig. 2a, any regular trend (a shift) is barely identified by visual examination in the initial set of the paleomagnetic poles. Neither is it detected by the mathematical methods based on the moving average and cubic spline approximation. This indicates that, firstly, the initial set of poles is very noisy and, secondly, a revision of these data is required in order to identify the most reliable poles.

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[2] In this work, the geological time scale (Gradstein et al., 2004) similar to that used in GPDB-4.6 (Pisarevsky, 2005) is used.

Table 2. The versions of the Meso-Cenozoic segment of the Siberian APWP

Version 1								Version 2							
moving average (1a)					cubic spline (1b)			moving average (2a)					cubic spline (2b)		
age, Ma	N	Plat, °	Plon, °	A_{95}, °	age, Ma	Plat, °	Plon, °	age, Ma	N	Plat, °	Plon, °	A_{95}, °	age, Ma	Plat, °	Plon, °
78	1	82.8	188.5	6.2	78	82.7	190.5	78	1	82.8	188.5	6.2	78	82.8	189.4
					91	77.5	210.4						91	78.6	197.5
					104	72.8	213.6						104	74.7	198.4
					117	70.3	207.2						117	71.7	193.9
128	2	70.1	181.3	13.4	130	69.5	188.1	128	2	70.1	181.3	13.4	130	69.6	183.4
138	4	68.3	173.0	6.9	138	67.5	168.6	138	4	68.3	173.0	6.9	138	67.7	174.5
					145	63.9	144.5						145	67.8	164.3
148	4	65.6	148.5	14.3	148	62.9	138.3	148	3	68.0	161.5	9.8			
					153	63.3	135.8						153	70.1	149.9
158	3	61.9	135.0	16.5	157	63.0	136.9	158	1	71.1	150.0	6.5			
					165	59.8	138.5						166	69.1	124.6
168	1	59.3	139.2	4.5	181	53.5	131.8						178	63.1	109.2
					197	48.6	121.4						191	55.9	103.9
													203	50.1	104.9
					212	45.8	116.0						216	47.0	110.8
228	1	47.1	121.6	5.0	228	47.4	123.3	228	1	47.1	121.6	5.0	228	47.5	122.9
					231	48.1	127.4						231	48.1	127.5
238	20	49.3	142.7	4.8	238	49.5	136.3	238	20	49.3	142.7	4.8	238	49.3	136.7
248	29	51.1	144.5	3.6	248	51.0	145.7	248	29	51.1	144.5	3.6	248	50.9	145.8

N is the number of the original paleomagnetic poles used in the calculations; Plat and Plong are the latitude and longitude of the paleomagnetic pole; A_{95} is the radius of confidence oval around the pole with 95% probability. Version 1a (Fig. 5a): based on all the 38 original paleomagnetic poles which passed the revision (Table 1). Version 1b (Fig. 5c): based on 9 original paleomagnetic poles with the ages 78, 130, 135, 139, 145, 149, 153, 165, 228 Ma (Table 1) and the average poles with the ages 248 and 238 Ma (this table). Version 2a (Fig. 5e): based on 36 original paleomagnetic poles; the poles with the ages of 149 Ma (GPDB-4.6 (4356)) and 165 Ma (Metelkin et al., 2008; Metelkin, 2010) are excluded from the analysis (Table 1). Version 2b (Fig. 5f): based on 7 original paleomagnetic poles with the ages of 78, 130, 135, 139, 145, 153, and 228 Ma (Table 1) and the average poles with the ages of 248 and 238 Ma (this table). The APWP are calculated using the GMAP program designed by T. Torsvik (Torsvik and Smethurst, 1999).

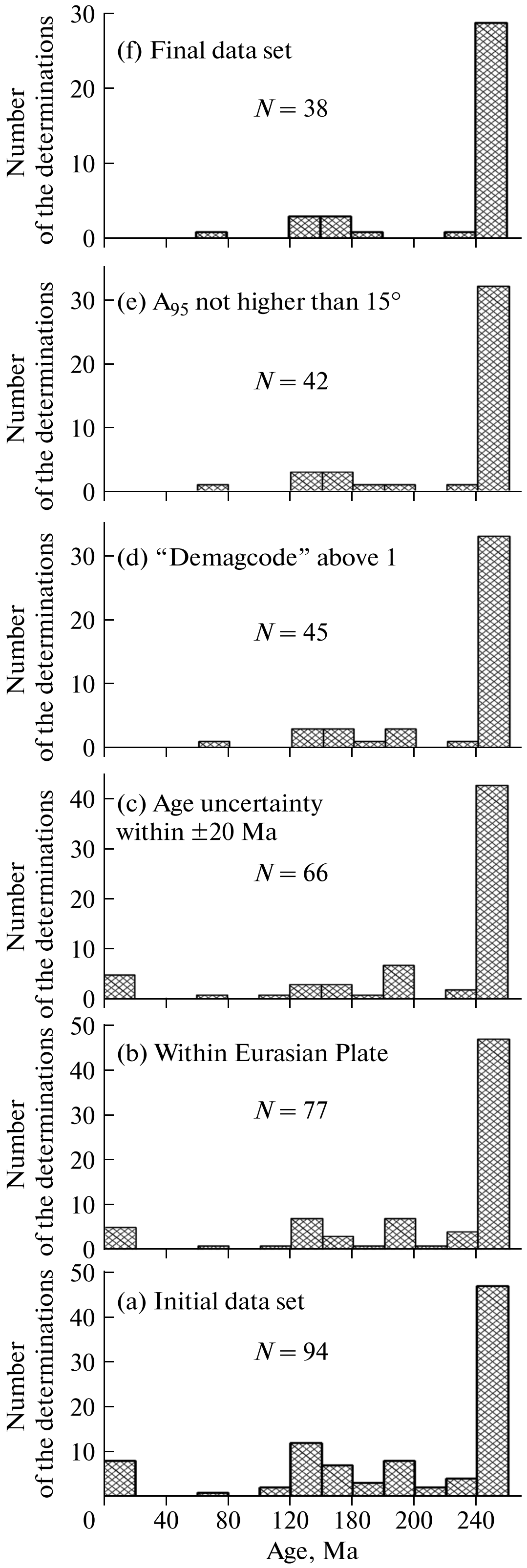


Fig. 3. The distribution of the studied Meso–Cenozoic 2 paleomagnetic poles of the Siberian Platform and the closest folded areas along the time scale: (a)–(f), the stages of the analysis, see the text.

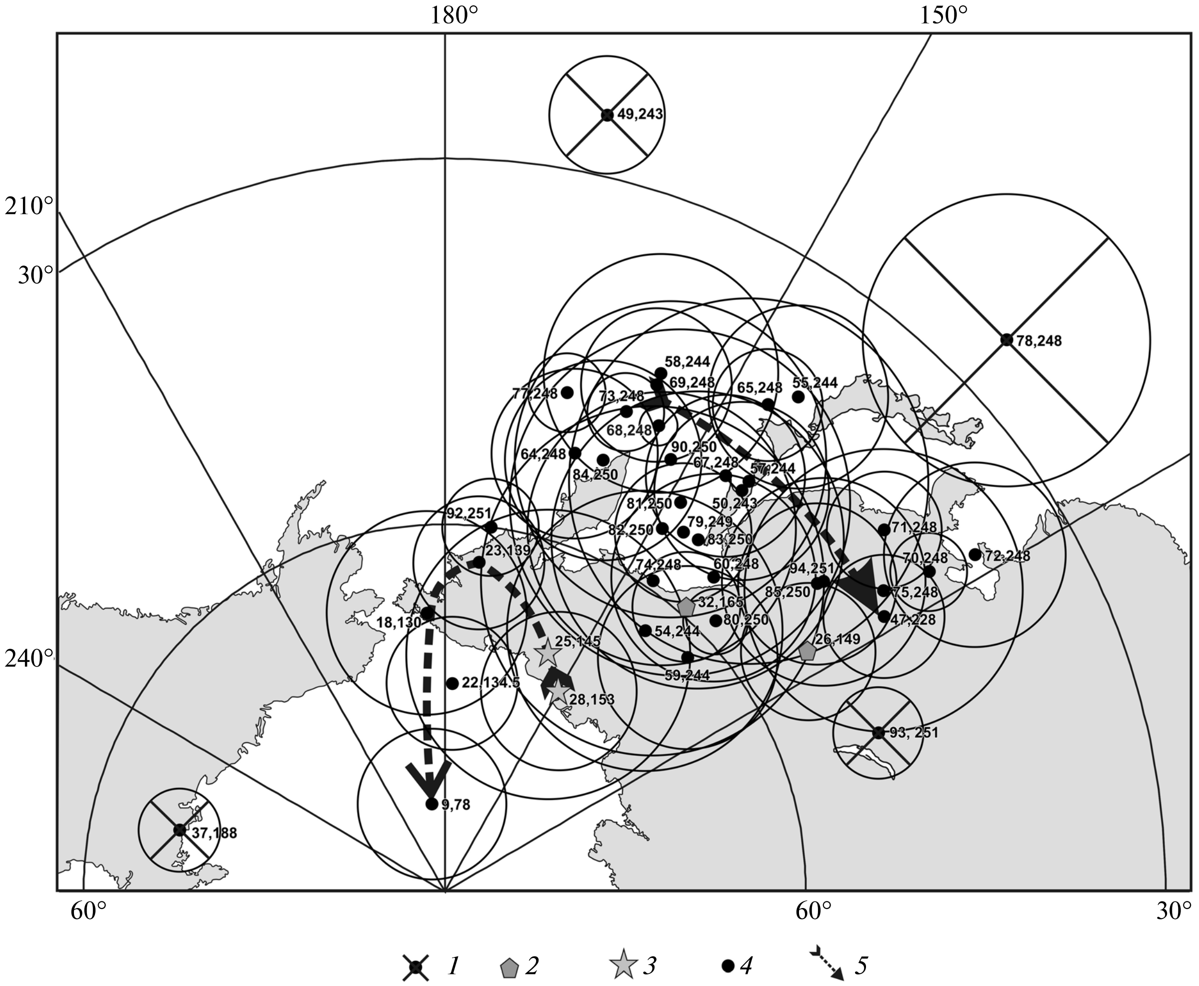
The first step taken was to distinguish the data obtained from the folded framing of the Siberian Platform. In order to do this, in Fig. 1, in addition to the boundary of the platform itself, we have also drawn the boundaries according to (Argus et al., 2011; DeMets et al., 2010) separating the Eurasian Plate (which includes a large part of the Siberian Platform) from the North American and Amur plates. It can be seen that many Meso-Cenozoic objects fall beyond the Eurasian Plate, although the paleomagnetic poles for 2 some of them are used for demonstrating the significant difference in their positions from the poles of the same age of stable Europe and for calculating the Mesozoic position of stable Siberia, and, in contrast, for demonstrating that these poles support the hypothesis of a single and tectonically rigid North Eurasia.

Our analysis of the Mesozoic paleomagnetic data 2 obtained from the rocks of the folded framing of the Siberian Platform beyond the Eurasian Plate has shown that there are significant distinctions in the paleomagnetic directions (and, correspondingly, in 2 the positions of the paleopoles) for the nearly coeval Barremian–Aptian rocks of the same zone—Transbaikalia (Supplement 1). Therefore, in our opinion, the data for the folded framing of the Siberian Platform cannot be used for territories beyond the Eurasian plate.

This strict constraint on the use of these data is supported by the following two facts. Firstly, "... the banana-like distribution of the Early Cretaceous paleomagnetic 2 determinations obtained from Transbaikalia ... suggests, with quite a high probability, that local rotations of the tectonic blocks are very common in this region" (Pavlov, 2012, pp. 70–71). Secondly (which confirms the first point), the instantaneous rate of rotation of the Amur Plate relative to the Eurasian Plate ranges, according to different estimates, from 0.4 to 0.03 deg/Ma (Timofeev et al., 2011) and 0.106 deg/Ma (DeMets et al., 2010).

As seen in Fig. 1, 14 determinations are derived from the objects located within the Amur Plate. Hence, during a few Ma, the rotation of the paleomagnetic 2 direction frozen in the rocks of the Amurian Plate sequences relative to the Siberian (Eurasian) direction could reach more than 10° assuming a rotation rate of 0.1 deg/Ma.

We excluded from the analysis two determinations for the Upper Jurassic sediments and the results for the Lower Cretaceous volcanic-sedimentary rocks of the Tas-Khayatakh Ridge (nos. 16, 21, 31, Fig. 1, Supplement 1), which are located in the immediate proximity of the boundary between the Eurasian and North American plates. We cannot rule out the Mesozoic displacements, mainly rotations, of the Tas-Khayatakh allochtonous block relative to the stable Siberia during the collision of the Kolyma–Omolon block against the paleocontinent. Moreover, there is direct evidence that these displacements occurred up to the end of the Late Cretaceous (Neocomian) (Tret'yakov, 2003).



2 **Fig. 4.** The positions on the sphere for the Meso–Cenozoic paleomagnetic poles of the Siberian Platform and the closest folded areas which passed the revision procedure: (1) the poles with the anomalous positions excluded from the analysis; (2) the Jurassic poles of the Tithonian sediments (26, 149) of the Khatanga Depression (4356 according to GPDB-4.6) and the Middle Jurassic Chekurovskaya and Kystatym formations (32, 165) of the Pre-Verkhoyansk Depression (Metelkin et al., 2008; Metelkin, 2010); (3) the Jurassic poles (25, 145; 28, 153) of intrusive complexes of the Aldan Shield (Pavlov and Maksimov, 2006; Pavlov and Karetnikov, 2008); (4) the poles which do not need additional comments; (5) the displacement trend of coordinates of the poles as a function of their ages. The numerical values near the poles in the figure correspond to the pole number in Supplement 1 and Table 1 and the age of the pole. The circle around the pole is the confidence oval with a probability of 95%. Polar azimuthal equidistant projection.

Seventeen original determinations from the objects within the Amur and North American plates (Fig. 1) have not passed the structural control and tectonic coherence criterion. As a result, the distribution of the poles on the time scale has been transformed towards an increased fraction of the Early–Middle Triassic poles (47 out of 77, Fig. 3b).

2 In order to be selected as most reliable, the paleomagnetic determinations were also required to satisfy the following three, rather formal conditions:

(1) the dating uncertainty is less than 20 Ma. This criterion was not met by 11 of the remaining 77 poles. This screening has transformed the time distribution of the poles towards an even greater increase of the fraction of the Early–Middle Triassic poles (43 of 66) (Fig. 3c);

(2) the DemagCode parameter is above 1. Among the remaining 66 poles, 21 did not fulfill this criterion. On the completion of this step of data revision, none of the Cenozoic poles occurred in the set of the reliable poles, and the time distribution of the remaining ones again shifted towards an increased fraction of the Early–Middle Triassic results (33 of 45) (Fig. 3d);

(3) $A_{95} < 15°$. This condition is not satisfied by three of the remaining 45 Mesozoic poles. The share of the Early–Middle Triassic poles again increased to 32 of 42 determinations (Fig. 3e).

The layout of the 42 poles which passed the revision tests is shown in Fig. 4. Here, the poles are ordered quite regularly, in accordance with their ages (Table 1). Almost all the Triassic poles lie in the latitudinal interval 40°–60° N from 165° E to 120° E longitude. The

1 Late Jurassic and Cretaceous poles fall in the meridional zone 190°–150° E from 60° N (the most ancient) to 85° N (the youngest poles).

Against this regular distribution, four poles (three Triassic and one Early Jurassic) have anomalous positions: (1) two Triassic poles, nos. 49 and 78 (4626 and 4560 in the nomenclature of GPDB-4.6), are located at 25° N (Fig. 4) at a distance of more than $2A_{95}$ from the mean pole (the average over all the poles of the Triassic group) (Table 1); (2) one Triassic pole, no. 93 (8280 according to GPDB-4.6) is located far west of the main group and also at a distance of $>2A_{95}$ from the mean (Fig. 4, Table 1); (3) the position of the Early Jurassic pole no. 37 (7321 according to GPDB-4.6) determined from the metamorphic Kuzbass rocks is also anomalous relative to all the other poles.

Based on this, we may quite objectively exclude these four poles from the further analysis. The elimination of these four poles, which satisfied the formal revision by the four criteria but have anomalous positions relative to the other poles, barely changed the time distribution of the poles towards an increased fraction of the Early–Middle Triassic poles (29 of 38) (Fig. 3f).

THE MESO-CENOZOIC SEGMENT OF APWP FOR THE SIBERIAN PLATFORM

2 The final set of the paleomagnetic poles (Table 1) has an extremely nonuniform distribution on the time scale (Fig. 3f). Three 20-Ma intervals (60–80, 160–180, and 220–240 Ma) are only characterized by one pole per interval; two 20-Ma intervals (120–140 and 140–160 Ma) have three poles for each; and one 20-Ma interval (240–260 Ma) accommodates 29 poles. In the intervals 0–60, 80–120, and 180–220 Ma, according to the selection, there are no paleomagnetically reliable poles. Nevertheless, we still try to use this final set of 38 poles for constructing the Mesozoic segment of the APWP curve of Siberia and compare it with the coeval APWP segments for Siberia (Fig. 5a) from (Metelkin, 2010; Metelkin et al., 2010) and the global APWP curve (Fig. 5b) in the coordinates of stable Europe (Torsvik et al., 2008).

Using the moving average and cubic spline method, we calculated the first version of the Mesozoic segment of the Siberian APWP (Table 2, Figs. 5c and 5d). Its comparison with the two other trajectories shows that (1) the Cretaceous (70–140 Ma) segments of all the three trajectories almost coincide within A_{95} (Figs. 5a, 5b, 5c, and 5e); (2) in terms of the developed trend and, partly, the positions of the reference poles, the Middle–Late Jurassic (145–170 Ma) segment of the new trajectory is similar to that from (Metelkin, 2010; Metelkin et al., 2012) (Figs. 5a, 5c, and 5e) and clearly distinct from the Jurassic trajectory of (Torsvik et al., 2008) (Figs. 5b, 5c, and 5e); (3) the Early Triassic (230–250 Ma) segment of the new trajectory is, in terms of the developed trend and positions of the reference poles within A_{95}, close although not identical to its counterpart in the trajectory from (Torsvik et al., 2008) (Figs. 5b, 5c, and 5e). In the trajectory from (Metelkin, 2010; Metelkin et al., 2012), the Triassic segment is absent.

The final set includes four Jurassic determinations (Table 1). Two of them are derived from the intrusive complexes of the Aldan Shield (Pavlov and Maksimov, 2006; Pavlov and Karetnikov, 2008). These are pole nos. 25 and 28 dated to 153 Ma and spaced more than 350 km apart from each other (Fig. 1). The paleomagnetic 2 directions of these intrusive complexes not only fairly well agree with each other (Table 1) but also with the recalculated directions from the 150-Ma pole of the global APWP in the coordinates of stable Europe (Torsvik et al., 2008). We note that the global APWP was calculated without the Siberian data although, in the opinion of the authors of the cited work, the allowance for the Late Paleozoic–Early Mesozoic trap poles would not have critically changed the obtained trajectory (Torsvik et al., 2008, p. 6).

Another two Jurassic determinations are based on the sedimentary complexes located at a distance of more than 1000 km from each other (Fig. 1). The first determination (no. 26) was obtained by G.A. Pospelova from the Tithonian sediments (149 ± 3 Ma) of the Khatanga depression, and the second result (no. 32) was derived from the sediments of the Chekurovskaya and Kystatym Middle Jurassic formations (165 ± 5 Ma) of the Pre-Verkhoyansk Depression (Metelkin et al., 2008; Metelkin, 2010). Their paleomagnetic 2 directions also agree with each other but significantly differ, in terms of declination (by more than 100°), from the other two Jurassic results (Table 1).

A reasonable explanation for the significant difference in the positions of these two pairs of Jurassic poles (Fig. 4) is absent. According to our analysis, they all pertain to the group of paleomagnetically reliable results. However, considering the fact that the paleo- 2 magnetic directions of the of the intrusive complexes of the Aldan Shield coincide with the recalculated directions from the 150 Ma pole of the global APWP (Torsvik et al., 2008), we excluded pole nos. 26 and 32 from the final set of the data for calculating the second version of the Mesozoic segment of the Siberian APWP (Table 2, Figs. 5d and 5f).

Based on the set of 36 paleomagnetic poles, we cal- 2 culated the second version of the Mesozoic segment of the Siberian APWP by the moving average and cubic spline methods (Table 2, Figs. 5d and 5f) and compared it with the Mesozoic segment of the global APWP in the coordinates of stable Europe (Torsvik et al., 2008). For doing this, for the point at the center of the Siberian Platform (65° N, 110° E), we calculated the magnetic declinations and inclinations from the Siberian and European poles (Fig. 6). It turned out

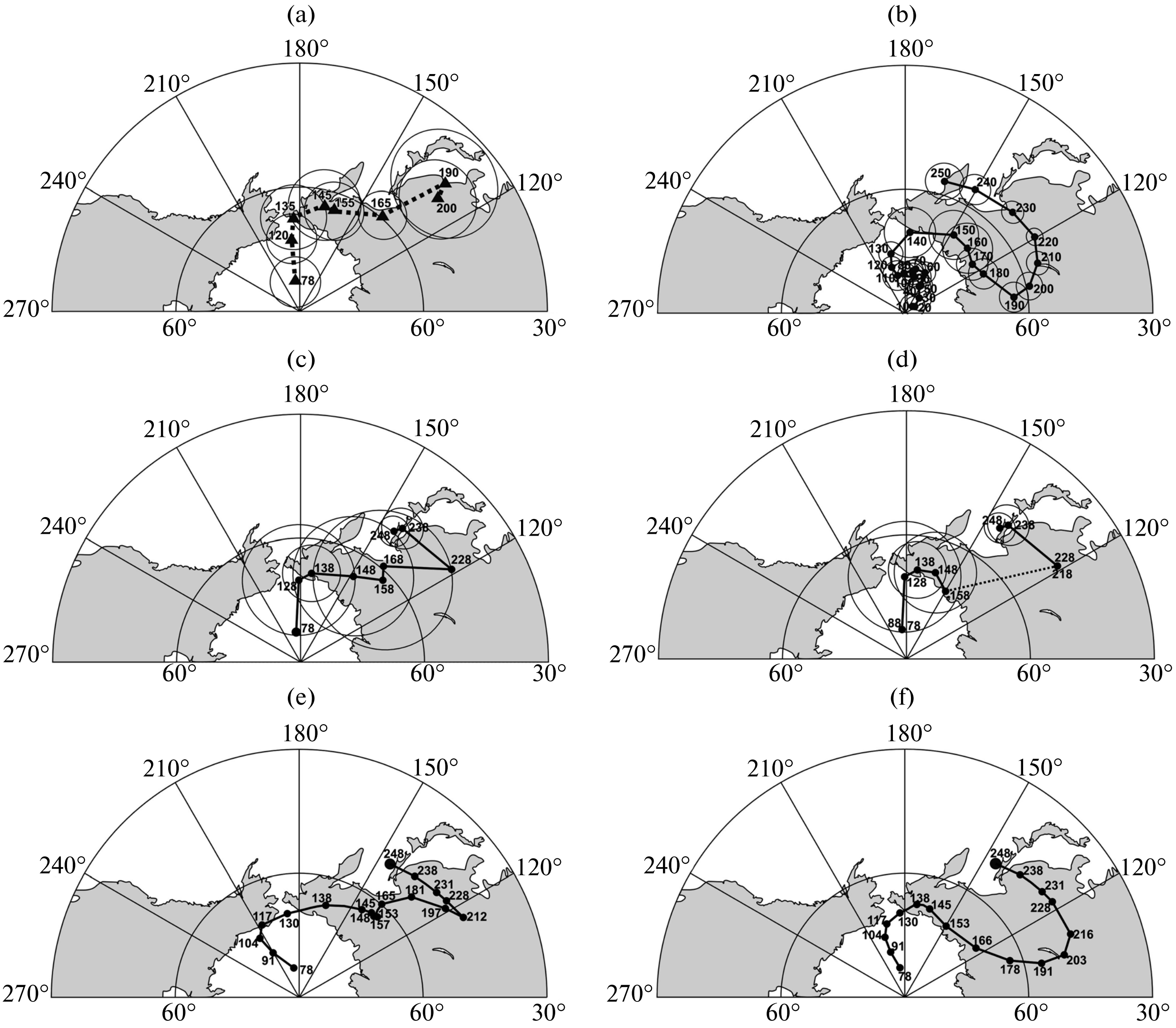
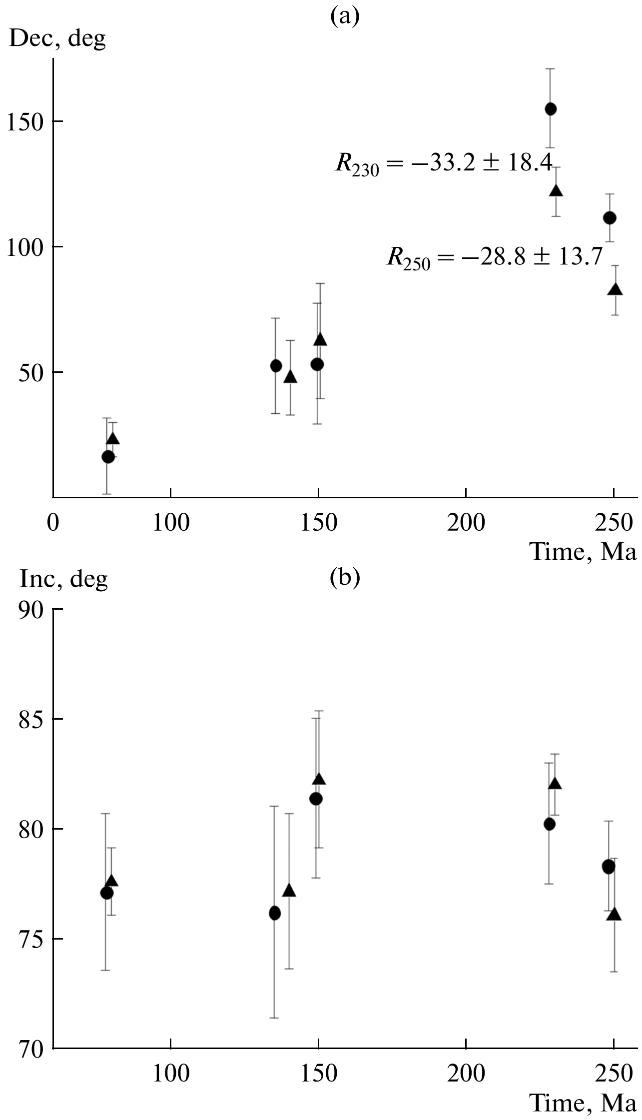


Fig. 5. The versions of the Mesozoic segment of APWP for Siberia obtained in this work and their comparison with the APWP for Siberia from (Metelkin, 2010; Metelkin et al., 2012) and global APWP in the coordinates of stable Europe (Torsvik et al., 2008): (a) APWP for Siberia according to (Metelkin, 2010; Metelkin et al., 2012); (b) the global APWP in the coordinates of stable Europe (Torsvik et al., 2008); (c) the first version of the Mesozoic segment of APWP for Siberia calculated by the method of moving average (Table 2, version 1a); (d) the first version of the Mesozoic segment of APWP for Siberia calculated by the cubic spline method (Table 2, version 1b); (e) the second version of the Mesozoic segment of APWP for Siberia calculated by the method of moving average (Table 2, version 2a); (f) the second version of the Mesozoic segment of APWP for Siberia calculated by the cubic spline method (Table 2, version 2b). Polar azimuthal equidistant projection.

that for the declinations from 248 and 228 Ma, there is a noticeable difference in their directions $R_{250} = -28.8 \pm 13.7°$ and $R_{230} = -33.2 \pm 18.4°$ (Fig. 6a); a significant difference in the inclinations calculated for these time intervals are not observed (Fig. 6b). For the three other time intervals (149, 135, and 78 Ma), the calculated declinations and inclinations from the Siberian and European poles coincide within the confidence intervals (Fig. 6).

2 Hence, the existing reliable paleomagnetic data for Siberia suggest that the Siberian Platform can be treated as fully tectonically coherent with stable Europe since the Late Jurassic (150 Ma). These two continental blocks have probably merged into the single North Eurasia earlier than the indicated time; however, reliable Siberian data to validate this assumption are absent. The position of the Siberian Triassic poles (248 Ma—-the average over 28 poles and 228 Ma according to one pole, Table 1) relative to the poles of the same age of the global APWP in the coordinates of stable Europe indicates the rotation of Siberia relative to Europe by at least 14°–15° (Fig. 6). It is most logical to associate this rotation with the formation of the structures of the extension in West Siberia (Metelkin, 2010), for example with the opening of the Ob Ocean in the 235–218 Ma interval (Aplonov, 1987).



2 **Fig. 6.** The comparison of the calculated paleomagnetic declinations from the Siberian (the circle) and European (the square) poles. The directions are recalculated to the coordinates 65° N and 110° E.

CONCLUSIONS

2 Our analysis of the Meso–Cenozoic paleomagnetic data for the Siberian Platform and its closest folded framing suggests the following conclusions.

2 (1) The reliable paleomagnetic data are extremely nonuniformly distributed along the time scale.
According to the conducted selection, the intervals 0–60, 80–120, and 180–220 Ma lack any paleomagnetically reliable poles. Three intervals (60–80, 160–180, and 220–240 Ma) are only characterized by one reliable pole per interval. For two intervals (120–140 and 140–160 Ma) there are three reliable poles for each
2 interval. The largest number of reliable paleomagnetic
poles (29) fall in the interval of 243–251 Ma.

(2) A remarkable feature of the obtained results is the significant difference in the positions of two pairs of Jurassic poles. Two poles are derived from intrusive rocks of the Aldan Shield, and the two other poles, from the sediments of the Khatanga and Verkhoyansk depressions. This again highlights the necessity of
obtaining reliable paleomagnetic directions for the 2
Upper Triassic and Jurassic rocks of Siberia.

(3) The analysis of the most reliable paleomagnetic 2
data for the Mesozoic of the Siberian Platform, the version of the Mesozoic APWP curve based on these data, and its comparison with the global APWP in the coordinates of stable Europe (Torsvik et al., 2008) refute the hypothesis of the tectonic incoherence of Siberia to stable Europe during the entire Mesozoic.
The existing reliable paleomagnetic data for Siberia 2
allow the Siberian Platform to be treated as fully tectonically coherent to stable Europe since the Late Jurassic (150 Ma). The positions of the Triassic poles of Siberia relative to the coeval poles of the global APWP in the coordinates of stable Europe indicate the rotation of Siberia relative to the stable Europe by at least 14–15° which probably occurred in the Late Triassic.

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SPELL: 1. meridional, 2. paleomagnetic