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Siberian Paleomagnetic Data and the Problem of Rigidity of the Northern Eurasian Continent in the Post-Paleozoic

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Abstract—The Meso-Cenozoic paleomagnetic poles from the Siberian platform and its folded margins, which comply with the modern technical and methodological standards, are analyzed. The analysis suggests the following conclusions. (1) The geometrical relationship between the Permo-Triassic poles of the Stable Europe and Siberian Platform prohibits the possibility of relative displacements of these platforms in the post-Paleozoic time. (2) The Mesozoic paleomagnetic poles of the Siberian Platform support the hypothesis of rigid Northern Eurasia. (3) The paleolatitudes of the Mesozoic sections located on the folded margins of the Siberian Platform closely agree with the Apparent Polar Wandering Path (APWP) for Europe. (4) The available data indicate that the vertical-axis rotation of separate local blocks within the folded margins of the Siberian Platform was a widespread phenomenon. Therefore, (1) the modern paleomagnetic data quite certainly show that consolidation of the Northern Eurasian continent was completed by the end of Permian, and, since the very beginning of the Mesozoic, the Siberian and East-European platforms have been parts of a single rigid megablock. (2) The Meso-Cenozoic segment of the APWP for Europe can be used as reference for the Siberian platform.

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INTRODUCTION

It is believed that consolidation of Northern Eurasia was largely completed by the end of the Paleozoic. However, some authors point out that the large tectonic blocks composing the Northern Eurasia may have experienced substantial relative displacements in the Mesozoic (*Paleomagnitnye*..., 1982; Bazhenov and Mossakovsky, 1986) and Cenozoic (Cogne et al., 1999). In particular, Cogne et al. (1999) consider the Northern Eurasia as a set of three subplates that moved relative to each other in the post-Eocene along the zones of diffusive dislocations, which probably extended along the Ural folded zone and the Tornquist-Teisseyre Line.

Some recent works (Kazanskii et al., 2005; Metelkin et al., 2007; 2008; Zemtsov, 2009) develop the idea of the so-called Siberian domain, which existed as a part of the structure of the Northern Eurasia in the Mesozoic and included the Siberian platform itself and a part of the adjacent folded areas. It is assumed that this domain existed (at least up to the second half of the Cretaceous) as a separate rigid tectonic unit, which experienced appreciable (by 20 degrees and probably even larger) rotations relative to the other continental blocks that composed Northern Eurasia.

Hereinafter, we will call the tectonic unit (the tectonic plate) rigid if this unit is nondeformable (on the considered spatial scale) and if its parts did not experience relative displacements with respect to each other during the considered time interval. The term "rigid" in this study is defined in the Encyclopedia Britannica (http://www.britannica.com) in the following way: "A body is formally regarded as rigid if the distance between any set of two points in it is always constant." Here, it is implied that, if we are dealing with a "rigid tectonic unit," this means that the motion of each point in it can be described as rotation by the same angle around the Eulerian pole, which is common for the whole considered tectonic unit.

With allowance for the position of the implied Eulerian pole (Metelkin, Gordienko, and Klimuk, 2007; Metelkin et al., 2008) and the size of the Siberian Platform, this rotation should be translated into rather large (500 km and more) linear displacements along the periphery of the domain. Obviously, these large-scale displacements would have had far-reaching implications for the geodynamical evolution of Northern Eurasia. In particular, Bazhenov and Mossakovski (1986) and Kazanskii et al. (2005) suggest that the graben structures of the West Siberian rift system (which played a significant role in the formation of the West Siberian oil field) were formed as a result of these displacements.

Thus, the question concerning the consolidation time of Northern Eurasia remains debatable. Its elucidation requires analyzing the entire set of the available paleomagnetic data for the Mesozoic (and, desirably, Cenozoic) formations of the Siberian platform and its folded margins. The results of this analysis are presented below.

THE METHOD

It is known (*Paleomagnitnye*..., 1982) that, if the tectonic blocks were moving together with each other (were parts of a single rigid plate) during some time, then, their Apparent Polar Wander Paths (APWPs) for this interval coincide. Conversely, if the APW paths of the blocks coincide on a certain time interval, this strongly suggests that these blocks were moving together (were parts of a single rigid plate) during this time interval. Therefore, the coincidence of the Meso-Cenozoic segments of the Siberian and European APWPs would prove that the Siberian Platform and Stable Europe (the East European Platform and pre-Alpine Europe) were indeed parts of a single rigid plate during the post-Permian time.

Thus, a straightforward and natural way to solve the question concerning the time of consolidation of Northern Eurasia is to compare the post-Paleozoic APWPs for Siberia and Stable Europe.

At present, the Meso-Cenozoic part of the European APWP curve is rather well elaborated, particularly for the time interval from 200 to 0 Ma (Besse and Courtillot, 2002). However, consideration of the Siberian data reveals a fact that is initially surprising: the Mesozoic segment of the Siberian path is studied and substantiated much worse than its Early Paleozoic segment. Moreover, no paleomagnetic pole for the Mesozoic of the Siberian Platform itself, which would have satisfied the contemporary criteria of paleomagnetic reliability (Van der Voo, 1993), has been published until recently. Several Mesozoic paleomagnetic results complying, to some extent, with the modern requirements for the quality of the paleomagnetic data were presented lately (Pavlov et al., 2004; Pavlov and Maksimov, 2006; Pavlov and Karetnikov, 2008). Nevertheless, the number of the modern paleomagnetic poles for the Siberian platform is extremely insufficient for constructing the Mesozoic segment of the Siberian APWP.

The problem is aggravated by the fact that dating of many Mesozoic objects, which are promising for paleomagnetic investigations, are often based on indirect data alone or on obsolete isotopic determinations.

Thus, we face the following alternative: either we have to wait until sufficient data are gained for constructing the detailed Siberian APW path (which may take dozens of years), or we may try to test the hypothesis of coincidence of the Meso-Cenozoic segments for the Siberian and European curves using the data that are available right now.

Until the trend of the Meso-Cenozoic poles for Siberia itself is reconstructed, we can apply a palliative approach that implies finding the pro and contra arguments for the coincidence of the corresponding segments of the European and Siberian paths. The idea behind this approach is the following. The Siberian Meso-Cenozoic poles are compared with the European APW path and, if no disagreement is found, this is considered as an argument supporting the coincidence of the European and Siberian curves; i.e., it is evidence of the rigidity of Northern Eurasia. On the contrary, inconsistency of the Siberian paleomagnetic data and the European APW path is interpreted as indication of the probable relative movements of Siberia and Europe.

This approach has several advantages:

(1) there is no need to wait for dozens of years in order to substantiate the important conclusion with rather high reliability;

(2) it is possible to use poorly dated paleomagnetic results;

(3) it is possible to use the paleomagnetic results for the folded margins of the Siberian Platform (normally, we cannot directly use such results for constructing the APWP; however, we can check the paleomagnetic correspondence of these determinations to the tested (European) curve).

However, this method is indirect; therefore, strictly speaking, it provides the arguments instead of the proofs. On the other hand, it seems obvious that, if the number of arguments in favor of the coincidence of the Siberian and European curves is sufficiently large, the probability of the opposite conclusion vanishes.

THE PALEOMAGNETIC POLES OF THE SIBERIAN PLATFORM

The Permo-Triassic Paleomagnetic Pole

The Permo-Triassic paleomagnetic poles for the Siberian Platform and the Stable Europe were thoroughly considered by Veselovskiy and Pavlov (2006) and Pavlov et al. (2007). They showed that, although the corresponding average poles are located very close to each other, they still significantly differ from each other. Here, it is extremely important that the Siberian pole is shifted relative to the European curve towards Europe, and this shift is observed practically along the great-circle arch (the paleomeridian that links the conventional center of Europe with the pole corresponding to it) (see Fig. 1a).

Since the considered poles are calculated using different procedures of data averaging and different data samples, the observed relative position of the poles (the “far-side” effect) cannot be interpreted as random and needs to be reasonably explained.

The observed discrepancies in the positions of the European and Siberian poles can stem from the following sources:

—the post-Late Paleozoic relative displacements of the Siberian Platform and Europe;

—different ages of the European and Siberian poles;

—significant contribution of the nondipole components to the geomagnetic field at the Paleozoic/Mesozoic boundary;

—shallowing of the magnetic inclinations in the European data;

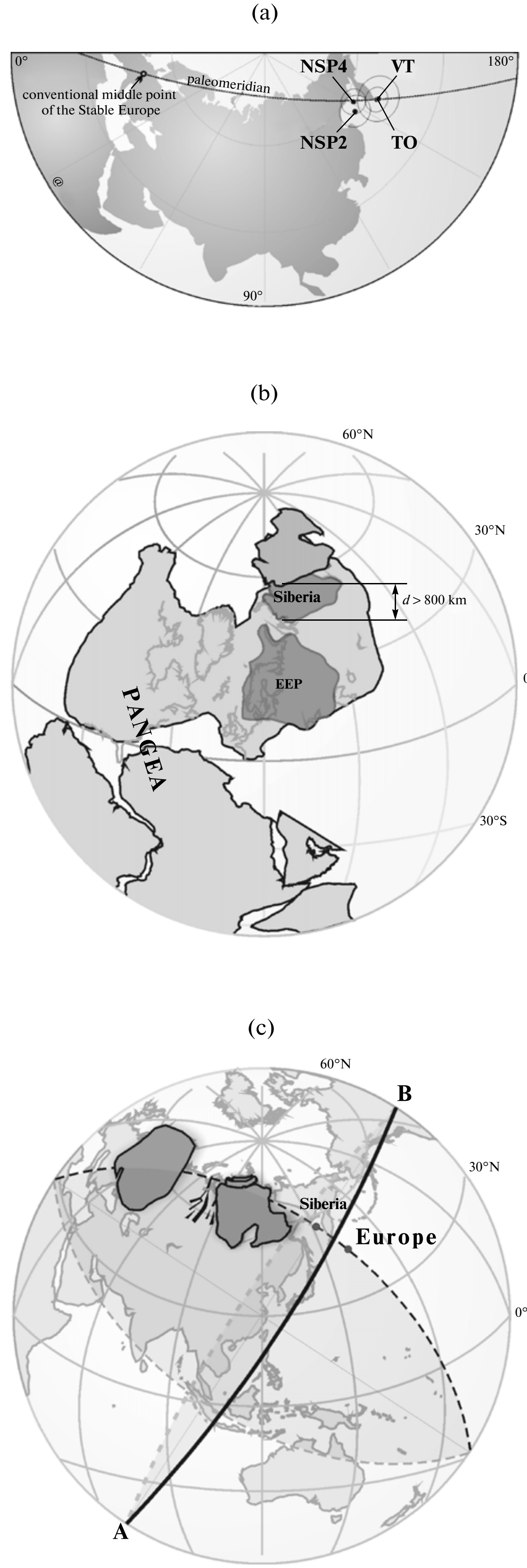

Fig. 1. (a) The geometrical relationship between the Permo-Triassic poles of the Siberian Platform and the Stable Europe. NSP2 and NSP4 are the average paleomagnetic poles of the Siberian Platform determined using various techniques of data averaging (Pavlov et al., 2007). VT and TO are the average paleomagnetic poles of the Stable Europe determined using various techniques of data averaging: VT corresponds to (Van der Voo and Torsvik, 2004) and TO corresponds to (Torsvik et al., 2001). (b) The post-Paleozoic displacement of the Siberian Platform (towards Europe), which is necessary for accounting for the misalignment of the average Siberian and European poles. The dark gray contours of the East European Platform (EEP) and Siberian Platform (SP) show their relative positions within the Pangea, had these platforms avoided mutual displacements in the Mesozoic and Cenozoic. The gray contour shows the position of SP relative to the EEP at the Permian-Triassic boundary if the observed discrepancy between the Permo-Triassic poles is due to the relative displacement of these platforms in the Meso-Cenozoic. (c) [AB] is the great circle on which the Eulerian pole of the Siberian Platform should have lain, had this platform rotated relative to the Stable Europe. [AB] is drawn through the middle of the arc, which connects the average poles of Europe and Siberia, perpendicular to this arc. The thick black lines show the relative position of the grabens in the West Siberia. The circle labeled “Europe” is the average European pole for the time of 250 Ma; it is calculated as an average over the data presented in (Pechersky and Didenko, 1995) and (Molostovskii and Khramov, 1997). The circle labeled “Siberia” is the average trap pole according to (Veselovsky, Gallet, and Pavlov, 2003). Compare (Fig. 1a) the positions of the European and Siberian paleomagnetic poles determined by different authors. See the text for other explanations.

—instability of the solution due to the small and inadequate sample of the initial data.

It is possible to assume that one of the probable factors accounting for the discrepancy of the Permo-Triassic poles in Siberia and Europe is the relative displacements of these continental blocks in the Mesozoic or Cenozoic.

The question of whether the relative displacements of the Siberian and East-Eurasian platforms are probable was repeatedly investigated in the Russian literature on the subject. On the basis on the paleomagnetic data available at that time, Khramov (*Paleomagnitnye…*, 1982) suggested that the northern edge of the Siberian Platform diverged from the East European platform.

A few years later, using the criteria of paleomagnetic reliability, M.L. Bazhenov and A.A. Mossakovskii (1986) carried out a thorough study of the Siberian and East European paleomagnetic data and revealed significant difference in the positions of the corresponding Early Triassic poles. They interpreted this difference as evidence of the clockwise rotation of the Precambrian Siberian continental block relative to the East European block by 10° (it was assumed that the pole of the rotation is located within the Siberian Platform). The analysis of the distribution of the Early Mesozoic structures of compression and extension along the margins of the Siberian platform (Bazhenov and Mossakovskii, 1986) seemed to have supported this conclusion. In particular, Bazhenov and Mossakovskii noted that the formation of a system of the Triassic grabens in West Siberia could be accounted for in the context of their hypothesis.

The history of the formation of a system of the West Siberian grabens is a subject of debate, and no unambiguous conclusion has been reached on it to date. The research in this field is briefly reviewed in (Kremenetskii, Alekseeva, and Didenko, 2002, p. 75). According to the interpretation of the extensive geophysical investigations in this region, the deep structure of the West Siberian Plate comprises a thick (up to 15 km) Meso-Cenozoic sedimentary basin, which rests on the Paleozoic and Proterozoic folded basement of uncertain composition. The basement is believed to be responsible for the linear submeridional anomalies in gravity, which have large dimensions (300–500 km) and a predominantly positive sign (Kremenetskii, Alekseeva, and Didenko, 2002). Different authors interpret these anomalies in different ways. For example, S.V. Aplonov (2002), who touches upon this question in several papers, supposes that the mentioned sedimentary cover is underlain by the crust of the Ob' paleo-ocean, which strikes submeridionally. The stage of rifting in the formation of this ocean started about 240–230 Ma ago (simultaneously with other rifts), while the stage of short-term spreading, due to which the rift boundaries moved apart from each other by 200–300 km, was completed about 215 Ma ago. As a result, in the opinion of Aplonov, the spreading of the hypothetical Ob' paleo-ocean caused Siberia to rotate clockwise relative to the East European Platform by 12°–14° around the pole of rotation which is located south of the 60° latitude.

However, we note that in the case of such a rotation, the Siberian pole should have moved east relative to the European pole; i.e., the situation would have been opposite to what is actually observed in our analysis (Fig. 1a).

The standpoint expressed in (Bazhenov and Mossakovskii, 1986; Aplonov, 2000) is opposed by the evidence suggesting that the West Siberian rift structures degenerate northwards, which is reflected in the rarer occurrence and poorer pronouncedness of their deep geophysical signatures. In particular, according to (Bogdanov et al., 1998), the transverse dimensions of the Koltogor–Urengoi rift in the region of the Tyumen superdeep TSG-6 borehole are 120–130 km and the amplitude of the rift zone is about 1.5 km. However, in the polar region, the width of the rift valley does not exceed 50–70 km, and the depth of the trough decreases to a few hundred meters. Further north, the rift dies out even more and completely disappears before reaching the Kara Sea. Similar data are obtained also for the Khudosei rift.

We also note that the results of coring the Tyumen superdeep SG-6 hole, which was drilled in the center of the Koltogor-Urengoi graben-rift, i.e., in the supposed center of the expected paleo-ocean, casts doubt on the hypothesis of the Ob' paleo-ocean, which was introduced by S.V. Alponov. The oceanic crust was not discovered; instead, volcanics largely composed of low-potassium P_2-T_1 tholeitic basalts were penetrated in the depth interval from 6424 to 7502 m (the bottom hole). The detailed investigation of these rocks allowed us to correlate them with the coeval tholeiites from the trap formation of the Siberian Platform (Kremenetskii and Gladkikh, 1997). In the opinion of Kazanskii et al. (1995), the textural and structural features of the basalts penetrated by drilling indicate that they were outpoured in the land environment. This depth interval is reported to contain the remains of continental plants (Kirichkova et al., 1999). The age of the West Siberian traps determined by the Ar-Ar dating by Reichow et al. (2002) is very close to the age of the traps of the Siberian Platform, which also contradicts Aplonov's hypothesis.

When considering the average paleomagnetic poles determined in our study, one can clearly see that, for their misalignment to be accounted for by only the mutual displacements of the considered cratons, it is necessary to assume that these platforms substantially approached each other (by a distance of about 8 degrees of the great-circle arc) in the post-Paleozoic (Fig. 1b). This convergence should have been a result of the rotation of Siberia around the Eulerian pole, which is quite far from its geometrical center.

Here, we give an explanation on this point. The Eulerian pole of the Siberian Platform in the case of its rotation with respect to Stable Europe should be located on the arc of the great circle that passes through the center of the arc connecting the considered poles and is perpendicular to this arc. It can be seen from the geometrical illustration (Fig. 1c) that the great circle on which the rotational pole of the Siberian Platform should lie is located quite far from its geometrical center, which determines the character of rotation of this platform. Namely, the rotation cannot be implemented through simple shear displacements on the western margin of the Siberian platform but instead it requires a significant westward displacement of the platform.

Such large displacements of the Siberian Platform (by 700–800 km) would have entailed the formation of large structures of compression on the present-day western boundary of the platform; however, geological evidence supporting the presence of such structures has not been found. As mentioned above, the territory of West Siberia is widely cut by Early Mesozoic grabens, and the Triassic and Early Jurassic sediments filling these grabens are often crumpled into folds (Bochkarev, 1973). This presents evidence of an episode of compression within the considered territory in the Mesozoic; however, the scale of this compression is incommensurate with the scale that might be expected in the case of the converging Siberian and East European Platforms, as mentioned above.

The only structure of large-scale compression between the East European and Siberian Platforms is the Urals folded mountain belt, which exhibits the signs of both Mesozoic and Cenozoic tectonic activity, including the deformations of compression and extension. However, the net (sum) scale of the structures of compression that were formed after the Late Hercynian orogeny corresponds to the maximal contraction by a few hundreds of meters, which is again incommensurate with the contraction estimated at a few hundreds of kilometers. In addition, the Mesozoic and Cenozoic tectonics was dominated by largely longitudinal faults (Bachmanov et al., 2001).

Thus, the interpretation of the relative position of the Siberian and European poles in terms of their relative displacements necessarily requires Siberia and Europe to approach each other by more than 700 km in the post-Paleozoic, which conflicts with all the existing geological data.

Any alternative displacement contradicts the paleomagnetic data. Therefore, the mutual displacement of the considered blocks in the post-Paleozoic is impossible, and the cause of the misalignment between the poles should be sought somewhere else.

The analysis carried out in (Veselovskiy and Pavlov, 2006) shows that the observed discrepancy in the locations of the poles can probably be associated with the effects of the nondipole components or with the shallowing of inclination in the data for Europe. The latter factor appears to be more probable.

The new Permo-Triassic paleomagnetic poles recently determined from the sediments in the eastern part of the East European Platform (Bazhenov et al., 2008; Khramov et al., 2006; Shatsillo et al., 2006) also lie on the line that connects the regions of the study and the Siberian Permo-Triassic paleomagnetic pole. This again supports the conclusion that significant relative rotations of the Siberian Platform and Europe did not occur in the post-Paleozoic.

The Mesozoic Paleomagnetic Poles

Even the relationship between the Permo-Triassic Siberian and European poles almost unambiguously shows that the Siberian Platform did not rotate (of course, within the accuracy of the paleomagnetic method) with respect to Stable Europe in the Cenozoic and Mesozoic. Generally speaking, one might still assume that such a rotation did occur at some moment, but it was then compensated by the opposite rotation of exactly the same value. This hypothesis is highly improbable; however, for completeness of the proof of our assertion concerning the absence of rotations, let us still examine the Mesozoic paleomagnetic poles of the Siberian Platform itself.

We note that the fact that only a few Mesozoic paleomagnetic poles of the platform were determined to date is not accidental. The Cretaceous and Jurassic sediments are widespread in the platform, and many of them participate in the structure of the Vilyui syneclise and the depressions in the basement where they are represented, as a rule, by the loose clayish or silty sediments, frequently rich in organics. The preliminary paleomagnetic investigations of this type of sediments (Yu.S. Bretstein, personal communication) show that they are not quite suitable for paleomagnetic studies.

There are a series of reference Triassic cross sections in the marginal part of the Siberian platform, which might be of significant interest for reconstructing the Mesozoic segment of the APWP curve. However, these cross sections are often composed of dark lithological varieties abundant with organics. The reconnaissance survey shows that these cross sections are of very little promise for conducting paleomagnetic studies (Bruno Calbrun, Ph.D. Dissertation, Institut de Physique du Globe de Paris).

At the same time, the south-southeastern periphery of the Siberian Platform is framed by a large belt of Jurassic and Cretaceous intrusions and subvolcanic formations. These were formed in the environment of an active continental margin above the zone of subduction, which existed throughout the Jurassic and Early Cretaceous up to the collision of the Amur superterrain with the North Asian continent. The magmatic formations of this belt can contain the paleomagnetic signal reflecting the characteristics of the geomagnetic field at the time of their formation, and therefore they are of undoubted interest as the objects for constructing the Mesozoic segment of the APWP curve for the Siberian platform.

Three of five Mesozoic paleomagnetic poles of the Siberian Platform, which are known to date, were determined with the aid of the modern procedure from exactly this belt of the Mesozoic magmatic activity. These are the poles for the Konder and Bokur massifs (Mukunda plutonic complex) located within the Ket-Kap ridge in the Uchur-Maya region, and the pole for the Ryabinovskii massif of the Central Aldan region (Fig. 2, Table 1).

As seen in Fig. 3, the paleomagnetic poles of the Konder and Bukur massifs agree quite well with the reference curve suggested by Besse and Courtillot (2002) for Europe and fall close to the European poles with an age of 150–160 Ma, which is perfectly consistent with the data (*Legenda*..., 2003) on the Late Jurassic age of the Mukunda complex.

The pole determined from the Ryabinovskii massif also closely agrees with the European reference curve and also lies near the poles 150–160 Ma in age (Fig. 3). These figures, overall, do not contradict the present-day estimates of the age of the studied objects, which are based on both the geological relationships

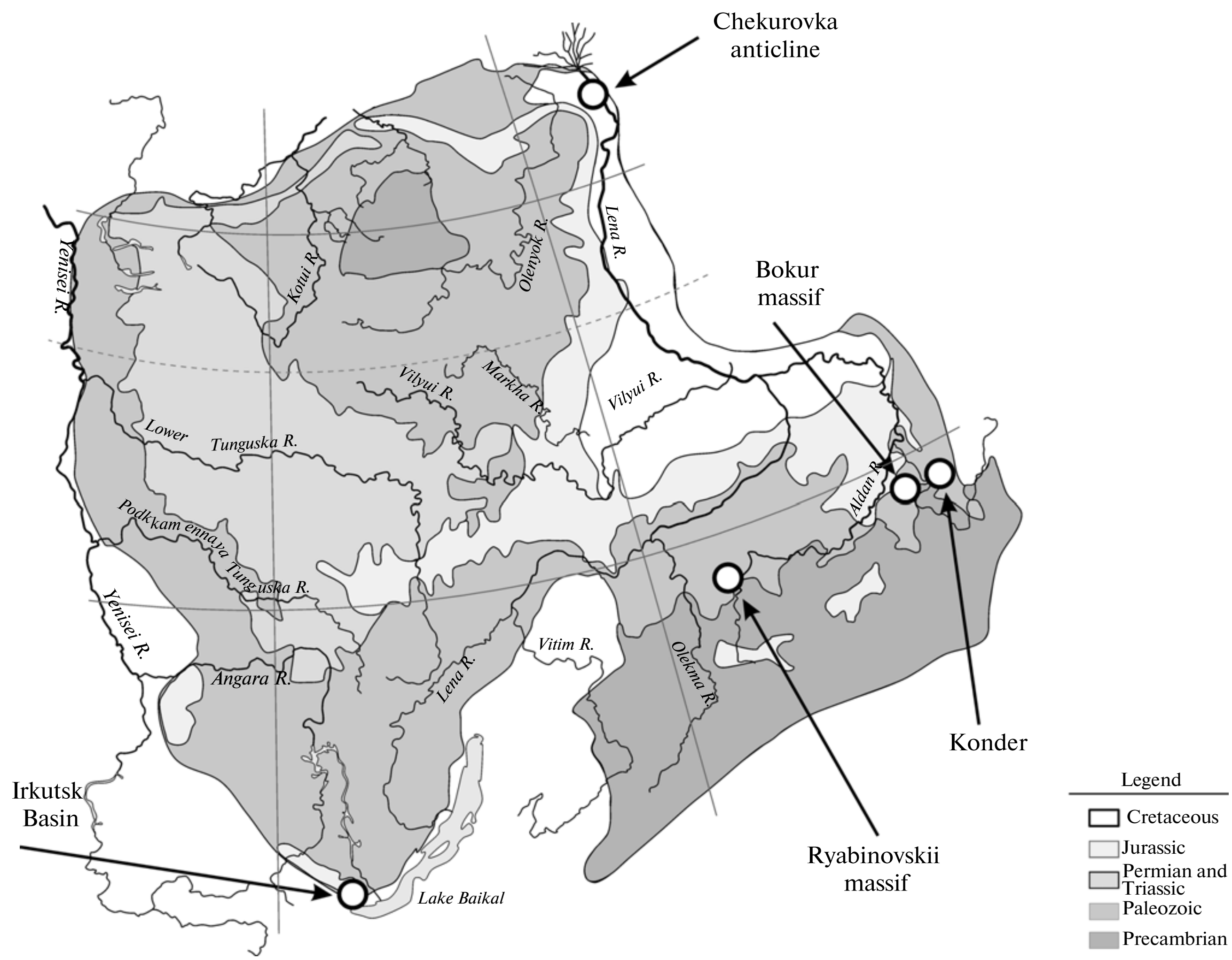

Fig. 2. The geographical positions of the objects from which the Mesozoic paleomagnetic poles of the Siberian Platform were determined.

and isotopic datings (see the review in (Maksimov, Uyutov, and Nikitin, 2004)).

It is instructive that the paleomagnetic pole of the Ryabinovskii massif is located in close vicinity of the poles for the Bokur and Konder massifs. This mutual geometrical relationship of the poles is an additional argument in favor of simultaneous or, at least, temporally very close occurrence of the processes that resulted in the formation of the magmatic complexes of the Central Aldan and Ket-Kap.

The remaining two poles (Table 1, Fig. 3) are determined from the sedimentary rocks of the Irkutsk Basin and Chekurovka–Bulkur anticline, which we relate to the Siberian Platform. We do it to some extent speculatively, taking into account that the Chekurovka–Bulkur anticline is located in the immediate proximity to the boundary of the platform.

The Late Cretaceous synfolding pole of the Chekurovka–Bulkur anticline falls very close to the Late Cretaceous poles of Stable Europe. The Late Cretaceous European pole with an age of 100 Ma is the closest to the mentioned Chekurovka–Bulkur pole ($\gamma/\gamma_c = 1.6°/7.7°$), which agrees well with the geological data on the age of the folding.

The Middle-Late Jurassic pole of the Irkutsk basin is determined from very noisy data and therefore has a rather large error. Kravchinsky et al. (2002) note that this pole "should be considered as a preliminary rough estimate of the Lower–Middle Jurassic magnetic field of Siberia." However, this pole also does not statistically significantly differ from the 160 Ma (Late Jurassic) pole of Europe.

Thus, all the known Mesozoic poles for the Siberian Platform support the hypothesis of Europe and Siberian Platform being parts of a single rigid plate in the Mesozoic and Cenozoic.

Table 1. The Mesozoic Paleomagnetic Poles of the Siberian Platform

No.	Object, region, coordinates	Age	Plat (°)	Plong (°)	α95 (°)	Source
1	Konder massif, dunites, metasomatic rocks 57.3°N, 134.6°E	J3–K1	76.7	158.8	11.6	(Pavlov et al., 2004)
2	Chekurovka anticline. Lower Cambrian sediments remagnetized during folding 71.4°N, 127.4°E	K2	82.3	169.8	4.2	(Pavlov et al., 2004)
3	Ryabinovskii massif. Central Aldan complexly structured intrusive formation 58.7°N, 125.9°E	160–130 Ma	68.8	156.0	11.8	(Pavlov and Maksimov, 2006)
4	Bokur massif. Mukunda plutonic complex, diorites, monzodiorites, granodiorites headstream of the Bokur brook (tributary of the Yarmarka Khapchana River, Ket-Kap ridge, northeastern slope of the Aldan shield), 57.7°N, 132.1°E	J3	71.1	150.0	6.5	(Pavlov and Karetnikov, 2008)
5	Irkutsk region, Irkutsk Basin 52.0°N, 104.0°E	J1–J2	69.3	202.5	22.4	(Kravchinsky et al., 2002)

Note: Plat—latitude of the pole, Plong—longitude of the pole, α95—radius of the confidence circle.

THE PALEOMAGNETIC DATA FOR THE FOLDED MARGINS OF THE SIBERIAN PLATFORM

General Considerations

As the data for the Siberian Platform are limited, the question remains whether the paleomagnetic poles determined from its folded margins can be used. Are the paleomagnetic poles of the folded framing of the Siberian platform in principle suitable for examining the rigidity of Northern Eurasia and testing the hypothesis of a rotating Siberian domain?

Obviously, the answer will be "yes" only if it is reasonable to attribute these poles to the Siberian platform. The poles can be attributed to the Siberian Platform if a set of the following rather stringent conditions are satisfied.

(1) The tectonic block for which the data are obtained has been part of the Siberian continent at least since the moment of recording the considered paleomagnetic signal.

(2) The block did not experience any significant (e.g., shear) displacements inside the continent, or there is clear independent information that allows one to take into account these displacements.

(3) The block did not experience any significant local rotations (the pole of rotation is located inside the block), or there is clear independent information that allows one to take into account these rotations.

In addition, a necessary requirement for such testing is that the statistics are quite extensive, i.e., that the number of the objects distributed along the periphery of the platform, which provide independent paleomagnetic determinations, should be sufficiently large. In our opinion, there should be at least 6–8 such objects.

Since the reliable independent data for points 2 and 3 (large displacements and local rotations) are often lacking and sometimes the data for point 1 (for the block to be part of the continent) are absent, the use of the paleomagnetic poles determined from the folded margins appears to be extremely speculative and full of highly unreliable conclusions.

However, it is possible to apply the paleomagnetic information inferred from the folded margins in any way for gaining more or less reliable conclusions on the subject of interest: this information is helpful if we only use the data on the paleolatitudes of the object, which are recorded in the paleomagnetic signal. In this case, one of the strong constraints governing the use of the paleomagnetic data is cancelled. Namely, this is the condition prohibiting local rotation. The determination of the paleomagnetic position of the object does not depend on whether this object experienced rotation or not, because its paleolatitude is calculated from the magnetic inclination which is insensitive to the rotation.

When using only the paleolatitude (paleoinclination), we lose a part of the information recorded in the paleomagnetic signal. However, this loss is compensated by the substantially larger number of objects that can be involved in the analysis, which will eventually improve the reliability of the conclusions.

The data on the paleolatitudes for the folded framing of the Siberian Platform can be checked against their correspondence to the expected paleolatitudes calculated from the reference European APW path. If

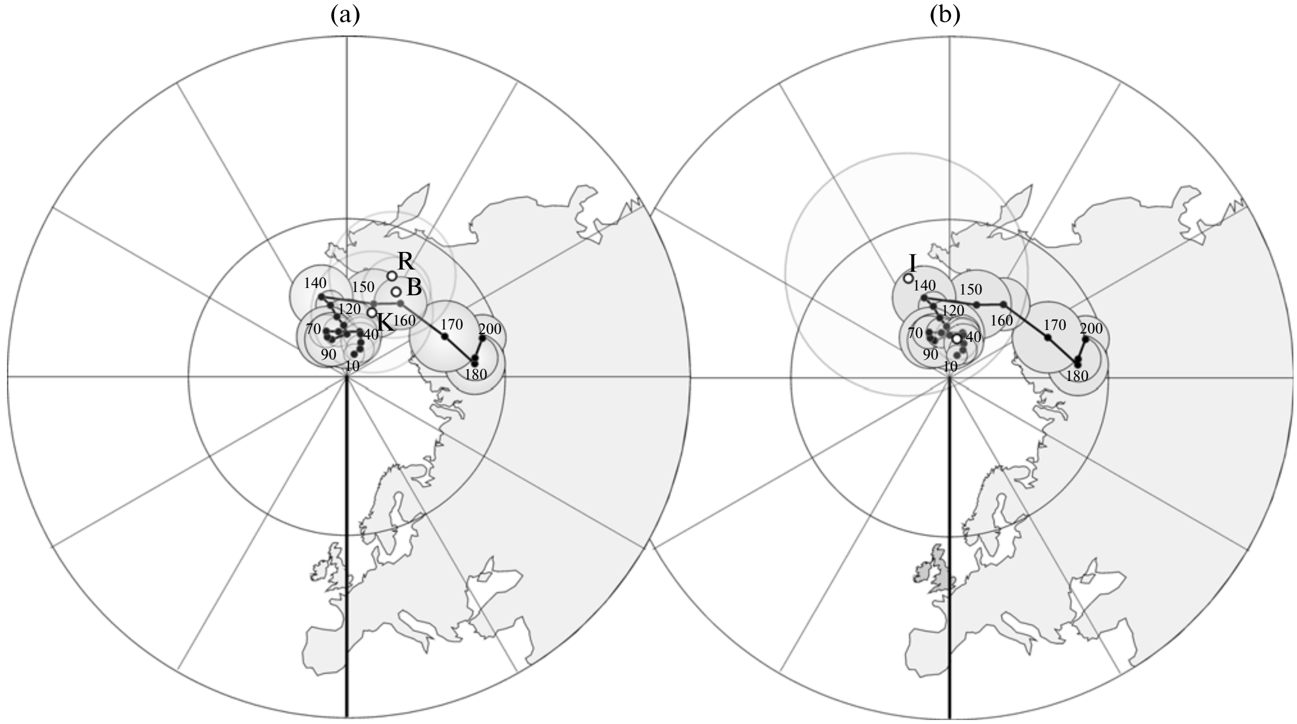

Fig. 3. (a) The comparison of the paleomagnetic poles of the Konder (K), Bokur (B), and Ryabinovskii (R) massifs with the Meso-Cenozoic segment of the European APWP curve (Besse and Courtillot, 2002); (b) the comparison of the paleomagnetic poles of the Chekurovka anticline (Ch) and the Irkutsk circus (I) with the Meso-Cenozoic segment of the European APWP curve (Besse and Courtillot, 2002). The black circles and the figures nearby indicate the positions of the average poles of the European path and their age; the gray circles show the corresponding circles of confidence. The open circles mark the Siberian poles.

the observed paleolatitudes correspond to the expected values; then, if the statistics are sufficiently large and the geographical distribution of the objects is favorable, this can be interpreted as substantially supporting the hypothesis of rigid northern Eurasia. Disagreement between the observed and expected paleolatitudes allows various interpretations (e.g., shear displacements, remagnetization, and low-quality extraction of the paleomagnetic signal).

The mismatch of the paleolatitudes can be considered as an argument in favor of the relative motion of the Siberian Platform and Stable Europe only if this mismatch is systematical (regular). As seen from Fig. 4, if block 1 rotates around block 2 (the Eulerian pole is located inside block 1), the paleolatitudes of different points of block 1 experience SYSTEMATICAL changes (in the coordinate system fixed to block 2), irrespective of whether the entire system of blocks moves or stands still (see explanations in Fig. 4). If these blocks are commensurate in size with the Siberian Platform, these changes can be detected by the paleomagnetic method (within its accuracy).

The note that the Eulerian pole is located inside block 1 is introduced in order to make the considered idealized example maximally close to the supposed rotation of the Siberian domain relative to the East European Platform (Kazanskii et al., 2005; Metelkin, Gordienko, and Klimuk, 2007; Metelkin et al., 2008; Zemtsov, 2009).

Thus, on exploring the possibility to use the paleomagnetic data determined from the folded margins, we arrive at the following conclusions.

(1) The use of the paleomagnetic poles determined from the folded setting is extremely risky, because this is conditioned by a series of strong constraints, which are satisfied very rarely.

(2) The information on the paleolatitudes, which is inferred from the folded margins of the Siberian Platform, can be used for testing the rigidity of Northern Eurasia.

(3) In order to prove the relative rotations of the Siberian Platform and Stable Europe, one has to prove the systematic discrepancy between the observed and expected paleolatitudes.

Comparison of the Meso-Cenozoic Poles of the Folded Margin with the European Reference Path

As of now, 20 paleomagnetic poles have been determined from the folded margins of the Siberian Platform with the aid of a modern paleomagnetic procedure. One pole relates to the Miocene; two poles are determined for the Late Cretaceous, and six poles, for

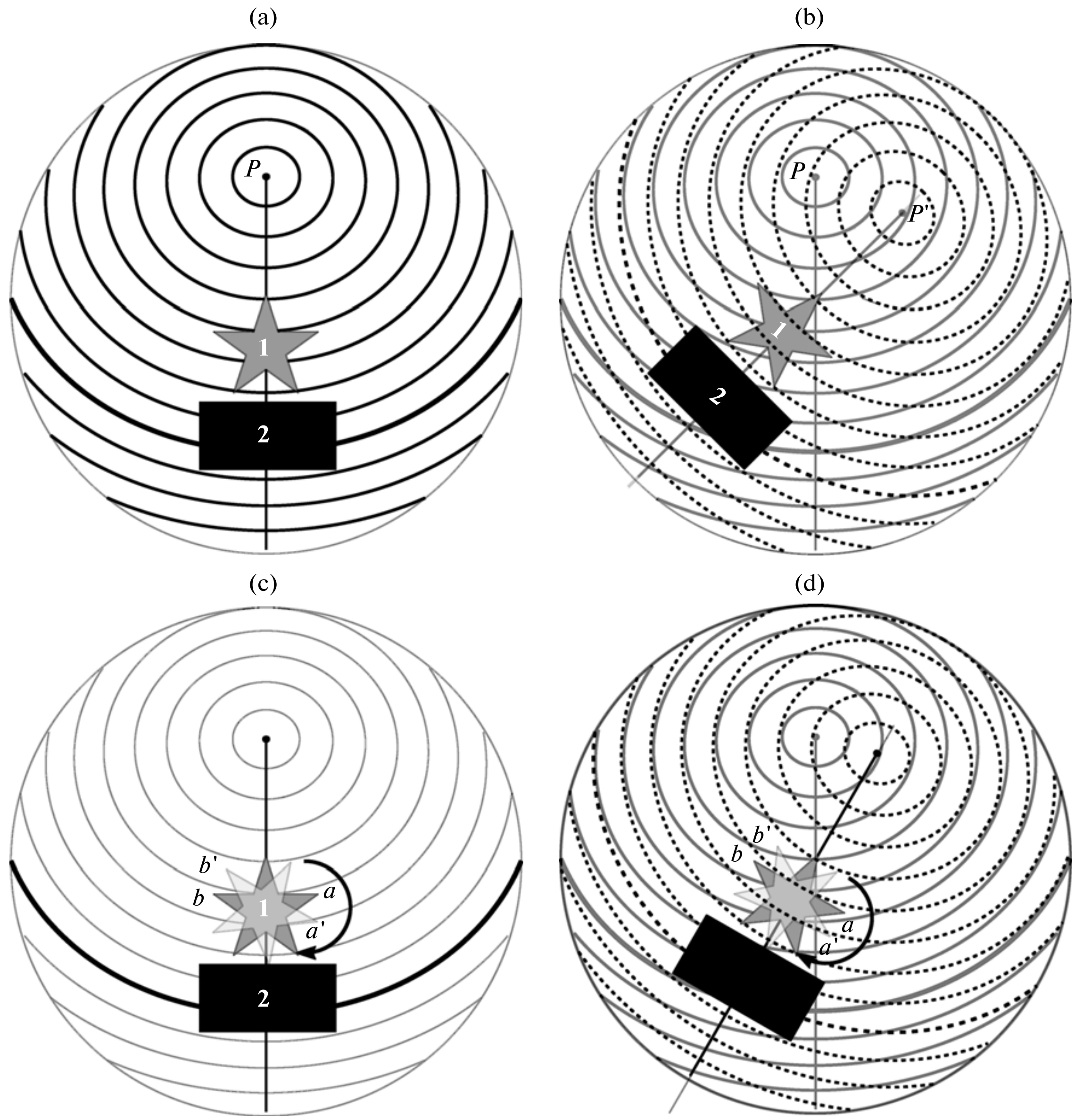

Fig. 4. The systematical change in the paleolatitudes in the case of rotation of one block relative to another block. *P* is the position of the geographic pole; *P*' is the position of the paleomagnetic pole of block 2 after rotation of this block. *P*' is also the paleomagnetic pole of block 1 if the latter was rigidly connected with block 2 during the rotation. The solid lines on the sphere depict the latitudes, and the dashed lines show the paleolatitudes in the coordinate system of block 2. *P*' and the paleolatitudes mark the new position of the coordinate system fixed to block 2 after its displacement. (a) The initial position of the blocks; (b) the blocks are rotated without changing their relative positions. The coordinate system fixed to block 2 is shifted; the points of block 2 do not change their positions in the coordinate system of block 1; (c) block 1 rotates as shown in the scheme; block 2 remains in its initial position. The coordinate system fixed to block 2 does not move. The latitudes of the points of block 1 (*a* and *b*) in this coordinate system change in a systematical (regular) manner: the latitudes of the points on the left increase, while the latitudes of the points on the right decrease; (d) the blocks move together, and block 1 experiences rotation relative to block 2. The latitudes of block 1 (*a* and *b*) systematically vary in the coordinate system fixed to block 2: the latitudes of the points on the left increase, while the latitudes of the points on the right decrease.

the Early Cretaceous; and three poles correspond to the boundary between the Jurassic and Cretaceous. One, four, and one poles are determined for the Late, Middle, and Early Jurassic, respectively. The two remaining poles are Middle Triassic. Geographically, these poles represent regions that are quite favorably distributed around the Siberian Platform: the Minusinsk Basin, the Sayan Mountains, the Transbaikalia, the Kharaulakh Mountains, and the Taimyr Peninsula.

Table 2 presents the comparison of inclinations and declinations calculated from the folded margins of the

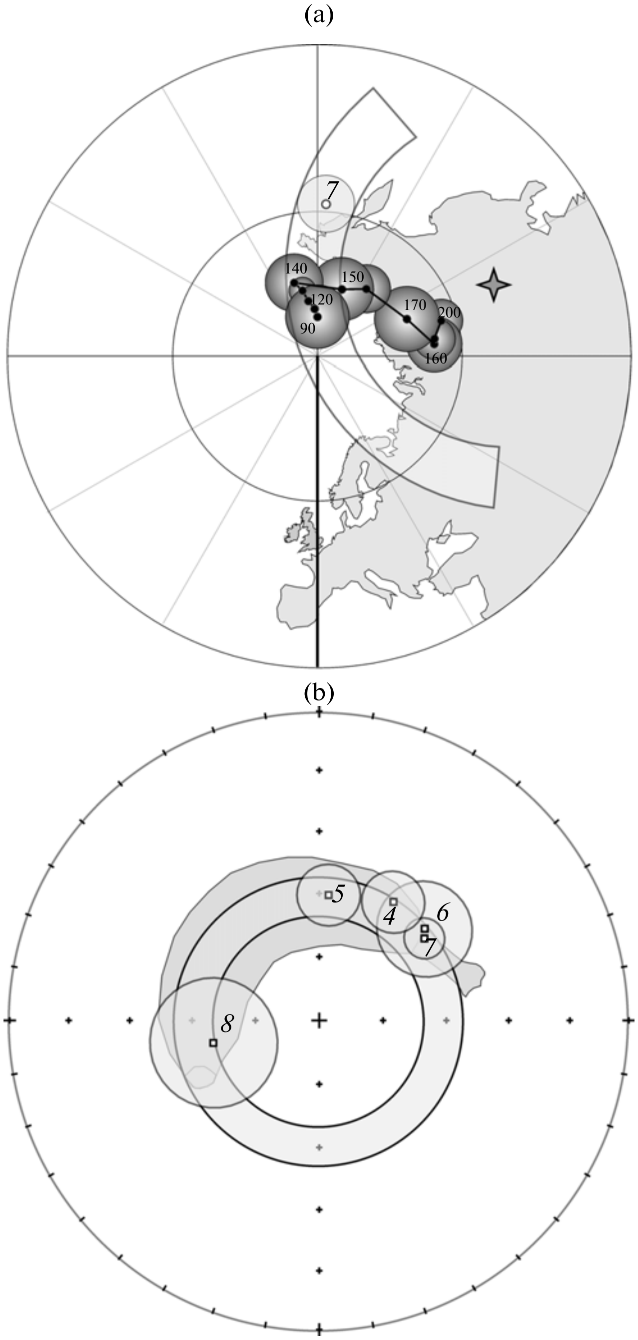

Fig. 5. (a) The illustration of correspondence in latitudes. The geometrical relationship between the Lower Cretaceous pole of Ingoda River and the Lower Cretaceous segment of the European reference APWP curve. The departure of the pole from the curve is easily explained by the local rotations in the region of Ingoda River.

The succession of the filled circles inside the open circles connected by the straight lines is the segment of the European reference curve (Besse and Courtillot, 2002). The poles are shown with the corresponding confidence circles. The figures near the circles indicate the age of the poles. The isolated circle numbered 7 is the pole of Ingoda River (see Table 2). The asterisk with four arms marks the location of the site where the pole was determined. The light arc is the segment of the small circle along which, probably, the pole of the Ingoda River was rotating.

(b) The banana-shaped distribution of the average paleomagnetic directions in the Early Cretaceous Transbaikalia indicates that the blocks in the region experienced significant local rotations. The squares with the circles mark the average directions and their confidence circles; the figures show the number of the paleomagnetic result in Table 2 which corresponds to the given paleomagnetic direction. The light circle around the center of the stereogram shows the small circle along which, the paleomagnetic directions were probably rotating.

Siberian Platform with the corresponding values calculated from the reference European path (Besse and Courtillot, 2002). We note again that the statistical coincidence of the calculated (expected) inclinations would testify to the considered objects being parts of a single rigid structure of Northern Eurasia, while the statistical difference of declination (if any) would most likely indicate local rotations of the blocks around the vertical axes (see Fig. 5 for illustration).

As seen from the table and Fig. 6, only two of the 20 paleomagnetic results show a statistically significant deviation of the observed paleolatitudes from the expected values. These are the paleomagnetic determinations for the lower reaches of the Lena River (Metelkin et al., 2008) and for the Minor Khamar-Daban volcano-tectonic structure.

The Middle Jurassic result determined from the lower reaches of the Lena River gives rise to some doubt because of the following points:

(1) this result emerges from a region where the Early-Late Cretaceous remagnetization is widespread;

(2) this result is based on unipolar data (although the geomagnetic reversals were very frequent in the Middle Jurassic);

(3) in terms of the paleolatitudes, this result closely agrees with the European poles from the time interval corresponding to the probable period of remagnetization.

Apparently, the result for the Minor Khamar-Daban volcano-tectonic structure also needs to be verified, since, in terms of the paleolatitude, it is inconsistent with the other volcano-tectonic structures of the same region, which are close in age. This inconsistency can be associated, for example, with the difficulties in determining the true tilting of the studied rocks.

Thus, 18 of the 20 paleomagnetic results completely agree in latitude with the European APW path. The misalignment of the two remaining determinations is easily permissible by either the geological situation or later remagnetization. Therefore, the paleomagnetic data for the folded setting of the Siberian Platform perfectly agree with the hypothesis of rigid Northern Eurasia.

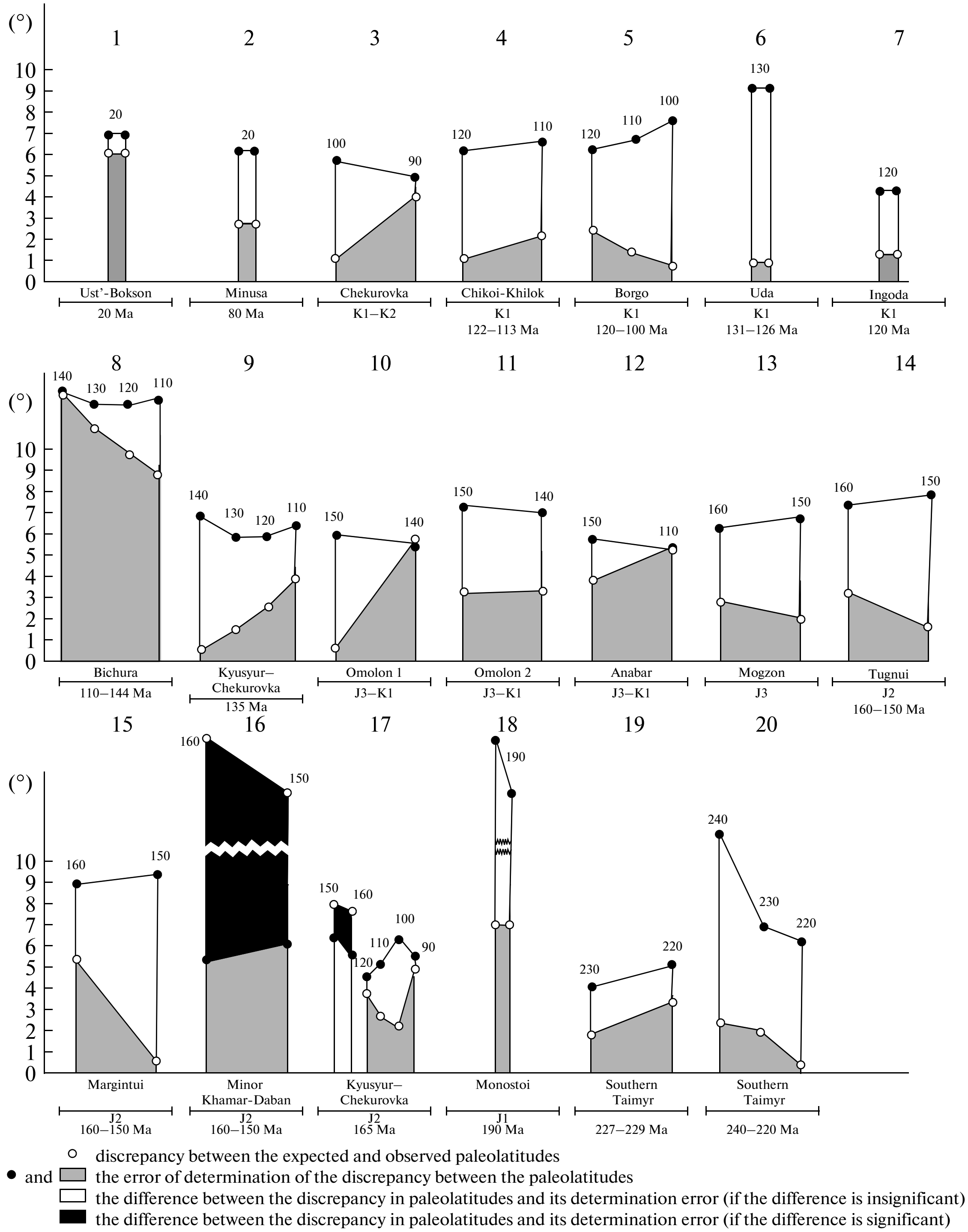

Fig. 6. The analysis of the discrepancies between the measured paleolatitudes and those calculated from the reference APWP curve (Besse and Courtillot, 2002). The small numerals near the tops of the columns indicate the time levels (in Ma).The number of the column (indicated above the center of the column) corresponds to the number of the paleomagnetic result in Table 2. In each column, the discrepancy between the observed paleolatitudes and the expected values estimated from the reference European APWP (Besse and Courtillot, 2002) are compared with the error of determination of this discrepancy. If the discrepancy between the paleolatitudes is statistically significant, it is shown in black; if it is insignificant, it is shown in white. Numbers above the columns are time levels (in millions years) for which the comparison has been carried out.

Table 2. Meso-Cenozoic paleomagnetic poles of the folded setting of the Siberian Platform

No.	Region, object, coordinates, number of sites (N)	Age according to the authors	Plat (°)	Plong (°)	α95/dp/dm (°)	Source	R ± ΔR Difference in paleodeclinations/age of the pole of comparison (Ma)	F ± ΔF Difference in paleolatitudes/age of the pole of comparison (Ma)	Result of comparison for paleolatitudes
	POLES DETERMINED BY THE ADVANCED PROCEDURE								
1	Ust-Bokson village, Oka River, Sayan Mountains, basalts 52.1°N, 100.3°E, $N = 9$	20 Ma	69.8	186.5	9.3	(Hankard et al., 2007)	23.1 ± 11.0/20 Ma	6.2 ± 7.1/20 Ma	+
2	Minusinsk Basin, alkali- and basic necks and dykes, 55°N, 90°E, $N = 18$	K2, 82–74 Ma	82.8	188.5	6.1	(Metelkin et al., 2007)	0.2 ±10.1/80 Ma	2.8 ± 6.3/80 Ma	+
3	Chekurovka anticline Lower Cambrian sediments with syn-folding remagnetization 71.4°N, 127.4°E $N = 28$	K1–K2	82.3	169.8	4.2	(Pavlov et al., 2004)	4.1 ± 22.9/100 Ma 2.8 ± 17.8/90 Ma	1.0 ± 5.8/100 Ma 4.2 ± 5.0/90 Ma	+
4	Chikoi–Khilok trough, Transbaikalia, basalts, $N = 13$ 51.7°N, 107.5°E	K1 122–113 Ma	70.3	188.0	8.3	(Metelkin, Gordienko, and Zhao, 2004)	12.5 ± 10.0120 Ma 15.4 ± 10.9/110 Ma	1.1 ± 6.4/120 Ma 2.3 ± 6.9/110 Ma	+
5	Borgoi trough, Transbaikalia, basalts, $N = 7$, 51.0°N, 105.5°E	K1 120–100 Ma	83.9	170.2	8.3	(Metelkin, Gordienko, and Zhao, 2004)	9.5 ± 10.6/120 Ma 6.8 ± 11.3/110 Ma 4.0 ± 13.0/100 Ma	2.6 ± 6.4/120 Ma 1.4 ± 6.9/110 Ma 0.8 ± 7.9/100 Ma	+
6	Uda trough, Transbaikalia, basalts, $N = 5$, 52°N, 110°E	K1 131–126 Ma	60.2	179.5	12.6	(Metelkin, Gordienko, and Zhao, 2004)	26.5 ± 15.5/130 Ma	1.0 ± 9.5/130 Ma	+
7	Ingoda River, Transbaikalia, basalts, 51.2°N, 112.2°E, $N = 12$	K1 118–128 Ma	58.5	176.8	5.2/6.0	(Cogne et al., 2005)	33.7 ± 7.5/120 Ma	1.4 ± 4.5/120 Ma	+
8	Bichura River, Transbaikalia, basalts, trachybasalts, 50.6°N, 107.6°E, $N = 10$	K1 110–144 Ma	37.0	70.4	15.8/17.5	(Cogne et al., 2005)	118.7 ± 25.3/110 Ma 121.5 ± 24.9 /120 Ma 125.0 ± 25.0 /130 Ma 127.4 ± 25.6 /140 Ma	9.0 ± 12.7/110 Ma 0.1 ± 12.4/120 Ma 11.3 ± 12.4/130 Ma 13.0 ± 13.0/140 Ma	+
9	Lower reaches of Lena River (Kyusyur–Chekurovka), terrigenous rocks (sandstones) 71.3°N, 127.5°E (conventional common point), $N = 11$	K1 (135 Ma – aut.)	67.2	183.8	7.8	(Metelkin et al., 2008)	41.3 ± 20.0/110 Ma 35.1 ± 18.2/120 Ma 27.9 ± 18.0/130 Ma 23.8 ± 21.4/140 Ma	4.0 ± 6.6/110 Ma 2.7 ± 6.0/120 Ma 1.4 ± 6.1/130 Ma 0.5 ± 7.1/140 Ma	+

Table 2. (Contd.)

No.	Region, object, coordinates, number of sites (*N*)	Age according to the authors	Plat (°)	Plong (°)	α95/dp/dm (°)	Source	R ± ΔR Difference in paleodeclinations/age of the pole of comparison (Ma)	F ± ΔF Difference in paleolatitudes/age of the pole of comparison (Ma)	Result of comparison for paleolatitudes
10	Omolon massif, terrigenous sedimentary rocks, syn-folding magnetization 64.5°N, 155.5°E, *N* = 14	Boundary J3–K1	75.2	164.0	5.3	(Savostin et al., 1993)	28.3 ± 25.2/140 Ma 5.2 ± 33.2/150 Ma	6.0 ± 5.7/140 Ma 0.6 ± 6.2/150 Ma	+
11	Omolon massif, terrigenous sedimentary rocks, 64.5°N, 155.5°E, *N* = 9	Boundar J3–K1	75	183	8	(Bondarenko and Didenko 1997)	9.7 ± 28.7/140 Ma 23.6 ± 35.6/150 Ma	3.4 ± 7.2/140 Ma 3.3 ± 7.6/150 Ma	+
12	Anabar Bay, 73.90°N, 113.1°E, Clayish siltstone deposits, black schists, *N* = 209	Boundary J3–K1	76.9	179.3	4.8	(Housa et al., 2007)	0.4 ± 17.5/140 Ma 13.9 ± 26.0/150 Ma	5.5 ± 5.5/140 Ma 3.9 ± 6.0 150 Ma	+
13	Mogzon trench, Chilok and Uda river basins, 51.8°N, 112.0°E Bada sedimentary and volcanic rocks, *N* = 9	J3	64.4	161.0	7.0	(Kravchinsky et al., 2002)	21.6 ±14.7/150 Ma 22.0 ± 14.0/160 Ma	2.1 ± 7.0/150 Ma 2.9 ± 6.4/160 Ma	+
14	Tugnui volcanotectonic structure, (Transbaikalia, Ichetui basalts), 50.9°N, 106.5°E (aut. midpoint), *N* = 8	J2 150–160 Ma	67.6	159.6	9.0	(Metelkin, Gordienko, and Klimuk, 2007)	13.2 ± 15.9 150 Ma 13.9 ± 15.3 160 Ma	1.7 ± 8.2/150 Ma 3.3 ± 7.6/160 Ma	+
15	Margintui volcanotectonic structure (Transbaikalia, Ichetui basalts), 50.9°N, 106.5°E (aut. midpoint), *N* = 6	J2 150–160 Ma	75.6	161.5	11.3	(Metelkin, Gordienko, and Klimuk, 2007)	0.8 ± 17.9/150 Ma 1.6 ± 17.3/160 Ma	0.4 ± 9.6/150 Ma 5.5 ± 9.1/160 Ma	+
16	Minor Khamar-Daban volcanotectonic structure, (Transbaikalia, Ichetui basalts), 50.9°N, 106.5°E (aut. midpoint), *N* = 4	J2 150–160 Ma	36.0	179.3	5.3	(Metelkin, Gordienko, and Klimuk, 2007)	53.5 ± 10.3/150 Ma 52.8 ± 9.4/160 Ma	20.6 ± 6.2/150 Ma 25.6 ± 5.4/160 Ma	–

Table 2. (Contd.)

No.	Region, object, coordinates, number of sites (*N*)	Age according to the authors	Plat (°)	Plong (°)	α95/dp/dm (°)	Source	R ± ΔR Difference in paleodeclinations/age of the pole of comparison (Ma)	F ± ΔF Difference in paleolatitudes/age of the pole of comparison (Ma)	Result of comparison for paleolatitudes
17	Iower reaches of Lena River (Kyusyur–Chekurovka) terrigenous rocks (sandstones) 71.3 °N, 127.5°E (conventional common point), *N* = 4	J2 (165 Ma—aut.)	59.3	139.2	5.7	(Metelkin et al., 2008)	107.1 ± 57.0/160 Ma 83.3 ± 44.3/150 Ma 113.0 ±19.7/120 Ma 119.6 ± 22.6/110 Ma 126.3 ± 26.6/100 Ma 127.3 ± 22.4/ 90 Ma	8.2 ± 6.6/170 Ma 7.8 ± 5.6/160 Ma 3.9 ± 4.6/120 Ma 2.6 ± 5.3/110 Ma 2.2 ± 6.5/100 Ma 5.4 ± 5.7/90 Ma	– +
18	Monostoi, Transbaikalia, basalts, 51.1°N, 106.8°E, *N* = 5	J1 (190 Ma—aut.)	43.3	131.4	22.7/23.6	(Cogne et al., 2005)	119.3 ± 55.0/190 Ma	1.5 ± 17.2 190 Ma	
19	Southern Taimyr, basalt sills, 74.8°N, 100.6°E	227–229 Ma	47.1	121.6	4.8/5.3	(Walderhaug et al., 2005)	10.1 ± 9.1/230 Ma 14.1 ± 12.7/220 Ma	1.8 ± 4.1/230 Ma 3.4 ± 5.2/220 Ma	+
20	Southern Taimyr, remagnetized sedimentary rocks, 75.2°N, 100°E	220–240 Ma	49.6	128.8	8.5	(Torsvik and Andersen, 2002)	22.0 ± 34.5/240 Ma 3.0 ± 16.6/230 Ma 0.8 ± 14.0/220 Ma	2.5 ± 11.7/240 Ma 2.0 ± 7.2/230 Ma 0.4 ± 6.4/220 Ma	+
					“OLD” POLES				
1	Popigai crater andesites, tuffs, 71.5°N, 111.0°E	K1–K2*	66	170	11.1	Gusev, 1973 in (*Paleomagnitnye* ..., 1973)	47.5 ± 24.5/40 Ma 53.9 ± 25.2/30 Ma	6.1 ± 8.5/40 Ma 6.3 ± 8.7/30 Ma	+
2	Chulym–Yenisei depression, clays, siltstones 56.5°N, 89.5°E	K1, 110–146 Ma	74	135	10.8	Pospelova, 1971 in (*Paleomagnitnye*..., 1971)	0.1 ± 21.1/150 Ma 4.3 ± 20.1/140 Ma 5.7 ± 19.2/130 Ma 8.5 ± 19.2/120 Ma 10.7 ± 19.7/110 Ma 13.2 ± 20.8/100 Ma	6.9 ± 9.3/150 Ma 16.7 ± 9.0/140 Ma 14.6 ± 8.2/140 Ma 12.7 ± 8.1/130 Ma 11.0 ± 8.5/120 Ma 10.0 ± 9.3/110 Ma	+
3	Khatanga trough, clays, siltstones, 70.50°N, 98.0°E	K1,Hauterivian 133–136 Ma	73	178	5.5	Pospelova, 1971 in (*Paleomagnitnye*..., 1971)	9.6 ± 14.0/140 Ma 12.3 ± 11.3/130 Ma	−3.9 ± 5.8/140 Ma −2.3 ± 4.6/130 Ma	+

Table 2. (Contd.)

No.	Region, object, coordinates, number of sites (*N*)	Age according to the authors	Plat (°)	Plong (°)	α95/dp/dm (°)	Source	R ± ΔR Difference in paleodeclinations/age of the pole of comparison (Ma)	F ± ΔF Difference in paleolatitudes/age of the pole of comparison (Ma)	Result of comparison for paleolatitudes
4	Anabar Bay, clays, siltstones, 75°N, 114°E	K1, Valanginian 138–140 Ma	63	174	5.4	Pospelova, 1968 in (*Paleomagnitnye*..., 1971)	20.6 ± 26.1/150 Ma 36.6 ± 16.0/140 Ma 38.8 ± 12.0/130 Ma 44.2 ± 11.8/120 Ma	11.8 ± 6.2/150 Ma 2.5 ± 5.8/140 Ma 4.6 ± 4.5/130 Ma 6.6 ± 4.4/120 Ma	+
5	Lower reaches of Lena River, sandstones, 72.6°N, 124.70°E	J3–K1, 100–161 Ma	71	145	8.0	Pisarevskii, 1982 in (*Paleomagnitnye*..., 1982)	12.6 ± 63.4/160 Ma 34.6 ± 58.9/150 Ma 42.4 ± 53.4/140 Ma 46.1 ± 52.3/130 Ma 52.9 ± 52.2/120 Ma 58.9 ± 53.2/110 Ma 65.7 ± 55.5/100 Ma	0.3 ± 7.0/160 Ma 3.9 ± 7.6/150 Ma –13.9 ± 7.2/140 Ma –12.0 ± 6.2/130 Ma –10.4 ± 6.2/120 Ma –9.0 ± 6.7/110 Ma 8.4 ± 7.7/100 Ma	+
6	Khatanga trough, sandstones, siltstones 70.5°N, 98.0°E	J1, Tithonian 146–151 Ma	54	123	5.6	Pospelova, 1971 in (*Paleomagnitnye*..., 1971)	72.4 ± 19.1/160 Ma 85.3 ± 19.8/150 Ma 96.0 ± 15.5/140 Ma	5.5 ± 5.6/160 Ma 2.0 ± 6.3/150 Ma 7.3 ± 5.9/140 Ma	+

* At present, the age of the Popigai crater is estimated at 35.7 ± 0.2 Ma;
Plat—latitude of the pole, Plong—longitude of the pole, a95—radius of confidence circle, dp/dm—semiaxes of the confidence oval;
R ± ΔR—the difference between the observed and expected (estimated from the reference European curve) declination and its determination error;
F ± ΔF—the difference between the observed and expected (estimated from the reference European curve) paleolatitude and its determination error;
J1, J2, J3—Early, Middle, and Late Jurassic; K1, K2—Early and Late Cretaceous.

Finalizing this section, we point out that the Early Cretaceous paleomagnetic results determined for the Transbaikalia (Table 2 a nd Fig. 5) show a banana-shaped distribution. This fact probably indicates that local rotations of the tectonic blocks were very common in this region.

CONCLUSIONS

Our analysis suggests the following conclusions:

(1) The mutual geometrical relationship between the Permo-Triassic poles of Stable Europe and the Siberian Platform contradicts the possibility of their relative motion in the post-Paleozoic.

(2) The Mesozoic paleomagnetic poles of the Siberian Platform support the hypothesis of rigid Northern Eurasia.

(3) The paleolatitudes of the Mesozoic objects located within the folded margins of the Siberian Platform perfectly agree with the European APWP curve.

This lead us to draw the following conclusions:

—The present-day paleomagnetic data quite definitely indicate that consolidation of the Northern Eurasian continent was completed by the end of the Permian; and from the very beginning of the Mesozoic, the Siberian and East European platforms were parts of a single rigid megablock.

—The Meso-Cenozoic segment of the European APW path can be used as the reference for the Siberian Platform.

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