Paleomagnetism of Vendian rocks in the southwest of the Siberian Platform

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[1] Presented in this paper are paleomagnetic data for the Vendian sedimentary rocks of the southwestern region of the Siberian Platform, obtained during the study of the reference rock sequences of the Central and Biryusa areas of the Sayan region and of the Yenisei mountain range in the lower reaches of the Angara River and its tributaries. This study proved the wide development of metachronous pre- and synfolding magnetization components which originated after the accumulation of the sedimentary rock sequences, yet, obviously not later than the Early Cambrian. All of the study rocks of the Nemakit-Daldynian age show two clearly distinguished paleomagnetic trends which seem to have formed during or soon after the accumulation of the rocks. Earlier, we got similar results for the Late Vendian rocks of the Southwest Baikal and East Sayan regions and also for the transitional Vendian-Lower Cambrian rock sequences of the Siberian Platform. This allowed us to infer the anomalous behavior of the geomagnetic field at the end of the Vendian to the beginning of the Lower Cambrian. The results obtained in the study reported here prove the actual basis of this hypothesis. During our study of the older Ediacarian and Ediacarian-Nemakit-Daldynian rocks, we managed to distinguish stable high-temperature magnetization components, obviously reflecting the trend of the geomagnetic field that existed during the accumulation of these rocks. The paleomagnetic poles corresponding to these components allowed us to reconstruct the late Vendian trend of the apparent migration of the pole and evaluate the character of the Siberian Platform movements during that time, which allowed us to chose the polarity for the Riphean paleomagnetic trends of Siberia. *INDEX TERMS:* 1520 Geomagnetism and Paleomagnetism: Magnetostratigraphy; 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics: regional, global; 1535 Geomagnetism and Paleomagnetism: Reversals: process, timescale, magnetostratigraphy; 9320 Geographic Location: Asia; *KEYWORDS:* paleomagnetism, Vendian, Cambrian, Siberian Platform, geomagnetic field behavior.

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Introduction

[2] The problem of the paleomagnetic poles of the transitional Late Precambrian-Phanerozoic period of the geological history is one of the most acute and morbid problems of the Siberian Platform paleomagnetology. First, the location of these poles is highly necessary for the solution of a number of actual problems in modern geology and geophysics. Secondly, the data available for the terminal Vendian time (see a brief review in [*Shatsillo et al.,* 2005]) and for the Early Cambrian are highly contradictory and are almost absent for the Late Riphean time (except for its beginning).

[3] The location of the Vendian–Early Cambrian and Late Riphean paleomagnetic poles of the Siberian Platform is highly important for solving the problem of timing the breakup of the Late Proterozoic Rhodinia supercontinent and for testing the numerous hypotheses explaining the geological evolution of our planet at the Precambrian-Paleozoic boundary. The results of this work will allow us to reconstruct the positions of the Siberian and East

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European cratons relative to each other at the Precambrian-Phanerozoic boundary and to carry out the paleomagnetic testing of the competing basic hypotheses [*Didenko et al.,* 1994; *Mossakovskii et al.,* 1993; *Sengör et al.,* 1993], describing the formation and evolution of the Central Asian foldbelt.

[4] The results of the latest studies [*Kazanskiy,* 2002; *Kravchinsky et al.,* 2001; *Pavlov et al.,* 2002; *Pisarevsky et al.,* 2000; *Smethurst et al.,* 1998] prove the importance of correlating the Phanerozoic and Riphean curves of the apparent migration of the pole for the Siberian Platform, of choosing the direction of the normal polarity of the paleomagnetic vectors of Siberia in Precambrian time, of the rate of the horizontal movements of the Siberian Craton at the Precambrian-Paleozoic boundary, of the adequacy of the regional and global paleotectonic reconstructions available, to name but a few.

[5] The lack of definiteness in the positions of the Vendian–Early Cambrian and Late Riphean poles of the Siberian Platform leads to the conventional minimization of the movements of the paleomagnetic poles in determining the polarity of the paleomagnetic trends during the Riphean. To sum up, in spite of having reliable data for the Middle and initial Late Riphean data for the Uchur-Maya and Turukhan regions, and for the Yenisei mountain range, we cannot be sure of the fact in which hemisphere the Siberian platform was situated in that time.

[6] *Kirschvink et al.* [1997] offered an Inertial Interchange True Polar Wander (IITPW) hypothesis, growing more and more popular, which is based to a significant degree on the paleomagnetic data obtained by this author for the Lower Cambrian rocks of East Siberia. However, this hypothesis need be verified because of the indefinite choice of the paleomagnetic pole of that time. The IITPW hypothesis suggests that the redistribution of rock masses in the lithosphere and mantle during the Lower Cambrian caused a change in the Earth inertia axes: the axis corresponding to the maximum moment of inertia became an axis with the intermediate moment, and vice versa. The change of the axes caused a rapid (15–20 million years) displacement of the lithosphere and mantle relative to the Earth rotation axis, that is, caused a significant displacement of the pole relative to the surface of the planet, which in turn triggered the significant tectonic, paleogeographic, climatic, and biospheric reconstruction of the planet at the beginning of the Cambrian. Since the IITPW hypothesis implies the significant displacement of the paleomagnetic pole in Vendian-Early Cambrian time, we must have modern reliable data for the Vendian and Early Cambrian paleomagnetic poles, which will allow us to prove or discard this widely discussed hypothesis.

[7] The collection of these data for the Siberian Platform and of similar data for the second half of the Late Riphean would be sufficient to test the IITPW hypothesis, to clarify the time of the final breakup of Rhodinia, to combine the Paleozoic and Riphean trends of the curve for the final migration of the Siberian pole, to determine the polarity of the Riphean paleomagnetic trends, and to advance substantially in the solution of other important problems.

[8] The aim of this study was to determine the reliable Vendian paleomagnetic poles of the Siberian Platform for plotting the Siberian curve of the apparent pole migration, necessary for solving the problems mentioned above. For this purpose detailed paleomagnetic studies of Vendian reference rock sequences were performed in the southwest of the Siberian Platform. The results of these studies are reported in this paper.

Objects of Study: Geology and Age

[9] During the field work done in 2001–2003 we collected Late Precambrian rock samples in the area of the Yenisei Ridge and also in the Biryusa and Central Sayan areas. Some reconnaissance work was done in the Yenisei Ridge to study the rocks of the Lower Cambrian Kliminskaya Formation.

[10] In the Yenisei Ridge (Figures 1 and 2), following the Angara, Irkineeva, and Taseeva rivers, we studied the variegated terrigenous and terrigenous-carbonate rock sequences of the Taseeva Series (Alesha, Chistyakova, and Moshakova formations) of Late Riphean (?) to Vendian age, the Redkolesnaya and Ostrovnaya formations of Vendian age, and the Kliminskaya Formation of Lower Cambrian (Atdabanian) age, and the Kliminskaya Formation of Lower Cambrian (Atdabanian) age [*Rozanov et al.,* 1992].

[11] The Alesha Formation consists of red and cherry-red polymictic sandstones. Samples were collected in the stratotype rock sequence at the right bank of the Taseeva R., below the Usolka R., from the Antoshka horst.

[12] The Chistyakova Formation is represented by gray and greenish gray polymictic sandstones with scarce dolomite interlayers. Samples of the green rocks were collected along the Angara R.: (1) at its left bank below the Man'zya Settlement; (2) at the right bank above the Greben Rock (Shalyga brachyanticline), and (3) at the right bank of the Taseeva R. below the Usolka R.

[13] The Moshakova Formation consists of brick-red and cherry-red sandstones and siltstones of quartz and feldspar-quartz composition. Samples were collected along the Angara R.: (1) at its left bank below the Man'zya Settlement and (2) along its right bank about 2 km below the Gremyachiy Creek to the Greben Rock.

[14] The Redkolesnaya Formation is composed mainly of brick-red, inequigranular, quartz-feldspar sandstone, some of the layers including reddish and greenish siltstone interbeds. Samples of these rocks were collected at the right bank of the Angara R. below the Gremyachiy Creek and in two outcrops at the left and right banks of the Irikineeva River (Irkineeva High) ~30 km and 27 km above the river mouth, respectively.

[15] The Ostrovnaya Formation is composed mainly of light-color dolomite alternating with layers of red dolomite marl and dolomite-bearing siltstone, this rock sequence being completed by brownish dolomitic sandstone. Samples of the red rocks were collected at the right bank of the Angara R., above the Gremyachiy Creek.

[16] The Kliminskaya Formation is composed mostly of dolomite and dolomitized limestone with the scarce interbeds of reddish-brown quartz sandstone. The red rock sam-

ples were collected at the right bank of the Taseeva R. at the base of the Dyrovatyi Cliff (Upper Taseeva anticline). The total number of the oriented samples collected from the Precambrian-Cambrian rocks of the Yenisei Range was about 450.

[17] The study objects belong to the eastern zone of the Yenisei Range and are represented by the deformed sedimentary cover of the Siberian Craton. As follows from the data available [*Orlov,* 2002], the folded structure of the Yenisei Range was shaped during several time periods ranging from the Precambrian to the Mesozoic. The modern structural pattern of the range was formed as late as the Early Jurassic [*Makarenko,* 1971]. The frequent rearrangements of the structural style are recorded by frequent erosion scarps and angular unconformities [*Orlov,* 2002]. The platform sedimentary cover of the Yenisei Range includes several structural stages: Late Riphean–Lower Cambrian, Middle-Late Cambrian–Early Ordovician, Carboniferous-Permian, Early Triassic, Early Jurassic, and Cenozoic.

[18] Studied in the Biryusa area of the Sayan region were the variegated terrigenous and terrigenous-carbonate rocks of the Aisa (Late Riphean (?)–Vendian) and Ust-Tagul (Vendian) formations in a series of outcrops along the Biryusa and Tagul rivers in the areas of the Serebrovo and Georgievka villages up to the area where these rivers flow together (see Figures 1 and 3).

[19] The Aisa Formation (the upper member of the Oselkova Series) is represented by the alternation of variegated polymictic sandstones, siltstones, argillites.

[20] The Ust-Tagul Formation rests with erosion and without visible unconformity on the rocks of the Aisa Formation and consists of two subformations. The lower subformation is composed mainly of red terrigenous rocks, ranging in particle size from conglomerates to argillite; the upper subformation is represented by terrigenous-carbonate rocks with interbeds of red sandstone and siltstone. About 180 oriented samples were collected from the Biryusa area of the Sayan region.

[21] The structural features investigated during this study are deformed monoclines of the NW-SE strike (from $\sim 120^\circ$ to 160°) dipping to the northeast at the angles of 7° to 35°. The modern fold structure of the Biryusa Sayan region was not formed during some single act event: the platform cover includes seven structural units: Late Riphean, Late Riphean–Vendian, Late Vendian–Early Cambrian, Middle-Late Cambrian, Ordovician–Silurian, Early Devonian, and Jurassic. On the whole, the region has a "general" monoclinal structure with the steady growth of the rock sequence to the northeast (that is, toward the center of the platform) [*Nalivkin,* 1967].

[22] Studied in the Central Sayan area (Figure 1) were the Vendian variegated terrigenous and terrigenous-carbonate rocks of the Mota (Shaman) and Irkutsk formations in two outcrops at the left bank of the Urik River, higher than the Shankhar Settlement, at a distance of about 5 km from each other.

[23] The Mota (Shaman) Formation is represented in the outcropping part of its sequence in the Krasnaya Mt. by a thick ($\sim$190 m) sequence of red fine-grained sandstones and siltstones. This outcrop is a gentle monocline with an average azimuth of 330° and a dip angle of 5°.

[24] The rocks of the Irkutsk Formation rest conformably on the rocks of the Mota Formation, have a terrigenous-carbonate composition, and are about 160 m thick. Samples were collected from the red and green rocks in the middle of the Seraya Mountain rock sequence (from Member 4, after [*Khomentovskiy et al.,* 1972]) and from the Urik variegated rock member crowning the Irkutsk Formation rock sequence in this region. The azimuth dip of the Urik rocks is 80° and dip angle 14°. 107 oriented samples were collected from the outcrops in the Urik R. outcrops.

[25] According to the modern views, the Late Precambrian rocks of the Sayan area and Yenisei Range area showed a fairly good correlation (Figure 4). However, because of the highly scarce fauna remains, the regional correlation was based mainly on the known historic events [*Khomentovskiy and Postnikov,* 2001; *Khomentovskiy et al.,* 1972]. Although the upper boundary of the Vendian rocks (traced along the top of the Nemakit-Daldynian rocks) in the southwest of the Siberian Platform is now fairly well supported by stratigraphic data. For instance, in the Yenisei Range the basis of the Tommotian Stage was placed in the vicinity of the basis of the Usolie (Irkineeva) Formation [*Khomentovskiy et al.,* 1998]. Yet, the boundaries of the "intra-Vendian" rock units and the position of the Vendian bottom are still the matter of hot discussion (see Figure 4). Recently, Yu. K. Sovetov discovered diamictite boulders, similar in lithology to tillite [*Sovetov,* 2002a, 2002b, 2002c]. Similar rocks were found by him in a number of other stratigraphic analogs of the Oselkova rock series (in particular, in the Taseeva rock series. This allowed *Sokolov* [1997] to combine these rocks into one tillite unit, corresponding to the Varangerian glaciation in terms of its Lower Vendian volume. Later, *Sovetov* [2002b] included the Aisa Formation into the Kotlin Horizon of the Upper Vendian rocks of the East European Platform [*Sovetov,* 2002b], that is, to the Late Ediacarian level in terms of Siberia.

[26] These views contradict the conventional views concerning the Vendian stratigraphy in the southwest of Siberia [*Khomentovskiy et al.,* 1972; *Kochnev,* 2002], according to which the Vendian basement is placed in the regions discussed at the bases of the Ust-Tagul and Redkolesnaya formations, and the underlying rocks of the Taseeva and Oselkova rock series are ranked as Baikalian (Late Riphean). At the same time, the recent isotopic and geochemical studies ($\delta^{13}C$ and $^{87}Sr/^{86}Sr$) of the rocks of the Baikalian Series in the stratotype area, compared with the standard ones, suggested the Vendian (pre-Nemakit-Daldynian) age of these rock sequences [*Letnikova et al.,* 2004]. Moreover, *Kochnev* [2002] discovered the traces of living organism activity at the base of the lower subformation of the Ust-Tagul Formation. These organisms were identified by D. V. Grazhdankin (Academic Institute of Paleontology) as *Treptichnus pedium*, which is known to be typical of the Nemakit-Daldynian Stage basement.

[27] In other words, these data suggest the Vendian age of the Taseeva and Oselkova rock series. Summing up the data accumulated by the present time for the Vendian rocks of the study areas, we can suggest the following reference ages for the Vendian rocks (Figure 4): (1) the basement of the

Vendian rocks correlates with the basement of the Oselkova rock series in the Biryusa area of the Sayan region; (2) the basement of the Nemakit-Daldynian Stage is located in the vicinity of the bottom of the Ust-Tagul Formation in the Biryusa area of the Sayan region, which suggests that the underlying rocks of the Aisa Formation of the Oselkova Series can be dated Ediacarian or some of its part; (3) the top of the Vendian (the boundary between the Nemakit-Daldynian and Tommotian stages) corresponds to the top of the island rock sequence of the Yenisei Range; (4) the Redkolesnaya Formation of the Yenisei Range may include the rocks of the Nemakit-Daldynian and Ediacarian (Vendian) rocks of the Vendian age, as has been proved by the finding of the *Cyclomedusa ex. gr. Davidi* fauna remains [*Chechel,* 1976].

[28] Up to now, no confident chemo- or biostratigraphic and geochronological data have been obtained to prove the Vendian age of the rocks of the Mota and Irkutsk formations in the Central Sayan (Urik R.). Therefore, in this paper we use the stratigraphic correlation version offered by *Kochnev* [2002]. According to this version, the stratigraphic units identified agree with the Ust-Tagul Formation of the Biryusa area of the Sayan region and can be attributed to the Nemakit-Daldynian Stage of the Vendian.

Paleomagnetic Analysis

[29] The processing of the samples was carried out at the Paleomagnetic Laboratory of the Paris Earth Physics Institute, at the Paleomagnetic Laboratory of the St. Petersburg Geological Institute, and at the Main Magnetic Field Laboratory of the Institute of Physics of the Earth, Russian Academy of Sciences. Measurements were made using a 2G Enterprise vertical SQUID magnetometer and JR-4 and JR-5 spin magnetometers. All samples were subjected to stepwise temperature demagnetization at temperatures of up to 560–680°C with the number of cleaning steps ranging from 10–15 to 18–20. The rock samples were demagnetized using special nonmagnetic stoves of the Schonstedt Instrument Company with a noncompensated field value of not more than 5–10 nT (TSD-1), and also the stoves manufactured at the laboratories of the Institute of Physics of the Earth and IPGP. Most of the measurements were made in the space screened off from the outer geomagnetic field. The measurement results were processed using the Enkin computer program package *Enkin* [1994], which identifies magnetization components by the PCA method [*Kirschvink,* 1980]. The SELECT program package, developed by *Shipunov* [1995], was used to calculate the intersection points of small circles and to perform the fold test (NFT).

Analysis of the Magnetization Components

Biryusa Area of the Sayan Region

[30] **Aisa Formation.** The large number of the study samples contain a noisy paleomagnetic signal, difficult to interpret, and characterized by the presence of several magnetization components with the overlapping spectra of the blocking temperatures. The pattern of the paleomagnetic record is somewhat different from one outcrop to another. Yet, each outcrop shows a confident magnetization component, which is referred to as a medium-temperature one in the text that follows. This component is a monopolar one, has a NW magnetic declination and intermediate inclination and decays over a wide temperature range, varying sometimes from 100°C to the Curie point of hematite. Its typical destruction interval varies form 250° to 500–560°C. In the Zijderveld diagrams (ZD) (samples B109 and B119 in Figure 5), its mean temperature component usually does not "move" to the origin of the coordinates, suggesting that the samples may often contain some more stable, high-temperature component. In some samples, in spite of the obvious presence of the high-temperature component, the latter could not be identified because of the beginning chemical alterations recorded by the notable growth of the magnetic susceptibility of the samples and resulting in the chaotic or quasichaotic behavior of the NRM vector at the high cleaning temperatures. Nevertheless, we managed to identify, with a variable accuracy, the most stable high-temperature magnetization component in 40 out of the almost 100 samples collected from the Aisa Formation. This component showed its bimodal distribution in the stereogram, its low inclinations, and SSW (NNE) declinations (see Figure 10). It was most often recorded in a fairly narrow temperature range from 600° C to 680°C (see Samples 243 and B148 in Figure 5), although there were some scarce exceptions.

[31] One of the outcrops studied in the Tagul R. area showed another stable component (see Sample 243 in Figure 5), which is referred to below as an intermediate one. This component disintegrated in the temperature range of 540–640°C and showed a trend close to that of the high-temperature component with southern declination and low inclination. In fact, the more or less confident recording of this component in the outcrop discussed was possible only because of the fact that the high-temperature component has a different polarity here. The problem of the time of this component formation relative to the high-temperature component will be discussed here somewhat later. The traces of the presence of the intermediate component have also been discovered in analyzing the Zijderveld diagrams of another Tagul outcrop. However, the trend of the intermediate in this outcrop could not been determined because of the high effect of the blocking spectra of the magnetization components.

[32] It is worth mentioning that the study samples did not show any modern component, which is usually widespread in all rock types as a low-temperature and poorly stable one. The magnetization vectors, destroyed in the low-temperature region of 100–250°C are distributed irregularly

(laboratory viscous magnetization?) possibly with some potential very poor grouping around the trend of the medium-temperature component.

[33] **Ust-Tagul Formation.** The magnetization of the rocks of this formation is distinguished usually by the presence of several magnetization components, often with the significant overlapping of their blocking temperature spectra. This is aggravated by the chemical alteration of the rocks, which often begins where the heating temperature is higher than 550–600°C. Thus, the identification and trend calculation of the magnetic components (especially, of the high-temperature component) in the study rocks of the Ust-Tagul Formation is not a simple and sometimes an unsolvable problem. Nevertheless, considering the general fairly unfavorable background, some of the study samples allow one to identify and classify their magnetization components.

[34] The low-temperature range (20–250°C) showed a poorly stable component, often with high inclination and variable declination, which can be interpreted as some irregular mixture of laboratory viscous, modern, and partially middle-temperature components.

[35] Similar to the rocks of the Aisa Formation, the Ust-Tagul samples showed the most distinct medium-temperature component, usually not extending to the origin of the coordinates and destructible in the temperature range of 250° to (500–600)°C (see Samples 173 and 286 in Figure 5). This is a monopolar component with NW declination and moderate inclination. In some cases (see Sample 173 in Figure 5) this component can be the only magnetization component in the study sample.

[36] The high-temperature component (see Samples 298, 274, and 166 in Figure 5) is usually distinguished in the temperature range higher than 600°C, although it often begins to decay significantly earlier in the temperature range, where the contribution of the medium-temperature contribution is fairly significant. The overlapping of the medium- and high-temperature components often leads to the fairly complex behavior of the paleomagnetic signal in the temperature range of 500–600°C. There are individual samples, where the contribution of the medium-temperature component is insignificant compared to that of the high-temperature component. In such cases, the behavior of the NRM vector is controlled in the course of cleaning mainly by the presence of the high-temperature component (see Sample 298 in Figure 5). Most of the identified vectors of the high-temperature component showed NNE declination, moderate and low (up to negative) inclination, and also SSE declination and low inclination. In the text that follows we attempt to demonstrate that the distribution of the high-temperature component vectors can be explained by the superposition of two highly temperature-stable components.

Central Sayan Region

[37] **Urik R. outcrops.** The samples of our collection, representing the Mota and Irkutsk formations, have similar paleomagnetic properties and, hence, are discussed here together.

[38] Similar in age and lithology to the rocks of the Ust-Tagul Formation, the samples collected in the outcrops of the Urik R. Valley, demonstrate the presence of several magnetization components often with the overlapping blocking temperature spectra. The low-temperature component, which is removed toward the temperature of 200–250°C tends to follow the modern field trend and seems to be largely a mixture of the modern and laboratory viscous components. The mean temperature component (Samples 151 and 25 in Figure 6) was identified in a number of samples over a wide temperature range, from 200–250°C to 550–620°C, showing NNW declinations and moderate inclinations. In some samples the spectrum of the deblocking temperatures of the mean-temperature component was found to extend as far as the Curie point of hematite, involving problems with its identification, because its maximum deblocking temperatures are similar to those of the component, which is referred to below as the high-temperature component. The identification criterium of this component was chosen in this study to be the width of the unblocking temperature spectrum, which is usually significantly lower in the high-temperature component.

[39] The high-temperature magnetization component (see Samples 16, 21, 59, and 182 in Figure 6) was identified confidently only in relatively few samples (usually at temperatures higher than 600°C), although some traces of its presence could be found in much more samples. The maximum deblocking temperatures of this component are close to 680°C, which proves that the carrier of this component is hematite. Generally speaking, the spectra of the deblocking temperatures suggest that the carrier of informative components, discussed in this paper, is hematite. Our thermomagnetic analysis of individual samples confirmed this conclusion. Similar to the Ust-Tagul Formation, the high-temperature magnetization component of the samples collected from the Urik outcrops shows either NNE declinations and moderate to low (up to negative) inclinations, or SSW declinations and low inclinations.

Yenisei Mountain Range

Alesha and Chistyakova Formations

[40] **Taseeva R. area.** Most of the rock samples collected in the Chistyakova Formation did not show any regular paleomagnetic signal. Most of the rock material that remained after our magnetic cleaning showed the behavior similar to that of the samples of the Alesha Formation.

[41] The results of the magnetic cleaning allowed us to identify conventionally the low-temperature magnetization which was often destroyed in the temperature range of 350–400°C and showed a trend similar to the trend of the modern geomagnetic field. In some cases this component was found to be very stable and was destroyed finally only at the Curie point of hematite (Figure 7, Sample TS594). In our opinion,

this component is of recent origin and has a chemical nature.

[42] A few tens of the nearly 80 study samples showed a high-temperature component at the temperatures higher than 600–620°C (Samples TS480, TS483, and TS506 in Figure 7). This component showed a fairly complex distribution pattern which will be discussed somewhat later.

Moshakova and Chistyakova Formations

[43] **Outcrop in the vicinity of the Man'zya Settlement.** The samples of the Moshakova and Chistyakova rocks, collected in the vicinity of the Man'zya Settlement, showed a very poor quality of the paleomagnetic record. Mane samples showed the irregular, quasichaotic variation of the NRM value and trend in the coarse of cleaning. The magnetization trend of most rock samples varied spasmodically, during the successive heatings from 100°C to 450–550°C, around or in the vicinity of the modern geomagnetic field trend, suggesting the presence of some recent magnetic component. At higher temperatures the NRM vector showed a chaotic behavior. In some samples the background was superposed at 300–400°C by some intermediate component, distinguished by a great scatter, SE, S, and SW declinations and moderate inclination. Averaged for eight samples, this component showed D=180.9°, I=46.4° with K=7.6 and α_{95}=21.1 in the modern system of the coordinates, and D=189.3° and I=39.8° with K=7.5 and α_{95}=21.6 in the old coordinate system. It is obvious that this estimate of the intermediate component is very approximate not only because of the low grouping and high α_{95} values, but also because of the obvious overlapping of this component spectrum with the spectra of the other magnetic components and because the highly noisy paleomagnetic signal. Here, we mention the presence of this component only for the sake of the complete description and similarity of its trend with the trend of the metachronous component identified earlier while studying the Ordovician reference rock sequence in the middle course of the Angara River in the vicinity of the Rozhkov R. mouth [*Shatsillo et al.,* 2004].

[44] Some of our samples showed a component similar to the component described below as a medium-temperature component for the outcrops of the Moshakova and Chistyakova suites in the vicinity of the Greben Cliff. This component decayed in the temperature range of 250–600°C and showed NW declination and moderate inclination (in the modern and old systems of the coordinates). We failed to identify this component in its uncontaminated form.

[45] Finally, in the temperature range of 500–530°C to 680°C we identified a high-temperature magnetization component in several samples (Samples MN194 and MN227 in Figure 8), which showed mainly SSE declination and low inclination. This component was also identified in the rocks of the same age outcropping in the vicinity of the Greben Cliff. For this reason the data obtained for the high-temperature magnetization component of the samples collected from these outcrops will be discussed below together.

[46] **Outcrops in the Greben Rock vicinity.** The quality of the paleomagnetic signal recorded in the rocks of the Chistyakova and Moshakova formations in the series of the outcrops located in the vicinity of the Greben Rock is not much better than that of the samples collected from the outcrop in the vicinity of the Man'zya Settlement. Their main difference is the more clearly manifested medium temperature component which decays at the temperatures of 250–550°C and shows the NW declination and moderate inclination, as well as the presence of the relatively larger number of samples including a high-temperature component, the latter almost always showing the maximum blocking temperatures in the vicinity of the hematite Curie point. The recording interval of this component and its preservation seem to be associated with the development of remagnetizing components in the samples, namely, of the low-temperature modern component and of the medium-temperature of the metachronous one (as will be discussed below). On the whole, the NRM behavior of the samples, collected from these outcrops, in the course of their cleaning, can almost always be explained by the development of these components and by their overlapping deblocking temperature spectra. The examples of the Zijderveld diagrams demonstrating the presence of low-, medium-, and high-temperature components are shown in Figure 8 for the sample numbers of AA381, AA429, AA439, AA441, and AA452.

Redkolesnaya Formation

[47] **Outcrops in the Irkineeva R. Valley.** We examined two outcrops of the Redkolesnaya rocks in the Irkineeva R. Valley. One of them, located up the river on its left bank, is composed mainly of brown and cherry-red, medium-grained sandstones. In the course of cleaning, the NRM vector trends of these samples varied irregularly or grouped with a large scatter around the trend of the modern geomagnetic field at the heating temperatures higher than 400–450°C. At the same time, some samples showed an easily interpreted paleomagnetic signal demonstrating the presence of the low- and high-temperature magnetization components (see Sample IRK145 in Figure 9). The former was almost completely destroyed at 350–500°C, being close to the trend of the modern geomagnetic field, the latter showed the maximum deblocking temperatures in the vicinity of the hematite Curie point, northern declination, and moderate positive inclination. A few samples from this outcrop showed a high-temperature component of opposite direction.

[48] In the other outcrop, located somewhat lower along the river at its right bank, the study rocks were represented by more fine-grained siltstone varieties of reddish and greenish colors. The paleomagnetic record was much more distinct there. The temperature cleaning showed the undoubted presence of two components: a conventionally low-temperature one with its direction close to that of the modern field and a high-temperature one showing mainly southern declinations and moderately negative inclinations (see Sample IRK-174 in Figure 9). The former component showed a significant destruction in the temperature range of

100–400°C, although in some cases the spectrum of its deblocking temperatures extended to higher-temperature regions and was overlapped significantly by the spectrum of the high-temperature component. In these cases the latter was difficult or impossible to identify. Nevertheless, a fairly large number of samples showed their high-temperature components at high temperatures (550–600°C).

[49] **The outcrops in the vicinity of the Greben Cliff.** The NRM values of the rock samples collected in several outcrops at the right bank of the Angara River, higher than the Greben Rock, usually show two magnetization components (see Samples ANG327 and ANG330 in Figure 9), namely, a low-temperature one with the single vector trends scattered around the trend of the modern magnetic field and a high-temperature magnetization component with the maximum blocking temperatures of 650–680°C. In some cases where the effect of the low-temperature component was low, the Zijderveld diagrams showed one high-temperature component with the deblocking temperatures ranging from 200°C to the Curie point of hematite (see Sample ANG331 in Figure 9). There were also some opposite cases where the "low-temperature" component predominates and even replaces wholly the high-temperature component up to the region of temperatures higher than 600°C. In most of the cases the high-temperature component shows NNE declination and moderate positive inclination. There are only a few examples where the Zijderveld diagrams showed the presence of the high-temperature component of opposite polarity. Unfortunately, in these cases, with only one exception, the high-temperature component could not be identified because of the overlapping of the blocking temperature spectra.

[50] **Ostrovnaya Formation.** The rock samples of this formation usually contain "noisy" paleomagnetic signal which cannot always be interpreted confidently. Some samples showed the directions which were not repeated in any other samples, that is, were not characteristic in the Zijderveld sense [*Zijderveld,* 1967]. In other samples the spectra of different components overlap in such a manner that the Zijderveld diagrams do not show any rectilinear segments. Nevertheless, even in the case of this generally unfavorable background, there are some samples which show though a nosy, yet, a regular paleomagnetic signal repeated in other samples. The samples of this kind usually show two magnetization components: the low-temperature component (decays toward the temperature of 300–350°C), scattered in its direction around the modern magnetic field, and an old high-temperature component of N and NNE declination and moderate to low inclination, the maximum blocking temperatures being around 590–600°C and 680°C. Some samples showed the opposite polarity of the ancient high-temperature magnetization (see Samples AA269, AA270, AA278, and AA300 in Figure 8). It should be noted that generally the character of the record and the distribution of high-temperature components in the rocks of the island-arc formation are close to those described in the rocks of the Mota, Irkutsk, and Ust-Tagul formations of the Sayan Region, having the same age. Some of the samples showed the medium-temperature, unipolar component of NW inclination and moderate positive declination (Figure 8, Sample AA305), similar to the medium-temperature component of the Moshakova and Chistyakova rock samples collected from the outcrop in the vicinity of the Greben Rock.

[51] **Kliminskaya Formation.** The samples collected in the rocks of this formation clearly showed a component with NW declination and moderate to low inclinations (in the modern system of the coordinates), see Samples TS524 and TS603 in Figure 7. Since in many cases this component overlies obviously some higher-temperature component, it is here referred to as the medium-temperature component, even though the spectrum of its blocking temperatures (beginning from 200–250°C) extends to 600°C and higher temperatures and has NNE declination, often being the only one stable component. The high-temperature component (see Samples TS533 and TS609 in Figure 7) was identified in 3–4 samples and has NNE declinations and low inclinations (in the old system of the coordinates).

Analysis of Paleomagnetic Trends

High-Temperature Components of the Aisa, Chistyakova and Moshakova Formations

[52] The high-temperature (HT) component identified in the rock samples of the Aisa Formation shows in the stereogram two almost antipodal clusters (Figure 10 and Table 1), which nevertheless show significantly different mean values (with the 180° reversal of one of them), namely, $\gamma/\gamma_{\rm cr} = 23.4°/14.9°$. This fact might have been indicative of the different ages of the direct and reverse polarity magnetization.

[53] However, taking into account the high noise of the signal, as well as the high overlapping of the magnetic component spectra, clearly seen in the analyses of the Zijderveld diagrams, we believe that differences in the mean directions are associated with these circumstances.

[54] Our fold test, performed both at the level of sites and rock samples, gave an indefinite result for the high-temperature component.

[55] The time of the HT component formation, identified in our study of the rocks of the Aisa Formation, can be reconstructed by comparing it with the high-temperature magnetization component of the rocks of the Chistyakova and Moshakova formations, which are comparable in age with the rocks discussed.

[56] This component also shows a bipolar distribution (Figure 11 and Table 2), yet, in contrast to the Aisa high-temperature component, passed a reversal test ($\gamma/\gamma_{\rm cr} = 1.8°/19.9°$). The fold test, carried out in its different modifications, proved its prefolding age (Table 2). All of these data suggest that the HT component of the Chistyakova and Moshakova rocks was formed during or soon after the deposition of these rocks.

[57] The paleomagnetic pole calculated for the high-temperature component of the Chistyakova and Moshakova

formations (Table 3) does not differ statistically from the respective pole of the Aisa Formation ($\gamma/\gamma_{\rm cr} = 6.9°/8.8°$). On the one hand, this supports the above conclusion, on the other hand, this allows us to rank the high-temperature magnetization component, identified in the Aisa Formation, as a primary one. It is important to note that the comparison of the respective poles, computed proceeding from the trends obtained in the modern coordinates, revealed that the angular distance between them grows and their difference becomes significant ($\gamma/\gamma_{\rm cr} = 15.5°/13.1°$). The latter means that the fold test, performed at the regional scale also gives the positive result.

[58] The fold test performed for the combined data sample including the paleomagnetic poles, calculated for the sites of the Aisa, Moshakova, and Chistyakova formations also suggests the pre-folding age of the magnetization.

[59] To sum up, the data obtained in this study prove with a high degree of confidence that the high-temperature components of the rocks of the Aisa, Moshakova, and Chistyakova formations originated during or soon after the accumulation of these rocks.

Medium-Temperature Magnetization Component of the Aisa and Ust-Tagul Formations

[60] The distribution of the vectors of the medium-temperature (MT) magnetization component in the rocks samples of the Aisa and Ust-Tagul formations is shown in Figure 10. In the stereograms, these vectors produce distinct clusters with the crowding notably greater in the ancient (stratigraphic) system of the coordinates, compared to the modern geographic system (Table 4). Both of the fold tests used in our study, namely, the Enkin test and the Shipunov NFT test, positively suggest the pre-folding age of the formation of the medium-temperature magnetization components of the Aisa and Ust-Tagul rocks. The comparison of these rocks showed that the trends of their MT components did not differ significantly in terms of their statistics ($\gamma/\gamma_{\rm cr} = 5.9°/6.2°$[*McFadden and McElhinny,* 1990]). This proves their almost simultaneous origin, and allows us to discuss them simultaneously. Our simultaneous analysis of the rocks of both formations suggested the pre-folding age of the medium-temperature component.

[61] The age of the MT component could be determined proceeding from the following considerations: first, it cannot be older than the Nemakit-Daldynian (the age of the Ust-Tagul Formation), secondly, the position of its respective paleomagnetic pole is clearly different from the positions of all Siberian paleomagnetic poles, beginning from the Amga one (Middle Cambrian onset). Therefore, the medium-temperature component of the magnetization of the rocks of the Aisa and Ust-Tagul suites took place either at the very end at the Vendian, or during the Early Cambrian. Therefore, since the computed pole resides in the direct vicinity of the Toyonian paleomagnetic pole [*Gallet et al.,* 2003], we have all reasons to believe that the component discussed can be dated Toyonian.

[62] It is of interest to compare our results with the data reported by *Gurevich* [1981], who studied the paleomagnetism of the Aisa and Ust-Tagul rocks about 25 years ago. Having studied more than 300 rock samples, E. L. Gurevich got very similar paleomagnetic poles for the rocks of these formations, namely, Plat=−53°, Plong=116°, A95=3° for the Aisa rocks and Plat=−56°, Plong=110°, A95=3° for the Ust-Tagul rocks. On the basis of these data he derived a conclusion concerning the absence of any significant latitudinal motions for the southern part of the Siberian Platform during the Late Precambrian.

[63] Our data, based on the significantly more detailed and intensive cleaning, confirmed the existence of the magnetization component identified by E. L. Gurevich. However, there are good grounds to believe that the trend reported by him agrees with our medium-temperature component (see Table 3), which seems to be a metachronous one, yet originated not much later than the time of the accumulation of the rocks that show this component.

Medium-Temperature Component of the Mota and Irkutsk Formations in the Urik R. Rock Sequence

[64] The practically horizontal bedding of the rocks in this sequence does not allow one to date confidently the origin of the medium-temperature magnetization component, relative to the folding age (Figure 12 and Table 4). Yet, since the time of the dislocation of the rocks in the Urik R. Sequence is unknown, even the results of the fold test could not allow us to tie the age of the medium-temperature component formation to the time scale. At the same time, we know that the paleomagnetic pole calculated using this component (both in the geographic and stratigraphic systems of the coordinates) resides close to the pole of the medium-temperature component, identified as a result of our study in the rocks of the closely spaced region, in the Biryusa R. and Tagul R. rock sequences. The formal test reported by *McFadden and McElhinny* [1990] confirms that the statistical difference of these poles is insignificant. This justifies our conclusion that the medium-temperature component of the Mota and Irkutsk formations in the Urik R. section originated roughly at the same time, when the medium-temperature component originated in the rocks of the Biryusa-Tagul objects of study.

Medium-Temperature Component in the Outcrops of the Moshakova, Chistyakova, and Ostrovnaya Formations in the Area of the Greben Rock, Yenisei Ridge

[65] The distribution of the vectors of the medium-temperature magnetization component in the outcrops of the rocks of the Moshakova, Chistyakova (Gr) and Ostrovnaya (Ostr) formations in the area of the Greben Cliff is presented in Table 5 and in Figure 13. The fold test in the Enkin modification, performed in our study at the level of sites, suggested the prefolding age of the MT component. However, the procedure of the proportional, 60-percent straightening of the folds in the respective curve showed the distinct crowding maximum, which could record the synfolding age

of this component formation. To verify this hypothesis, we used the Watson-Enkin test [*Watson and Enkin,* 1993], the result of which showed, with a 95-percent probability, that this component originated at the time when the deformation of the study rocks amounted to 38.0–82.8% of their present-day deformation, which suggests the magnetization to be a synfolding process. The NFT test performed by *Shipunov* [1995] confirms this result. The calculated paleomagnetic pole resided in the area between the Tommotian [*Pisarevsky et al.,* 1997] and Toionian [*Gallet et al.,* 2003] poles of the Siberian Platform, which allows us to suggest the Early Cambrian age of the medium-temperature component concerned.

Intermediate-Temperature Magnetization Component of the Aisa Formation

[66] Unfortunately, in the course of this study we failed to obtain a sufficient amount of information to date the intermediate component identified in two Biryusa outcrops of the Aisa Formation (see Figure 10 and Table 1). Moreover, the character of the Zijderveld diagrams, from which this component was obtained, does not allow us to be sure that we succeeded to get this component in its "pure" form and that its mean value was free from the effects of other magnetization components. We believe it possible to admit that the intermediate component is the "antipode" of the high-temperature component and that it originated at the stage of the early diagenesis in the course of the same process during which the high-temperature component was formed, or somewhat later, when the geomagnetic field had a different polarity. This component will not be discussed in this paper.

High-Temperature Magnetization Component of the Redkolesnaya Formation

[67] The distribution of the trends of the high-temperature (HT) magnetization component in the rocks of this formation exposed by the Irkineeva River and in those of the Greben Rock is shown in Figure 11 and in Table 6. The HT component identified in the outcrops of the river shows two polarities and produces two almost antipodal groups of the vectors. The reversal test gave a positive result (γ/γ_{cr} = 11.2°/13.9°), indicating that during the vector reversal of one of these groups, the difference between the average groups is statistically insignificant. The presence of the antipodal groups of the vectors and the positive result of the reversal test can be classified, on the one hand, as the argument in favor of the primary character of the magnetization identified, and on the other hand, as an indication of the "purity" of its identification, that is, the absence of any significant admixture of other magnetization components in the component identified in the Irkineeva River outcrops.

[68] Unfortunately, because of some difficulties of separating the magnetization components described above, this statement cannot be applied to the rocks studied in the Greben Rock area. The fact that the angular distance between the average trends of the direct and reversed polarity, calculated using the trends identified using the outcrops of the Greben Rock, is higher than its critical value (γ/γ_{cr} = 13.0°/8.0°) confirms this apprehension. Nevertheless, even in this case the deviation from the antipode pattern is not high suggesting that during the averaging of the vectors of the resulting trend of the HT (high-temperature) component would be slightly displaced relative to its true value.

[69] Taken separately, the data obtained for the outcrops of the Greben Rock do not allow one to perform a fold test (obviously, because of the low variations in the dips and strikes of the rocks). However, the fold test performed using the Irkineeva rock samples and also the whole collection of the Redkolesnaya rock samples proved the pre-folding age of the high-temperature component.

[70] The pre-folding magnetization, the presence of the antipodal groups of the vectors, the difference of the calculated paleomagnetic pole (Table 3) from all of the known younger poles of the Siberian Platform, and the similarity of the average HT directions obtained for the rock sequences, remote from one another, prove that the high-temperature component identified in the Redkolesnaya rocks originated during or soon after the accumulation of the rocks.

High-Temperature Magnetization Components of the Ust-Tagul, Mota, Irkutsk, and Ostrovnaya Rock Formations

[71] The vector distribution of the high-temperature components of the rocks of the Ust-Tagul, Mota, Irkutsk, and Ostrovnaya formations are very similar (Figure 12). Proceeding from the close ages of these formations, this similarity can hardly be a random one, obviously reflecting the similar magnetization history of the respective rocks. In order to enhance the systematic constituent of these data distributions, all of the trends were recalculated to the geographical coordinates of the Ostrovnaya rock formation in the vicinity of the Gremyachiy Creek. The resulting total distribution of the high-temperature component vectors is shown in Figure 12. Presented in this Figure is the stereogram of the density distribution of the respective axes. The analysis of these stereograms revealed two obvious clusters corresponding to the two magnetization components, HT1 and HT2. The former, more distinct cluster consists of the vectors with northern and northeastern declinations and moderate positive inclinations (HT1 component). The latter cluster (HT2 component), which is less pronounced, yet, obviously existing one, includes the axes (trends) of NE (and SW) declinations and low (positive and negative) inclinations. All of the clusters are located not far from one another and include an overlapping region. Nevertheless, the distribution of their vectors (axes) suggests that the clusters can be confidently separated. The natural boundary for this separation is the distinct "saddle" clearly manifested between the clusters in the northeast of the stereogram for the density distribution of the axes. It is obvious that this separation is somewhat conventional, because it does not allow one to discard the vectors of the second cluster from the first cluster, which could get into it as a result of the statistical scatter, and

vice versa. The consequence of this must be some displacement of the calculated average trend of the first cluster toward the second one, and vice versa. Therefore our average data might have been displaced slightly relative to the true values. However, we hope that this systematic displacement could not be higher than the errors common for paleomagnetic studies.

[72] The average trends of the clusters (components) identified in this study are listed in Table 7. The fold test suggested the pre-folding age of the formation of these components.

The Stable Magnetization Components of the Kliminskaya and Alesha Formations in the Taseeva R. Rock Sequence

[73] **Kliminskaya Formation.** The high-temperature magnetization component of NNE declination and low inclination is close to the trend of the HT2 component which we identified in the rocks of the Ust-Tagul, Ostrovnaya, Mota, and Irkutsk formations. However, since this component was recorded only in a few out of the almost fifty samples of the rocks of the Kliminskaya Formation, we will not discuss it here and mention it just for the sake of our complete description.

[74] The medium-temperature magnetization component (see Table 8 and Figure 14) is of undoubted post-folding age, as follows from our Enkin and NFT tests.

[75] **Alesha Formation.** The vectors corresponding to the most stable high-temperature magnetization components of these rocks show a fairly complex distribution (Figure 14 and Table 8). However, the analysis of the distribution density of the axes, along which the vectors discussed were directed, the stereogram showed at least two clusters: a large SE-NW one and a smaller, yet, fairly distinct NE one with its center in the region of low inclinations.

[76] The last cluster corresponded to the magnetization component (here referred to as the C component), which showed a bipolar distribution and was ranked as a pre-folding one according to the Enkin and NFT tests.

[77] The C component was ranked as that of the "C" class [*McFadden and McElhinny,* 1990] of the reversal test ($\gamma/\gamma_{cr} = 17.7°/18.9°$) which can be taken, along with the positive fold test, as an argument in favor of its primary origin.

[78] The first cluster, which was examined carefully in the geographical system of coordinates, can be divided into two subclasses (see Figure 14), corresponding to two different magnetization components, namely, the A component (distinguished by its steep inclinations) and the B component. These subclusters and the vectors corresponding to them can be divided conventionally along the "saddle" located in the stereogram between their centers. The fold test performed after their division for the respective vector series showed, in both cases, a negative result, suggesting that the A and B components originated after the folding time. The A component coincided exactly with the trend of the modern magnetic field, which suggested its young age. The B component was found to be close in terms of its trend to the high-temperature component of the Redkolesnaya Formation which seems to be a primary one was formed at the end of the Vendian. At the same time the direct interpretation of the B component as the result of the remagnetization during the Redkolesnaya time is complicated by some difficulties associated with the presence in this region of the dislocated Early and even Late Paleozoic rocks (including the Permian ones). Ranking this fact as the indication that the folding of these rocks continued up to the end of the Paleozoic, then, proceeding from the fact that the direction of the B component is highly discordant to the Late Paleozoic–Cenozoic segment of the Siberian APWP curve, we face the problem that we cannot explain the observed trend in remagnetization terms.

[79] A similar problem arises during the interpretation of the medium-temperature component recorded by us in the Kliminskaya Formation. The pole corresponding to it rests in the vicinity of the Toyonian Pole of the Siberian Platform, suggesting some Early Cambrian remagnetization. On the other hand, if the rock deformation ended only toward the Permian, then, formally speaking, the age of this rock component must be later than Permian, which again leads to the contradiction between the observed trend and the trend corresponding to the APWP segment.

[80] The solution of this contradiction problem might be achieved by admitting the fact that the region of our study might have been poorly subjected to Post Early Cambrian deformation. This can be proved indirectly by the poor deformation of the Middle-Upper Cambrian rocks of the Verkholenskaya (Evenki) Formation [*Nalivkin,* 1968]. These rocks occur as a gently dipping synform, resting unconformably on the relatively steeply dipping rocks of the Taseeva and Kliminskaya rock series and the horizontal bedding of the Carboniferous rocks in the vicinity of the study area [*Nalivkin,* 1968]. This contradiction can also be explained by the assumption that the observed rock components occur as an undifferentiated mixture of magnetization components of different ages.

[81] Proceeding from the fact that the data available are definitely insufficient for solving this problem, we do not offer any conclusions concerning the formation time of the medium-temperature component of the Kliminskaya Formation and of the B component of the Alesha Formation. As for the C component of the Alesha Formation, we also restrain from confirming its primary character because the C component has been recorded only in one outcrop. Further studies must confirm or refute its primary character and the very fact of its real existence.

Estimation of the Reliability of the Results Obtained

[82] In the course of this study we derived several paleomagnetic determinations. Some of them were discarded as not sufficiently well founded (the data available for the Alesha and Kliminskaya formations from the Taseeva area). The remaining ones will be used here for the further interpretation.

[83] The data used here (Table 3) were obtained for the high-temperature magnetization components of the Aisa, Moshakova, and upper Chistyakova formations of the Taseeva Series. Proceeding from the fact that these sedimentary rock sequences are close in terms of their age [*Kochnev,* 2002; *Sovetov,* 2002a, 2002b, 2002c], and their paleomagnetic poles are not different statistically, we will discuss their common paleomagnetic pole obtained from the averaging of the data obtained for all of the informative outcrops (sites) of these rock sequences. The next important result we used in our study was the paleomagnetic pole calculated using the high-temperature component of the Redkolesnaya Formation. The poles corresponding to the high-temperature components, HT1 and HT2, of the Ust-Tagul, Ostrovnaya, Mota, and Irkutsk formations, and to the medium-temperature components of the outcrops from the Greben Rock area and from the valleys of the Biryusa, Tagul, and Urik rivers will be included into the discussion of the data obtained in this study.

[84] Before proceeding to the interpretation of these results, we will attempt to estimate their reliability. Several formal schemes were offered in the practice of paleomagnetology for this purpose [*Li and Powell,* 1993; *Pecherskiy and Didenko,* 1995; *Van der Voo,* 1993], which may differ in some details, yet, rely on similar criteria. Each of these schemes has its own merits and drawbacks. For this reason we decided to use in this study the most popular of them, namely, the Van der Voo scheme [*Van der Voo,* 1993], in which, irrespective of the fact whether a given paleomagnetic determination does or does not agree with the successively considered criteria, it gets its Qv estimate in terms of a seven-mark scale. The higher this estimate, the more reliable is the respective paleomagnetic determination. It should be noted that the procedure used to estimate the reliability of the paleomagnetic poles obtained (as expected during testing) using the primary magnetization, that is, the magnetization which was formed during the accumulation of the study rocks or soon after it. In our case, these are the Aisa-Taseeva AT pole, the RDK pole obtained for the rocks of the Redkolesnaya Formation, and also the HT1 and HT2 poles calculated using the respective components of the Ust-Tagul, Ostrovnaya, Mota, and Irkutsk formations. In the text that follows we attempt to estimate the reliability of our results using the R. Van der Voo method (see Table 9).

[85] 1. The ages of the study rocks were determined sufficiently well. The modern dating of the accumulation of the rocks of the Aisa Formation and of the formations of the Taseeva Series are based not on the direct geochronological data, nor on the biostratigraphic data, but on the basis of their geological history and inter-regional correlations. Moreover, the problem of dating these rocks Ediacarian (Vendian) or Late Baikalian (Late Riphean) is still a matter of hot discussion. Although the dating of the rocks discussed Late Baikalian or Ediacarian is not significant for the further discussion of the pre-Phanerozoic trend of the APWP of the Siberian Platform, our estimate of the former criterion is zero for the “AT” pole.

[86] As regards the RDK, HT1, and HT2 poles, the rocks for which they were obtained are treated by all researchers as Vendian. Moreover, the fauna findings and the chemostratigraphic data [*Chechel,* 1976; *Khomentovskiy et al.,* 1998] confirm that these rocks accumulated from the Late Ediacarian to the beginning of the Tommotian. This allows us to offer an estimate of 1 for the RDK, HT1, and HT2 poles in terms of the first criterion.

[87] 2. This result is based on more than 25 samples. The crowding of the vectors was higher than 10, the confidence angle was less than 16°. All of the estimates, except the estimate obtained for the HT2 pole, based merely on 11 samples, satisfied this criterion.

[88] 3. Our detailed laboratory measurements made using detailed magnetic cleaning and component analysis yielded the values satisfying this criterion.

[89] 4. The reliability of our paleomagnetic determinations was confirmed by the positive results of the field tests. All of the results reported in this paper were based on the positive results of fold and reversal tests.

[90] 5(a). All of the geological objects examined in this study were located in the areas the tectonic positions of which (the belonging to some or other craton or tectonic block) were defined exactly.

[91] The study rocks outcrop in the regions which are ranked by all of their researchers as the parts of the Siberian Platform. However, it should be taken into account that all of the study rocks are folded and belong to the regions which had experienced notable tectonic deformations, which often show significant faults some of them being of unknown kinematics. These circumstances admonished us from the mechanical application of the results obtained in this study to the whole of the Siberian Platform. For this reason, while choosing the strategy of studying the paleomagnetism of of the Vendian rocks in the southwest of the Siberian Platform, we preferred to study the largest number of the remote rock sequences representing different regions. The results obtained justified this approach. For each time interval, we obtained data for the rock sequences (RDK pole) from different, far-spaced regions (AT, HT1, and HT2 poles), which correlated well with one another, proving the absence of any notable rotations of the study objects relative to one another and relative to the Siberian Platform. This allowed us to refer our results to the whole of the Siberian Platform. The fact that our study areas were spaced far from one another ensured the absence of errors associated with the potential disregard of local tectonics.

[92] 5 (b). The good structural control provided the presence of reliable field data, necessary for the reconstruction of the initial (predeformation) positions of the study objects. The study rocks were perfectly layered. This allowed us to measure their strikes and dips, necessary to determine the trends of the magnetization component identified in the ancient (predeformation) system of the coordinates. The absence of any rotations around the vertical axes, which might have distorted significantly the directions of the ancient magnetization components in the course of their transformation to the stratigraphic coordinate system is proved, as has been mentioned above, by the similarity of the paleomagnetic trends obtained for remote objects. In the cases where we doubted the reliability of the structural control and where the old trends were determined only in some local areas (Taseeva rock sequence), we discarded the data

available.

[93] 6. In the cases where the study objects showed the vectors of the direct and reversed polarity with the statistical difference of 180°, the result obtained satisfied this criterion for the RDK and AT poles. The HT2 component was found to be bipolar, yet, the small number of samples precluded any definite conclusion of the antipodal types of the respective direct and reversed polarity. The HT1 pole was obtained mostly for the monopolar component (only 6 samples, out of 39, showed direct magnetization). The McFadden and McElhinny tests performed for the samples of direct and reversed polarity gave a negative result ($\gamma/\gamma_{\mathrm{cr}} = 14.5°/12.5°$), probably associated with the inadequate removal of the overlapping components. Thus the HT1 pole did not satisfy the criterion 6 mentioned above.

[94] 7. The absence of similarity between the position of the paleomagnetic pole derived in this study and the positions of the younger poles compared with the Phanerozoic segment of the Siberian APWP [*Smethurst et al.,* 1998] prove that this condition is observed in all of the poles obtained.

[95] To sum up, as follows from the Van der Voo model, the paleomagnetic poles derived show a high-grade reliability with the Qv estimates ranging from 5 (HT2 pole) to 7 (RDK pole).

Interpretation of the Results

[96] Before discussing the results of our interpretation, it should be noted that the territories of the study areas show the ubiquitous metachronous magnetization components which originated, judging by the positions of the respective paleomagnetic poles (GR, BT, UR), at the end of the Vendian to the beginning of the Cambrian (Figure 15). The observed remagnetization is local and seems to be associated with some large tectono-thermal event, or with several events which acourred at the southwestern margin of the Siberian Platform at the end of the Vendian to the Early Cambrian. With all poles calculated from their metachronous components fitting within the same area of the Indian Ocean south of Australia, there is a notable, statistically significant difference between the Urik and Biryusa-Tagul poles, on the one hand, and the Lower Angara pole, on the other, which proves that remagnetization took place in these areas during some close though not simultaneous periods of time.

[97] Since the Angara (GR) pole is located in the area of the potential location of the Tommotian pole of the Siberian Platform [*Pisarevsky et al.,* 1997], while the Urik (UR) pole and, especially, the Biryusa-Tagul (BT) pole tend to closer to the Toyonian pole [*Gallet et al.,* 2003], it can be inferred that the remagnetization front (and, possibly, the deformation front) moved from the northwest to the southeast (in modern coordinates). However, in connection with the potential existence of a small Late Vendian–Early Cambrian APWP loop (see Figure 15), the Urik and Biryusa-Tagul poles can be correlated also with the B1 Nemakit-Daldynian pole [*Shatsillo et al.,* 2005]. In this case, it can be expected that the displacement of the remagnetization front was directly opposite. Be it as it may, the results of our study provide a basis for carrying out detailed paleomagnetic studies aimed to study the history of tectonic movements in the southwest of the Siberian Platform.

[98] Since the metachronous magnetization of the rocks outcropping in the Greben Rock area has a synfolding age, its trend can be used to date the folding in this part of the Lower Angara area. The position of the GR pole at the base of the Phanerozoic trend of the Siberian APWP suggests that the folding, or at least one of its stages, occurred at the beginning of the Cambrian, obviously, during the Tommotian-Atdabanian.

[99] While discussing the regional remagnetization of the rocks in the southwest of the Siberian Platform, it is worth mentioning the independent data obtained recently by *Metelkin et al.* [2005] for the sedimentary rocks of the Karagas Series and for the basic rocks of the Nersa Complex (Late Riphean) in the rock sequences exposed by the Biryusa R., slightly south of the rocks investigated in our study. In the same area, we also identified a metachronous magnetization component, the paleomagnetic pole of which falls onto the Cambrian segment of the APWP of Siberia (see Pole BKN in Figure 15). Unfortunately, for some objective reasons we failed to date the formation time of the metachronous BKN magnetization, relative the deformation time. *Metelkin et al.* [2005] offered the potential synfolding age of this component.

[100] The results we obtained in this study for the high-temperature rocks of the Ust-Tugul, Ostrovnaya, Mota, and Irkutsk formations contribute substantially to the discussion of the hypothesis offered for the anomalous behavior of the geomagnetic field at the Vendian-Cambrian boundary and for the reality of the Early Cambrian episode of the true polar wander – IITPW [*Kirschvink et al.,* 1997; *Pavlov et al.,* 2004]. The vector distribution of the high-temperature magnetization components in these rocks resemble amazingly the similar pattern we obtained earlier for the boundary Vendian-Cambrian layers in the Kharaulakh, Baikal, and East Sayan areas [*Pavlov et al.,* 2004; *Shatsillo et al.,* 2005].

[101] Similar to the transitional Vendian-Cambrian rocks in the East Sayan and Baikal regions (South Siberian Platform), as well as in the Kharaulakh area in the northeast of the Siberian Platform, the Vendian-Cambrian rocks studied in the same structural sequence showed two characteristic magnetization components, often replacing each other. One of these components has a reverse polarity and is similar to the so-called "Khramov" directions of the Lower Cambrian, the other showing the alternative "Kirschvink" trend. It is important to note that the respective pair of poles (B1-HT1 and B2-HT2) for the rocks having the same Nemakit-Daldynian age in the Baikal-Central Sayan region generally show a good agreement (Figure 15). Some difference between the HT1 and B1 poles can be explained by the statistic scatter, or by the imperfect quality of the procedure used for the separation of the vector distributions into clusters. In any case, the data obtained in this study confirm confidently the validation of our previous conclusion that the significant number of the Vendian-Cambrian transitional layer of the Siberian Platform show two stable high-temperature components of magnetization, each of

which can be regarded as a primary one, which had been formed not later than the Early Cambrian.

[102] Proceeding from this conclusion, earlier, we offered the supposition that some anomalous conditions existed at the Vendian-Cambrian boundary for the generation of the geomagnetic field, when two quasistable states might have existed interchangeably, namely, a dipole field with a dipole oriented averagely along the axis of the Earth rotation and an anomalous dipole field with the substantial deviation of the dipole axis from the Earth rotation axis, or a nondipole field [*Pavlov et al.,* 2004; *Shatsillo et al.,* 2005].

[103] The potential alternative explanation of this supposition follows from the fact that the observed distributions were formed as the result of the superposition of the secondary metachronous magnetization of the Middle-Late Cambrian age over the Kirschvink trends. The assumption of the primary origin of the Kirschvink trends suggests the abnormally high-velocity drifting of the paleomagnetic pole at the end of the Early Cambrian, being one of the corner-stones of the Inertial Interchange True Polar Wander (IITPW).

[104] This explanation seemed to be probable in the case of the Early Cambrian rocks, the "normal (Khramov)" trend of which suggested a pole, close to the Middle and Late Cambrian poles of the Siberian Platform. In this paper, like in the case of the previous one [*Shatsillo et al.,* 2005], we studied older rocks whose normal trend (HT1, B1) differs from all of the known Phanerozoic poles.

[105] However, it should be noted that our discovery of the regional Late Vendian–Early Cambrian remagnetization complicated the interpretation of the observed vector distributions in terms of the anomalous field hypothesis. Since this remagnetization does exist, we can admit that at least some of the two-cluster vector distributions in the Late Vendian rocks can be interpreted as the superposition of the metachronous "Khramov" signal over the primary "Kirschvink" one. However, taking into account the Vendian age of the rocks discussed, the potential Late Vendian or Early Cambrian age of their remagnetization (showing the "Khramov" trend), and the fact that the "Kirschvink" trends were discovered in the Tommotian and Atdabanian rocks [*Kirschvink and Rozanov,* 1984], we have to admit some short period of time which witnessed the 40 to 50-degree jumps of the paleomagnetic pole from the "Kirschvink" positions to the "Khramov" ones and back, which seems to be scarcely probable.

[106] The important, if not decisive, argument against the IITPW hypothesis is the paleomagnetic determination obtained in the course of this study for the rocks of the Redkolesnaya Formation, which had accumulated in the Late Ediacarian to the Early Nemakit-Daldynian. The high-quality pole obtained for the rocks of this formation lies at a distance of more than 40° from the Tommotian pole, located by J. L. Kirschvink (pole KirCorr in Figure 15) which, in turn, is shifted from the Middle Cambrian pole of the Siberian Platform [*Gallet et al.,* 2003] by a distance of about 67°. When we used the Kirschvink pole, corrected for the relative rotations of the Aldan and Anabar blocks [*Pavlov and Petrov,* 1997] (Pole KirCorr in Figure 15), the respective values were 40° and 49°. The large distance between the Middle Cambrian pole of the Siberian Platform and the Tommotian-Atdabanian pole obtained by J. L. Kirschvink was explained by him by the IITPW episode. In this case a question arises concerning the explanation of a great distance between the Redkolesnaya pole of fairly similar age and the Tommotian pole obtained by J. L. Kirschvink. Should we admit one more IITPW episode? In our opinion this explanation seems to be highly artificial and improbable. In the case of admitting our hypothesis of the anomalous character of the Vendian–Early Cambrian geomagnetic field instead of the large-scale reciprocating displacement of the pole to the east, following from accepting the Kirshvink pole as the only one possible, we get the monotonous movement of the pole in the eastern direction for a distance which is two-times smaller than the one offered by the Kirschvink version (Figure 15).

[107] To conclude, the data obtained in our study can be regarded as contradicting the IITPW hypothesis and supporting the hypothesis of the anomalous geomagnetic field.

[108] In any case, it is not sufficiently substantiated to use the Kirschvink Tommotian dating, nor our datings, of the respective B2 and HT2 poles performed in this study and earlier [*Shatsillo et al.,* 2005] for plotting the Siberian curve of the apparent pole migration.

[109] The paleomagnetic datings performed in the work of this project allow us to approach the solution of the long-lived and exceptionally acute problem of the Late Riphean–Vendian trend of the Siberian APWP. The essence of this problem is illustrated schematically in Figure 16 and consists of the fact in spite of having a number of fairly good paleomagnetic determinations available for the Middle and the beginning of the Late Riphean of the Siberian Platform, we cannot use all of them, because we do not know the polarities of the Siberian paleomagnetic trends of that time. Accordingly, we do not know whether we deal with the northern or southern poles and cannot be sure in which hemisphere the Siberian Platform was located during the Riphean time. It is obvious that under these conditions the use of the Siberian Precambrian paleomagnetic data for paleotectonic reconstructions and solving other important problems of geology and geophysics is fairly problematic. The importance of this problem can be illustrated by the fact that the confirmation or negation of the possibility of Siberia to be a part of the Rhodinia supercontinent and the very existence of this supercontinent depend critically on the choice of the polarity of the Siberian Precambrian trends [*Pavlov et al.,* 2002].

[110] The uncertainty of the polarity choice for the Siberian Precambrian trends is associated with the total of nearly total absence of reliable paleomagnetic data for the Siberian Platform in the time interval of 950–520 million years. Our data allow us to make an important step of filling this gap.

[111] Up to recently, the Pacific trend of the paleomagnetic poles was believed to be the most preferable one for the Late Riphean to Vendian time (Figure 16a). This choice was made proceeding from the principle of minimizing the movements. However, since the time of getting reliable poles of Siberia for the beginning of the Late Riphean, it seemed to be strange that during the time period measuring hundreds of million years the paleomagnetic pole was displaced

merely by 50–60°, whereas this displacement amounted to more than 130° during the time period slightly longer than the Phanerozoic time.

[112] The data available for the other continents [*Torsvik et al.,* 1998] also suggested the significantly larger velocities for the movements of the respective paleomagnetic poles in this time interval.

[113] The new paleomagnetic poles of the Siberian Platform, corresponding to the Ediacarian and Late Ediakarian to Nemakit-Daldynian time turned out to be located at the moderate latitudes of the central part of the Indian Ocean. This means that the previous views of the Pacific trend of the Late Riphean and Vendian poles were wrong. The new data reported in this paper suggest that from the Aisa to the Redkolesnaya time (from the end of the Ediacarian to the beginning of the Nemakit-Daldynian) the paleomagnetic pole of the Siberian Platform moved rapidly southward from the central areas of the Indian Ocean. The Siberian Platform itself, whose first southwestern and later south-south western edge were turned to the north, was also located in the southern hemisphere and moved from the tropic latitudes (5–20°S) to moderate ones (30–50°S). The data obtained in this study suggest that at that time the Siberian Platform resided at the most southern point of its motion for the last 600 million years. Up to the end of the Vendian and to the beginning of the Tommotian, the Siberian Platform remained at the same latitudes, continuing to rotate clockwise relative to the meridian network. At the beginning of the Tommotian time, facing northward was its southwestern part. That time witnessed the beginning of the slow drifting of the Siberian Platform to the north, which lasted hundreds of million years, with some periods of slowing down and acceleration. In the middle of the Mesozoic the modern northern regions of the Siberian Platform crossed the northern, pole-bordering regions of the planet and continued the movement, initiated about 550 million years ago, now in the southern direction. Our analysis of the migration of the paleomagnetic pole of the Siberian Platform suggests that the end of the Vendian and, possibly, the very beginning of the Cambrian witnessed some very important tectonic rearrangement which caused a cardinal change in the movement of the Siberian Platform and, possibly, of the entire planetary assemblage of the tectonic plates. It appears that the coincidence of the time of the regional remagnetization of the rocks and the change in the drifting pattern of the Siberian Platform was not accidental.

[114] It can be supposed that by the middle-end of the Vendian the moving Siberian Platform encountered some serious obstacle which first slowed down and later stopped its migration to the south. It is possible that the traces of this event are imprinted in the Vendian accretion-collision rock complexes described in the Taimyr folded region [*Vernikovskii,* 1996].

Conclusions

[115] 1. The Vendian rocks of the Lower Angara, Biryusa, and Central Sayan regions show the widely spread regional remagnetization of the rocks, which seems to have recorded the major tectonic and thermal events which developed at the southern and south-western margins of the Siberian Platform at the end of the Vendian to the beginning of the Cambrian.

[116] 2. As a result of our detailed study of the rocks of the Aisa, Chistyakova, and Moshakova formations (Ediacarian or Late Baikalian?), of the Redkolesnaya Formation (Late Ediacarian-Nemakit-Daldynian), as well as of the insular Ust-Tagul, Mota, and Irkutsk formations (Nemakit-Daldynian), we managed to identify the old magnetization which seems to have recorded the trend of the geomagnetic field that had existed during the time of the accumulation of these rocks.

[117] 3. The paleomagnetic poles, corresponding to the primary magnetization trends, obtained for the rocks of the same ages in different regions or in different rock sequences do not differ statistically. This proves the absence of any large-scale tectonic rotations in the study areas, at least since the middle of the Taseeva time, and suggests that the resulting paleomagnetic poles can be referred for the whole of the Siberian Platform.

[118] 4. Our data contradict the IITPW hypothesis and support the assumption that the anomalous geomagnetic field had existed from the Late Vendian to the beginning of the Cambrian.

[119] 5. Our paleomagnetic data suggest that the later half of the Vendian and the beginning of the Cambrian witnessed an important tectonic rearrangement which resulted in the cardinal change of the Siberian Platform movement and possibly in that of the total planetary assemblage of the tectonic plates.

[120] 6. The results of this study proved that the Vendian segment of the Siberian of the APWP resided in the Indian Ocean and that the earlier views concerning the Pacific trends of the Late Riphean and Vendian poles were erroneous.

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Table 1. The trends of the high- and intermediate-temperature components in the outcrops of the Aisa Formation rocks

Outcrop		Geographic coordinates				Stratigraphic coordinates				Fold test	
$\varphi = 55.5$ $\lambda = 97.75$	N	D	I	K	α_{95}	D	I	K	α_{95}	DC	NFT
High-temperature component											
bir1	5	19.9	45.3	11.6	23.5	25.0	24.4	12.8	22.2		
bir2	14	23.6	25.1	8.1	14.9	24.8	14.4	8.1	14.9		
bir7	16	349.3	30.7	24.9	7.5	359.0	12.2	25.9	7.4		
bir8	8	15.1	24.4	9.5	18.9	20.7	5.5	10.6	17.9		
Direct polarity	12	210.7	−25.7	11.2	13.6	211.4	−14.5	11.0	13.7		
Reversed polarity	31	359.5	31.1	11.2	8.1	7.4	12.6	12.0	7.8		
Averaged for the sites	4	11.9	32.1	24.6	18.9	17.3	14.4	32.1	16.5	?	?
Averaged for the samples	43	8.4	30.4	9.1	7.6	14.0	13.4	10.1	7.2		
Intermediate component											
bir 7–bir 8 (for the samples)	14	183.9	−14.5	15.2	10.5	185.1	7.2	14.9	10.7	?	?

Note: φ and λ denote the geographical latitudes and longitudes of the study objects; D is the declination; I is the inclination; K is the close grouping, and α_{95} is the radius of the confidence oval. DC denotes the direction-correction fold test [*Enkin,* 1990]; NFT – the new fold test [*Shipunov,* 1995].

Table 2. The trends of the high-temperature component in the outcrops of the rocks of the Moshakova and Chistyakova formations (Taseeva Series)

Outcrop	N	Geographic coordinates				Stratigraphic coordinates				Fold test	
		D	I	K	α_{95}	D	I	K	α_{95}	DC	NFT
$\varphi = 58.5$ $\lambda = 96.2$						Man'zya outcrops					
manz1	8	18.0	−15.8	5.4	26.4	19.9	−11.0	5.4	26.3		
manz2	6	13.2	8.0	5.1	32.7	12.3	19.5	5.1	32.9		
Averaged for the samples	14	15.9	−5.6	5.1	19.5	16.7	2.0	4.8	20.3	?	?
$\varphi = 58.2$ $\lambda = 95.0$						Greben Rock outcrops					
greb1	5	14.7	9.8	5.4	36.4	16.2	−4.2	6.7	31.8		
greb2	4	10.9	11.2	8.7	33.1	12.1	−7.8	8.7	33.1		
greb3–4	3	16.4	25.0	8.4	45.6	22.1	2.8	5.3	60.2		
greb5	3	18.1	27.6	3.8	74.5	27.4	14.7	4.6	66.0		
greb6	3	5.3	25.5	8.0	47.0	16.9	22.8	8.4	45.5		
greb7–8	5	7.5	6.1	9.4	26.3	5.5	4.0	7.9	29.1		
greb9	5	16.6	−11.7	4.0	43.6	17.1	6.1	4.0	43.6		
Averaged for the sites	7	12.7	13.5	30.2	11.2	16.7	5.5	41.7	9.5	?	?
Direct polarity	11	190.8	−17.5	7.7	17.6	194.4	−7.9	7.7	17.5		
Reversed polarity	17	13.7	6.8	5.8	16.3	16.5	1.8	6.1	15.8		
Averaged for the samples	28	12.5	11.1	6.5	11.7	15.6	4.2	6.8	11.3		
$\varphi = 58.2$ $\lambda = 95.0$						All Taseeva rock series (of the Moshakova and Chistyakova formation rocks outcrops in the Man'zya area and Greben Cliff)					
Average values for the sites	9	13.4	9.6	25.4	10.4	16.6	5.2	36.5	8.6	+	? (cft+)
Direct polarity	18	193.5	−6.2	6.3	15.0	196.0	−2.5	7.3	13.8		
Reversed polarity	24	13.8	5.4	5.3	14.3	15.9	4.3	5.3	14.3		
Averaged for the samples	42	13.6	5.7	5.8	10.0	16.0	3.5	6.1	9.7	+	+

Note: φ and λ denote the geographical latitudes and longitudes of the study objects; D is declination; I is inclination; K is compactness, and α_{95} is the radius of confidence oval. DC denotes the direction-correction fold test [*Enkin,* 1990]; NFT – the new fold test [*Shipunov,* 1995].

Table 3. Paleomagnetic poles

Object of study	Pole	N	Coordinates: φ	λ	Plat	Plong	A95 (dp/dm)	K
Medium-temperature component								
Greben Cliff rocks of the Moshakova, Chistyakova, and Ostrovnaya formations	GR	8	58.2	95.0	−48.0**	149.1**	3.6 (2.9/4.6)	
Biryusa R. and Tagul R. rock sequences (Aisa and Ust-Tagul formations)	BT	8	55.5	97.75	−54.2**	125.7**	3.2 (2.5/4.2)	
					−54.3*	125.8*	3.2	307.3
Urik R. rocks of the Mota and Irkutsk rock sequences	UR	24	52.8	101.7				
GSK					−63.8*	122.8*	6.3	23.3
SSK					−61.5*	121.1*	6.5	21.5
High-temperature component								
Biryusa R. and Tagul R. rock sequences (Aisa Formation)		4	55.5	97.75	−39.9**	75.1**	12.1 (8.7/16.9)	
Angara R. Moshakova and Chistyakova rocks		9	58.2	95.0	−32.9**	75.1**	6.1 (4.3/8.6)	
Site-averaged pole for the rocks of the Aisa, Moshakova and Chistyakova formations	AT	13			−35.1*	75.1*	6.3	63.0
Site-averaged pole for the Redkolesnaya Formation	RDK	8			−60.8*	68.1*	5.1	121.1
Sample-averaged pole for the Ust-Tagul, Ostrovnaya, Mota, and Shaman formations, HT1*** component	HT1		58.2	95.0	−58.8**	94.3**	4.5 (3.6/5.6)	
Sample-averaged pole for the Ust-Tagul, Ostrovnaya, Mota, and Shaman formations, HT2*** component	HT2		58.2	95.0	−29.5**	74.1**	4.5 (3.2/6.4)	

Note: *Pole was calculated as the average virtual geomagnetic pole; **Pole was calculated proceeding from the average trend of the magnetization component; ***Pole was calculated after its directions had been recalculated for the Greben Rock coordinates; N is the number of the sites or samples used; Plat and Plong denote the latitude and longitude of the pole; φ and λ are the latitudes and longitudes of the study objects; A95 (dp/dm) is the radius (half-axis) of the 95-percent confidence circle; K denotes close grouping.

Table 4. The trend of the medium-temperature component in the outcrops of the Aisa and Ust-Tagul formation rocks (Biryusa R. and Tagul R. rock sequences) and of the Mota and Irkutsk formation rocks (Urik R. rock sequence)

		Geographic coordinates				Stratigraphic coordinates				Fold test	
Outcrop	N	D	I	K	α_{95}	D	I	K	α_{95}	DC	NFT
$\varphi = 55.5$ $\lambda = 97.75$		Aisa Formation									
bir1	20	327.2	40.7	23.6	6.9	344.3	35.8	21.4	7.2		
bir2	10	339.8	37.2	13.7	13.5	346.3	31.8	14.9	12.9		
bir7	12	315.5	42.3	16.5	11	345.3	37.2	17.9	10.5		
bir8	25	319.9	45.4	37	4.8	347.6	44.3	34.5	5		
Average of the sites	4	325.9	41.8	86	10	345.8	37.3	231.6	6	+	+
$\varphi = 55.5$ $\lambda = 97.75$		Ust-Tagul Formation									
bir3	7	315.2	50.4	30.7	11.1	338.4	44.6	32	10.8		
bir4	18	327.8	39.9	23.6	7.3	339.5	40.9	25	7.1		
bir5	9	333.6	40.9	39	8.3	337.8	38.1	37.2	8.5		
bir9	11	320.4	48.5	22.1	9.9	342.8	39	21.5	10.1		
Average of the sites	4	324.8	45.1	108.9	8.8	339.6	40.7	585.7	3.8	+	+
$\varphi = 55.5$ $\lambda = 97.75$		Aisa and Ust-Tagul formations									
Average of the sites	8	325.4	43.5	106	5.4	342.8	39.0	244.9	3.5	+	+
$\varphi = 52.8$ $\lambda = 101.7$		Mota and Irkutsk formations									
Average of the samples	24	349.5	45.8	29.2	5.6	349.8	42.7	26.8	5.8	?	?

Note: φ and λ denote the geographical latitudes and longitudes of the study objects; D is declination; I is inclination; K is the grouping density; α_{95} is the confidence circle radius; DC is the direction-correction fold test [*Enkin,* 1990]; NFT is a new fold test [*Shipunov,* 1995].

Table 5. The trend of the medium-temperature component in the outcrops of the Greben Cliff in the Yenisei Range

		Geographic coordinates				Stratigraphic coordinates				Fold test	
Outcrop	N	D	I	K	α_{95}	D	I	K	α_{95}	DC	NFT
$\varphi = 58.2$ $\lambda = 95.0$		Moshakova and Chistyakova formations of the Greben Rock									
GR1	5	301.6	23.9	13.5	21.6	320.7	42.8	15.2	20.3		
GR2	6	305.8	32.4	23.5	14.1	324.5	46.7	15.1	17.8		
GR3	8	320.5	42.5	29.1	10.4	343.6	57.7	23.8	11.6		
GR4	8	325.8	45.8	25.0	11.3	335.8	53.0	23.9	11.6		
GR5	8	346.2	46.9	15.5	14.5	320.5	34.8	18.1	13.4		
GR6	9	329.5	43.4	18.2	12.4	312.1	31.8	12.5	15.2		
OSTR1	18	312.3	33.2	13.0	10.0	313.7	37.5	13.7	9.7		
OSTR2	3	334.2	48.5	129.2	10.9	339.6	51.4	37.3	20.5		
Average values for the Greben outcrop sites	8	320.5	40.5	31.6	10.0	324.7	45.0	42.9	8.6	+	two-component or synfolding test
Test for synfolding: proportional site straightening	$K_{max} = 85.7$ for D = 322.4, I = 43.6 with $\alpha_{95} = 6.9$ for the straightening of 58.9% and the Watson-Enkin test ranging from −38.0 to −82.8%										
Same with nonproportional site straightening	$K_{max} = 211.7$ with D = 323.2, I = 43.2, and $\alpha_{95} = 3.7$										

Note: φ and λ denote the geographical latitudes and longitudes of the study objects; D is declination; I is inclination; K is the grouping density; α_{95} is the confidence circle radius; DC is the direction-correction fold test [*Enkin,* 1990]; NFT is a new fold test [*Shipunov,* 1995]. In the case of the nonproportional straightening of the fold the average trends of the sites were calculated using the SFT function of the "SELECT" Program Package written by *Shipunov* [1995].

Table 6. The trend of the high-temperature component in the outcrops of the Redkolesnaya Formation rocks

		Geographic coordinates				Stratigraphic coordinates				Fold test	
Outcrop	N	D	I	K	α_{95}	D	I	K	α_{95}	DC	NFT
$\varphi = 58.6$ $\lambda = 97.0$					Irkineeva R. outcrops						
Irk1	8	0.6	57.4	23.5	11.7	13.8	48.0	41.8	8.7		
Irk2	17	200.5	−28.2	18.1	8.6	203.8	−39.0	18.8	8.5		
Direct polarity	18	200.8	−30.7	15.0	9.2	204.3	−40.1	18.9	8.2		
Reversed polarity	7	358.2	54.7	23.5	12.7	11.4	46.3	45.2	9.1		
Average for the samples	25	196.0	−37.8	12.0	8.7	200.8	−42.0	21.3	6.4	+	+
$\varphi = 58.2$ $\lambda = 95.0$					Greben Rock outcrops						
RDK1–2	6	353.8	52.2	29.7	12.5	24.4	53.5	43.1	10.3		
RDK3	6	352.2	60.9	27.0	13.1	18.7	55.2	21.0	15.0		
RDK4	4	348.5	55.9	131.2	8.1	14.6	50.4	94.5	9.5		
RDK5	5	351.1	54.8	10.5	24.7	7.1	51.5	16.9	19.1		
RDK6–7	7	351.6	49.9	18.0	14.6	14.6	50.2	17.8	14.7		
RDK8–9	7	338.3	52.2	17.6	14.8	4.5	50.6	23.6	12.7		
Average for the sites	6	349.2	54.4	251.7	4.2	13.8	52.1	270.6	4.1	?	?
$\varphi = 58.2$ $\lambda = 95.0$		All Redkolesnaya Formation (Irkineeva R. and Greben Cliff outcrops)									
Average for the sites	8	355.9	52.2	38.9	9.0	15.3	50.0	146.3	4.6	+	+

Note: See Figure 4 for the explanations.

Table 7. The high-temperature components of the Insular Formation (Greben Cliff). Ust-Tagul Formation (the outcrops in the area where the Tagul R. and Biryusa R. flow together), and the Mota and Irkutsk Formations (Urik River Valley)

$\varphi = 58.2$ $\lambda = 95.0$		Geographic coordinates				Stratigraphic coordinates				Fold test	
Component	N	D	I	K	α_{95}	D	I	K	α_{95}	DC	NFT
					Total distribution						
HT1* is the average of the samples	45	350.6	50.8	19.2	5.0	0.4	45.6	24.0	4.4	+	+
HT2* is the average of the samples	11	197.3	−7.5	28.2	8.8	198.1	1.1	51.8	6.4	+	+
HT1 is the average values for the samples of the Ostrovnaya formation	10	353.7	42.8	22.1	10.5	357.5	44.2	20.3	11.0	?	?
HT1 is the average values for the samples of the Mota, and Irkutsk formations	14	0.6	51.2	29.0	7.5	5.1	49.1	31.6	7.2	+	+
HT1 is the average values for the samples of the Ust-Tagul formation	21	341.5	53.7	17.7	7.8	358.9	43.9	21.9	7.0	?	?
HTL* are the values averaged for all regions	3	352.2	49.5	94.5	12.8	0.4	45.8	404.5	6.1	+	+

Note: All trends were calculated for the coordinates of the Greben Cliff. φ and λ are the geographic latitudes and longitudes of the study rocks, D is declination, I is inclination, K is crowding, α_{95} is the radius of the confidence circle, DC is the direction correction fold test [*Enkin,* 1990], NFT is a new fold test [*Shipunov,* 1995].

Table 8. The high-temperature components of the Alesha rocks and the medium-temperature component of the Kliminskaya rocks in the Taseeva R. area

		Geographic coordinates				Stratigraphic coordinates				Fold test	
Component	N	D	I	K	α_{95}	D	I	K	α_{95}	DC	NFT
$\varphi = 57.8$ $\lambda = 94.5$						Alesha Formation					
A	10	5.6	73	96.5	4.9	123.8	−21.6	29.4	9.1	–	–
B	17	0.8	49.7	34.3	6.2	118.3	−0.4	25.4	7.2	–	–
C, direct polarity	6	207.9	20.8	14.2	18.4	226.6	−30.7	30.6	12.3		
C, reversed polarity	11	21.7	-1.5	9.8	15.3	65	23.8	13.4	12.9		
C, all samples	17	23.8	-8.4	10	11.8	58.6	26.6	14.7	9.6	+	+
Outcrop $\varphi = 57.8$ $\lambda = 94.7$						Kliminskaya Formation					
KL1	4	312.6	50	24.3	19	303.3	0.7	32.5	16.4		
KL2	11	319.5	58.8	28.8	8.7	307.1	20.8	19.3	10.6		
KL3	5	336.7	42.2	19	18	325.5	31.8	20.5	17.3		
Average for the sites	3	323.9	50.8	48.1	18	311.3	18	17.9	30	–	–
Average for the samples	20	323.3	53.3	20.7	7.4	310.5	19.7	14.6	8.8	–	–

Note: φ and λ denote the geographic latitudes and longitudes of the study objects; D is declination, I is inclination; K is crowding, and α_{95} is the confidence circle radius. DC is the direction-correction fold test [*Enkin,* 1990]; NFT is a new fold test after *Shipunov* [1995].

Table 9. Estimation of the reliability of the paleomagnetic poles

Poles	Criteria							Qv
	1	2	3	4	5	6	7	
AT	0	1	1	1	1	1	1	6
RDK	1	1	1	1	1	1	1	7
HT1	1	1	1	1	1	0	1	6
HT2	1	0	1	1	1	0	1	5

Note: See the text for the explanation.

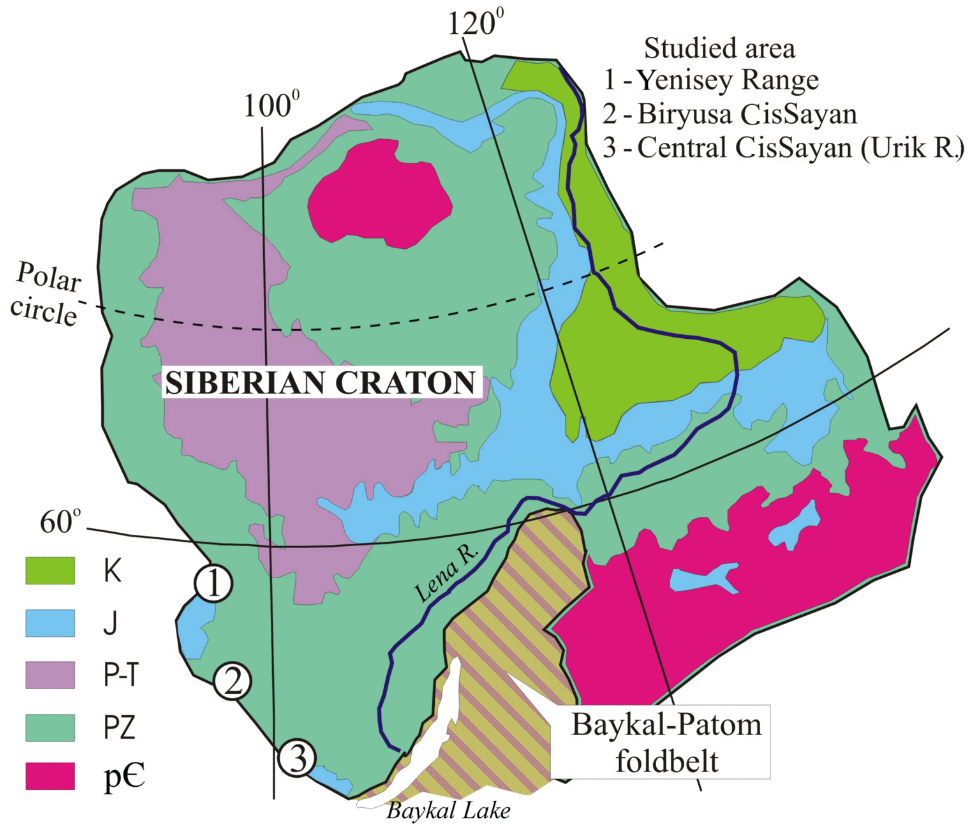

Figure 1. The general schematic geological map of the Siberian Platform showing the study areas.

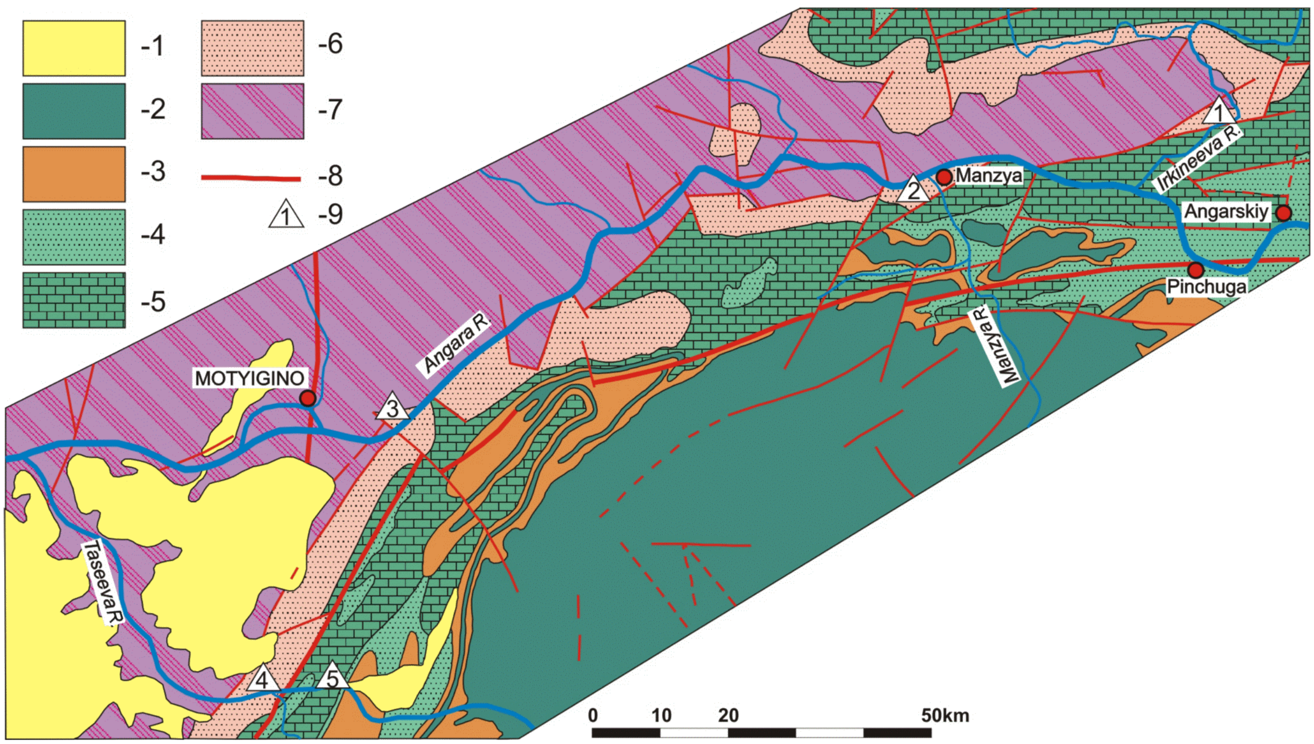

Figure 2. The schematic geological structure of the Yenisei Ridge study area. Legend: 1 – Neogene, 2 – Permian-Triassic traps, 3 – Carboniferous and Permian rocks, 4 – Middle-Upper Cambrian (Upper Lena Formation), 5 – Lower Cambrian, 6 – Upper Riphean(?) to Vendian rocks (Taseeva Series: Redkolesnaya and Ostrovnaya formations), 7 – pre-Vendian rocks, 8 – faults; 9 – objects of study: (1) the Irkineeva R. area: the rocks of the Redkolesnaya Formation; (2) the left bank of the Angara R. below the Man'zya Settlement: the rocks of the Chistyakova and Moshakova formations, (3) the right bank of the Angara R. from the Gremyachiy Creek to the Greben Cliff: the Chistyakova, Moshakova, Redkolesnaya, and Ostrovnaya formations, (4) the right bank of the Taseeva R. below the mouth of the Usolka River: the Alesha Formation, and (5) the right bank of the Taseeva R. in the area of the Dyrovatyi Cliff: the Kliminskaya Formation.

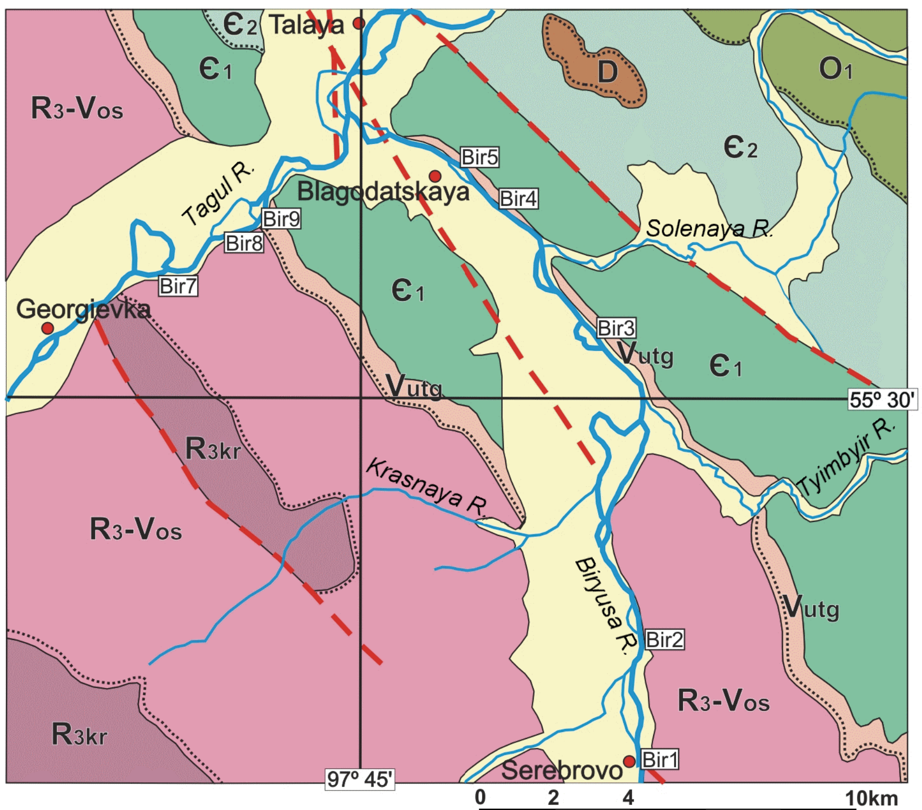

Figure 3. The schematic geological structure of the study area in the Biryusa area of the Sayan region. The index “kr” is used for the Karagas Series, “os” for the Oselkova Series, and “utg” for the Ust-Tagul Formation. The rectangles and the respective indices mark the outcrops examined.

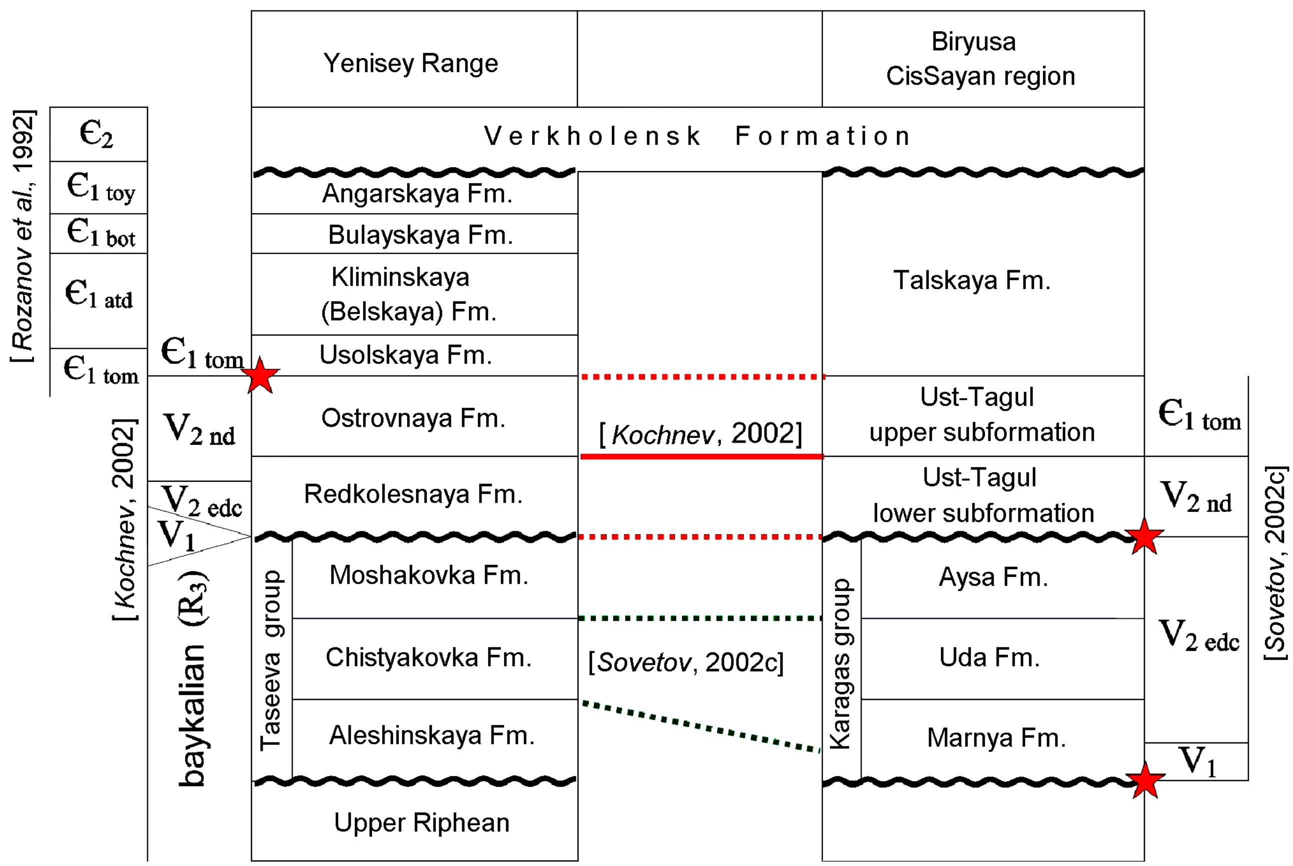

Figure 4. Correlation of the rock sequences studied in the Yenisei Ridge and in the Biryusa area of the Sayan region. The red stars indicate the most important stratigraphic bench marks (see the text for the explanation).

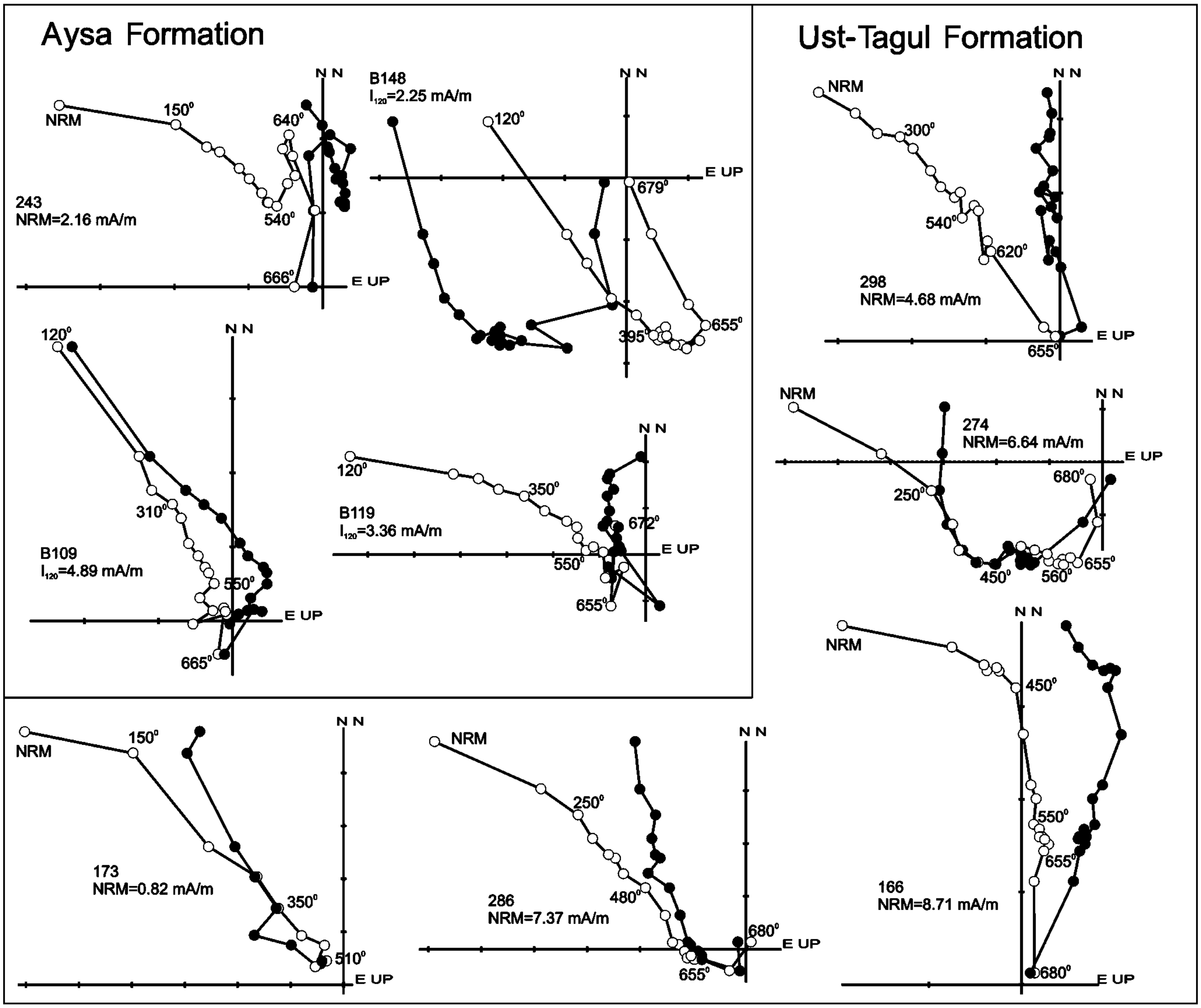

Figure 5. The Zijderveld diagrams typical of the rocks of the Aisa and Ust-Tagul formations in the Biryusa area of the Sayan region. The solid circles mark the projections of the rocks onto the horizontal plane, the open circles, onto the vertical plane. All diagrams are plotted in the stratigraphic system of the coordinates.

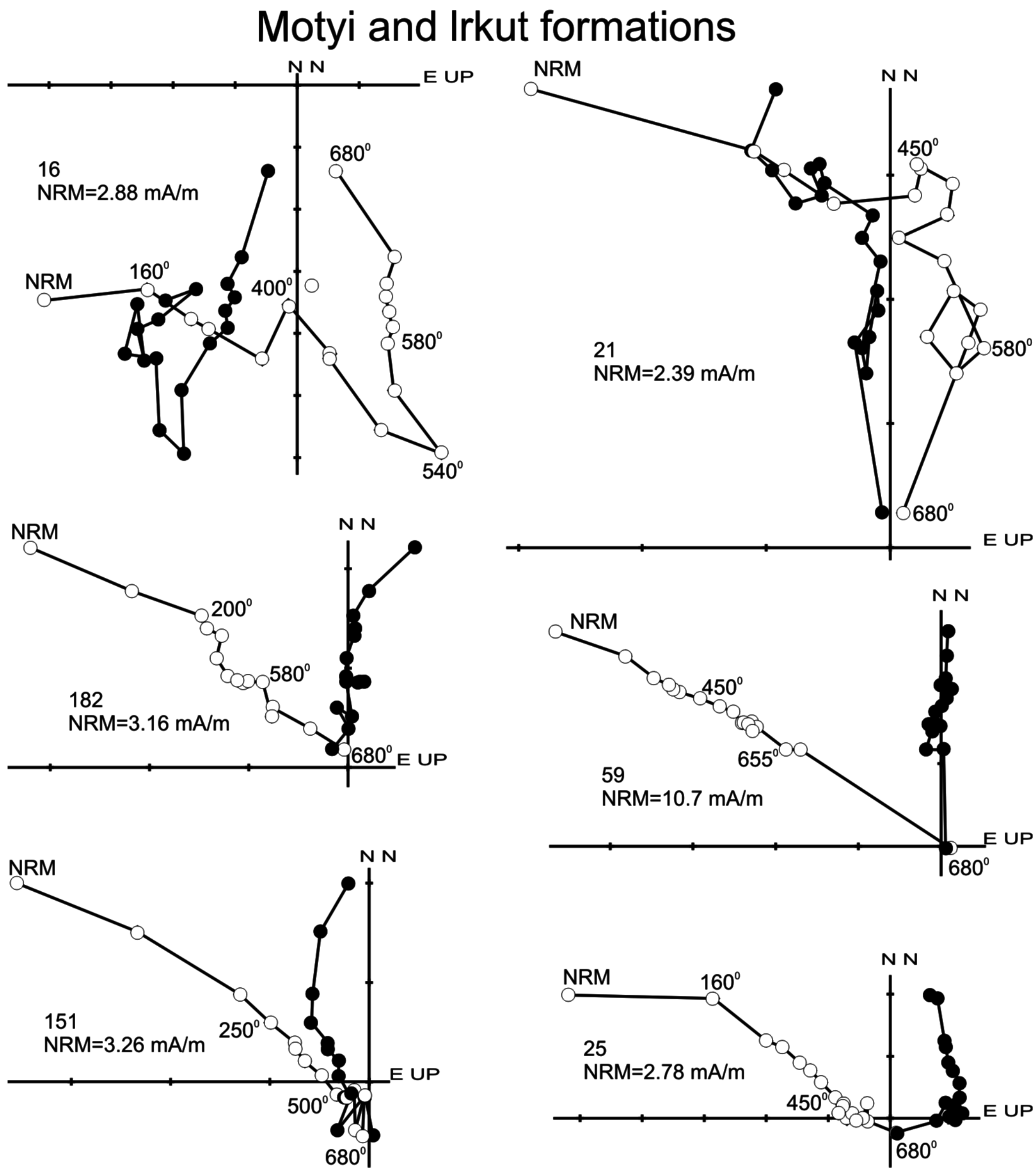

Figure 6. The Zijderveld diagrams typical for the rocks of the Mota and Irkutsk formations of the Central Sayan region (Urik R. area). The solid circles show the projection of the magnetization vector onto the horizontal plane, the open ones, onto the vertical. All diagrams are plotted in the stratigraphic coordinates.

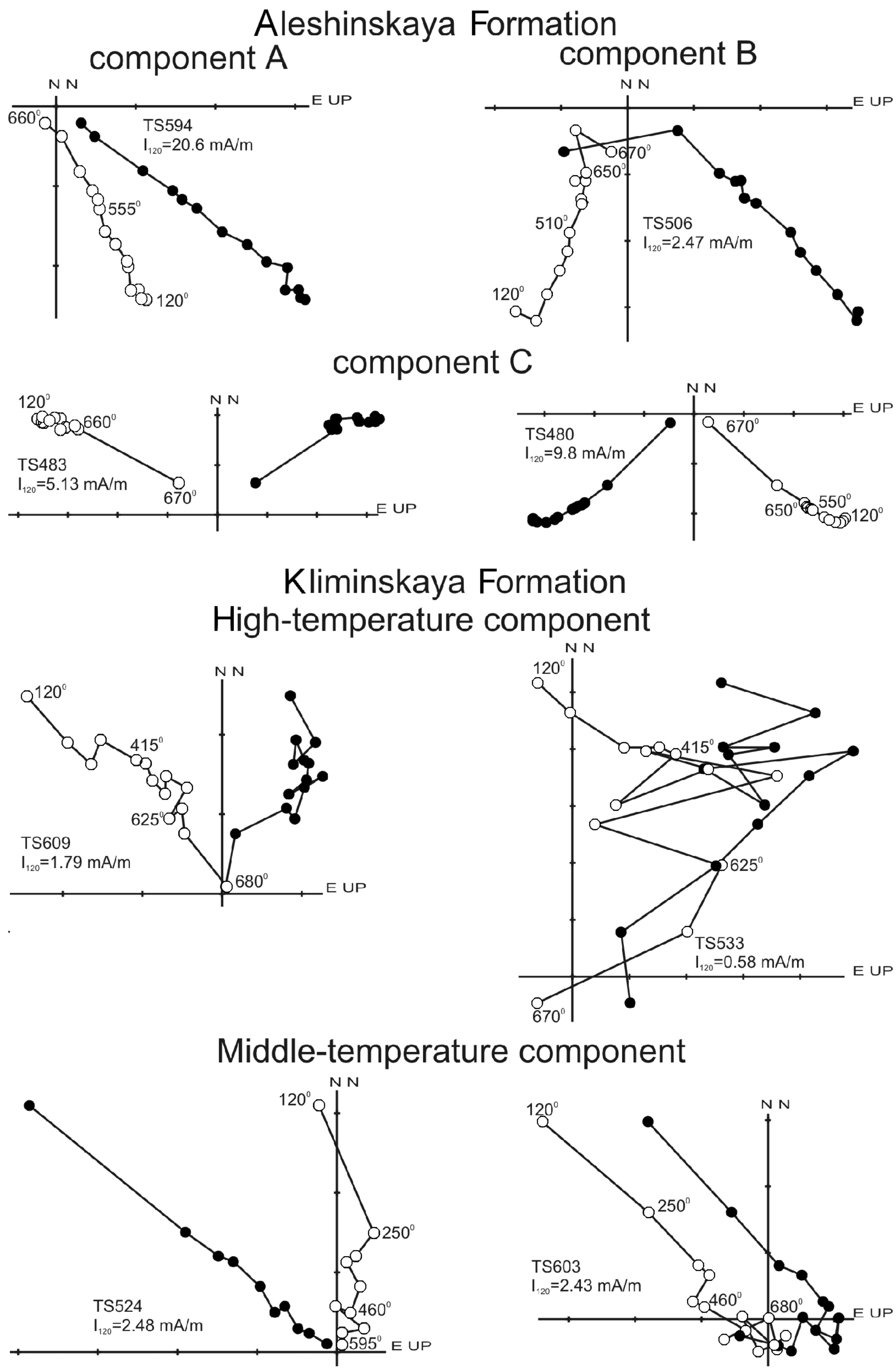

Figure 7. The typical Zijderveld diagrams for the rocks of the Alesha and Kliminskaya formations of the Yenisei Range (Taseeva R. area). The solid circles show the projections of the magnetization vector onto the horizontal plane, the open ones, onto the vertical. All diagrams are plotted in the stratigraphic system of the coordinates.

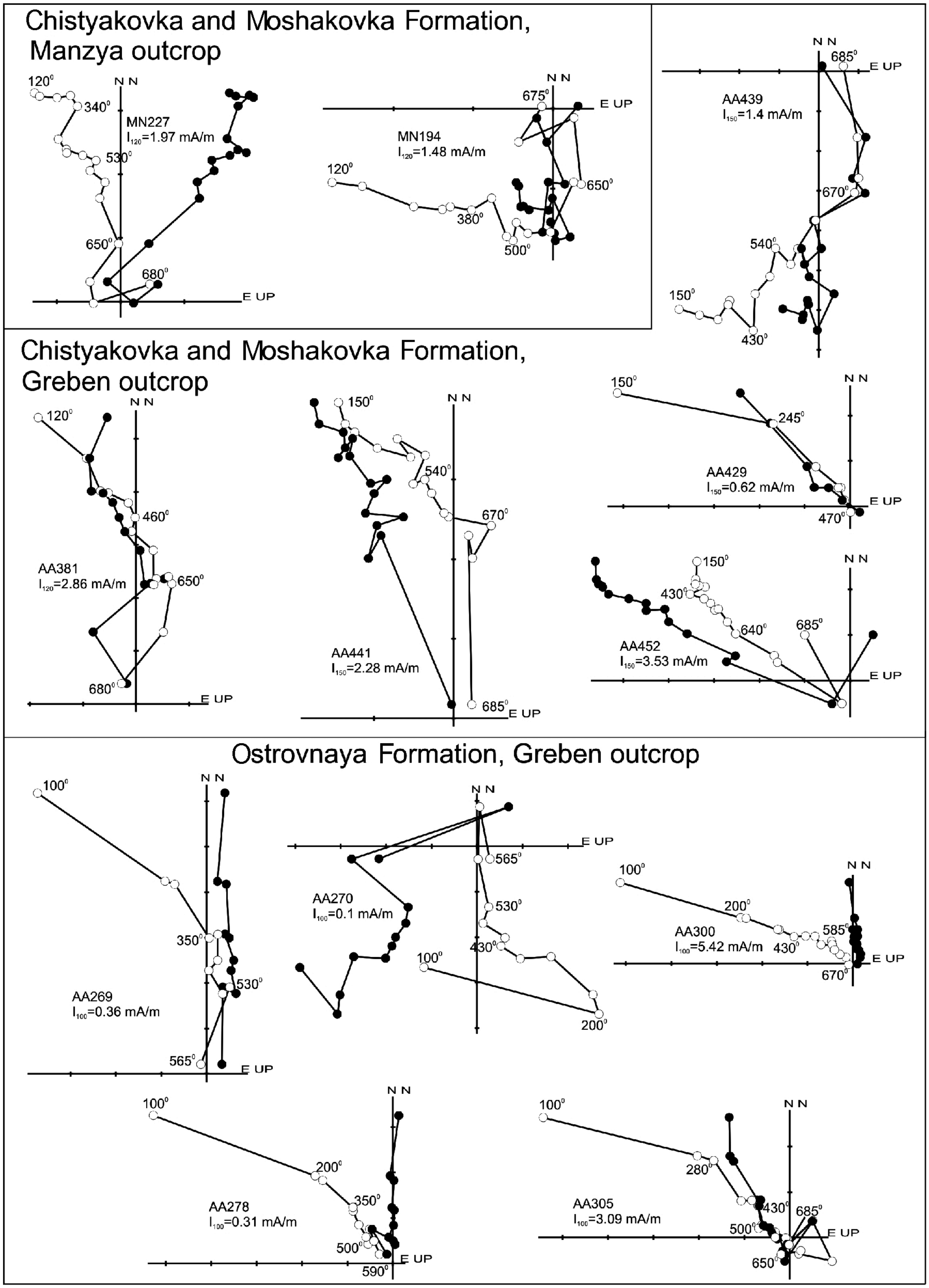

Figure 8. The typical Zijderveld diagrams for the rocks of the Taseeva Series and for the insular rocks of the lower Angara R. sequences of the Yenisei Range. The solid circles show the projections of the magnetization vector onto the horizontal plane, the open ones, onto the vertical plane. All diagrams are plotted in the stratigraphic system of the coordinates.

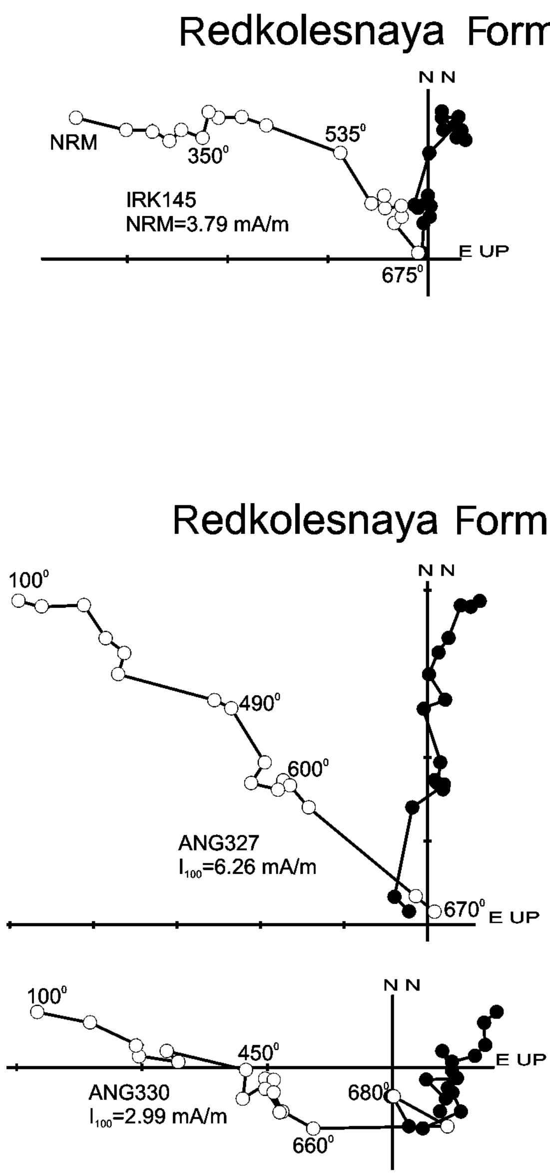

Figure 9. The typical Zijderveld diagrams for the rocks of the Redkolesnaya Formation in the Yenisei Range. The solid circles mark the projections of the magnetization vector onto horizontal plane, the open ones, onto the vertical. All diagrams are given in the stratigraphic system of the coordinates.

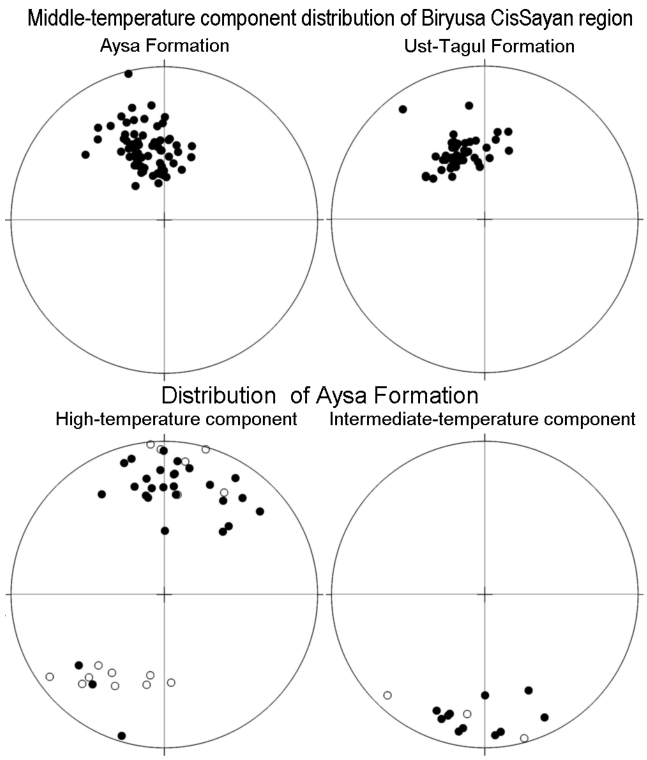

Figure 10. The distribution of the vectors obtained for the medium-temperature, intermediate, and high-temperature magnetization components of the Aisa Formation and for the medium-temperature component of the Ust-Tagul Formation in the Sayan region bordering the Biryusa R. The stereograms are presented in the stratigraphic coordinates. The solid circles show the projections to the lower hemisphere, the open ones, for the upper one.

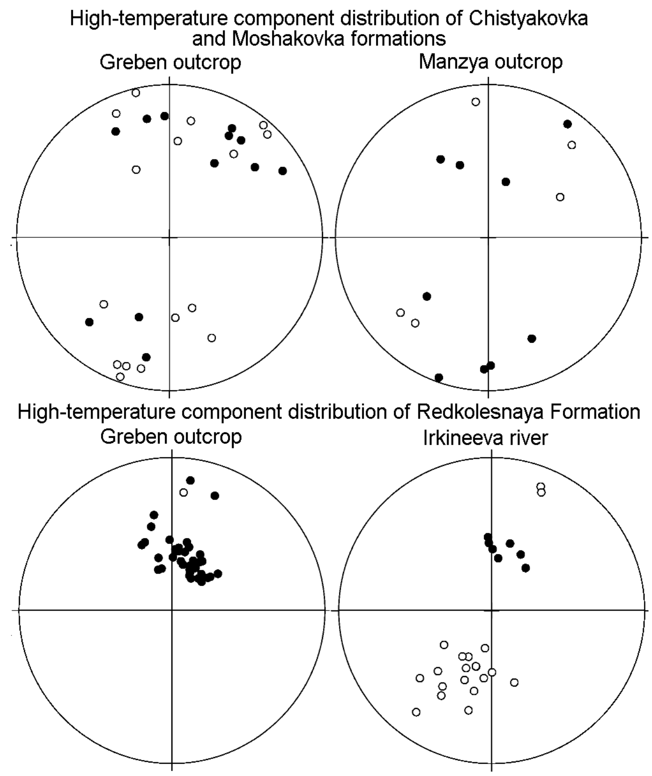

Figure 11. The distribution of the vectors of the high-temperature magnetization component in the rocks of the Taseeva Series and Redkolesnaya Formation of the Yenisei Range. The stereograms are presented in the stratigraphic system of the coordinates. The solid cycles mark the projections to the lower hemisphere, the open ones, those to the upper one.

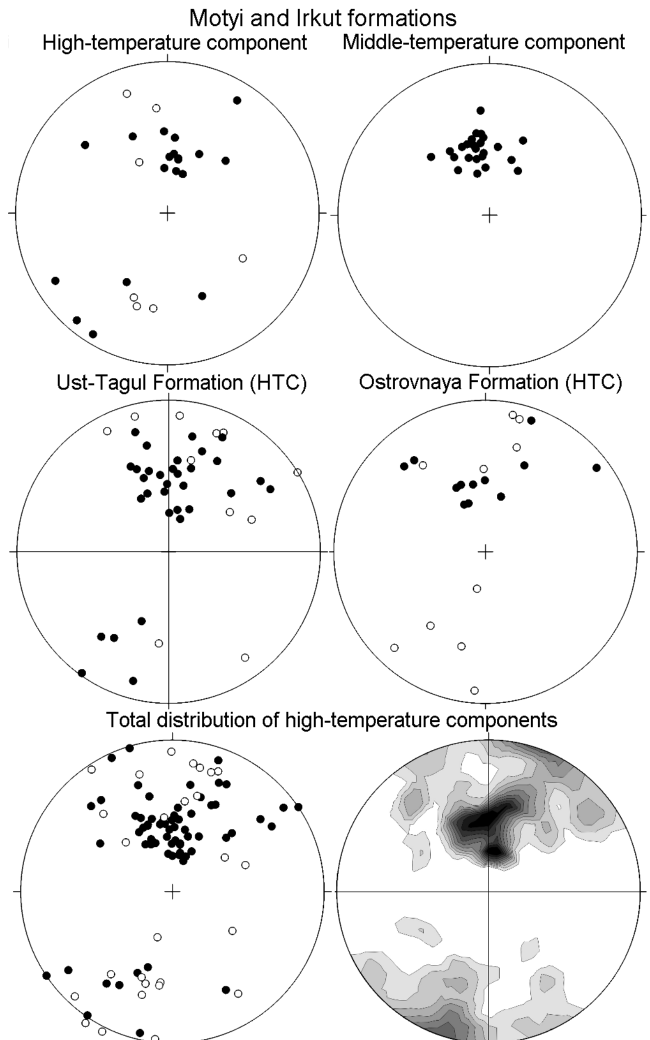

Figure 12. The distribution of the vectors of the high-temperature magnetization component in the rocks of the Mota and Irkutsk formations (Urik R. area), in those of the Ust-Tagul Formation (Biryusa R. and Tagul R. areas), Ostrovnaya Formation (Angara R. area), and also of the medium-temperature component of the Urik rock sequence. This Figure also shows the summarized stereogram for the density distribution of the axes of the respective high-temperature magnetization components. The stereograms are plotted in the stratigraphic system of the coordinates. The solid circles show the projections to the lower hemisphere, the open ones, to the upper. All axes of the density stereogram face the lower hemisphere.

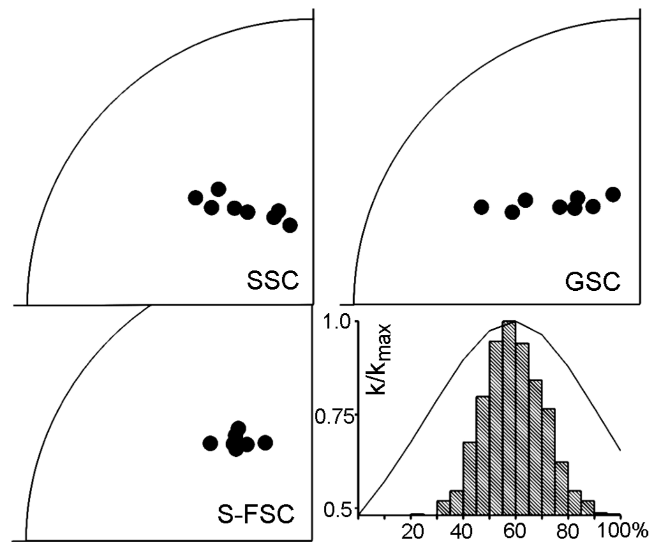

Figure 13. The distribution of the site-averaged values for the medium-temperature component of the Taseeva rock series and the Ostrovnaya rocks of the Greben sequence from the Yenisei Range. The proportional fold flattening and the Watson-Enkin test for the average values are given for the values averaged for the sites. SSC is the abbreviation for the stratigraphic system of the coordinates; GSC, for the geographical system of the coordinates, S-FSC, for the syn-folding system of the coordinates (the nonproportional straightening of the fold by the method of the intersection of small circles). The solid circles are used for the projections onto the lower hemisphere.

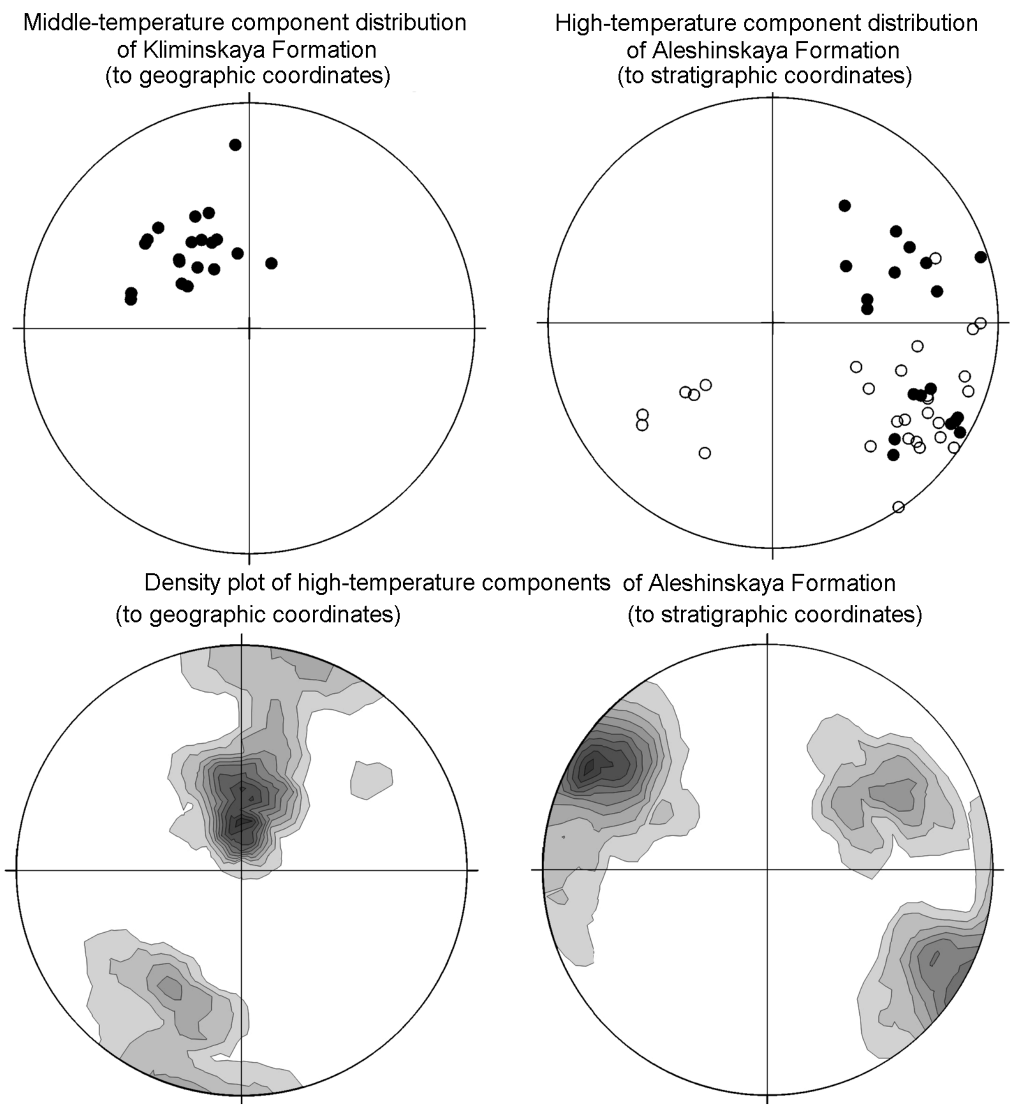

Figure 14. The distribution of the vectors of the magnetization components in the rocks of the Kliminskaya and Alesha formations of the Yenisei Range where it is crossed by the Taseeva River. The stereograms of the density distribution of the respective high-temperature magnetization components of the rocks of the Alesha Formation. The solid circles denote the projections to the lower hemisphere, the open ones, to the upper one. All axes of the density stereograms face the lower hemisphere.

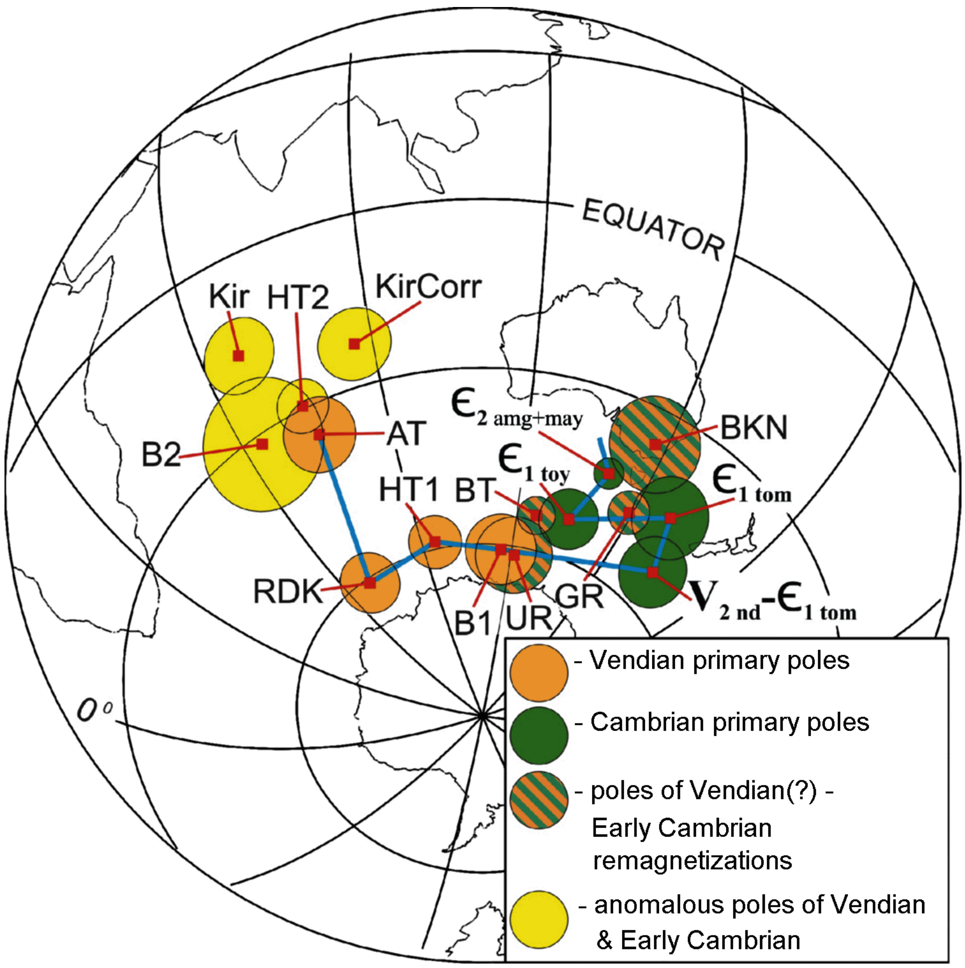

Figure 15. Paleomagnetic poles: AT is the average Aisa-Taseeva pole; RDK is the Redkolesnaya Formation pole; HT1 and HT2 are the average poles for the respective components of the Mota, Irkutsk, Ust-Tagul, and Ostrovnaya rock formations; B1 and B2 are the average poles for the Late Vendian rocks in the southwest of the Cisbaikalia and in the east of the Sayan regions [*Shatsillo et al.,* 2005]; BT is the Biryusa-Tagul remagnetization pole; UR is the pole of the Urik remagnetization; GR is the pole of the Greben rock remagnetization (Angara region); BKN is the remagnetization pole of the Karagas rock series and the Nersa rock complex (Biryusa R. area) [*Metelkin et al.,* 2005]; Kir is the Kirschvink Tommotian Pole [*Kirschvink and Rozanov,* 1984]; KirCorr is the same pole corrected for the Vilyui Rift opening; V_{2nd}-EEE_{1tom} is the pole for the boundary of the Nemakit-Daldynian and Tommotian beds of the Chekurov anticline (Lena R. lower course) [*Pavlov et al.,* 2004]; EEE_{1tom} is the Tommotian pole of the Olenek Rise [*Pisarevsky et al.,* 1997]; EEE_{1toy} is the Toyonian pole of the Olenek Rise [*Gallet et al.,* 2003]; $EEE_{2amg+may}$ is the Amga-Maya Pole of the Olenek Rise [*Gallet et al.,* 2003]. The blue line shows the inferred Vendian-Cambrian trend of the apparent migration of the pole of the Siberian Platform.

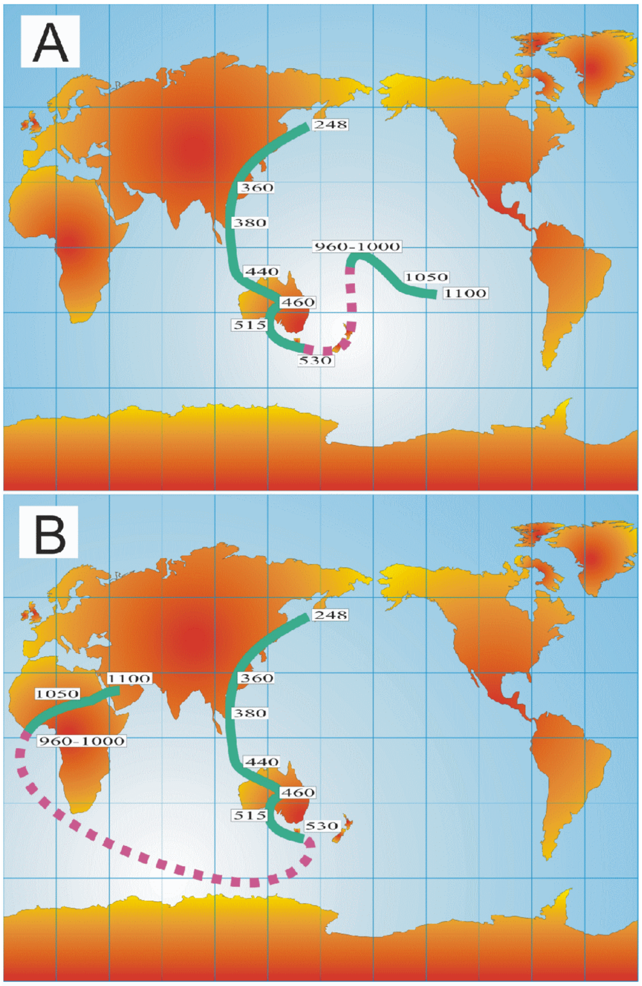

Figure 16. The configuration versions for the curve of the apparent migration of the Siberian Platform pole as a function of the positions of the Late Riphean–Vendian paleomagnetic poles. (A) - classic [*Pechерskiy and Didenko*, 1995; *Smethurst et al.*, 1998] and (B) - alternative approach to poles of Late CisCambrian paleomagnetic orientations.