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Magnetostratigraphy of the Ordovician Angara/Rozhkova River Section: Further Evidence for the Moyero Reversed Superchron

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Abstract—We present new magnetostratigraphic results obtained from a well-dated Ordovician key section located along the Angara River, near the terminus of the Rozhkova River (southern Siberian platform). More than 220 samples were thermally demagnetized up to 670°C in order to isolate their characteristic ancient magnetization. Samples from the Arenig, the Llanvirn and the Llandeilo stages are all (but two) of reversed magnetic polarity. In contrast, samples dated of the Caradoc yield a sequence of several magnetic polarity intervals. These new data therefore confirm the occurrence of a long reversed magnetic polarity interval during the Ordovician, the so-called Moyero superchron, which ended during the middle or late Llandeilo.

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INTRODUCTION

Based on the results of magnetostratigraphic studies for the key section of the Ordovician rock sequence on the Moyero River, we suggested in 1996 the existence of the third Phanerozoic superchron—the Early–Middle Ordovician superchron of the reversed polarity (Gallet and Pavlov, 1996). The data of our later survey and the results obtained by our colleagues (e.g., (Gurevich et al., 2005; Rodionov and Gurevich, 2010)) seemed to generally support this hypothesis. At the same time, some peculiarities identified in the magnetostratigraphic record in a number of East European sections (Trench and Torsvik, 1991a; 1991b; Trench et al., 1991; Smethurst et al., 1998; Khramov and Iosifidi, 2009) might be interpreted as indications of several zones with normal geomagnetic polarity in the post-Tremadocian Lower Ordovician sediments. In order to verify the existence of these zones, we carried out an additional investigation of the Arenigian and Llanvirnian magnetostratigraphy. The section of the Ordovician rocks in the middle reaches of the Angara River, which outcrops close to the outlet of the Rozhkova River ($\varphi = 58.5°N$, $\lambda = 99.8°E$), was selected as the object of our research.

THE GEOLOGICAL SETTING

The selected section is the reference section for the Ordovician formations in the southern part of the Siberian Platform. The Ordovician sediments of Tremadocian to Caradocian age, inclusive, are exposed here over a distance of more than 3 km along the left bank of the Angara River. In the first approximation, the rocks form a monocline with slightly varying dip azimuths and dip angles. The layers gently dip south-southwestwards at 5°–15°. Regionally, the Ordovician rocks are conformably (although with a stratigraphic gap) overlain by the carbonate-terrigenous Lower Silurian (Middle to Upper Llandoveri) rocks of the Kezhma Formation and the overlying Yara formation. According to the rare faunal remains, the latter formation cannot be dated more precisely than Silurian–Devonian. The Yara and older formations are overlain (with angular unconformity) by nearly horizontal Bayeronnian Early Carboniferous light siltstones, sandstones, and conglomerates. Thus, the dislocations in the Ordovician rocks in the studied region can be dated to the Late Silurian or Devonian.

The lithology and biostratigraphy of the Rozhkova section are described in detail in the paper by Knyazev (1978) and in the book by Kanygin et al. (1984). This section is composed of five formations (Fig. 1): the Ust'-Kut Formation (over 30 m in thickness), the Iya Formation (with a thickness of 75 m), the Badaran Formation (90 m in thickness), the Mamyr Formation (130 m thick), and the Bratsk Formation (about 130 m in thickness). During the field campaigns of 2001 and 2003, we acquired more than 220 oriented samples representative for the stratigraphic interval from the upper horizons of the Iya Formation to the top layers of the Bratsk rocks. Compositionally, all the sampled formations are terrigenous carbonate rocks with a different proportion of the terrigenous and carbonate components. Overall, the rocks are largely reddish with significant intervals (almost all of Llandeilo age)

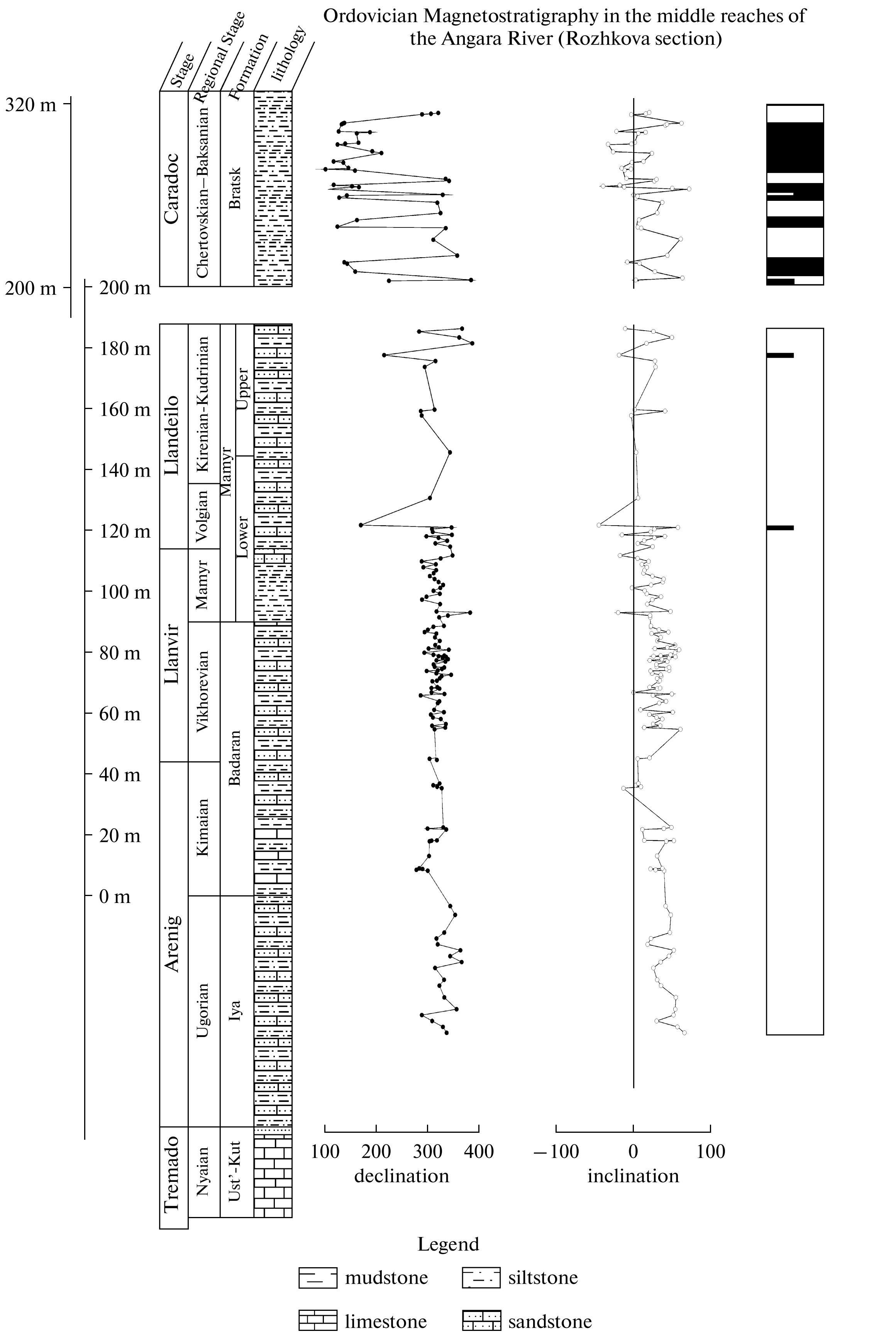

Fig. 1. The lithostratigraphic column of the Ordovician deposits in the middle reaches of the Angara River and the magnetic stratigraphy of the studied rock section along the Rozhkova River.

dominated by light-colored and grayish rocks. Some parts of the entire section are not well exposed. Throughout the studied stratigraphic interval, there are buried intervals that attain 10 m and more in thickness. The rocks at the boundary of the Mamyr and Bratsk Formations (close to the Llandeilo and Caradoc boundary) are least exposed while the llanvirnian part of the section, which lies in the focus of the present study, is rather well exposed.

The Iya rocks are largely composed of fine- and medium-grained red sandstones interbedded with siltstones of the same color. The bottom of the Badaran Formation is formed by gray and greenish gray limestones intercalated with discrete interbeds of red siltstones and mudstones. The upper part of the Badaran Formation is dominated by greenish, reddish, and, sometimes, gray sandstones; brown siltstones and, less frequently, mottled marls are also present.

The bottom part of the Mamyr Formation is composed of alternating layers of gray, greenish gray, sometimes reddish siltstones, mudstones, and, rarely, sands. Separate interbeds of limestones and shelly limestones are present. Sandstones are more abundant in the upper layers of the Mamyr Formation.

The Bratsk Formation is mainly composed of red mudstones interbedded with siltstones.

The faunal remains found in the Rozhkova section provide a good basis for correlating the formations composing this section to the regional biostratigraphic scale of Siberia. According to the data of Knyazev (1978) and Kanygin et al. (1984), the Ust'-Kut rocks correspond to the Nyaian regional stage (Fig. 1), and the Iya Formation is correlated to the Ugorian horizon. The lower portion of the Badaran Formation contains rich faunal complex, which refers these rocks to the Kimaian regional stage. The top layers of the Badaran Formation and the bottom layers of the Lower Mamyr subformation correspond to the Mukteian and Vikhorevian regional stages. The upper portion of the Lower Mamyr subformation pertains to the Volgian regional stage, while the Upper Mamyrian rocks relate to the Kirenian-Kudrinian regional stages. The Bratsk sediments contain conodonts typical for the Chertovskian and bottom Baksanian regional stages. The correlation of these regional stages to the Global stratigraphic scale (according to (Kanygin et al., 1984; Kanygin, Moscalenko, and Yadrenkina, 1987)) is presented in Fig. 1.

THE PALEOMAGNETIC ANALYSIS

The thermal demagnetization of the most samples from the Arenig and Llanvirn deposits clearly demonstrates that the natural remanent magnetization (NRM) has a characteristic component with a moderate inclination, northwestern declination, and maximal unblocking temperature close to the Curie point of hematite (Fig. 2). Besides the characteristic magnetization component, almost all samples, to some extent, contain a poorly stable, low-temperature component oriented close to the direction of the present-day geomagnetic field, which suggests that it is a recent magnetization component. Some samples also contain a third, intermediate component that is destroyed in the temperature interval from 150–300°C to 400–600°C (Fig. 2, sample ANG-24; Fig. 3, samples ANG70 and AA-63). The paleomagnetic record in the samples is noisy, and the noise level is sample-specific. Some samples have clear, almost perfect Zijderveld diagrams while other samples, which are rather numerous, only provide a hint of general trends in the behavior of magnetization during the thermal cleaning. The mean directions of the characteristic magnetization component for the Arenig and Llanvirn rocks are presented in the table. As can be seen in Fig. 5, both the Arenig and Llanvin mean directions on the stereogram are located in the immediate proximity of the corresponding directions recalculated from the sections in the northern (the Moyero River) and northwestern (the Kulumbe River) parts of the Siberian Platform studied previously (Gallet and Pavlov, 1996; Pavlov and Gallet, 1998) into the coordinates of the Rozhkova section. This fact strongly suggests that these magnetization components have been formed simultaneously or soon after the formation of the studied rocks. However, it is remarkable that the angular distances between the corresponding mean directions still slightly (by 1°–2°) exceed the critical angle (MacFadden and McElhinny, 1988); i.e., these mean directions statistically significantly differ (at a confidence level of 95%). In our opinion, this difference is due to a certain relatively small contribution of the low-temperature component (which we failed to completely remove by thermal cleaning) to the calculated mean directions.

The samples of the Lllandeilo age exhibit very noisy, often irregular behavior. At the same time, there are some samples, in which the behavior of the NRM vector during the thermal demagnetization clearly indicates the presence of the high-temperature component with the maximal unblocking temperature close to 670–680°C.

Except for two cases (e.g., the sample AA-99 in Fig. 3), this high-temperature component has a northwestern–northern declination and a shallow inclination. In the two other samples, this component has a southeastern–southern declination and, probably, corresponds to the geomagnetic field with reversed polarity. The identified characteristic directions are rather broadly scattered on the stereogram; therefore, in the further analysis, we only used them for determining the polarity of the characteristic magnetization.

The samples representing the rocks of the Bratsk Formation in our study can be classified into three groups according to the pattern of the NRM behavior during the thermal cleaning. The first group includes the rocks that exhibit the irregular behavior of NRM.

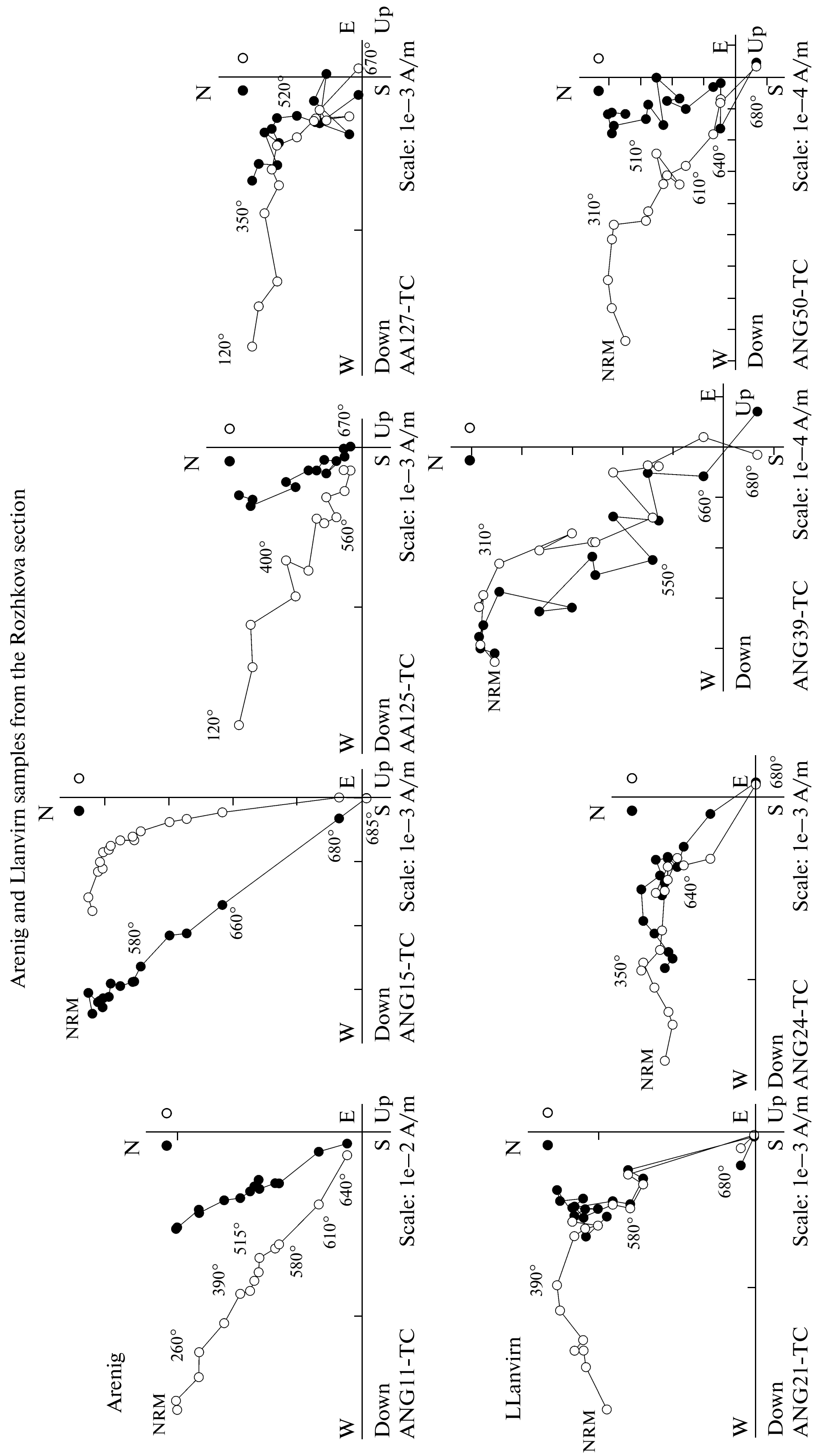

Fig. 2. The results of magnetic cleaning of the Ordovician rocks from the Rozhkova River (Arenig and Llanvirn).

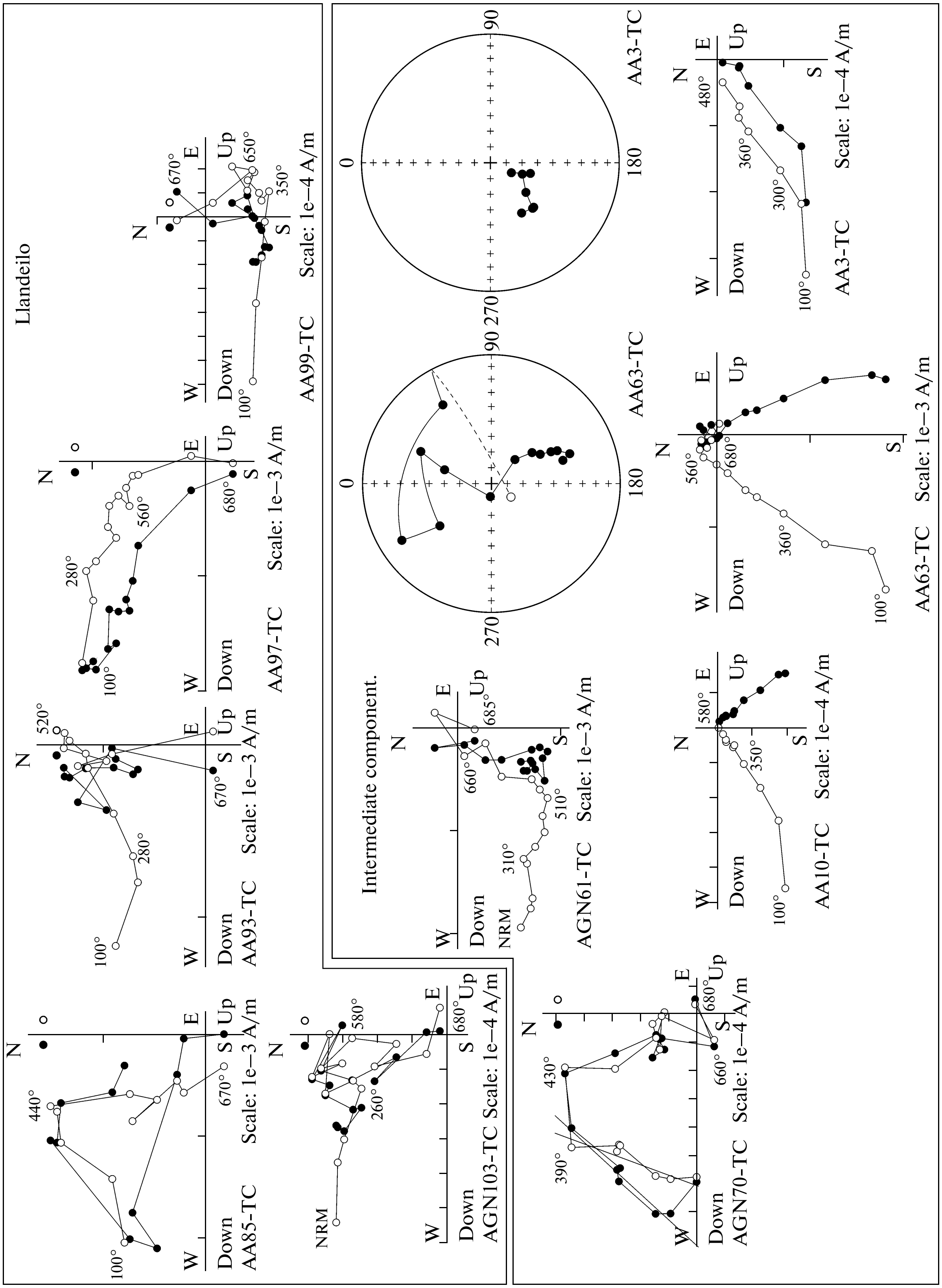

Fig. 3. The results of magnetic cleaning of the Ordovician rocks from the Rozhkova River (Llandeilo and the intermediate component).

The paleomagnetic directions and the poles of the Ordovician rocks from the section near the outlet of the Rozhkova River (middle reaches of the Angara River, 58.5°N, 99.8°E)

Age Object Polarity	*N*	Geographical coordinates				Stratigraphic coordinates			
		D	I	K	alfa95	D	I	K	alfa95
Arenig *Upper part of the Iya Formation and lower part of the Badaran Formation*									
Reverse	26	315.6	25.9	12.4	8.4	314.3	30.8	14.2	7.8
Plat = –36.4; Plong = 158.2; dp/dm = 4.9/8.7									
Llanvirn *Middle and upper parts of the Badaran Formation and lower part of the Mamyr Formation*									
Reverse	50	318.3	19.6	20.0	4.6	317.5	26.0	21.0	4.5
Plat = –35.2; Plong = 153.2; dp/dm = 2.6/4.9									
Caradoc *Bratsk Formation*									
Normal									
All	19	152.3	6.7	6.1	14.8	152.3	0.7	6.1	14.1
Without outliers	16	143.0	4.0	11.8	11.2	143.0	–1.9	11.9	11.1
Reverse									
All	9	338.0	16.3	9.8	17.4	337.6	20.1	9.4	17.7
Without outliers	8	331.6	18.3	27.5	10.8	330.9	21.0	20.9	12.4
Total (without outliers)	24	145.9	–3.7	11.7	9.0	145.6	–8.4	12.0	8.9
Plat = –29.5; Plong = 140.2; dp/dm = 4.5/9.0									
Intermediate temperature component (over the entire section) (over the entire section)	16	191.5	43.7	7.2	14.8	188.1	39.6	6.9	15.2
Present-day (geographic) coordinates: **Plat = –5.4; Plong = 89.4; dp/dm = 11.5/18.5;**									
Ancient (stratigraphic) coordinates: **Plat = -8.7; Plong = 92.2; dp/dm = 10.9/18.2;**									

Notes: *N* is the number of samples used; D is declination; I is inclination; K is concentration parameter; alfa95 is the radius of the oval of confidence; Plat and Plong are the latitude and longitude of the paleomagnetic pole, respectively; dp/dm is the radius of the semiaxis of the 95%-confidence oval.

The samples of the second group, which contain some intermediate component, will be discussed a bit later. The third group comprises the samples that contain a distinct high-temperature magnetization component with a maximal unblocking temperature of 620–680°C, rather shallow inclination, and either northwestern or southeastern declination (Fig. 4). The vectors corresponding to this component constitute two almost antipodal clusters on the stereogram (Fig. 5), whose mean directions after the reversal of one of these clusters, are very close in declination, but noticeably differ in inclination (by almost 20°), probably, due to the incomplete elimination of the steep component of recent magnetization. Although the distinguished component does not pass the reversal test ($\gamma/\gamma c$ = 21°/18°), we believe that the mean value calculated by averaging the vectors with normal and reversed polarity does not strongly deviate from the true mean value. The paleomagnetic pole calculated from the obtained mean direction (table) falls between the Llandeilo and the Ashgill–Lower Silurian poles for the Moyero River (Gallet and Pavlov, 1996), which, to some extent, confirms the Caradoc age of the revealed magnetization component.

Quite a few samples taken from the Rozhkova River section (mainly from its Caradocian part) contain an intermediate component of magnetization (Fig. 2) with the unblocking temperature spanning from 200–400°C to 580–644°C. In some cases, the intermediate component is followed by a clear high-temperature

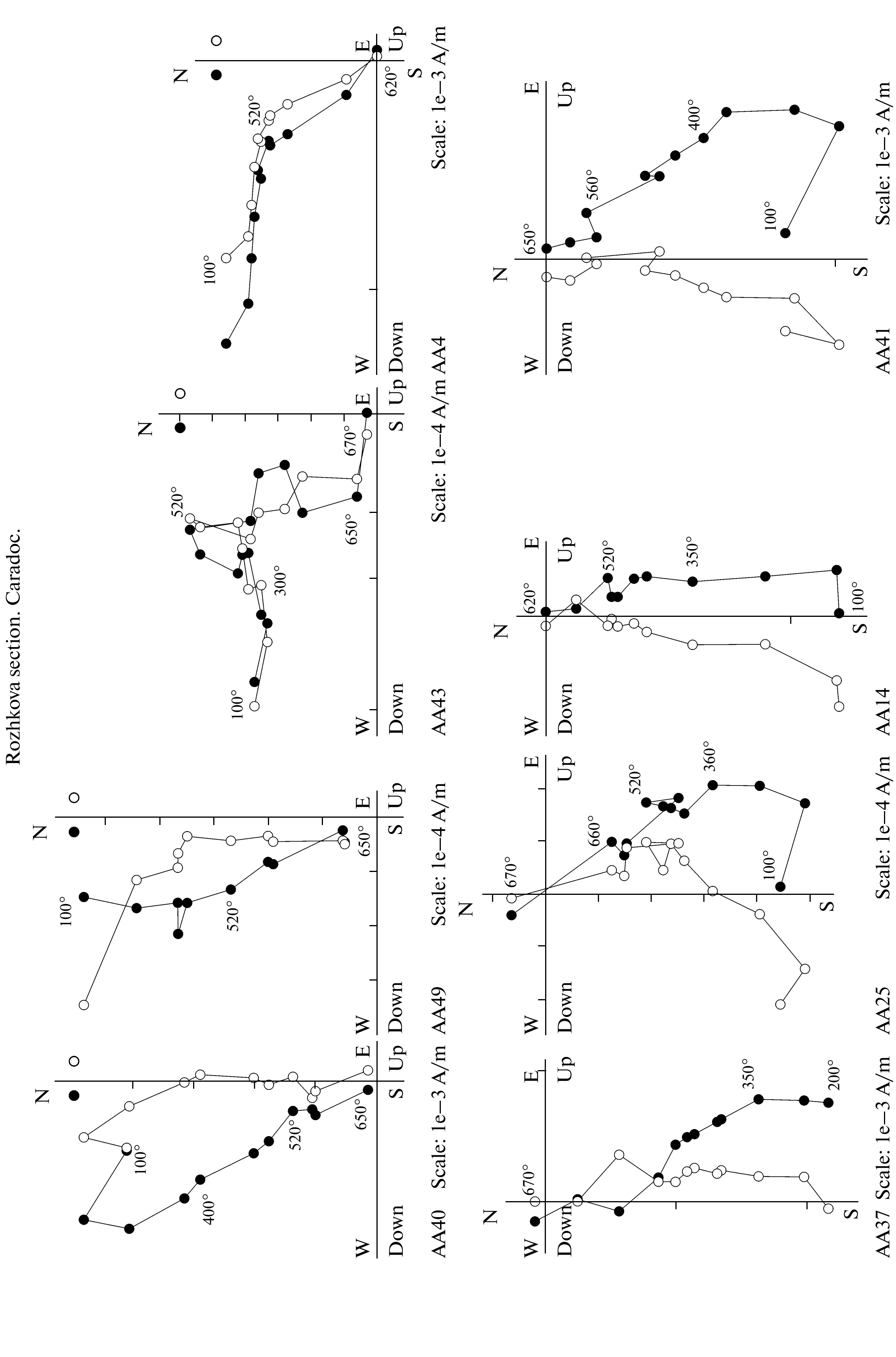

Fig. 4. The results of magnetic cleaning of the Ordovician rocks from the Rozhkova River (Caradoc).

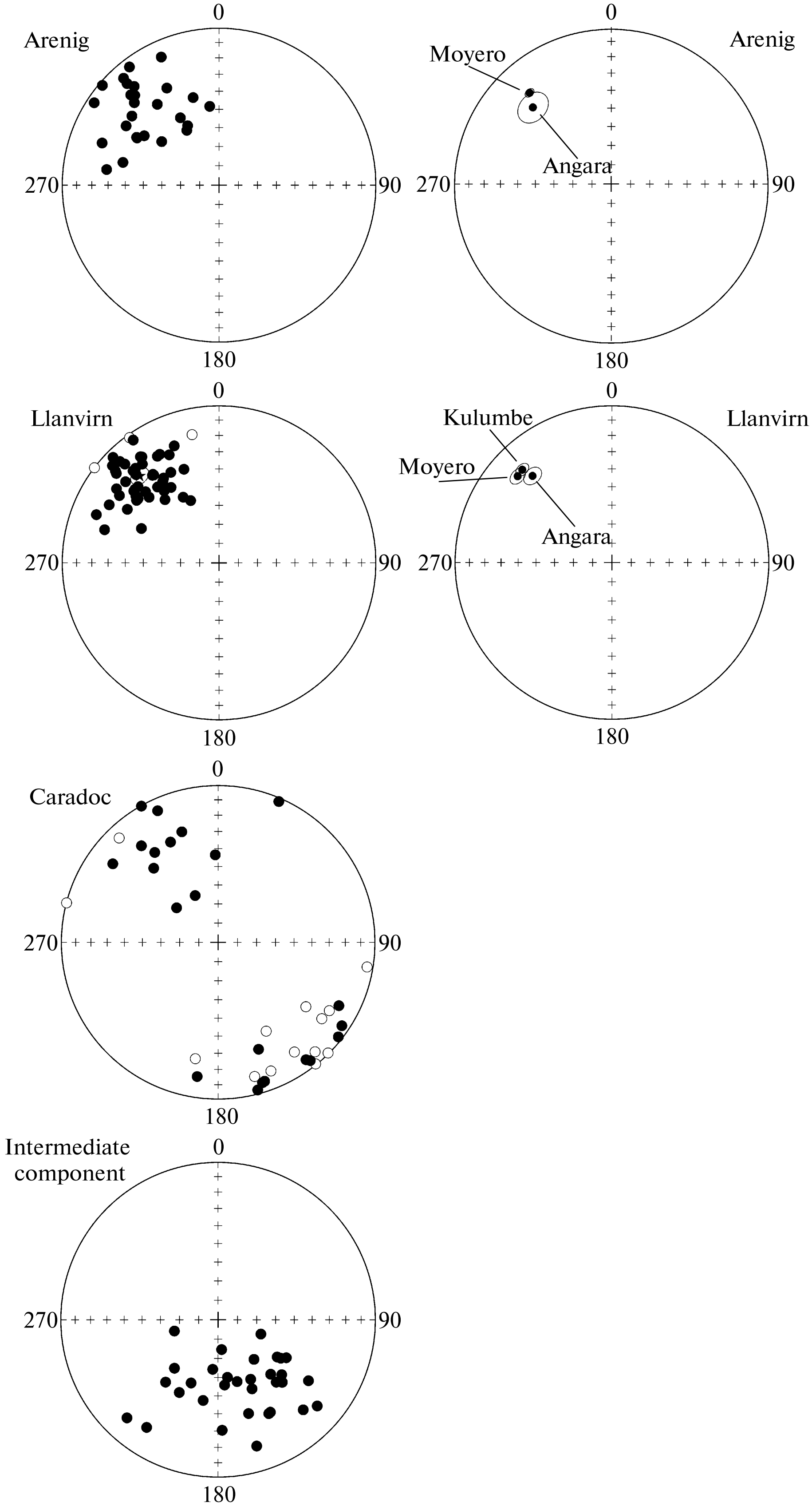

Fig. 5. The paleomagnetic directions for the Rozhkova River rock sequence and their mean directions as compared to the corresponding mean directions recalculated from the Moyero River section and the Kulumbo River sections. The filled and the open circles denote the projections onto the lower and the upper hemispheres, respectively.

characteristic component on the diagram. However, most often, the intermediate component is the most stable magnetization component in the samples. Typically, these components can readily be distinguished due to the different spectra of their unblocking temperatures. However, in the samples where the intermediate component is the most stable magnetization component, distinguishing between the intermediate and the high-temperature components is far more difficult, since the temperature spectra of these components may overlap.

With these considerations taken into account, we excluded the samples that leave room for ambiguous interpretation from the set of the samples intended for calculating the average magnetization directions.

THE MAGNETIC STRATIGRAPHY

The distribution of the magnetic polarity zones across the studied section is shown in Fig. 1. As can be seen, the Arenig and the Llanvirn parts of the section are totally dominated by the reversed geomagnetic polarity. The first allusions to a possible existence of the zones with normal polarity appear only in the Llandeilo, but, due to the poor quality of the paleomagnetic record there, we are not able to clearly establish the exact location of these zones and to determine their thicknesses. Moreover, we cannot study the distribution of the zones of different magnetic polarity close to the Llandeilo–Caradoc boundary due to the discontinuous outcrop of the rocks of this part of the Rozhkova section. On the other hand, in the present study we have obtained quite a detailed magnetostratigraphic record of the Caradoc part of the section. Unfortunately, the existing biostratigraphic data, as of now, are neither suitable for precisely locating the upper boundary of the Caradoc rocks in the studied section nor for determining the boundaries of the Caradoc biostratigraphic zones. Nevertheless, there are grounds to believe (Knyazev, 1978; Kanygin et al., 1984) that the studied part of the section is located somewhat lower than the Caradoc–Ashgill boundary, which, therefore, suggests that the magnetostratigraphic section of the Bratsk rocks reflects the changes in the geomagnetic polarity during the Caradoc time.

Despite certain lacunae in the magnetostratigraphic record of the Rozhkova section, the main objective of the present research has been achieved. The Arenig and Llanvirn parts of the section with a total thickness of more than 110 m contain a clearly readable paleomagnetic signal, which again indicates that the Arenig and the Llanvirn times were strongly (and, probably, even totally) dominated by the geomagnetic field of reversed polarity.

REFERENCES

Gallet, Y. and Pavlov, V., Magnetostratigraphy of the Moyero River Section (North-Western Siberia): Constraint on the Geomagnetic Reversal Frequency during the Early Paleozoic, *Geophys. J. Int.*, 1996, vol. 125, pp. 95–105.

Gurevich, E.L., Khramov, A.N., Rodionov, V.P., Dekkers, P., and Fedorov, P.V., Paleomagnetism of Ordovician and Devonian Sedimentary Rocks in the Northwest of the Russian Platform: New Constraints on the Baltica Kinematics in the Paleozoic and the Remagnetization in the Permian–Triassic, *Izv. Phys. Earth*, 2005, vol. 41, no. 7, pp. 555–570.

Kanygin, A.V., Moskalenko, T.A., Divina, T.A., Matyukhina, V.G., and Yadrenkina, A.G., The Ordovician in the Western Part of the Irkutsk Circue, *Tr. Inst. Geol. Geofiz., Akad. Nauk SSSR, Sib. Otd.*, 1984, vol. 529.

Kanygin, A., Moscalenko T., and Yadrenkina A., *Ordovician System of the Siberian Plaform*, Novosibirsk: Nauka, 1987.

Khramov, A.N. and Iosifidi, A.G., Paleomagnetism of the Lower Ordovician and Cambrian Sedimentary Rocks in the Section of the Narva River Right Bank: for the Construction of the Baltic Kinematic Model in the Early Paleozoic, *Izv. Phys. Earth*, 2009, vol. 45, no. 6, pp. 465–481.

Knyazev, S.A., Ordovician Deposits in the Latitudinal Flow of the Angara River, *Geol. Geofiz.*, 1978, no. 10, pp. 54–61.

McFadden, P.L. and McElhinny, M., Classification of Reversal Test in Paleomagnetism, *Geophys. J. Int.*, 1990, vol. 103, pp. 725–729.

Pavlov, V. and Gallet, Y., Upper Cambrian to Middle Ordovician Magnetostratigraphy from the Kulumbe River Section (Northwestern Siberia), *Phys. Earth Planet. Inter.*, 1998, vol. 108, pp. 49–59.

Rodionov, V.P. and Gurevich, E.L., Key Magneto-Stratigraphic Sequence of the Lower Ordovician Deposits, North-Western Siberian Platform, *Petrol. Geol. Theor. Appl. Stud.* (electronic journal), 2010, vol. 5, no. 3. http://www.ngtp.ru.