

Two competing Paleomagnetic directions in the Late Vendian: New data for the SW Region of the Siberian Platform

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[1] New paleomagnetic data have been obtained for the Late Vendian sedimentary rocks of the East Sayan and Southwest Baikal regions in the southwest of the Siberian platform. Two substantially different paleomagnetic components are isolated within the investigated stratigraphic interval in all objects of study. The pre-folding age of these components, as well as their difference from all of the known Phanerozoic paleomagnetic directions of the Siberian platform, indicate the almost simultaneous formation of the respective magnetization components during the earliest stages of the existence of these rocks. The angular distance between the paleomagnetic poles calculated for these components is about 45°. The analysis of the World Paleomagnetic Database shows that the presence of the discordant paleomagnetic directions in the Vendian-Early Cambrian rocks is characteristic not only of the Siberian objects but is also manifested in other continents and, hence, can be considered as the phenomenon of the planetary scale. We reckon that this fact can be explained by the anomalous behavior of the magnetic field of the Earth around the Precambrian-Cambrian boundary. In this paper we suggest a model describing the “geometry” of the Earth magnetic field in the Late Vendian-Early Cambrian, which allows one to explain the observed pattern of the paleomagnetic record. *INDEX TERMS:* 1500 Geomagnetism and Paleomagnetism; 1527 Geomagnetism and Paleomagnetism: Paleomagnetism applied to geologic processes; 9320 Geographic Location: Asia; *KEYWORDS:* paleomagnetism, Vendian, Cambrian, Siberian platform, anomalous geomagnetic field behavior.

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Introduction

[2] By the present time about 30 paleomagnetic determinations have been obtained for the Vendian rocks of the Siberian Platform. The paleomagnetic studies of the Vendian rocks in Siberia were initiated in the early 1970s and embraced almost all of the regions where these rocks outcrop at the ground surface. These regions include the peripheral part of the platform in its southwestern area, its northeastern area (Kharaulakh Mts.), the Patom Highland, the Udzha and Olenek uplifts, the Uchur-Maya region, and other areas [Gurevich, 1981, 1983; Komissarova, 1983, 1984, 1991; Komissarova and Osipova, 1986; Konstantinov, 1998; Kravchinsky et al., 2001; Pavlov and Petrov, 1997; Pavlov et

al., 2004; Pisarevsky et al., 2000; Rodionov, 1984; Shatsillo et al., 2001]. However, in spite of the numerous studies that have been carried out for more than thirty years, the position of the Vendian paleomagnetic pole of Siberia has not been determined unambiguously. Almost each new paleomagnetic determination is an alternative to the previous ones, the distribution of the paleomagnetic poles showing a scatter of 120° in longitude and 60° in latitude [Shatsillo et al., 2001]. Attempts of correlating the paleomagnetic data with the age levels of the Vendian System for the purpose of identifying any significant movement of Siberia in Vendian time, explaining observed poles scattering, also failed. It should be noted that both the younger Paleozoic rocks (beginning from the Middle Cambrian), and the older Middle and Late Riphean rocks of the Siberian platform fairly often show a distinct paleomagnetic signal, the paleomagnetic determinations available for the rocks of the same age from far-spaced regions showing good agreement.

[3] The significant number of the paleomagnetic determinations available for the Vendian rocks of Siberia does not meet the criteria of paleomagnetic reliability and formally

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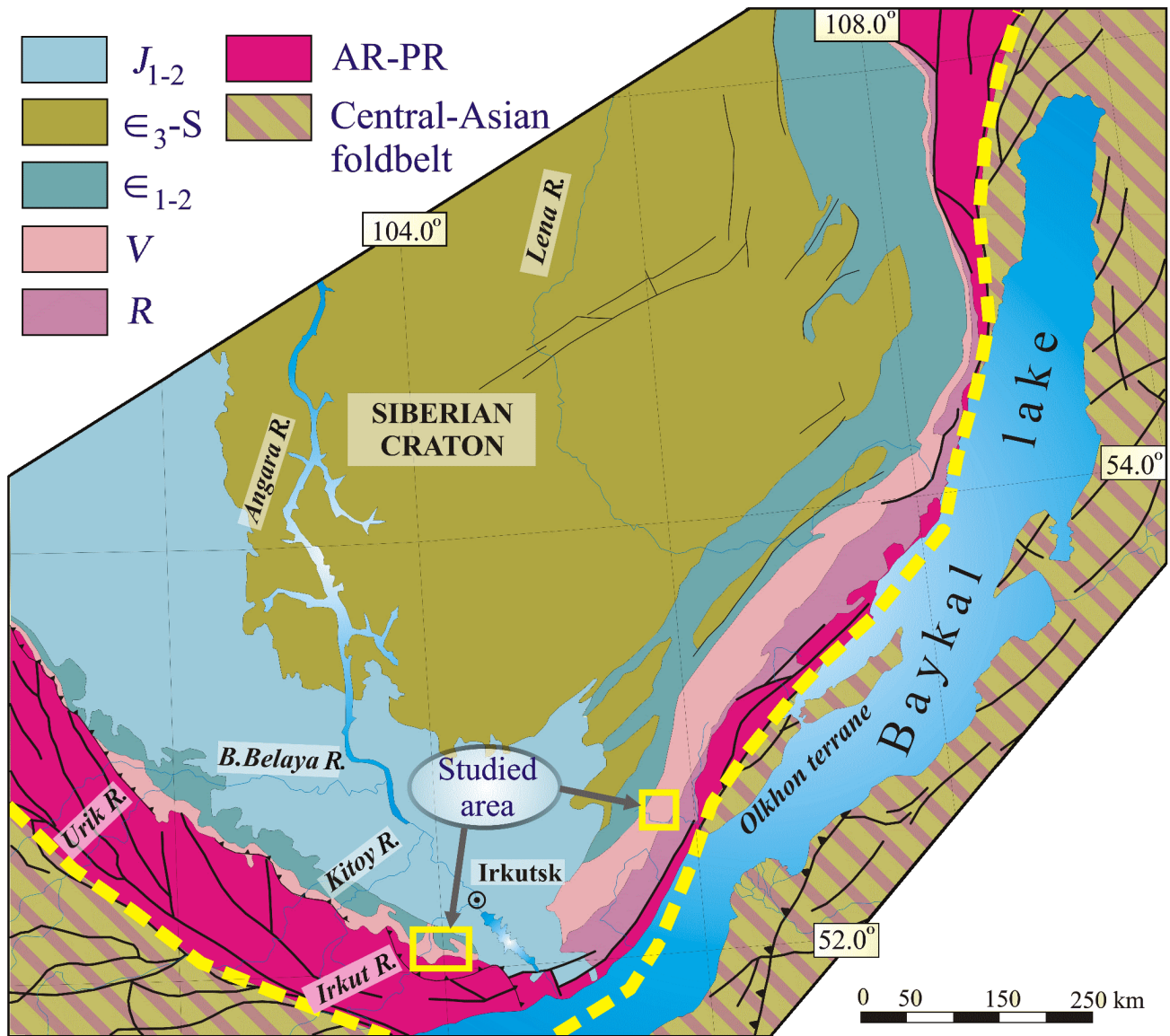


Figure 1. Sketch geological map of the SW Siberian Platform.

can be discarded. However, even the highly rigid selection of the data accumulated does not allow one to select any preferential direction.

[4] In the recent years a number of new papers has been published on the paleomagnetism of the Vendian rocks of Siberia; the data they reported had been obtained in accordance with the modern requirements for methods and instruments (detailed magnetic cleaning, component analysis, etc.) [Konstantinov, 1998; Kravchinsky et al., 2001; Pisarevsky et al., 2000]. However, even these paleomagnetic determinations have a number of drawbacks. First, these determinations were obtained for far-spaced objects from different, not always clearly determined stratigraphic levels. In most cases no tests were made to verify the primary character of the paleomagnetic directions obtained. One of

the best determinations (in paleomagnetic aspect), obtained for the Baikal region [Pisarevsky et al., 2000], cannot apparently be classified as a “Siberian” pole, since the study object resides in the zone of intensive Paleozoic deformation and in accordance with the data of structural-geological researches [Aleksandrov et al., 2001; Malykh, 1997] has an allochthonous position.

[5] Uncertainty in locating poles for the Precambrian-Phanerozoic boundary has been indicated also for other old ancient platforms and is still a matter of hot discussion [Meert, 1999; Torsvik et al., 1998], to mention but a few.

[6] The study reported in this paper was an attempt to investigate the single Vendian stratigraphic level in the volume of the Nemakit-Daldynian Stage in the remote sections of the Southwest Baikal and East Sayan regions (Figure 1).

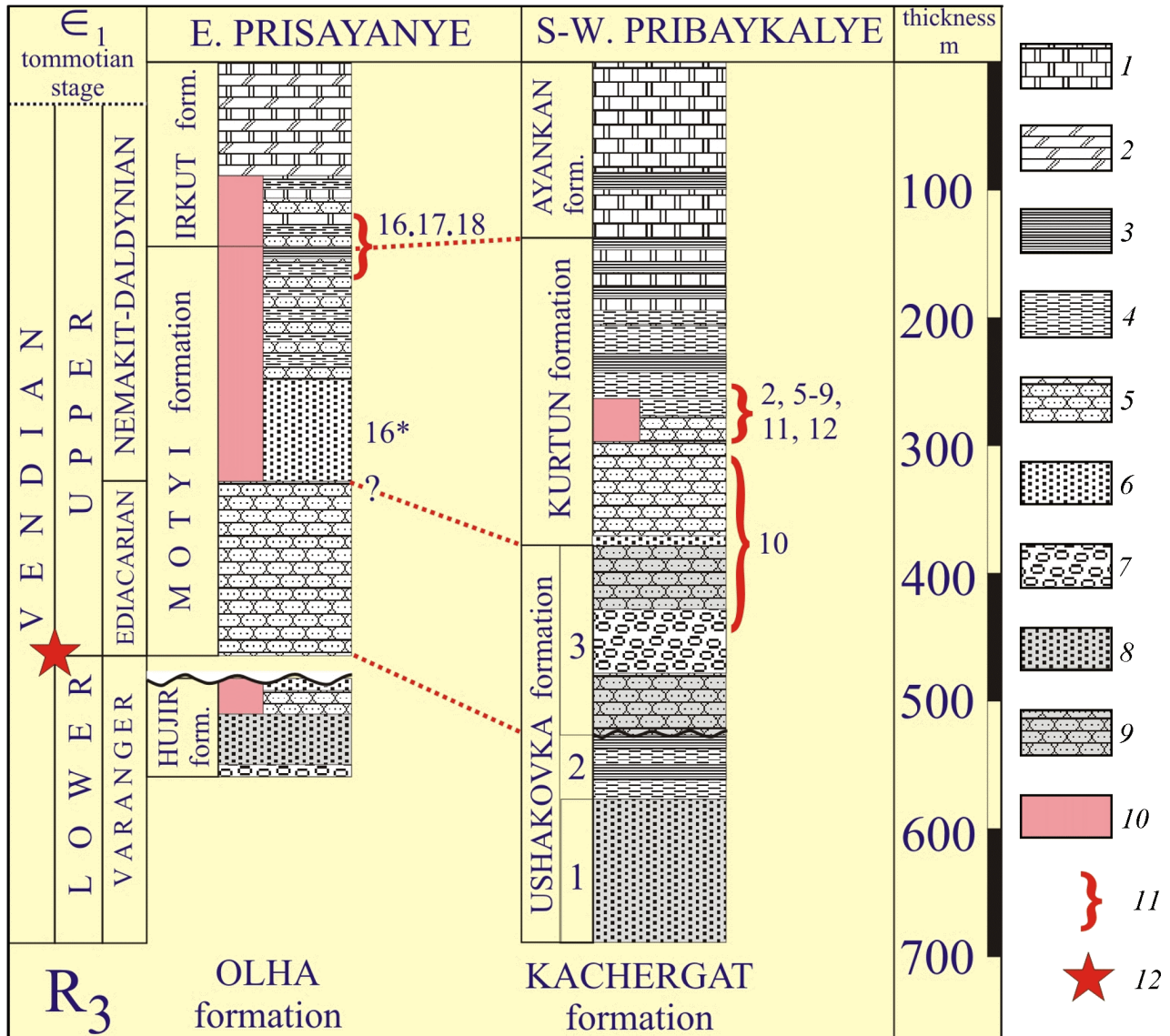


Figure 2. Lithostratigraphic column and schema of stratigraphic subdivision of sections studied [after Kochnev, 2002]: (1) dolomite; (2) dolomitic marl; (3) argillite; (4) siltstone; (5) fine- to medium-grained sandstone; (6) coarse-grained sandstone and gravelite; (7) conglomerate; (8) polymictic coarse-grained sandstone and gravelstone; (9) polymictic fine- and medium-grained sandstone; (10) red rocks; (11) intervals of study, the figures denote site nos.; (12) the lower boundary of the Nemakit-Daldynian stage (see the text). The mark 16* denotes the rock interval investigated by Kravchinsky et al. [2001].

In tectonic respect, the sections considered belong to sedimentary cover of the Siberian platform.

Geology and Age

[7] The Vendian rocks of the southwestern margin of the Siberian Platform [Khomentovskiy et al., 1972; Kochnev, 2002] occur in the present-day erosion cut as a narrow band of outcropping rocks surrounding the Siberian Craton along its periphery (Figure 1). Generally, the Vendian rocks inherited the structure of the older Riphean troughs, resting

on the Riphean rocks with a regional unconformity. The Vendian rocks are conformably overlapped by the carbonate deposits with Lower Cambrian fauna. As follows from the traditional stratigraphic scheme (see Figure 2), the Vendian rocks of this region occur as a thick sedimentation cycle, which begins with a terrigenous molasse formation (with the size of the clastic material ranging from conglomerate to argillite), represented by the Khuzhir, Ushakovka, Moty, and Kurtun formations, and terminates as a terrigenous-carbonate, mainly dolomite, sequence of the Irkut and Ayanka formations totaling 600–1500 m in thickness.

[8] The areas discussed in this paper vary greatly in their

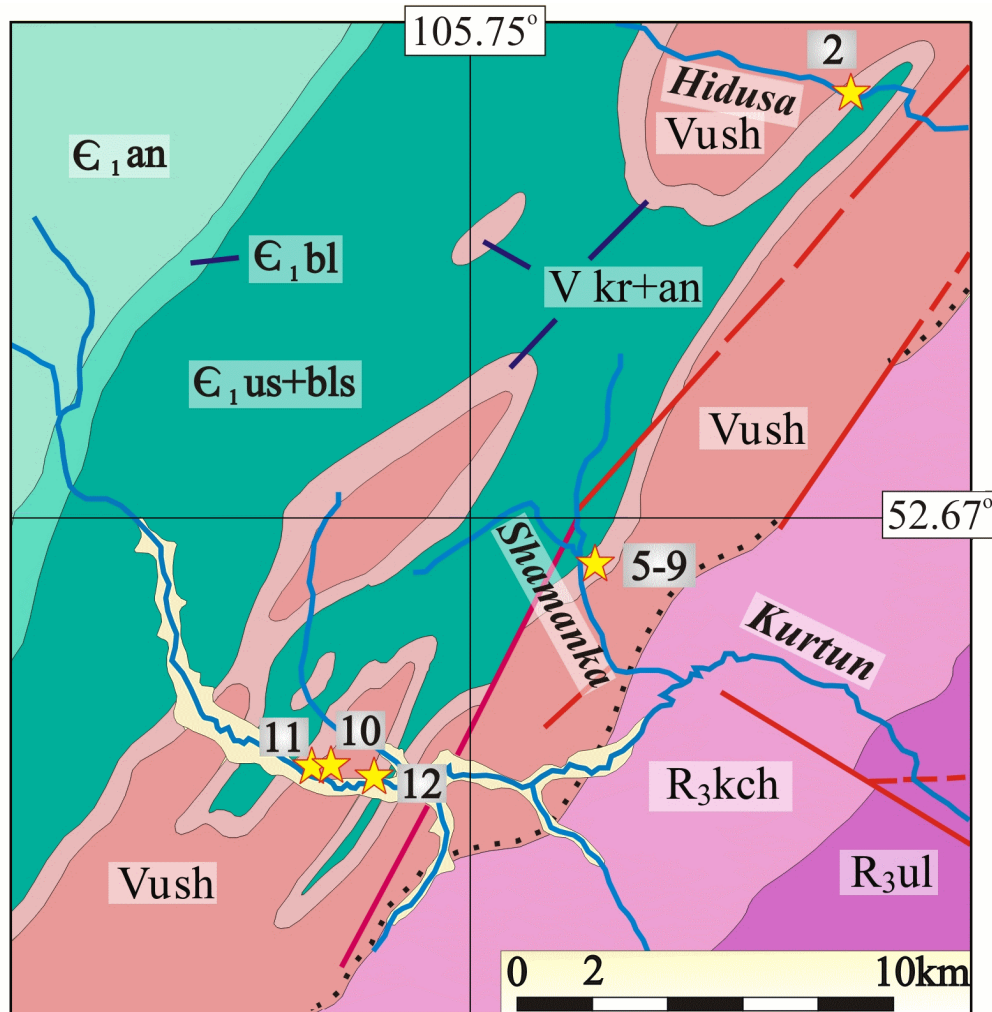


Figure 3. Schematic geological map of the study area in the southwest Baikal region. The indices denoting the rock formations: (an) Angara Fm; (bl) Bulai Fm; (us+bls) Usole and Belsk Fms, undifferentiated, (kr+an) Kurtun and Ayankan Fms, undifferentiated, (ush) Ushakovka Fm, (kch) Kachergat Fm., (ul) Uluntui Fm; the asterisks and numbers denote the studied outcrops.

tectonic histories. The Vendian rocks of the Sayan region are almost undeformed and compose gentle monoclines dipping toward the platform at angles of a few degrees. At the same time the Vendian rocks of the Baikal region are deformed to steep and long linear folds of the northeast strike, broken by faults of the same orientation. It is believed that this folding was caused by Caledonian events which expressed themselves in the collision of the Olkhon Terrain and the Siberian Platform and can be dated as Early Ordovician, as follows from the latest geochronologic data [Rozen and Fedorovsky, 2001] for the isotopic rejuvenation of the basement rocks.

[9] Views differ as to the volume of the Vendian rocks in this region, the fossil remains proving only their upper boundary (by the first findings of Cambrian-Tommotian forms) [Kochnev, 2002; Rozanova et al., 1992]. As follows from conventional views [Khomontovsky et al., 1972], the main criterion for drawing a boundary between the Vendian and Baikalian (Late Riphean) rocks is to proceed from the events of geologic history. On this basis, judging by the

broadening of the sedimentation basin, associated with a change in the structural style, the lower Vendian boundary is correlated with the bases of the Ushakovka (Baikal region) and the Khuzhir (Sayan region) formations [Kochnev, 2002; Khomontovsky and Postnikov, 2001] (Figure 2). Very important for the Vendian stratigraphy of the region were the Ediakarian fossils (*Baicalina sessilis* Sok., *Cylindrichnus* sp., and *Pteridinium* sp.) found in the rocks of the Late Ushakovka member of the Ushakovka Formation [Sokolov, 1975]. On this basis these rocks and their stratigraphic analogs can be dated 560–580 Ma. The upper member of the Kurtun Formation was found to contain the skeletonless fauna represented by *Paleolina* aff. *Evenkiane* Sokolov [Khomontovsky et al., 1972], and vendoteniun flora [Sokolov, 1975]. The rocks of the Ayankan Formation are known for their complete assemblage of Vendian stromatolites: *Jurusania sibirica* (Yak.), *Linella simica* (Kryl.), *Boxonia allachjunica* (Kom. et Semikh.), and *Colleniella singularis* Kom. [Korolyuk and Sidorov, 1969]. Also available for the

rocks of the Kurtun Formation are K-Ar ages of 606 Ma and 609 Ma of glauconite [Anisimova and Titorenko, 1976], yet they are now considered to be obsolete.

[10] Because of the scarcity of fauna remains in the Vendian rocks of the study region, the rock sequences are compared and correlated on the basis of their lithologies [Khomentovskiy et al., 1972; Kochnev, 2002].

[11] There is a different view for the volume of the Vendian rocks in the southwest of the Siberian Platform, as well as for the position of their lower boundary and their subdivision, which is accepted in present paper. Yu. K. Sovetov [Sovetov, 2002a, 2002b] discovered diamictite boulders showing the typical lithologic features of tillite at the base of the Marnia Formation (Oselok Series) in the Uda River area (Prisayanie). He discovered similar rocks in some other stratigraphic analogs of the Oselkovo Series. On this basis they were combined into one tillite horizon corresponding to the Varangerian glaciation, corresponding in terms of its volume to the Lower Vendian [Sokolov, 1997]. According to these data, the Ediacarian+Nemakit-Daldynian stages of the conventional Vendian must correspond to the Nemakit-Daldynian Stage (Figure 2).

[12] More arguments are being accumulated each year in favor of the larger stratigraphic volume of the Siberian Vendian rocks, at the expense of the Baikalian rocks. The isotopic and geochemical studies ($\delta^{13}\text{C}$ and $^{87}\text{Sr}/^{86}\text{Sr}$) using the rocks of the Baikalian Series from a stratotype area, compared with the “reference” curves available for the Late Precambrian, suggest the Vendian (pre-Nemakit-Daldynian) age of these rocks [Letnikova et al., 2004].

[13] In addition, B. B. Kochnev (Institute of Geophysics and Petroleum Geology, Novosibirsk, unpublished data) reported in the lower member of Ust-Tagul formation, where the base of Ediacarian was traced according to conventional schema, the traces of the living activity of the organisms, identified by D. V. Grazhdankin (Paleontological Institute, Russian Academy of Science) as *Treptichnus pedum*, a typi-

cal fossil for the base of the Nemakit-Daldynian Stage.

[14] Hence, on the basis of the recent data, the objects of this study (see below) can be attributed to the Nemakit-Daldynian Stage of the Vendian.

[15] Another point that calls for a study is the argued position of a boundary between the Vendian and the Lower Cambrian. Most of the Russian geologists include the Nemakit-Daldynian Stage into the Vendian System [Khomentovskiy, 2000; Khomentovskiy et al., 1998; Kochnev, 2002; Rozanov et al., 1992, 1997; Sokolov, 1997], to name but a few. At the same time, foreign geologists place the lower boundary of the Cambrian at the base of the Nemakit-Daldynian Stage [Brasier et al., 1994; Harland et al., 1990; Landing, 1994; Tucker and McKerrow, 1995]. Thus, presently, it is more correct to classify the Nemakit-Daldyn stage as a Vendian-Lower Cambrian transition unit.

Objects of Study

Southwest Baikal Region

[16] Samples for the paleomagnetic study were collected in the drainage basin of the Kurtun River and its tributaries, known as the Shamanka and Khidusa Rivers (Figure 3). The Vendian rocks are deformed there into a complex syncline of a NE strike, grading toward the center of the platform into an undeformed, subhorizontal platform cover.

[17] No large faults that might have caused any displacements of the study rocks relative to the platform area have been recorded in the survey scale of 200 000. Samples for the paleomagnetic study were collected from the thin variegated member of the Kurtun Formation (ranging from 8 m to 40 m in thickness) composed of red and green feldspar-quartz sandstones (sampling sites 2, 5–9, 11, and 12 – 125 samples), and also from the top of the Ushakovka to the bottom of the Kurtun Formation, represented by light greenish-gray polymictic and quartz sandstones (sampling site 10 where 60 samples were collected from about 200 m of the rock sequence) (Figure 2). In the Baikal region samples were collected from the rocks of the Ushakovka and Kurtun formations along the Kolesma Derevenskaya River and in the area of the Goryachii Klyuch Village. However, no representative paleomagnetic information was obtained there, and this object of study will not be discussed here.

East Sayan Region

[18] The object of study here was the transitional part of the Moty and Irkut formations in the stratotype key section along the Irkut River, namely, at the Shaman Mountain (Site 16), where 27 samples were collected along about 30 m of the rock sequence, and in the area of the Moty Settlement (Site 18), where 33 samples were collected along about 40 m of the rock sequence, the rocks being mainly red quartz sandstone and siltstone (see Figure 2 and Figure 4). The Vendian rocks, composing the studied section along the Irkut

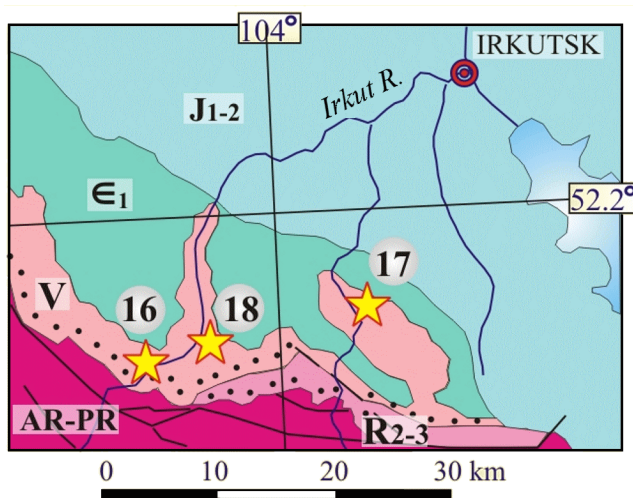


Figure 4. Schematic geological map of the East Sayan area of study, the asterisks and numbers denoting the studied outcrops.

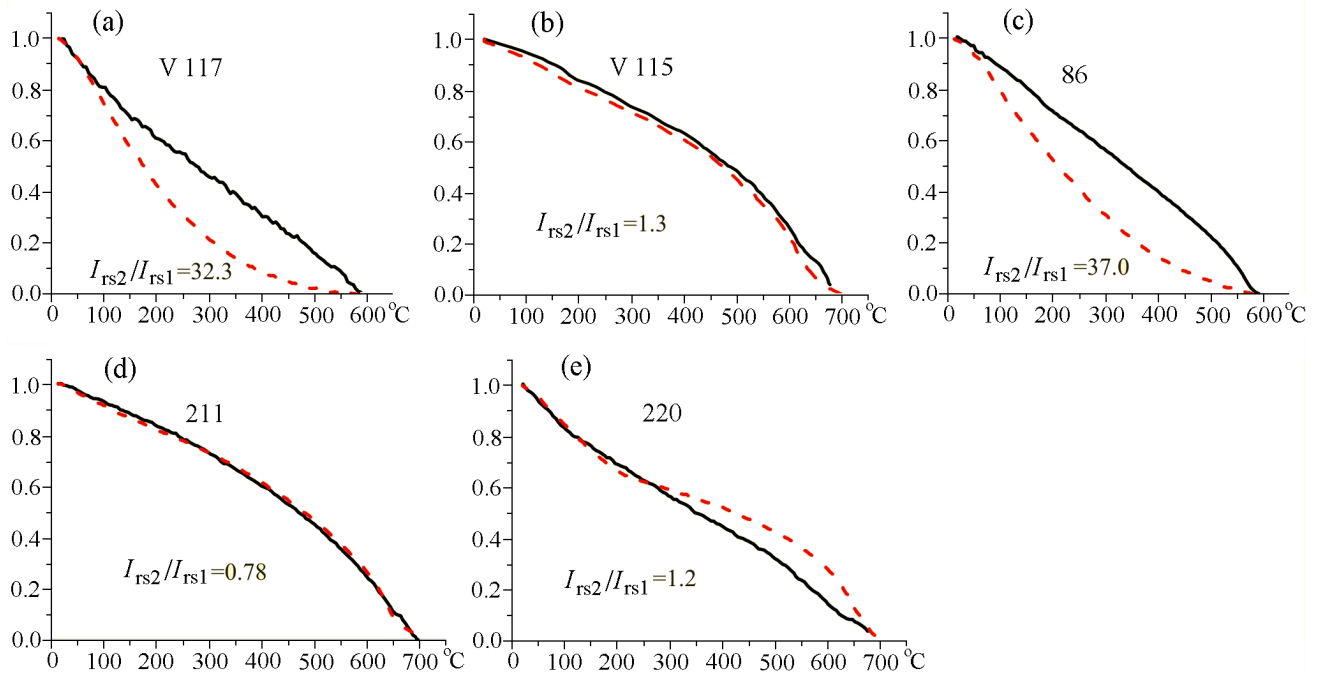


Figure 5. Curves of remanent saturation magnetization vs temperature for the rocks of (a–b) Kurtun Fm., (c) Ushakovka Fm., (d) transition from the Moty to Irkut Fms., (e) Irkut Formation. The red broken line shows the results of the second heating.

River, are nearly horizontal, showing insignificant variations in their dips and strikes. 15 samples of pink-grey quartz sandstones were also collected at the bank of the Olkha River (Site 17) from a small outcrop of the Irkut Formation rocks, located at anticline flank, dipping to the north at 19° to 35° .

Methods of Study

[19] The rock samples were processed at the paleomagnetic laboratories of the Institute of Physics of the Earth (IPE), Russian Academy of Sciences (Moscow), Institut de Physic du Globe (IPGP, Paris), and All-Russian Geological Institute (VSEGEI, St. Petersburg). Remanent magnetization was measured using the JR-4, JR-5, and 2-G Enterprise instruments magnetometers, magnetic susceptibility was measured using a KLY-2 kappa-bridge. All samples were subjected to detailed temperature cleaning up to 680°C , the number of steps being not less than 16. All laboratory procedures were performed in the rooms protected from the outer magnetic field. Some samples of the Ushakovka Series rocks were processed using a combined thermal and alternate-field cleaning. The efficiency of this method was found to be low in the case of the rocks concerned. The behavior of the remanent magnetization vectors in the course of magnetic cleaning was analyzed using a component analysis following the conventional procedure using the computer programs written by R. J. Enkin and S. V. Shipunov [Bazhenov and Shipunov, 1991; Enkin, 1990, 1994; Shipunov, 1995; Shipunov and Muraviev, 2000], to name but a few.

Magnetic Cleaning Results

Southwest Baikal Region

[20] **Kurtun Formation (Sites 2, 5–9, 11, and 12).** The natural remanent magnetization (NRM) of the variegated sandstones of the Kurtun Formation varies from 0.2 mA m^{-1} to 4.8 mA m^{-1} , averaging 1.6 mA m^{-1} , the values of magnetic susceptibility varying from 93 to 340×10^{-6} SI units, the average value being 195×10^{-6} SI. As follows from the curves of the remanent saturation magnetization vs. temperature $I_{rs}(T)$ (Figure 5a and b), the magnetic carriers of the studied rocks are hematite and magnetite. As a rule, the I_{rs} values grow notably (in some cases by more than an order of magnitude) after the first heating. Magnetic susceptibility also grew with heating, averaging 86% at the last cleaning steps ($T = 560\text{--}680^{\circ}\text{C}$). This seems to be associated with magnetite formation during the oxidation of pyrite, the presence of which was recorded in the rocks of the Kurtun and Ushakovka formations [Pisarchik, 1963]. It should be noted that because of the low significance of Sites 2, 5–9, and 11 and of their geographic proximity, we combined them with Site 12 (Figure 3), which is the stratotype of the Kurtun Formation, and is more representative, both in the number of the samples available, and in the better exposure and larger thickness of the rocks. The magnetic cleaning of studied samples of Kurtun formation allowed to isolate (in addition to the laboratory viscous component) three magnetization components, which produce three fairly distinct clusters in the stereogram:

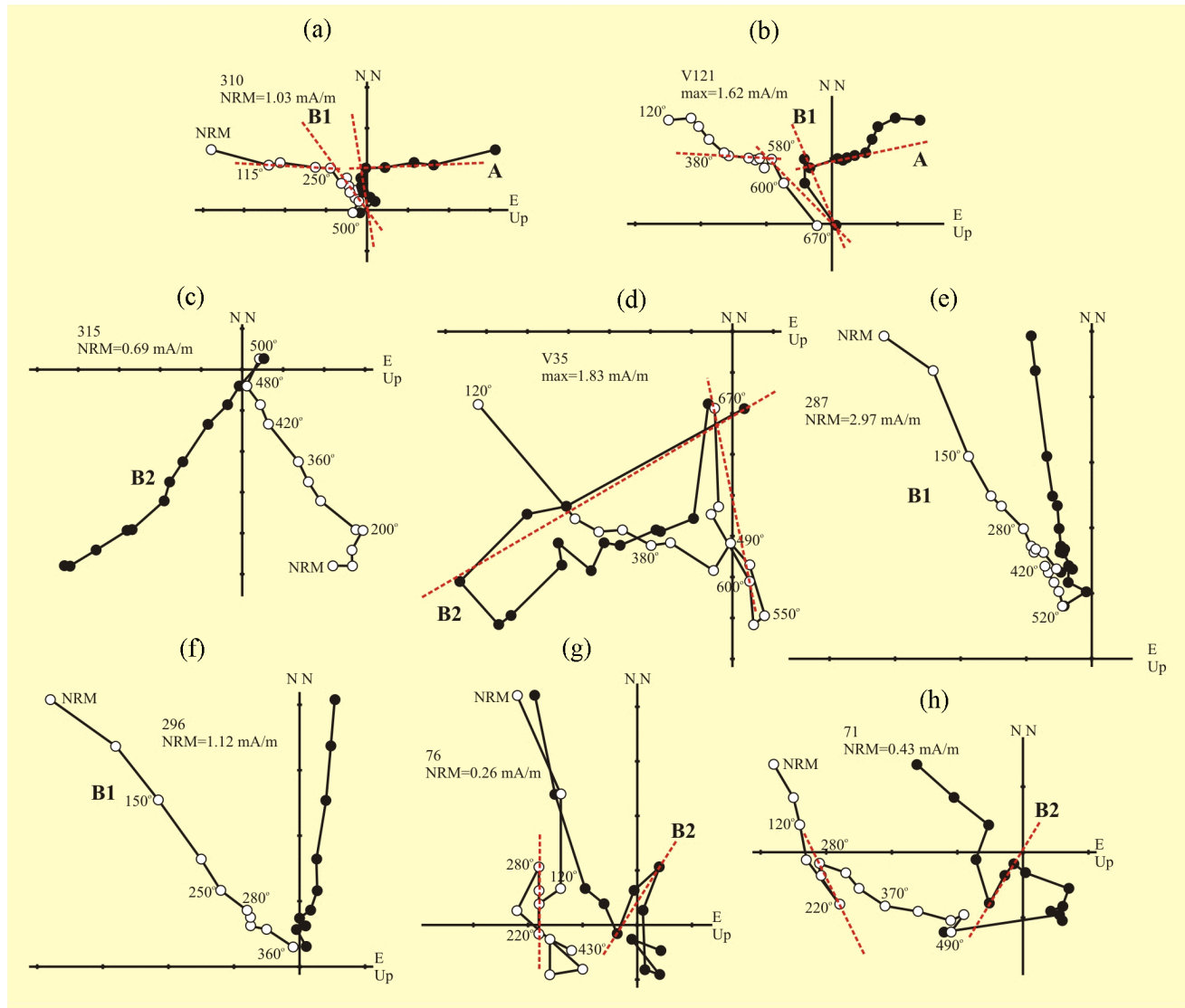


Figure 6. Typical Zijdeveld diagrams for the rocks of the SW Baikal region: (a–d) Kurtun Formation, (e–h) Ushakovka Formation. The solid circles show the projections of the magnetization vectors onto the horizontal plane; the open circles show the same onto the vertical plane. All diagrams are given in the stratigraphic system of the coordinates.

[21] (1) the intermediate component A, recorded in the temperature range of 100°C to 200–350°C and found in most of the study samples. In some cases A is the only component found in the sample, being destroyed at the temperatures close to T_c (Curie temperature) of magnetite (Figure 6a and b);

[22] (2) the high-temperature B1 component (Figure 6a and b), found roughly in 30% of the study samples, is destroyed in a temperature range of 420–680°C (up to the T_c for magnetite and hematite);

[23] (3) the high-temperature B2 component distinguished in the temperature range of 300–520°C to 480–680°C in 15%

of the samples, up to the T_c of magnetite and hematite (see c and d in Figure 6);

[24] The A component is a single-polarity one and has a post-folding age (see Figure 7 and Table 1). B1 component is a pre-folding, predominantly single-polarity component (Figure 7 and Table 1), although in some samples it has a reversed polarity.

[25] We failed to estimate the time of the B2 component formation relative to the folding event using all kinds of tests, apparently, because of a “noise signal” and, possibly, because of the small number of samples for which it was obtained (Figure 7, Table 1). Note that the B2 component is a bi-

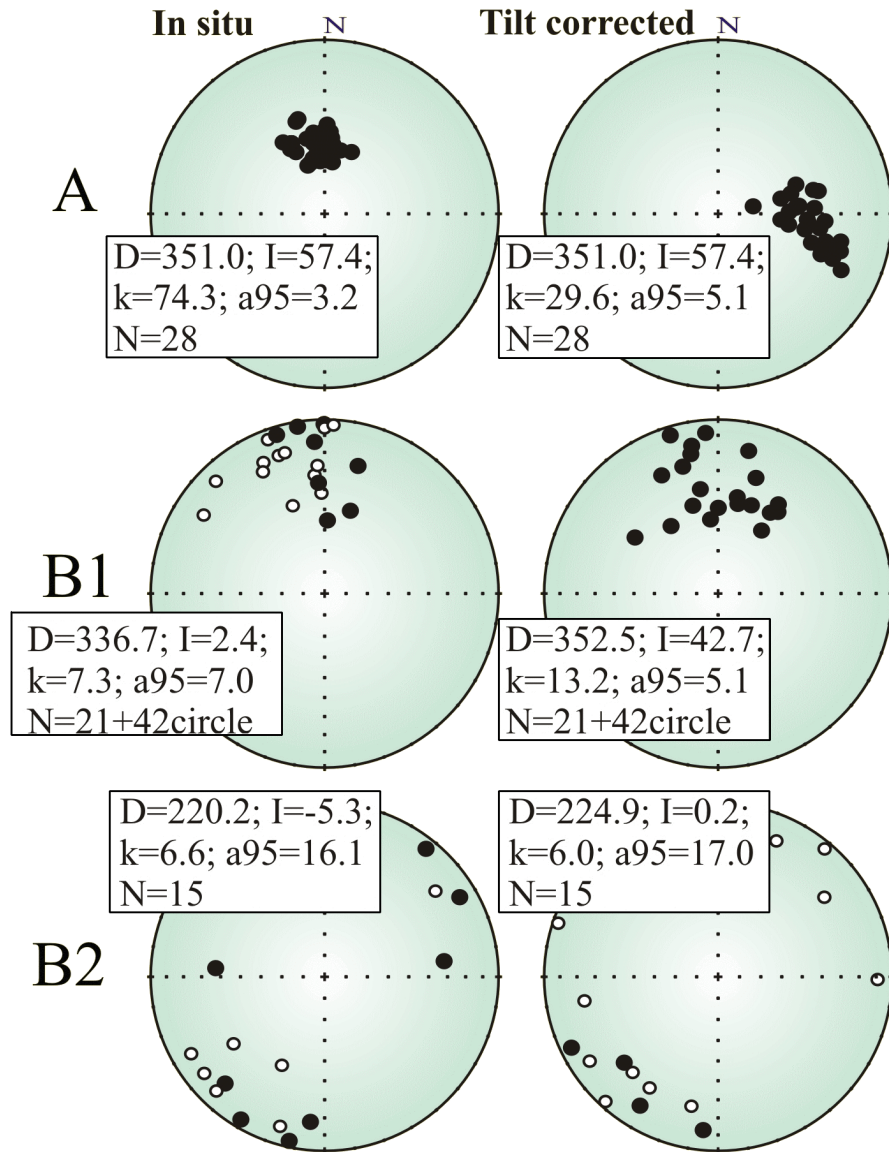


Figure 7. The distribution of the vectors of the A, B1, and B2 components of the Kurtun Formation in the southwest Baikal region. The solid circles denote the projection on the lower hemisphere, the open ones, on the upper.

lar one, and its direction does not coincide with any of the known younger ones.

[26] **Ushakovka Formation (Site 10).** The polymictic and quartz sandstones from the top of the Ushakovka to the bottom of the Kurtun Formation showed the following magnetic parameters: NRM ranging from 0.1 mA m^{-1} to 9.0 mA m^{-1} , the average value being 1.8 mA m^{-1} ; magnetic susceptibility value ranging from 140 to $530 \times 10^{-6} \text{ SI}$ units, the average value being $309 \times 10^{-6} \text{ SI}$ units. The $I_{rs}(T)$ curves (Figure 5c) suggest the presence of magnetite as a magnetization carrier. Generally, most of NRM (>80%) is removed during heating to 450°C . At higher temperatures the NRM vector varies chaotically in its direction, the

magnetic susceptibility value begins to grow up to 50% at $T = 500^\circ\text{C}$, and the paleomagnetic signal cannot be interpreted.

[27] Like in the case of the variegated rocks of the Kurtun Formation, strong parasitic remagnetization is observed which is caused by the newly formed magnetite.

[28] Magnetic cleaning revealed three magnetization components:

[29] (1) the low-temperature ($<200^\circ\text{C}$) postfolding component, close to the modern magnetic field of the Earth in direction (not discussed here);

[30] (2) the high-temperature prefolding B1 component isolated in the temperature range of 250 – 500°C and having one polarity (Figure 6e, f; Figure 8; Table 1);

Table 1. The mean directions and paleomagnetic poles of the study objects

no.	Comp.	N	D	I	k	α_{95}	Fold test			Φ	Λ	dp/dm	
							DC	NFT	CFT				
South-western Priбайkalye													
site 12 (Kurtun formation) $\varphi = 52.7$; $\lambda = 105.8$													
1	A	28	s	92.7	44.8	29.6	5.1	–	–	–	–74.0	132.4	3.4/4.7
			g	351.0	57.4	74.3	3.2						
2*	B1	21	s	352.5	42.7	13.2	5.1	+	+	?	–61.5	120.2	3.9/6.3
			g	336.7	2.4	7.3	7.0						
3	B2	15	s	224.9	0.2	6.0	17.0	?	?	?	–25.3	54.5	8.5/17.0
			g	220.2	–5.3	6.6	16.1						
site 10 (Ushakovka formation) $\varphi = 52.7$; $\lambda = 105.8$													
4	B1	29	s	347.2	37.7	30.0	5.0	+	±	+	–56.9	128.1	3.5/5.9
			g	36.6	79.1	12.7	7.8						
5	B2	16	s	218.0	–8.4	7.1	14.8	?	?	?	–32.3	59.2	7.5/14.9
			g	248.9	–27.9	6.6	15.5						
Eastern Prisaуanye													
site 16–18 (transit zone of Motyi-Irkut formations) $\varphi = 52.1$; $\lambda = 103.7$													
6	A	40	s	341.8	56.7	90.2	2.4	?	+	+	–70.4	151.6	2.5/3.5
			g	337.9	58.4	82.4	2.5						
7	B1	22	s	356.7	40.3	20.2	6.8	+	?	+	–60.8	109.9	5.0/8.2
			g	356.0	42.2	20.1	6.8						
8**	B2		s	207.3	2.3	13.3	13.8				–32.0	71.0	6.9/13.8
			g	206.8	–3.5	10.7	15.5						
site 17 (Irkut formation) $\varphi = 52.1$; $\lambda = 104.1$													
9	B1	12	s	359.9	43.0	22.6	9.3	+	+	+	–62.9	104.3	7.1/11.5
			g	356.0	60.6	9.5	14.9						
10	B2	11	s	25.8	5.3	102.1	4.5	+	+	?	–36.1	71.6	2.3/4.5
			g	28.2	30.1	62.3	5.8						
Mean directions of B1 and B2 components (all sites) for $\varphi = 52.7$; $\lambda = 105.8$													
	B1	4	s	354.4	41.4	238.2	6.0	+	+	?	–60.8	116.3	4.5/7.3
			g	351.3	48.2	5.6	42.8						
	B2	4	s	214.8	–3.9	73.6	10.8	+	+	?	–31.6	63.7	5.4/10.8
			g	221.2	–18.3	13.2	26.3						

Note: Comp. – denotes the magnetization components; no. – the number of the samples; D – the declination; I – the inclination; k – precision parameter; α_{95} – the radius of the confidence circle; Φ and Λ – denote the latitude and longitude of the paleomagnetic pole; dp/dm are the semiaxes of the pole confidence oval; φ and λ are the geographical latitude and longitude of the study object; s and g denote the stratigraphic and geographic systems of the coordinates, respectively. The fold tests: DC (direction-correction fold test [Enkin, 1990]; NFT (new fold test) [Shipunov, 1995]; CFT (correlation fold test [Bazhenov and Shipunov, 1991]. * The average direction calculated for 21 “end points” and 42 remagnetization circles. **The direction reported by [Kravchinsky et al., 2001].

[31] (3) 15 samples were found to contain the intermediate B2 component of the SW declination and shallow inclination, identified in the temperature range of 220–280°C (see g and h in Figure 6; Figure 8; Table 1). One sample showed

this component in the temperature range of 310–460°C; it seems to be the final one, going to origin of the diagram of Zijdeveld. We failed to date the B2 component relative to the folding event, like in the case of the Kurtun Formation.

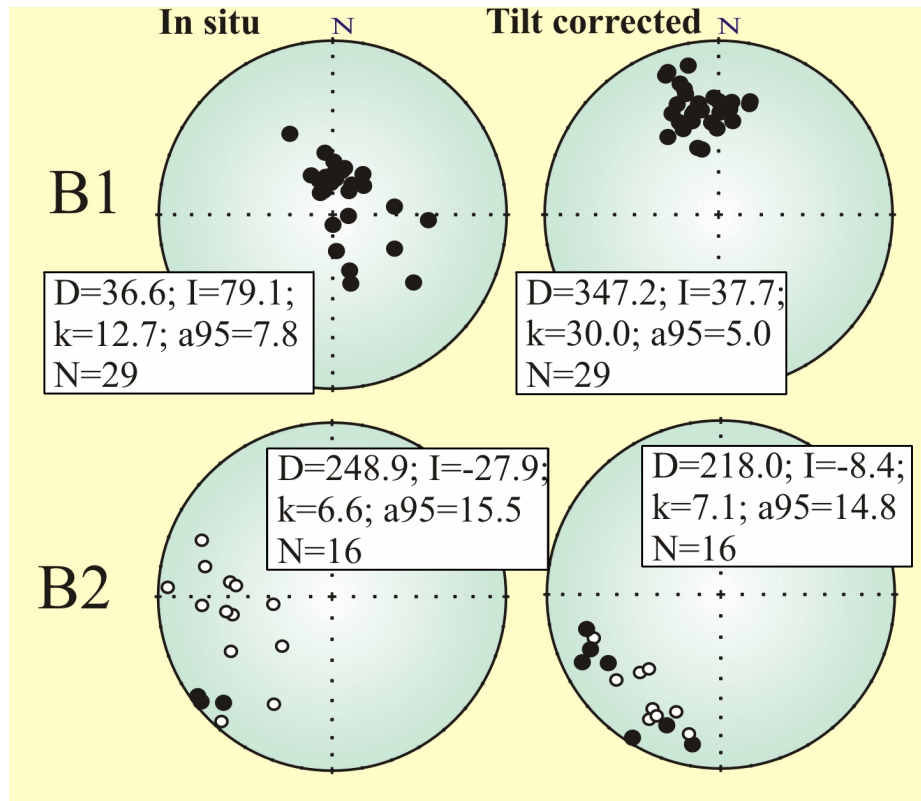


Figure 8. The distribution of the vectors of the B1 and B2 components of the Ushakovka Formation in the southwest Baikal region (Kurtun River area). The solid circles denote projections on the lower hemisphere, the open ones, on the upper.

East Sayan Region

[32] **Transition from the Moty to the Irkut formation, Sites 16 and 18.** The NRM values of the red sandstone and siltstone vary from 3 mA m^{-1} to 13 mA m^{-1} , the average value being 5 mA m^{-1} , the magnetic susceptibility values ranging from 80 to 170×10^{-6} with an average value of 120×10^{-6} SI units. The $I_{rs}(T)$ curves (Figure 5d) indicate the presence of one magnetic mineral, hematite. The heating of up to 200°C removes 50% of the magnetization. The further heating causes a gentle NRM decay almost to zero at the temperature close to T_c of hematite. At the temperature of 550°C the magnetic susceptibility value begins to grow, its growth amounting averagely to 40% during the last heating (680°C).

[33] The I_{rs} value did not grow essentially, although the $I_{rs}(T)$ curves of the second heating showed sometimes the newly formed magnetite. The “material” for its formation seems to be the iron oxide present in the sandstone cement, and also hydromica [Psarchik, 1963].

[34] The identical magnetic properties and component composition of the rocks at Sites 16 and 18, as well as the same stratigraphic level, the insignificant variations in the dip and strike, and the geographical vicinity of the outcrops allow one to consider these rocks as one object.

[35] The magnetic cleaning showed three components of magnetization:

[36] (1) the low-temperature component which breaks down during the heating of more than 200°C . This component is close to the direction of the modern magnetic field (not discussed here);

[37] (2) the medium- to high-temperature A component, identified in the temperature range of 150 – 200°C and higher either as a intermediate one (not extending to the coordinate origin of the Zijdeveld diagram), or (locally) as the only component identified in the sample, destroyed at the Curie temperature of hematite (Figures 9a and 10);

[38] (3) the high-temperature B1 component of the same polarity (Figure 9a, b, and c, and Figure 10), which usually follows the “intermediate” A component and decays at 680°C . The A and B1 components are formally pre-folding ones (Table 1).

[39] For Site 16, using the rocks older than those investigated in our present study, Kravchinsky *et al.* [2001] obtained the bipolar directions of shallow inclinations, corresponding (in our terminology) to the B2 component (Table 1). We obtained the B2 direction only in one sample collected at Site 18 (Figure 9d) in the upper part of the studied outcrop.

[40] **Irkut Formation, Site 17.** The NRM values vary from 2.0 mA m^{-1} to 10.1 mA m^{-1} , averaging 5 mA m^{-1} ; the magnetic susceptibility value varies from 110

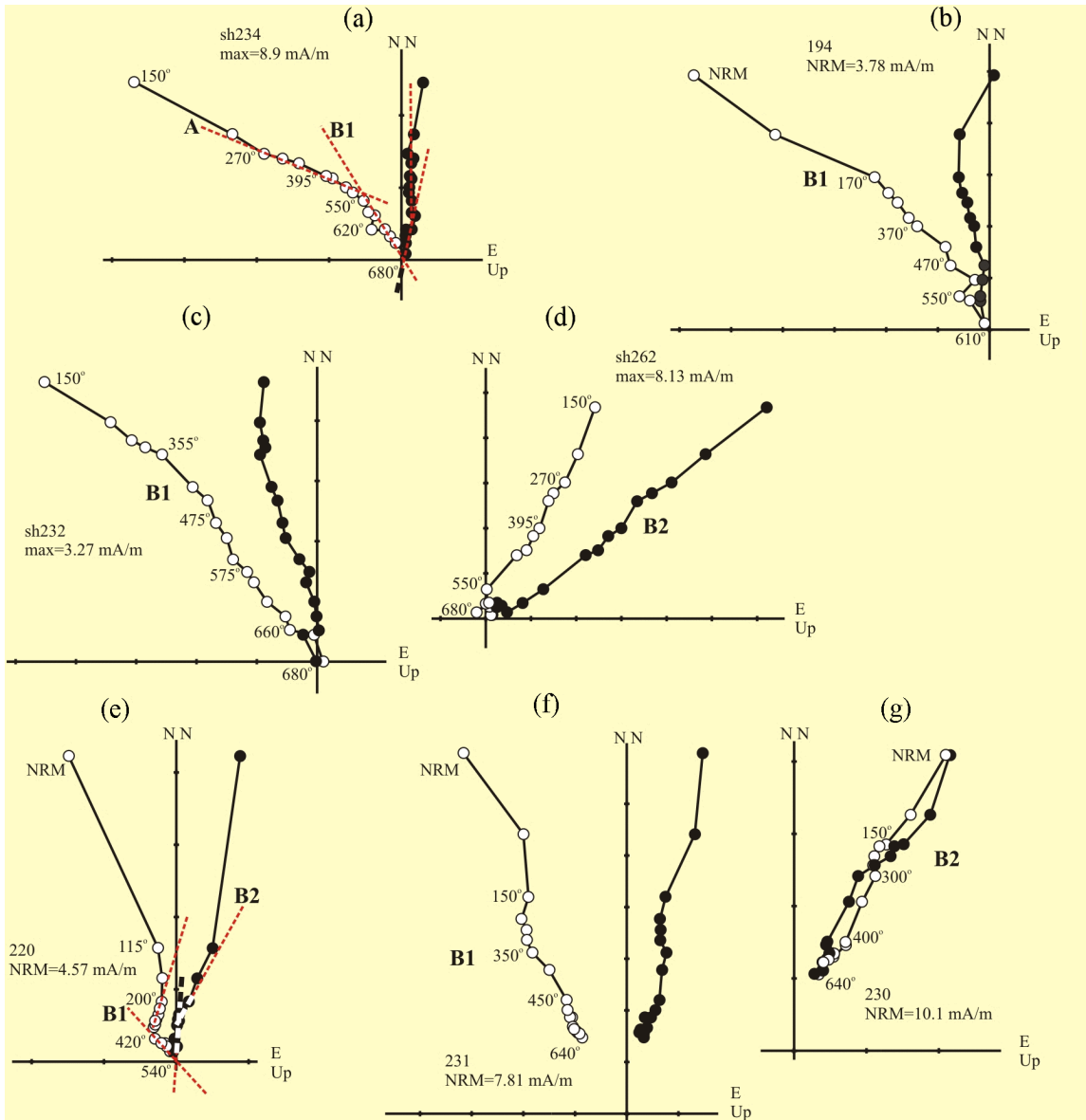


Figure 9. The typical Zijderveld diagrams for the rocks of the East Sayan area. The a–d – diagrams show the transition from the Moty to the Irkut formations, e–g – presenting the Irkut Formation. The solid circles denote the projections of the magnetization vector onto the horizontal plane, the open ones, onto the vertical plane. All diagrams are presented in the stratigraphic system of the coordinates.

to 260×10^{-6} SI units, averaging 180×10^{-6} SI units. The magnetization carrier is hematite, the $I_{rs}(T)$ curves of second heating generally repeating the initial $I_{rs}(T)$ curves (see e in Figure 5). The characteristic feature is the magnetic susceptibility decay at the end of the heating, amounting to 50% at the last cleaning steps. The viscous remanent magnetization is higher than 50% NRM, being removed by heating up to 100°C .

[41] Two magnetization components were clearly resolved in all 15 samples that were studied: 1) the intermediate B2 high-temperature component isolated in the temperature interval of 115°C to $200\text{--}300^\circ\text{C}$ (Figure 9e). In one sample this component is final one (g in Figure 9) and 2) high-

temperature B1 component revealing from $250\text{--}475^\circ\text{C}$ and destroying completely at T_c of hematite (Figure 9e and f). Another sample showed the B1 component of reversed polarity. Both components had a pre-folding age (Figure 11, Table 1).

Comparison of the Average Directions

[42] As follows from the above data, the Vendian rocks of the Baikal and Sayan regions, differing both in their lithologies and magnetic characteristics, show three magnetization

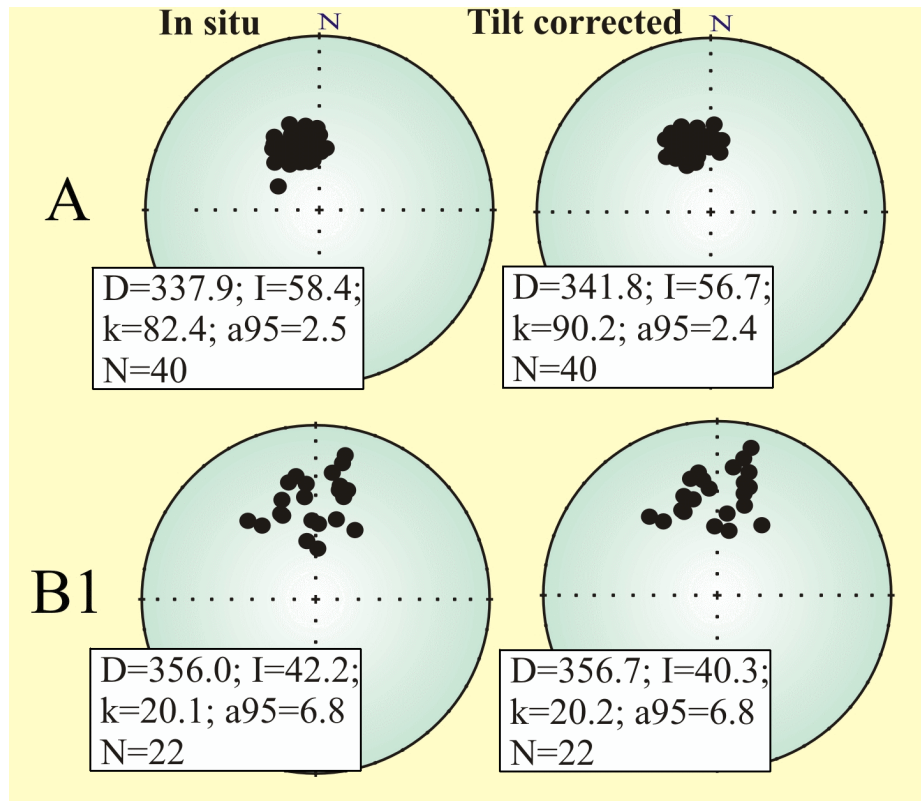


Figure 10. The distribution of the B1 and B2 component vectors in the Moty-Irkut Fms transitory zone in the East Sayan area (Irkut River). The solid circles denote the projection onto the lower hemisphere, the empty ones, onto the upper.

components of different nature, which are preserved in the objects of our study in different combinations (Figure 12, Table 1).

[43] **A component.** The metachronic component has been recorded in the rocks of the Kurtun Formation in the Baikal region, where its post-folding age has been proved, and also in the transition parts of the Moty and Irkut formations in the Sayan area. Some insignificant differences in the dips and strikes between Sites 16 and 18 (Sayan area) preclude the exact dating of the A component relative to the time of the Sayan deformations, however the average directions of this component in Sites 16 and 18 are notably closer in the stratigraphic system of the coordinates, as compared to the geographical one. The single polarity A component is characterized by NNW declinations and inclinations of about 60°.

[44] Our analysis of the paleomagnetic data available for the Siberian platform shows that the pole of the A component differs significantly from all post-Early Cambrian paleomagnetic poles, this suggesting its Early Cambrian or Precambrian age (Figure 13). In this case, however, the post-folding age of this component suggests that the folding in the studied areas of the Southwestern Baikal region has the Late Vendian age, which has not been confirmed in terms of structural geology yet.

[45] **The B1 component** has been isolated in all areas of study, has a pre-folding age, both in site volumes and in the comparison of the sites average directions and is predominantly a monopolar one. This component has northern declinations and inclinations of about 40°.

[46] **The B2 component** is a bipolar component characterized by low inclinations and NE-SW declinations. It is usually distinguished in Zijderveld diagrams either as an intermediate or as a final component. The pre-folding age of the B2 component was proved only in one outcrop, using a small number of samples where it is intermediate relative to the B1 component (Site 17). The comparison of the data obtained for the B2 component at the regional level suggests the pre-folding time of its formation.

[47] None of the directions corresponds to any of the known post-Vendian paleomagnetic poles of Siberia (Figure 13). At the same time the directions, close to the B1 component, were obtained for the Vendian Ust-Tagul and Moty Formations (Tagul and Toysuk rivers) [Gurevich, 1981; Shatsillo et al., 2001].

[48] From the other hand the bipolar components, close to the B2 direction, are known for some Vendian formations of North Baikal and Patom Upland regions (Minia Formation and Nokhtuisk Formation) [Konstantinov, 1998]. Besides, as it has been mentioned above, B2 direction has been isolated in the rocks of the Moty Formation exposed in

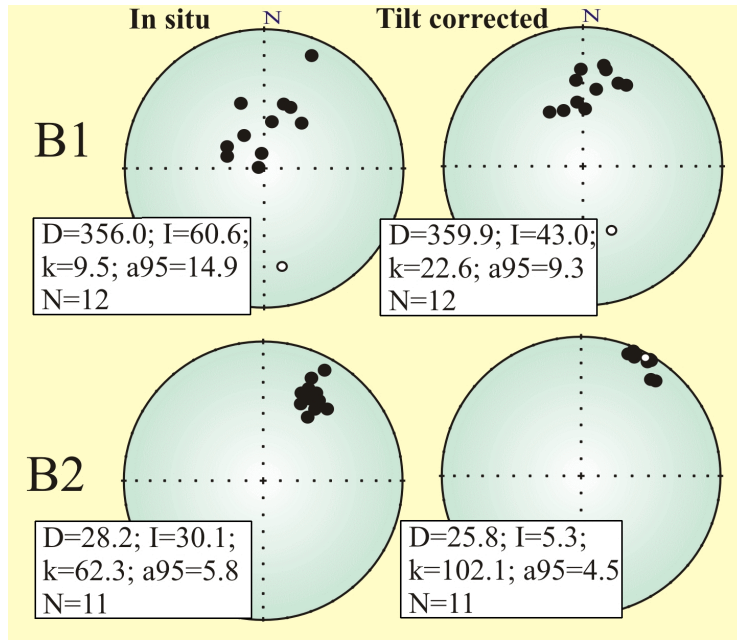


Figure 11. The distribution of the B1 and B2 components of the Irkut Formation in the East Sayan area (Olkha River). The solid circles denote the projection onto the lower hemisphere, the open ones, onto the upper one.

the Irkut River valley (Shaman Mountain) in the Sayan area [Kravchinsky et al., 2001].

Discussion of the Results

[49] Thus, besides the metachronous A component (not discussed here), two substantially different paleomagnetic directions, B1 and B2, were found in the rocks investigated in the SW Baikal and East Sayan areas. Below follow their main characteristics.

[50] 1. The magnetization components corresponding to these directions exist objectively and are not any artifacts associated with the data processing.

[51] 2. Both components are often found in the sections, spaced dozens and hundreds of kilometers apart, representing different areas of the Siberian Platform with different geologic histories.

[52] 3. The B1 direction is usually more distinct, characterized by moderate positive inclinations and northern declinations, is usually a monopolar one and is interpreted as a pre-folding one, both at the sites level and regional levels.

[53] 4. The B2 direction is a bipolar one and is characterized by low inclinations and NE-SW declinations. The fold tests performed in site volumes usually give inconclusive results, this being obviously caused by a “noisy” paleomagnetic signal. Yet, the fold test at the regional level indicates the obvious pre-folding age of this direction.

[54] 5. No association of these directions with any definite rock type has been found. Both of them are carried by hematite as well as by magnetite.

[55] 6. The B2 direction has been distinguished either as a final (“end-points”) one or as an intermediate component relative to the B1 direction, none of the samples showing inverse relationships.

[56] 7. The B1 and B2 directions were found in all objects studied, which precludes the explanation of their existence by the effect of local tectonics.

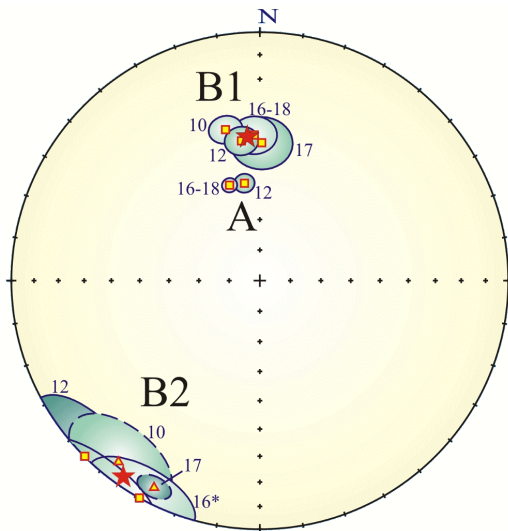


Figure 12. The average directions of the A, B1, and B2 components for all objects of study. The squares show the projections of the vectors onto the lower hemisphere, the triangles, onto the upper one. Site 12 for the A component is given in the geographic system of the coordinates, the others, in the stratigraphic one. Site 16* is given after Kravchinsky et al. [2001].

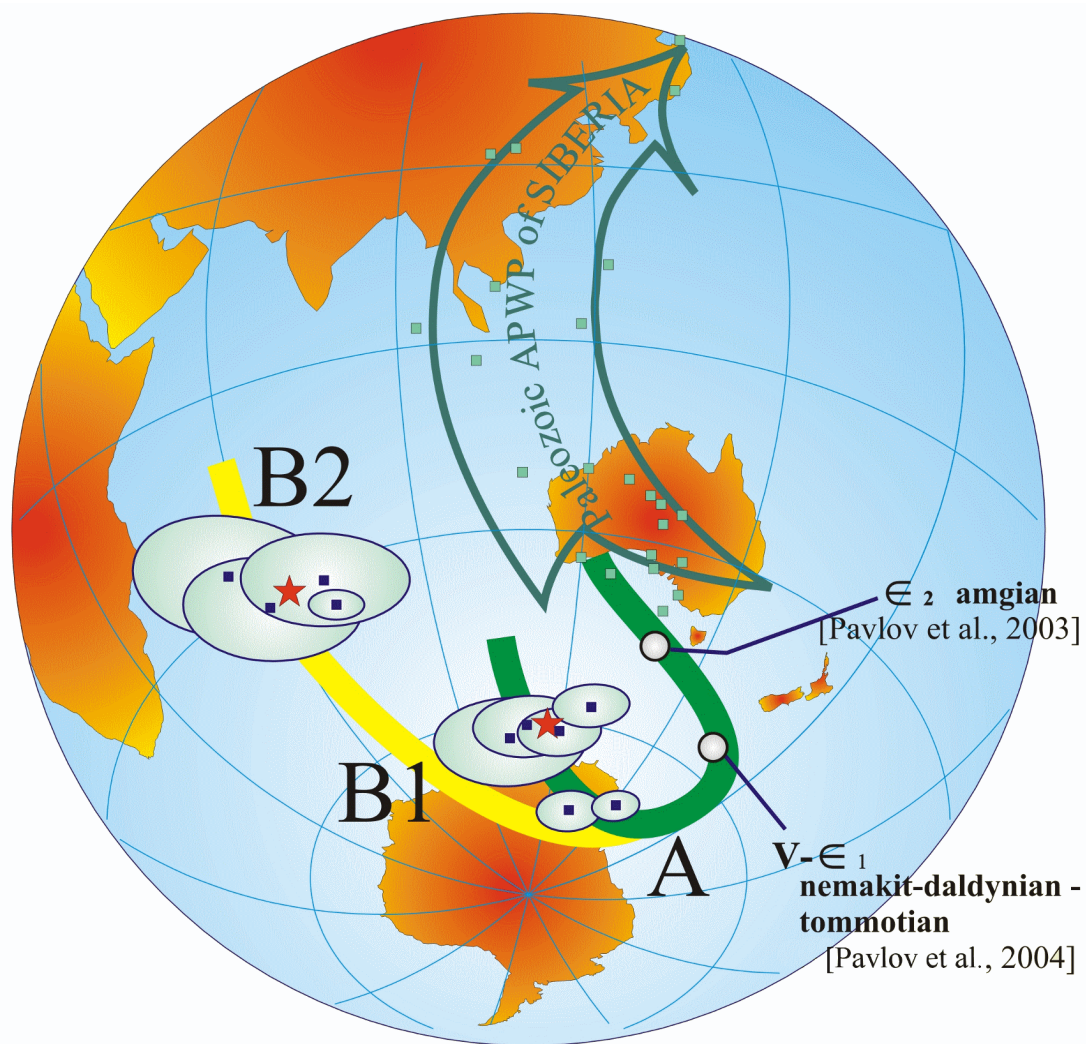


Figure 13. The paleomagnetic poles for the A, B1, and B2 components.

[57] 8. In continuous monofacies rock sequences these directions often replace each other, producing their complex combinations.

[58] 9. Both directions yield paleomagnetic poles which differ significantly from the known Phanerozoic poles of Siberia, that, in some degree, suggests the Precambrian age of their formation.

[59] 10. The angle between the B1 and B2 directions is about 45° .

[60] No objective arguments have been obtained so far in favor of the priority of one of these directions, or in favor of the fact that either of them has been produced by the remagnetization of rocks. The paleomagnetic pole, corresponding to the B1 component, is relatively close to the Middle and Late Cambrian poles of the Siberian Platform (Figure 13), this allowing one to infer the Middle-Late Cambrian age of the B1 component. However, in spite of its relative proximity, the pole corresponding to this component differs significantly from the Middle-Late Cambrian poles [Gallet *et al.*, 2003; Pavlov and Gallet, 1998], this precluding the for-

mation of the B1 component as a result of the Middle-Late Cambrian remagnetization.

[61] It is somewhat more difficult to correlate the B1 component with the Early Cambrian pole of the platform (Figure 13), because the position of the latter is a subject of hot discussion, for example, see [Pisarevsky *et al.*, 1997; Smethurst *et al.*, 1998a]. However, even in this case the pole of the B1 component resides at some distance from the Early Cambrian poles proposed earlier [Kirschvink and Rozanov, 1984; Pavlov *et al.*, 2004; Pisarevsky *et al.*, 1997], this providing a basis for the early formation of the B1 component.

[62] Therefore, we have to admit that the observed directions seem to have originated during or soon after the accumulation of the rocks, that is, during the Nemakit-Daldynian time. However, the simultaneous occurrence in rocks of two discordant directions, almost of the same age, contradicts the hypothesis of a geocentric axial dipole, characterizing the “geometry” of the time-averaged magnetic field of the Earth.

[63] The data reported in this paper may indicate some unusual (different from the modern) behavior and structure of the magnetic field of the Earth at the end of Vendian time. It's obvious that if the presence of two competing directions of the same age is the consequence of the anomalous behavior of the magnetic field, this phenomenon must have a planetary scale and be observed in other continents.

[64] Our analysis of the World Paleomagnetic Database (GPMDB2002 <http://dragon.ngu.no> [Pisarevsky and McElhinny, 2003b]) revealed that the presence of two discordant paleomagnetic directions is characteristic of not only the rocks of the Siberian platform. Similar objects have been observed for the Late Precambrian-Early Cambrian rocks of North America, West Europe, Mongolia, and Altai (Table 2).

[65] Below follow the criteria used in this study to locate the objects in question:

[66] 1. We analyzed all paleomagnetic determinations that covered the time interval of 650–518 Ma.

[67] 2. Then we selected the paired determinations obtained for the same geological structures with strictly coinciding geographic coordinates of sampling sites for each pair of poles. This choice allowed us to avoid the potential effect of tectonic movements in the respective areas, the ignorance of which would have resulted in errors during the comparison of the paleomagnetic directions.

[68] 3. The aim of the next step was to identify and select paired paleomagnetic determinations obtained strictly for the rocks of the same age (as it is indicated in World Paleomagnetic Database).

[69] After this kind of selection we calculated the angular distances “gamma” (Table 2) between the paired paleomagnetic poles for each object.

[70] As a result of our selection, we discovered 17 objects for which 2 to 4 paleomagnetic determinations are available, the “gamma” values of which embrace almost the whole spectrum of the potential values (5° to 88°), the average value being about 45° (see Table 2). The most frequently observed gamma values belong to the $44\text{--}55^\circ$ interval, which is illustrated by the presence of a plateau in the diagram (Figure 14). A similar plateau was found in the interval of $5\text{--}10^\circ$ and reflects the presence of pairs with closely similar paleomagnetic directions, which looks to be fairly natural. The intervals with the “gamma” values higher than 10° and lower than 44° , as well as those higher than 55° , can be interpreted as a mixture of competing components in different proportions and (or) as the presence, in addition to ancient “primary” magnetization components, of some younger remagnetization ones (Figure 15). Thus, it can be concluded that the value of $44\text{--}55^\circ$ between the discordant paired Vendian-Early Cambrian poles is a characteristic, most frequently observed value. The average “gamma” value for the plateau is about 50° .

[71] To sum up, 9 pairs of paleomagnetic poles with an angular distance “gamma”, similar to that of the Siberian objects, were determined for the time interval discussed (Table 2). These data were obtained for the objects that had been formed in different geodynamic environments, in different continents, and are composed of different sedimentary, volcanic, or intrusive rocks.

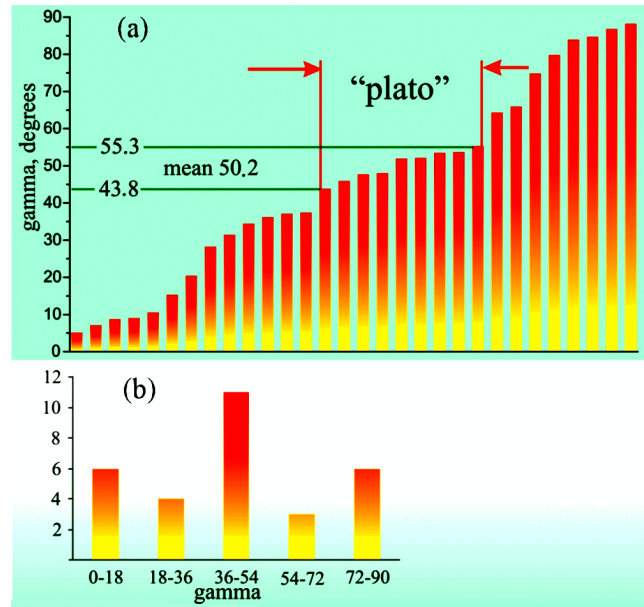


Figure 14. (a) The diagram of “gamma” values for the paired poles of the world (analysis of the Paleomagnetic Database). Corresponding to each column is the angle between the two directions; (b) is a histogram of the “characteristic” gamma values of the world. The horizontal axis shows the “gamma” values with step of 18° , the vertical axis showing the number of the paired poles.

[72] It should also be mentioned that some weakening of requirements of above point 3 (the ages overlapped but did not show any exact coincidence) allowed us to locate 1.5–2 times more paired poles with an expected angular distance between them. That is, even a fairly simple testing procedure, based on the formal data selection criteria, proves that the presence of two discordant directions in the Vendian-Early Cambrian is a planetary feature, apparently reflecting the anomalous behavior of the Earth’s magnetic field in this time.

[73] In addition to the above, new paleomagnetic data that have been obtained recently for transitory Upper Vendian-Lower Cambrian beds of “Chekurovka” section (northeastern Siberian Platform, [Pavlov *et al.*, 2004]) should be mentioned. In this section the “primary” mono- and bipolar discordant directions, different from the Phanerozoic ones, also have been found. The angle distance between the paleomagnetic poles corresponding to these directions is 58° .

[74] To sum up, we have two paleomagnetic directions, one of which (B1) corresponds to the paleomagnetic pole which continues gradually the Siberian Phanerozoic Apparent Polar Wander, the other (B2) producing a pole located at a significant distance from the known Phanerozoic poles of close age (Figure 13). The comparison of the poles corresponding to the B1 and B2 components with the Amga pole of the Siberian Platform [Pavlov *et al.*, 2003] showed the respective angular distances between the poles to be 23° and 57° . Thus, proceeding from the principle of movement minimization, we can rank the B1 and B2 components as responding

Table 2. The paired discordant paleomagnetic directions in the Vendian-Lower Cambrian rocks of the world (derived from the analysis of the paleomagnetic database <http://dragon.ngu.no>):

No.	Det. no.	Continent	Authors	Rockname	Place	L. Age	H. Age	DC	PLAT	PLOG	gamma com	SLAT	SLONG	Rocktype
1	1	North America	[<i>French et al.</i> , 1977]	Intrusive Rocks	Colorado, U.S.A.	485	704	3	48.0	107.0	43.8	1+2	38.5	-105.5 intrusives
1	2	North America	[<i>French et al.</i> , 1977]	Intrusive Rocks	Colorado, U.S.A.	485	704	3	15.0	142.0			38.5	-105.5 intrusives
2	1	North America	[<i>Tanczyk et al.</i> , 1987]	Sept-Iles Layered Intrusion	Quebec, Canada	535	586	3	20.0	141.0	64.3	1+2	50.2	-66.5 intrusives, gabbro, anorthosite
2	2	North America	[<i>Tanczyk et al.</i> , 1987]	Sept-Iles Dykes and Baked Contacts	Quebec, Canada	535	586	3	-44.0	134.5			50.2	-66.5 intrusives
3	1	North America	[<i>Murthy et al.</i> , 1992]	Long Range Dykes	Labrador, Canada	613	617	4	11.6	346.0	45.9	1+2	53.7	-56.7 intrusives, mafic dykes
3	2	North America	[<i>Murthy et al.</i> , 1992]	Long Range Dykes	Labrador, Canada	613	617	4	35.5	29.4			53.7	-56.7 intrusives, mafic dykes
4	1	South America	[<i>D'Agrella-Filho et al.</i> , 1988]	Acampamento Velho Formation	Brazil	510	530	3	44.0	345.0	74.8	1+2	-30.5	-53.9 extrusives, rhyolites, ignimbrites
4	2	South America	[<i>D'Agrella-Filho et al.</i> , 1988]	Acampamento Velho Formation	Brazil	510	530	3	61.0	158.0			-30.5	-53.9 extrusives, rhyolites, ignimbrites
5	1	North America	[<i>Seguin and Giasson</i> , 1987]	Harbour Main Group	Newfoundland, Canada	610	770	2	56.0	109.0	36.2	1+2	47.5	-53.0 sediments
5	2	North America	[<i>Seguin and Giasson</i> , 1987]	Harbour Main Group	Newfoundland, Canada	610	770	2	24.0	132.0	51.9	1+3	47.5	-53.0 sediments
5	3	North America	[<i>Seguin and Giasson</i> , 1987]	Harbour Main Group	Newfoundland, Canada	610	770	2	39.1	186.4	48.0	2+3	47.5	-53.0 sediments
6	1	Europe	[<i>Tarling</i> , 1974]	Port Askaig Formation	Scotland, U.K.	600	650	3	39.0	190.0	5.1	1+2	56.2	-5.8 sediments, varved siltstone
6	2	Europe	[<i>Urrutia-Fucugauchi and Tarling</i> , 1983]	Eocambrian glacial	Garbh Eilach, Garvellach Islands, U.K.	600	650	3	35.5	194.6			56.2	-5.8 sediments, varves, limestones

Table 2. Continued

No.	Det. no.	Continent	Authors	Rockname	Place	L. Age	H. Age	DC	PLAT	PLONG	gamma	com	SLAT	SLONG	Rocktype		
7	1	Europe	[Hagstrum et al., 1980]	Gabbro de Kerlain France	Armorican Massif, France	581	585	3	31.3	268.3	10.5	1+2	48.8	-3.1	intrusives, gabbro sill		
7	2	Europe	[Ruffet et al., 1990]	Keralain Diorite Stock	France	581	585	3	33.6	256.2			48.8	-3.1	intrusives, diorite		
8	1	Europe	[Piper and Strange, 1989]	Eastern Uriconian Volcanics	England, U.K.	600	664	3	5.2	77.8	55.3	1+2	52.5	-3.0	extrusives, basalts, andesites, rhyolites		
8	2	Europe	[Piper and Strange, 1989]	Eastern Uriconian Volcanics	England, U.K.	600	664	3	43.3	228.3			52.5	-3.0	extrusives, basalts, andesites, rhyolites		
9	1	Europe	[Morris, 1980]	Redbeds	Carteret, France	518	545	3	20.5	148.1	79.8	1+2	49.7	-1.7	sediments, redbeds		
9	2	Europe	[Robardet, 1982]	Redbeds	Carteret, France	518	545	3	59.0	337.0			49.7	-1.7	sediments, redbeds		
10	1	Europe	[Piper and Strange, 1989]	Charnian Plutons	England, U.K.	524	568	3	-41.0	286.0	88.2	1+2	52.8	-1.3	intrusives, diorite, tonalite		
10	2	Europe	[Piper and Strange, 1989]	Charnian Plutons	England, U.K.	524	568	3	46.0	253.0	53.7	1+3	52.8	-1.3	intrusives, diorite, tonalite		
10	3	Europe	[Piper and Strange, 1989]	Charnian Plutons	England, U.K.	524	568	3	72.0	204.0	34.4	2+3	52.8	-1.3	intrusives, diorite, tonalite		
11	1	Europe	[Bylund and, Zellman, 1980]	Sarv Nappe Dolerites	Sweden	615	715	3	16.0	274.7	86.8	1+2	62.6	12.9	intrusives, dolerite dykes		
11	2	Europe	[Bylund and, Zellman, 1980]	Roysing Dyke	Sweden	615	715	3	15.9	176.5			62.6	12.9	intrusives, dolerite		
12	1	Europe	[Krs and Viasimsky, 1976]	Sediments, Bohemian Massif	Czech Republic	518	545	3	-7.1	113.6	20.4	1+2	49.7	14.0	sediments		
12	2	Europe	[Bucha et al., 1976]	Sadetzky beds	Barrandov, Czech Republic	518	545	3	25.5	284.3	53.5	1+3	49.7	14.0	sediments, sandstones		
12	3	Europe	[Bucha et al., 1976]	Sadetzky beds	Barrandov, Czech Republic	518	545	3	-36.4	260.4	28.2	1+4	49.7	14.0	sediments, greywacke		
12	4	Europe	[Bucha et al., 1976]	Sadetzky beds	Barrandov, Czech Republic	518	545	3	-9.4	270.6	65.9	2+3	49.7	14.0	sediments, greywacke		
12															37.4	2+4	
12																31.4	3+4

Table 2. Continued

No. Det.no.	Continent	Authors	Rockname	Place	L.Age	H.Age	DC	PLAT	PLONG	gamma	com	SLAT	SLONG	Rocktype
13	1	Africa	[<i>Abdullah et al.</i> , 1984] Dykes	Esh El Mellaha	Eastern Desert, Egypt	495	545	3	87.3	25.9	9.0	1+2	27.7	33.3 intrusives
13	2	Africa	[<i>Abdullah et al.</i> , 1984] Dykes	Esh El Mellaha	Eastern Desert, Egypt	495	545	3	81.6	120.8	8.7	1+3	27.7	33.3 intrusives
13	3	Africa	[<i>Abdullah et al.</i> , 1984] Dykes	Esh El Mellaha	Eastern Desert, Egypt	495	545	3	82.7	273.5	15.3	2+3	27.7	33.3 intrusives
14	1	Asia	[<i>Kazansky et al.</i> , 1996] and Sedimentary Rocks	Altai Volcanic and Sedimentary Rocks	Katun Northern Altai, Russia	505	545	2	37.0	266.0	84.7	1+2	51.0	86.0 extrusives, sediments
14	2	Asia	[<i>Kazansky et al.</i> , 1996] and Sedimentary Rocks	Altai Volcanic and Sedimentary Rocks	Katun Northern Altai, Russia	505	545	2	-14.4	180.2	47.7	1+3	51.0	86.0 extrusives, sediments
14	3	Asia	[<i>Kazansky et al.</i> , 1996] and Sedimentary Rocks	Altai Volcanic and Sedimentary Rocks	Katun Northern Altai, Russia	505	545	2	-35.6	146.2	37.1	2+3	51.0	86.0 extrusives, sediments
15	1	Asia	[<i>Pechersky and Didenko</i> , 1995] Gabbro and Sediments	Karashat	Karashat Massif, Southern Tuva, Russia	505	545	3	34.2	328.5	83.9	1+2	50.1	95.1 intrusives, gabbro, sediments
15	2	Asia	[<i>Pechersky and Didenko</i> , 1995] Gabbro and Sediments	Karashat	Karashat Massif, Southern Tuva, Russia	505	545	3	22.7	230.2		50.1		95.1 intrusives, gabbro, sediments
16	1	Asia	[<i>Pechersky and Didenko</i> , 1995] Dykes and Pillow-Lavas	Mongolian	Khan-Tayshir mountains, Western Mongolia	518	545	3	-24.1	103.3	52.1	1+2	46.3	96.1 intrusives, diabase, extrusives, basalt
16	2	Asia	[<i>Pechersky and Didenko</i> , 1995] Tayshirskaya Suite	Khan-Tayshir	Khan-Tayshir mountains, Western Mongolia	518	545	3	-14.7	48.6		46.3		96.1 intrusives, diabase, extrusives, basalt
17	1	Australia	[<i>Schmidt et al.</i> , 1991] Formation	Elatina	South Australia	590	610	4	54.3	146.9	7.1	1+2	-32.4	138.0 sediments, rhythmites
17	2	Australia	[<i>Embleton and Williams</i> , 1986] Formation	Elatina	Adelaide Geosyncline, South Australia	590	610	4	50.9	157.1		-32.4		138.0 sediments, redbeds, sandstone

Note: No. is the number of the study object; Det.no. are the numbers of the paleomagnetic determinations made for each object of study; L.Age and H.Age denote the youngest and oldest ages of the magnetization; DC is the demagnetization code (varying from 0 to 5 for low and high intensity of cleaning, respectively); PLAT and PLONG denote the latitude and longitude of the paleomagnetic pole; gamma denotes the angular distance between the poles obtained for different objects of study; com denotes the comments concerning the poles between which the gamma value was calculated; SLAT and SLONG denote the latitude and longitude of a given object of study. Shown in red are the determinations the gamma values of which produced a plateau (Figure 14).

to a normal and an anomalous directions correspondingly.

[75] Proceeding from the above considerations, following the authors of paper [Pavlov et al., 2004] we suggest, as one of possible variants, the following model which allows one to describe the “geometry” of the Earth magnetic field for the Vendian-Early Cambrian time.

[76] The observed behavior of the geomagnetic field can be explained by the existences of two modes of its generation, periodically replacing one another (Figure 16): the normal, mostly monopolar mode, recorded in the B1 paleomagnetic direction, when the magnetic dipole aligned with the axis of the Earth rotation, and the anomalous mode, marked by the B2 direction, which was characterized by frequent polarity changes and by the deviation of the geomagnetic dipole by angle of about 50° from the rotation axis.

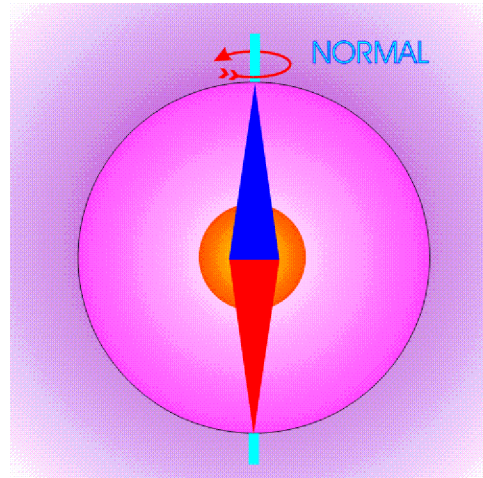


Figure 16. Model, describing the geomagnetic field behavior in Late Vendian-Lower Cambrian.

Testing of the Model

[77] As follows from the above evidence, the world paleomagnetic data do not contradict the model the geomagnetic field behavior proposed here. However, a question arises concerning the reliability of these data. Some of them were obtained using some “old” techniques and have a low reliability index (Table 2). Moreover, most of the data were obtained for fold (Hercynian and Caledonian) belts, where remagnetization is rather probable. At the same time, such the universal tool for dating of magnetization components as apparent polar wander paths (APWP) of ancient platforms is, can be very rarely used in fold areas. Hence, the most reliable way to test the model suggested here is the analysis of the Vendian paleomagnetic data obtained for the ancient platforms, where the APWP’s are most substantiated.

[78] **Laurentia.** At the present time two contradicting views are discussed for the Vendian pole of Laurentia (Figure 17, Table 3), this matter being the subject of hot discussion [Meert and Van der Voo, 2001; Pisarevsky et al., 2000, 2001].

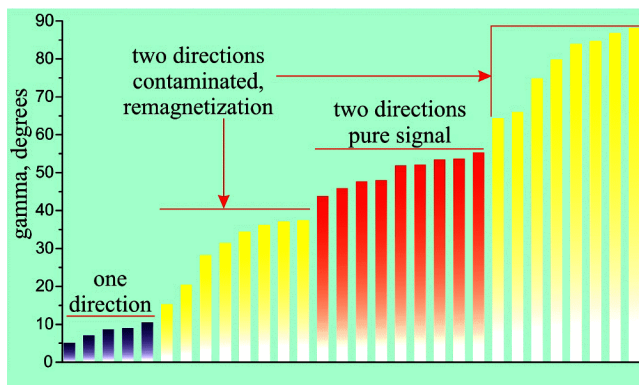


Figure 15. The diagram of “gamma” values for the paired poles of the world (based of the analysis of the paleomagnetic database). See the text for explanations.

[79] The supporters of “version-2” [Meert and Van der Voo, 2001] believe that the poles of Group 1 were produced as the result of the rock remagnetization in Late Cambrian time (because of the vicinity of these poles to the basement of the Phanerozoic APWP of Laurentia).

[80] In particular, the pole Catoctin-B (Group 1), corresponding to prefolding and bipolar direction of the Catoctin volcanic rocks, was interpreted as a metachronous (Late Cambrian) one, because, in contrast to the Catoctin A pole (Group 2), no baked contact test was made proceeding from the specific geological situation [Meert and Van der Voo, 2001; Meert et al., 1994] (Table 3, Figure 17). One cannot agree with this view for the following reasons:

[81] (1) the positive baked contact test carried out for the “Catoctin A” rocks [Meert et al., 1994] can be extended to some degree (in terms of proving the absence of regional remagnetization) to the “Catoctin B” rocks;

[82] (2) the poles obtained for the Buckingham volcanics and Long Range dykes (Group 1) were confirmed by a baked contact test.

[83] This means that, like in the case of the Siberian data, there are grounds to interpret both directions as the primary ones. The “gamma” value for the averaged poles of Groups 1 and 2 is 55°. If we agree with J. Meert’s assumption concerning the Late Cambrian age of the Catoctin B and other poles of Group 1, not supported by positive baked contact tests, and use merely the tested determinations available for “Buckingham Volcanics” and “Long Range Dykes”, the resulting “gamma” value will be 49° (Table 3). Note that the “Buckingham Volcanics” and “Long Range Dykes” poles are younger and older than poles of Group 2 (Table 3).

[84] Figure 17 shows that the mean pole of Group1 agrees well with the Neoproterozoic [Pisarevsky and Natapov, 2003a] and Phanerozoic [McElhinny and McFadden, 2000] APWP segments, which suggests the moderate movements and smooth drift of Laurentia (the velocity of the paleomagnetic pole drifting being about 2 cm year⁻¹) in the time interval of 723–535 million years. At the same time, the mean pole of Group 2 resides at a significant distance from

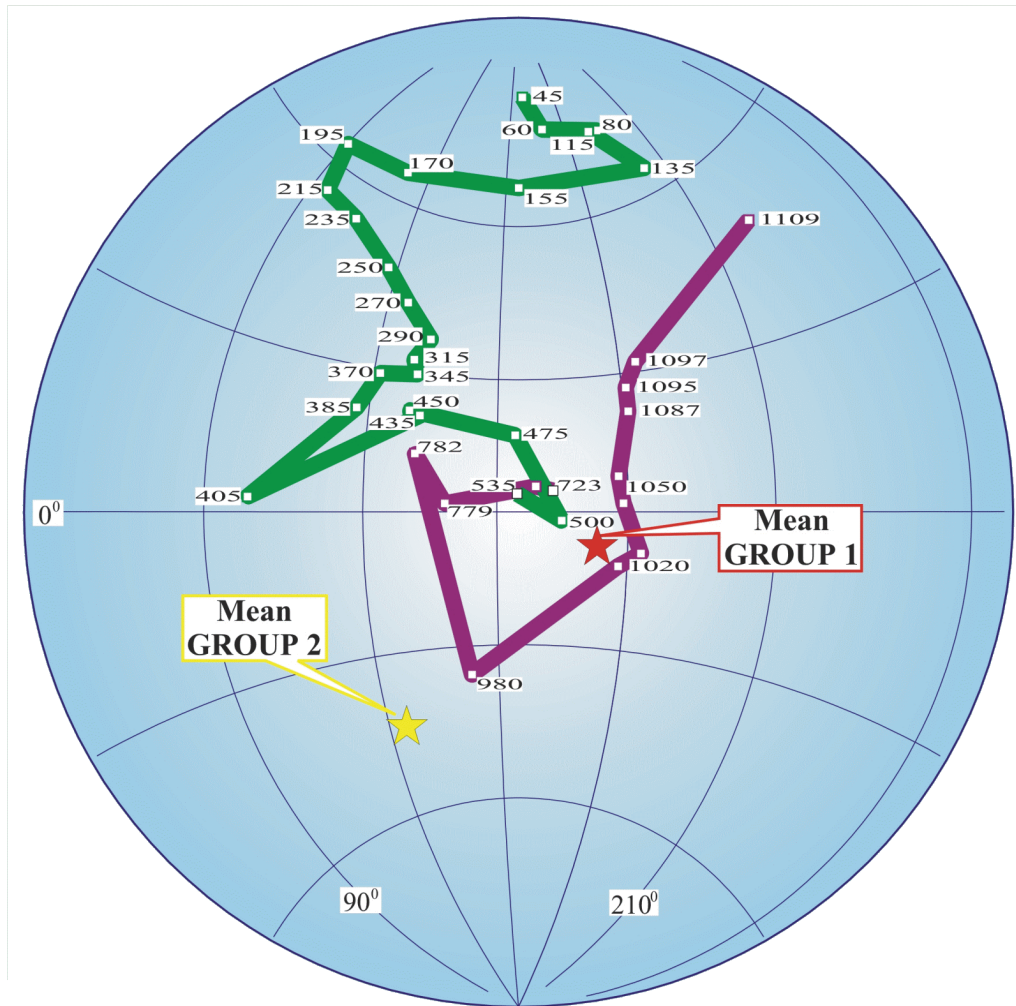


Figure 17. in Late Vendian-Lower Cambrian. of Laurentia. The Phanerozoic APWP of Laurentia is given after [McElhinny and McFadden, 2000], the Meso-Neoproterozoic one, after [Pisarevsky and Natapov, 2003].

the older and younger poles, nearest in age. This means that the choice of Version-2 as a Vendian pole complicates the APWP configuration, on one hand, and suggests the relatively higher velocities of the Laurentia paleomagnetic pole movement ($\sim 7 \text{ cm year}^{-1}$), on the other.

[85] Assuming the poles of groups 1 and 2 to be the true ones, reflecting the position of the Earth rotation axis, and tracing via them the Vendian APWP segment (Long Range Dykes (615 Ma) – the average of Group-2 (570 Ma) – Buckingham Volcanics ($\sim 550 \text{ Ma}$)), the velocity of the merely latitudinal motion of Laurentia for the time interval of 615–550 Ma must have been about 13.5 cm yr^{-1} , which seems to be hardly probable, taking into account the data available for the modern plate movements [Kreemer et al., 2003].

[86] Therefore, proceeding from the principle of minimizing the displacements, we suggest, in accordance with our classification, to rank the poles of Group 1, as the “normal” ones, and those of Group 2, as anomalous ones.

[87] **Baltica.** By the present time, about 10 paleomagnetic determinations are available for the Vendian rocks of the Baltic region. They are reported in [Popov et al., 2002; Torsvik et al., 1996]. As demonstrated in the latter paper, all of the poles, except for two of them, (see Table 3 and Figure 18 in our paper) fit in the Permian-Triassic interval of the Baltic APWP [Smethurst et al., 1998b]. This fact combined with the absence of baked contact tests for these paleomagnetic determinations (all obtained using igneous rocks), as well as the regional Permian-Triassic remagnetization widespread in the Baltic territory [Shatsillo and Shipunov, 2005], allow one to date the poles as Permo-Triassic. The “Winter Coast” poles [Popov et al., 2002] and those of the “Alnon Complex” [Piper, 1981] (see Figure 18 and Table 3 in this paper) reside, irrespective of the polarity choice, at considerable distances from the Baltic APWP, being, in turn, far spaced from one another, although the rocks from which they were determined have about the same age.

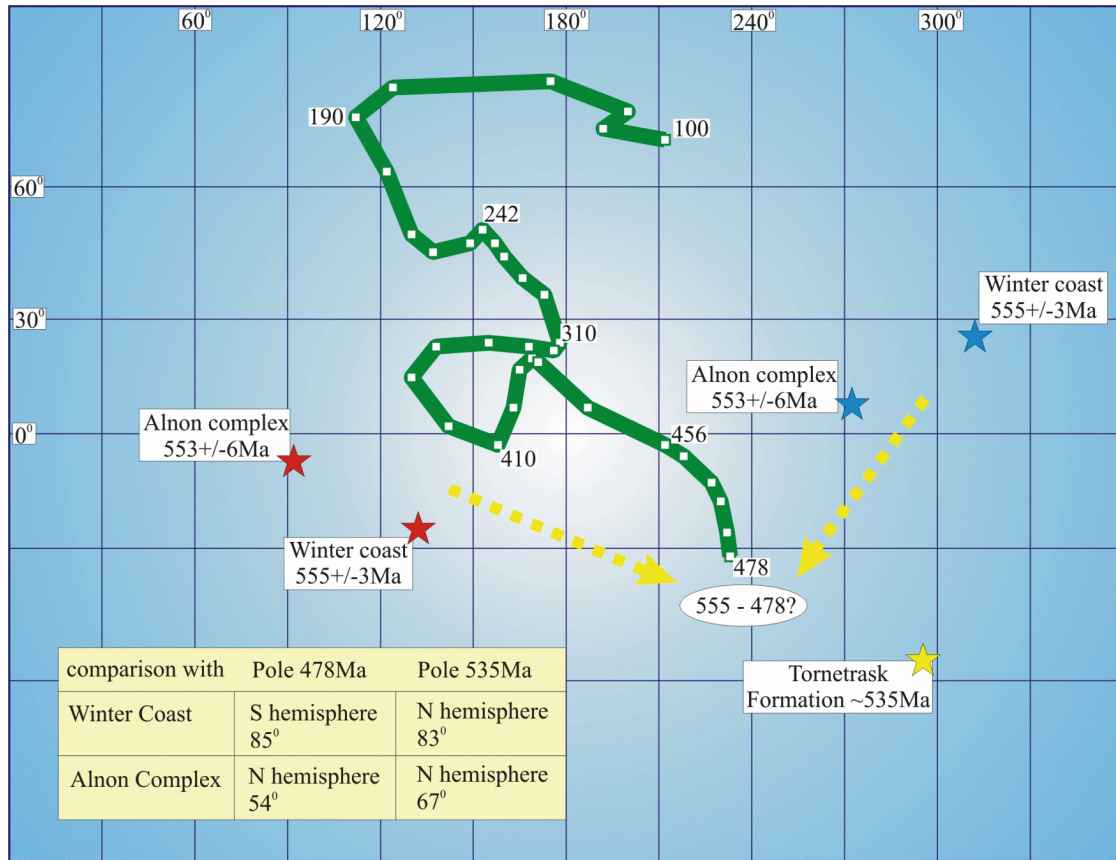


Figure 18. Model testing: Paleomagnetic poles of the Vendian and Lower Cambrian rocks of the Baltic region, compared with the Ordovician and Early Cambrian poles. The Phanerozoic APWP of the Baltic region is given after [Smethurst et al., 1998b].

[88] The “gamma” value for the “Winter Coast” and “Alnon Complex” rocks was found to be 42° (see Table 3). Still somewhat problematic is the determination of the polarities of these poles since the most substantiated post-Vendian pole being the Early Ordovician one [Smethurst et al., 1998b].

[89] The recently reported data [Torsvik and Rehnstrom, 2001], obtained for the Lower Cambrian sedimentary rocks of Sweden (Tornetrask Formation), have not been confirmed by field tests, corresponding pole being close to the Triassic APWP segment of the Baltic region. Comparing the Vendian poles both with the Early Ordovician ones and with the Cambrian (?) pole derived using the Tornetrask Formation [Torsvik and Rehnstrom, 2001], taking into account the principle of the minimization of movements, the “Alnon Complex” (see inset in Figure 18) should be chosen as a “normal” pole (see inset in Figure 18). However, if the “Tornetrask Formation” pole is the result of remagnetization, then between the Vendian poles and the Early Ordovician basement of the Baltic APWP, we have a window of 80 million years, this making the use of principle of minimizing the movements to be significantly conventional. In other words, the identification of the “Alnon Complex” and

“Winter Coast” as the “normal” and “anomalous” poles, respectively, looks to be premature.

[90] As follows from Table 3, the “gamma” values for Laurentia, Baltica, and Siberia are in good agreement and coincide, within a confidence interval, indicating that our model is supported by fairly strong factual data.

Conclusion

[91] The Upper Vendian sedimentary rocks of the southwestern Siberian Platform contain two primary or nearly primary discordant paleomagnetic directions, with angle between them being ~45°. The analysis of the paleomagnetic data available for the Vendian-Early Cambrian time suggests that the existence of two discordant directions can be considered as a phenomenon of planetary scale. This fact can be attributed to the anomalous behavior of the Earth’s magnetic field in that period of time. In this paper we suggest a work model describing the “geometry” of the Earth magnetic field during the Vendian-Early Cambrian period of time, which allows one to explain the observed character of

Table 3. The competing Vendian paleomagnetic poles of Laurentia, Baltica, and Siberia

Pole name	Age	Pole latitude	Pole longitude	A ₉₅	gamma	Reference
LAURENTIA						
Group 1						
1. Johnnie Formation	~550	-10.0	162.0	10.0		[<i>Van Alstine and Gillett, 1979</i>]
2. Unicoi Basalts	~550	-0.4	178.6	13.8		[<i>Brown and Van der Voo, 1982</i>]
3. Catoctin Basalts B	564±9	-3.8	183.7	13.0		[<i>Meert et al., 1994</i>]
4. Buckingham Volcanics	~550	-9.5	160.8	7.3		[<i>Dankers and Lapointe, 1981</i>]
5. Double Mer Formation	~550	-13.7	176.2	11.7		[<i>Murthy et al., 1992</i>]
6. Long Range Dykes	615±2	-11.6	166.0	18.0		[<i>Murthy et al., 1992</i>]
Group 2						
Callander Complex	575±5	-46.3	121.4	3.1		[<i>Symons and Chiasson, 1991</i>]
Catoctin Basalts A	564±9	-42.0	116.7	9.0		[<i>Meert et al., 1994</i>]
Sept Iles Complex B	564±4	-44.0	134.5	5.1		[<i>Tanczyk et al., 1987</i>]
Mean Group 1 (all)		-7.9	173.1	8.9	54.5±13.5	
Mean Group 1 (4+6)		-10.6	163.4	12.1	47.8±12.7	
Mean Group 2		-44.4	124.1	10.7		
BALTICA						
Winter Coast	555±3	-25.3	132.2	3.0	42.2±7.8	[<i>Popov et al., 2002</i>]
Alnon Complex	553±6	-7.6	92.0	9.3		[<i>Piper, 1981</i>]
SIBERIA						
Pribaykalye and Prisayanye sediments Mean B1	545-530	-60.8	116.1	6.7	44.6±10.3	This study
Pribaykalye and Prisayanye sediments Mean B2	545-530	-31.6	63.8	9.8		This study; [<i>Kravchinsky et al., 2001</i>]
MEAN GAMMA = 47.1(44.9°)						

the paleomagnetic record. Proceeding from this model, one of the directions can be ranked as a normal one, reflecting the position of the geographic pole, the other, as an anomalous one, discordant with the axis of the Earth rotation.

[92] Our results contradict the interpretation of the paleomagnetic data obtained earlier by *Kirschvink and Rozanov, [1984]* on Lower Cambrian of the Siberian platform as proving the hypothesis of the Inertial Interchange True Polar Wander [*Kirschvink et al., 1997*], our model being an alternative relative to this hypothesis.

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