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Multicomponent magnetization of Vendian sedimentary rocks in Podolia, Ukraine

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Abstract. This paper presents the results of studying Vendian rock samples collected along the middle coarse of the Dniester River in the Ukrainian territory. The results of their demagnetization revealed seven components of their natural remanent magnetization. Five of them are the results of Paleozoic (Cambrian to Permian) remagnetization. The last high-temperature NRM component was recorded in all of the studied rock units (the Redkino and Kanilov rock units and the Baltic rock series) and showed an mean paleomagnetic pole: $\Phi = 40.0°$S, $\Lambda = 96.5°$E, $A_{95} = 7.5°$. This paleomagnetic pole agrees well with the pole that has been recently found for the Late Vendian rocks of the White Sea Zimnii Bereg area [*Popov et al.,* 2002]. Combined with the results of the earlier determinations for the Late Vendian rocks of the White Sea Zimnii Bereg area, these data form a group of poles residing outside of the trajectory of the apparent migration of the paleomagnetic pole (APWP) for the Baltic plate. An alternative APWP version is offered for the Vendian-Cambrian segment of the curve.

Introduction

The recent years have been marked by a growing interest in the study of Vendian and Early Paleozoic rocks. In our opinion, this has been associated with a significant progress in the methods and techniques of paleomagnetic studies and with the growing interest in the geological history of the Earth at the Vendian-Cambrian boundary which marked the time of the significant reconstruction of both the biosphere and the geodynamics of the Earth crust. At the end of the last century the paleomagnetic data available for the major tectonic plates of the Earth were generalized. The examples are the papers of *Meert and Van der Voo* [1994] and *Torsvik et al.* [1996]. These papers proved a necessity for expanding a paleomagnetic data base for the Vendian and Early Cambrian time for the major tectonic plates, including the East European platform [*Glevasskaya et al.,* 2000; *Elming et al.,* 2004, submitted; *Iglesias et al.,* 2004, submitted; *Popov et al.,* 2002, 2004, submitted]. Some of these and earlier data [*Bylund,* 1994; *Piper,* 1981] produce a group of paleomagnetic poles which do not agree with the Vendian segment of the trajectory for the apparent polar wander path (APWP) for the East European Platform suggested by *Torsvik et al.* [1996] and by *Smethurst et al.* [1998]. To verify this situation a new study of the Vendian rocks exposed at the southwestern slope of the Ukrainian Shield (Podolia, Ukraine) was carried out. The results of this work are discussed in this paper.

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Geology of the Study Area

The geotectonic position of the area is controlled by the fact that it belongs to the area where the southwestern and western slopes of the Ukrainian Shield join together in the

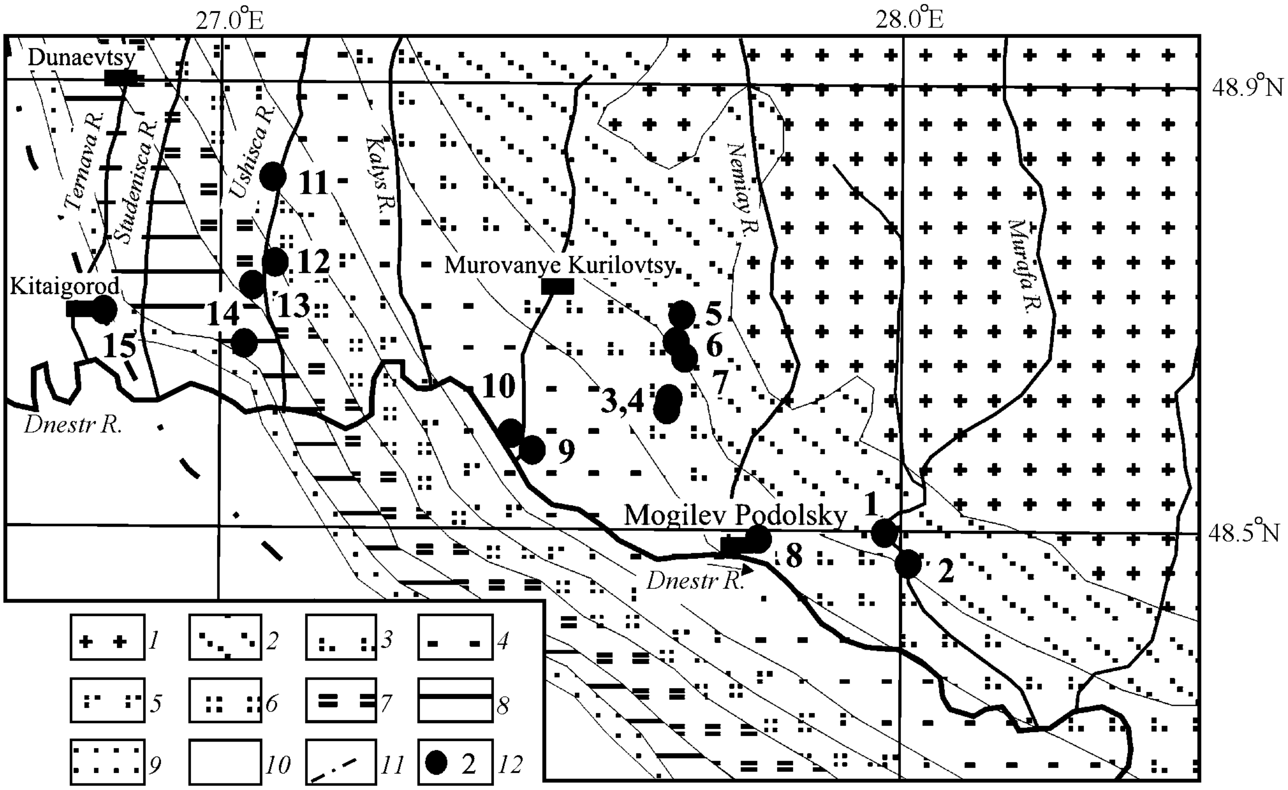

Figure 1. Schematic geological map of the study area [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990, simplified]: (1) crystalline basement, (2–8) formations and series: (2) Mogilev Fm and Grushka Fm, (3) Yaryshevo Fm, (4) Nagoryanka Fm, (5) Danilov Fm, (6) Zharnovsky Fm, (7) Krushanov Fm, (8) Studenitskaya Fm; (9) Ordovician; (10) Silurian; (11) boundaries of the Baltic Series rocks; (12) sampling site.

form of the Podol Protrusion. This structural feature controlled the distribution of sediments which accumulated in the southwestern termination of the East European Platform during the accumulation of the sediments beginning from the Late Proterozoic. The geological structure of the region consists of two megacomplexes, the lower of which is the intricately dislocated crystalline basement, the upper being the sedimentary cover. The latter rests on the crystalline basement with a distinct angular and stratigraphic unconformity and consists of two structural rock complexes: the Late Precambrian–Early Paleozoic rock complex and the Mesozoic-Cenozoic one. These rock complexes differ in their structural styles and are separated from each other by a distinct planation surface which had been formed during a long break in sedimentation from the Vendian (from the Silurian in the west of the region) to the Cenomanian. The rocks composing the lower complex occur in the study area as the Podol monocline of the NW strike, which dips gently (about 1°) to the southwest. In terms of the modes of their occurrence and interrelationships, the rocks have been subdivided into the Volynian, Mogilev-Podolian, Kanilov-Baltic, and Ordovic-Silurian structural stages. The geologic map of the area is presented in Figure 1. The simple geologic conditions of the Vendian deposits, their good exposure, allowing one to observe the relations among all of the stratigraphic units, the completeness of the rock sequence, and the wide distribution of diverse organic remains contributed to their excellent knowledge. Each of the fine subdivisions of the Vendian rocks in the Podolian Ridge of the Ukrainian Shield shows its own facies and lithological features, consistent over large areas. This allows one to identify and trace these rock units in areas remote from one another. This allowed the geologists who studied these rocks to identify and trace these rock units in areas located far from one another and to devise a very detailed local stratigraphic diagram [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983]. The relationships of the stratigraphic units identified in the study area are shown in Figure 2. As regards the oldest rocks of the Volynian Series, there are recent U-Pb datings for the basalts [*Schumlyansky and Andréasson,* 2004]: 576±14 Ma, and also $^{40}Ar/^{39}Ar$ datings [*Elming et al.,* 2004, submitted]: 580±9 Ma and 561±13 Ma. These age estimates allow one to believe that the Vendian sedimentary rocks of Podolia are at least not older than 560–570 Ma and not younger than 545 Ma (Vendian-Cambrian boundary) and embrace the time interval of 15–25 Ma.

Subjects and Methods of Study

In the course of the field work in 1995 and 1999 oriented rock samples were collected from all stratigraphic units of the Podolian Vendian rocks. The sampling areas are shown in Figures 1 and 2. The sample collection was subdivided into groups in terms of the rock formations, following the conventional stratigraphic subdivision of the Podolian rocks [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983]. Samples were collected following the stratigraphic sequence of the rocks at the intervals of 0.1 m to 2 m of their thickness.

Ranked as the Volynian Series were the oldest rocks identified as the Grushka Formation. These are coarse clastic rocks (gravelites and conglomerates) in the lower part of the sequence and gray argillaceous rocks (argillite and aleurolite) in its upper part. The upper rocks of the Grushka Formation are exposed also in the area north of the Podolian rocks, in the Goryn R. Valley, where they are represented by brown argillite, siltstone, and grayish sandstone. The samples of these rocks were collected in outcrops 17 and 18 (Figure 2) in the vicinities of the Putrintsa and Tashka villages, the average sampling site coordinates being $\varphi = 50.2°$ and $\lambda = 27.0°$.

The Mogilev-Podolian rock series includes the Mogilev, Yaryshev, and Nagoryanka Formations. The Mogilev Formation includes the Mogilev, Yaryshev, and Nagoryanka formations. The Mogilev Formation includes (upward) the Olchedaev beds (composed mainly of coarse and inequigrained arkose sandstone and gravelite), up to 20–25 m thick, the Lomozov beds, composed of alternating dark gray argillite and fine-grained sandstone beds, up to 15–20 m thick, and the Yampol beds of light-gray oligomictic sandstone, varying from 15 m to 20 m in thickness. The Lomozov beds can be classified as the oldest rocks, showing *Metazoa* imprints [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983]. The samples of the Mogilev Formation rocks were collected in outcrops 1–8 in the vicinities of the Grushka, Vinoz, Bukatinka, Iraklievka, and Borshovy Yar villages, the average coordinates of the sampling sites being $\varphi = 48.6°$ and $\lambda = 27.8°$, in Figures 1, 2. The sampling interval varied from 0.2 m to 2.0 m.

The Yaryshev Formation is composed (upward) of the Lyadov, Bernashev, Bronnitsy, and Zinkov beds. The Lyadov beds consist of greenish gray and brown thin-layered slightly micaceous argillite and silty argillite. The Bernashev beds consist of three members. The lower member (10 m thick) is composed of sandstone and siltstone. The intermediate member, up to 7 m thick, consists of dark gray, gray, and green argillite, and the upper member, 5 m thick, is composed of dark gray sandstone. The average thickness of the Bernashev beds is 20 m. The Bronnitsy beds consist of tuffaceous argillite and pelitic tuffite of chocolate-brown and light green, often mottled, color. The upper parts of these beds include several layers of bentonite clay (less than 1 cm thick) and grade slowly to fine micaceous argillite. The thickness of the Bronnitsy beds varies from 15 m to 20 m. The Zinkov beds are represented by greenish- and bluish-gray and grayish-green argillite and siltstone. These beds are as thick as 25–30 m [*Sokolov and Fedonkin,* 1985;

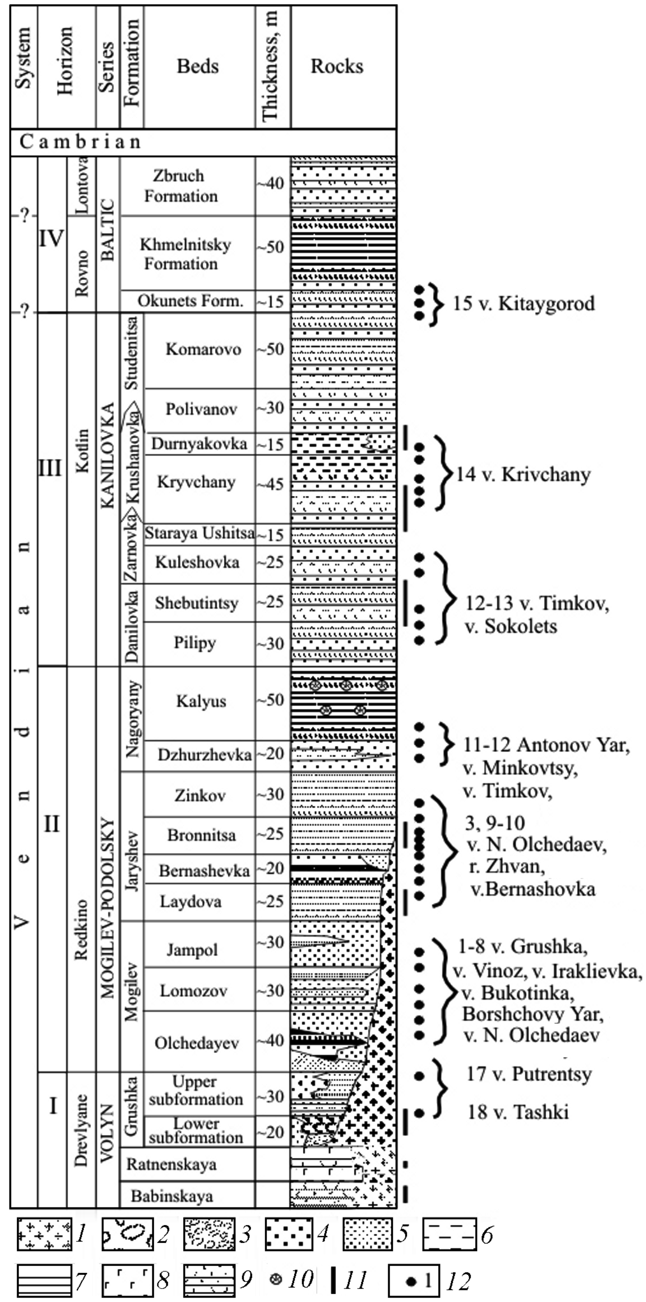

Figure 2. Composite section of Vendian rocks in Podolia [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990, simplified]: (1) basement rocks; (2) breccia; (3) conglomerate and gravelite; (4) very coarse- and large-grained sandstones; (5) medium-, fine-, and very fine-grained sandstones; (6) siltstone; (7) argillite; (8) basalt; (9) tuffaceous siltstone; (10) phosphorite concretions; (11) rocks of brown color, (12) sampling depth and outcrop numbers.

Velikanov, 1990; *Velikanov et al.,* 1983]. The samples of the Yaryshev Formation rocks were collected at Sites 3, 9, and 10 in the vicinities of the Bernashevka and N. Olchedaev villages, their average coordinates being $\varphi = 48.6°$ and

$\lambda = 27.6°$ (see Figures 1 and 2). The sampling interval varied from 0.1 m to 1.5 m.

The Nagoryanka Formation combines the Dzhurdzha and Kallyusa beds. The Dzhurdzha beds are represented by greenish light gray inequigranular sandstones, often interbedded by greenish-gray argillite and siltstone. These beds vary from 20 m to 25 m in thickness. The Kallyusa beds are represented by a sequence of dark-gray thin-laminated argillite up to 50 m thick. These rocks contain phosphorite concretions [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983]. The rock samples of the Nagoryanka Formation were collected in outcrops 10 to 13 in the vicinities of the Bernashevka, Timkov, and Antonov Yar villages at the average coordinates of $\varphi = 48.74°$ and $\lambda = 27.25°$, in Figures 1 and 2. The sampling interval was 1–2 m.

The Kanilov rocks resting on the underlying rocks with a stratigraphic unconformity are represented by four sedimentation cycles each cycle corresponding to a respective formation, namely, the Danilov, Zharnov, Krushanov, and Studenitskaya formations following one another upward.

The Danilov Formation consists of interbedded fine- to medium-grained siltstones and argillite, often variegated. This formation has been subdivided into the Pilipov and Shebutinets beds, its total thickness being 34–40 m [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983]. The samples of the Danilov rocks were collected in outcrops 12 and 13 near the Timkov and Sokolets villages (the average coordinates being $\varphi = 48.79°$, $\lambda = 27.08°$), in Figures 1 and 2. The sampling interval was 1 m and 2 m.

The Zharnovsky Formation is composed of coarse-grained sandstone at the base, which are overlain by interbedded medium- and fine-grained sandstone, argillite, and siltstone. This formation has been subdivided into the Kuleshev and Staraya Ushitsa beds totaling 30–35 m in thickness [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983].

The Krushanov Formation consists of greenish-gray and white sandstones. The upper part of the formation includes red sandstones, siltstones, and argillite. This formation has been subdivided into the Krivchan and Durnyakov beds. Its total thickness varies from 57 m to 62 m [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983]. The samples of the Krushanov rocks were collected in outcrop 14 near the Krivchany Village at the average coordinates of $\varphi = 48.6°$ and $\lambda = 27.07°$, in Figures 1 and 2. The sampling interval was 1–2 m.

The Studenitskaya Formation is represented by interbedded coarse- and fine-grained sandstones, argillites, and siltstones. This formation has been subdivided into the Polivanovo and Komarovo beds totaling up to 70 m in thickness. Samples were collected from the upper part of the formation in outcrop 15 near the Kitaigorod Village with the coordinates of $\varphi = 48.7°$ and $\lambda = 26.5°$ in Figures 1 and 2. The sampling interval was 0.1 m to 0.5 m.

The rocks of the Kanilov Series grade upward without any interruption to the rocks of the Baltic Series, which is represented in the Podolia region by three formations, Okunets, Khmelnitsky, and Zbruch, the rocks of the latter being found only in boreholes. The Okunets Formation is composed of gray, greenish, and brownish argillites and siltstone lenses. The Khmeltitsky Formation consists of dark-gray, gray, and greenish-gray argillites, interbedded by gray siltstone layers [*Sokolov and Fedonkin,* 1985; *Velikanov,* 1990; *Velikanov et al.,* 1983]. Some geologists believe that the Baltic rock series (Okunets and Khmelnitsky Formations) may include the Vendian-Cambrian boundary *Velikanov,* 1990. The samples of the Baltic Series rocks were collected at outcrop 15 near the Kitaigorod Village, $\varphi = 48.7°$, $\lambda = 26.5°$, in Figures 1 and 2. The sampling interval was 0.1–0.5 m.

Where the samples of the same formation were collected from different outcrops (usually not farther than 50 km from one another), their average geographic coordinates were used to calculate average paleomagnetic poles for a respective formation.

The collected oriented lumps were sawed into cubes, 2×2×2 cm in size. Each lump was represented by 2–5 samples. The total number of the cubes was 1250 derived from 386 lumps. The laboratory paleomagnetic measurements and the processing of the results were performed using conventional techniques. Most of the samples were studied at the laboratories of the Department of Paleomagnetic Reconstructions in the All-Russia Petroleum Research and Exploration Institute (VNIGRI) and in the Department for Earth and Environmental Sciences, Geophysics Section, Ludwig-Maximilians University, Munich, Germany. The components of natural remanent magnetization were identified by the method of stepwise thermal demagnetization using the measuring instruments placed into 5-layer Permalloy screens of the VNIGRI construction or into Schoenstedt TSD-1 screens (USA). Measurements J_n were conducted with the use of rock generators JR-4 and JR-5 (Agico, Czech Republic) and criogenic magnetometer 2G (USA). The chemical transformations that occurred in the course of thermal cleaning were controlled by measuring magnetic susceptibility after each heating interval using a KLY-2 Kapp bridge (Agico, Czech Republic).

The magnetic minerals were identified as NRM carriers studying their normal and saturation magnetization versus temperature using a VFTB (Variable Field Translation Balance) and the Lowrie method [*Lowrie,* 1990]. The samples of two pilot collections (each collection consisting of 50 samples) were demagnetized at the Lamont-Doherty Observatory, USA, by M. Smethurst and at the Paleomagnetic Laboratory of the Tectonic Special Research Center in Perth, Australia, by S. Pisarevskiy. As a result of analyzing these data, the NRM components were identified using orthogonal projections [*Zijderveld,* 1967]. The directions of these components were computed using the least squares method [*Kirschvink,* 1980]. All of these operations and the graphic representation of the results were performed using computer programs available [*Enkin,* 1994; *Torsvik and Smethurst,* 1999].

Experimental Data

Magnetic properties of the rocks. The values of the natural remanent magnetization of the studied rocks were found to vary widely for all rock formations. The red sediments showed the highest NRM values ranging from

1 mA m^{-1} to 5 mA m^{-1}. The magnetic susceptibilities of these rocks varied over the range of $(0.3–0.6)\times10^{-3}$ SI units. The gray rocks yielded the values of (0.1–2) mA m^{-1} and $(0.2–0.4)\times10^{-3}$ SI units. Figure 3 shows the examples of studying the samples of various rocks using a VFTB equipment. Sample 58 (gray siltstone, Okunets Formation of the Baltic Series, outcrop 15) showed a remanence coercivity field of 35 mT (Figure 3A) and a Curie temperature of 580°C (Figure 3B), these values suggesting magnetite. Sample 222 (grayish green siltstone, Krushanovo Suite, outcrop 14) showed a remanence coercivity field of 68 mT (Figure 3A) and the Curie temperatures of 650°C and 435°C (Figure 3B), these results suggesting the existence of two magnetic phases. The low-temperature phase seems to be associated with a secondary mineral, maghemite. The second magnetic mineral of this sample seems to be hematite, which is proved by the unblocking temperatures recorded during the thermal cleaning of this sample. Sample 110 (dark-brown argillite, Bronnitsy beds, Yaryshev Formation, outcrop 11) showed a remanence coercivity field of 147 mT (Figure 3A) and a Curie temperature of 666°C (Figure 3B), which suggest the mineral to be hematite. The examples of using the Lowrie method [*Lowrie,* 1990] are presented in Figures 3C and 3D. The development of normal remanent magnetization (Isothermal Remanent Magnetization (IRM)) along the three axes (1.4T along the X, 0.3T along the Y, and 0.1T along the Z axes) and its further destruction by the temperature allows one to distinguish the soft, intermediate, and hard components of magnetic agents and to estimate their contributions to the total magnetization. Sample 90-7 (glauconite-quartz sandstone, Baltic Series, outcrop 15) includes a hard component with a unblocking temperature of 580°C, which makes the basic contribution to the natural remanent magnetization and seems to be associated with the content of magnetite in the rock. Sample 114-3 (dark-gray argillite, Bronnitsy beds, Yaryshev Formation, outcrop 11) has two significant components with the unblocking temperatures of 560°C and 660°C, this suggesting the presence of hematite and, possibly, magnetite. The results of our thermal magnetic analysis, combined with the results of stepwise temperature demagnetization, suggest that the magnetite and hematite are the main magnetic carriers of highly coercitive NRM components.

Component Analysis

The stepwise temperature demagnetization of the collected rock samples revealed seven components of natural remanent magnetization. These components were identified by way of analyzing the orthogonal projections of the NRM components in accordance with their unblocking temperatures and directions, and were denoted as A, B, C, D1, D2, P1, and P2. These NRM components were identified during the first phase of the analysis inside each of the studied rock formations, the components of similar directions being then combined over the whole rock sequence by way of averaging their paleomagnetic poles. It should be noted that the component composition of the rocks has a complex character. In many cases (usually in the cases of gray and greenish-gray rocks) the samples collected from the same lump show a varying assembly of NRM components, both in terms of unblocking temperatures and directions, this suggesting the operation of secondary processes which had caused the remagnetization of some rock types. In this case NRM components were identified using the clusters of the same directions in each rock sequence and their statistical significance. Since the rocks lie almost horizontal and their NRM components vary insignificantly in the geographic and stratigraphic coordinates, all data are reported here in the geographic coordinates.

The examples of the NRM behavior in the course of temperature cleaning are given in Figure 4 for the samples of different types and ages. The NRM usually consisted of 2 or 3 components. The A component, identified in the low-temperature range (100–350°C), showed a direction close to that of the Cenozoic geomagnetic field and might have been associated with the remagnetization of the rocks by the modern geomagnetic field. The distribution of the A component directions for the samples collected from all rock formations is shown in Figure 5, and the average trend of this component is given in Table 1. One can see that some of the samples showed the direction of the A component different from the average one. We associate this fact with the potential biasing of these samples by the laboratory magnetic field (viscous component) during their 3–6 year storage. The samples that showed this anomalous direction of the A component were used in the subsequent component analysis only in the case of convergence for the higher-temperature NRM components in the rock lump ($K>3$).

The second medium- and high-temperature B component was identified in the temperature range of 300–600°C in the red rocks (Figure 4, 114-1 and Figure 5, 242v1) and at the temperatures of 300–535°C and 580°C in the gray rocks. The B component was identified in all rock sequences, being the terminal one in the gray rocks. This component is a bipolar one in the red rocks of the Krushanov Formation, although showing a negative reversal test [*McFadden and McElhinny,* 1990]. The distribution of the B component in the rock formations is shown in Figure 5b. The next unipolar component C was identified mainly in gray rocks in the temperatures ranges of 300–500°C and 550–600°C, and also in the red rock samples collected from the Zharnovsky Formation (Figure 4, Sample 190-3). The distribution of the C component directions is shown in Figure 5, the average directions of the individual rock suites being presented in Table 1. The D1 and D2 components were identified both in the old rock suites (Grushka, Mogilev, and Yaryshev), and in the younger formations (Krushanov, Okunets, and Khmelnitsky). The D1 and D2 components were identified in the range of 250–500°C (Sample 6V, Mogilev Formation, Figure 4) and in the ranges of 300–580°C and 600–670°C of the gray rocks (Sample 244-1, Baltic rock series, Figure 4). The D1 (Baltic Series) and D2 (Krushanov Formation) components are bipolar ones, showed a positive reversal test [*McFadden and McElhinny,* 1990] and were ranked as class C. The rocks of the Baltic Series showed the angle between the average directions of the direct and reverse polarities of the D1 component to be 13.8°, with the critical angle of 15.8°,

Table 1. Mean paleomagnetic directions and poles for the secondary NRM components in the Vendian rocks of Podolia, Ukraine

No	Age of the NRM-component	Component index, formation	Statistics of the NRM components					Statistics of the pole positions				Test
			N/n	D°	I°	K	$\alpha°_{95}$	Φ,°N	Λ,°E	dp,°	dm,°	
1		A, gr	20/40	344.3	73.4	10.0	10.9	−77.3	348.0	17.5	19.5	
2		A, m	60/80	38.6	79.6	4.6	9.6	−61.9	235.0	17.5	18.3	
3		A, yr	69/165	339.8	77.6	4.2	9.5	−69.5	184.3	16.7	17.8	
4		A, n	14/29	344.9	71.8	21.3	4.5	−77.9	164.0	7.0	7.9	
5	Kz	A, d	22/55	341.1	67.3	17.3	7.7	−77.7	130.2	10.6	12.8	
6		A, z	11/32	335.7	67.9	42.2	7.1	−74.3	134.1	10.0	11.9	
7		A, k	22/66	347.5	72.2	15.8	8.1	−78.5	171.0	12.7	14.3	
8		A, o-kh	104/249	0.1	65.8	14.9	3.7	−89.3	200.6	4.9	6.0	
9	Kz	A	M=8					−81.6	180.8	A_{95} = 8.9		
10		B gr	5/6	203.4	0.9	35.9	11.3	−35.5	357.8	5.7	11.3	
11		B m(NR)	6/6	197.4	−13.4	45.7	10.0	−45.7	2.7	5.2	10.2	
12		B, yr	31/83	210.5	2.1	31.6	4.7	−33.8	350.0	2.4	4.7	
13		B, n	12/25	210.6	12.0	14.1	10.7	−29.0	351.9	5.5	10.9	
14	C-P	B, d	16/39	198.5	−1.2	31.0	6.7	−39.2	2.9	3.4	6.7	
15		B, z	8/12	232.1	9.4	19.3	12.9	−20.0	330.3	6.6	13.0	
16		B, k1	4/10	9.5	4.0	31.2	16.7					
17		B, k2	9/25	207.6	2.8	18.8	12.2					
18		B, k	13/35	202.0	0.7	17.8	10.1	−37.5	358.9	5.1	10.1	R−
19		B, o-kh	50/74	211.9	4.0	12.0	6.1	−32.3	347.9	3.1	6.1	
20	C-P	B	M=8					−34.0	352.4	A_{95} = 7.5		
21		C, gr	6/8	226.5	55.6	17.5	13.6	5.7	350.9	13.9	19.4	
22		C, m	12/14	217.4	47.7	15.0	10.3	−5.7	355.5	8.7	13.4	
23	S-D?	C, yr	16/35	230.6	52.7	19.4	8.6	3.5	347.3	8.2	11.9	
24		C, z	6/14	231.3	38.2	25.9	13.4	−6.2	340.2	9.4	15.9	
25		C, o-kh	27/37	209.9	51.5	19.0	6.2	−4.9	1.4	5.7	8.4	
26	S-D?	C	M=5					−1.5	351.1	7.6		
27		D, gr	8/14	148.0	33.8	47.7	5.8	−15.7	58.5	3.8	6.6	
28	O?	D, o-kh1	11/16	155.4	46.3	19.0	10.8	−10.6	48.5	8.9	13.9 7	
29		D, o-kh2	7/11	315.4	−45.9	23.5	12.7	−8.1	55.1	10.5	16.3	
30		D, o–kh, sum(28+29)	18/27	147.6	46.6	18.9	8.2	−8.1	55.1	6.8	10.6	R+, C
31	O?	D1	M=3					−10.2	57.4	A_{95} = 10.1		
32		D, m1	13/16	138.3	64.1	34.8	7.1	11.2	56.0	9.0	11.3	
33		D, m2	5/5	305.1	-48.3	13.6	16.1	2.0	73.4	13.8	21.1	
34	O?	D, k1	5/9	107.2	47.2	48.4	11.1					
35		D, k2	3/6	276.8	-57.4	59.0	16.2					
36		D, k, sum(34+35)	8/15	103.8	51.1	44.5	8.4	15.1	85.8	7.7	11.4	R+, C
37	O - Є	D, yr	10/15	127.0	66.7	32.3	8.6	18.0	60.8	11.7	14.2	
38	O?	D2	M=4					11.8	69.0	A_{95} = 12.7		

Note. N is the number of the bulk samples, n is the number of samples; M is the number of poles; D° and I° denote the declination and inclination of the average NRM directions; K is the grouping of the vectors; $\alpha°_{95}$ is the radius of the confidence circle for the probability of 95% for the mean direction; Φ° and Λ° are the latitude and longitude of the southern paleomagnetic pole; dp°, dm° are the half axes of the confidence circle; A_{95} is the radius of the confidence circle for the probability of 95% for the average position of the pole; R-, R+, C means that the polarity reversal test in the McFadden and McElhinny modification is negative (−) or positive (+) and corresponds to the C class [*McFadden and McElhinny,* 1990]. The statistical data are given for the lump samples. The NR index means the average value obtained for the components of normal and reversed polarities. The components were averaged at the formation level. The indexes of the formations are: (gr) for the Grushka Formation, (m) for the Mogilev Fm, (yr) for Yaryshev Formation, (n) for the Nagoryanka Fm, (d) for the Danilov Fm, (z) for the Zharnovsky, (k) for the Krushanov Fm, (o-kh) for the Okunets, Studenitskaya, and Khmelnitsky formations taken together.

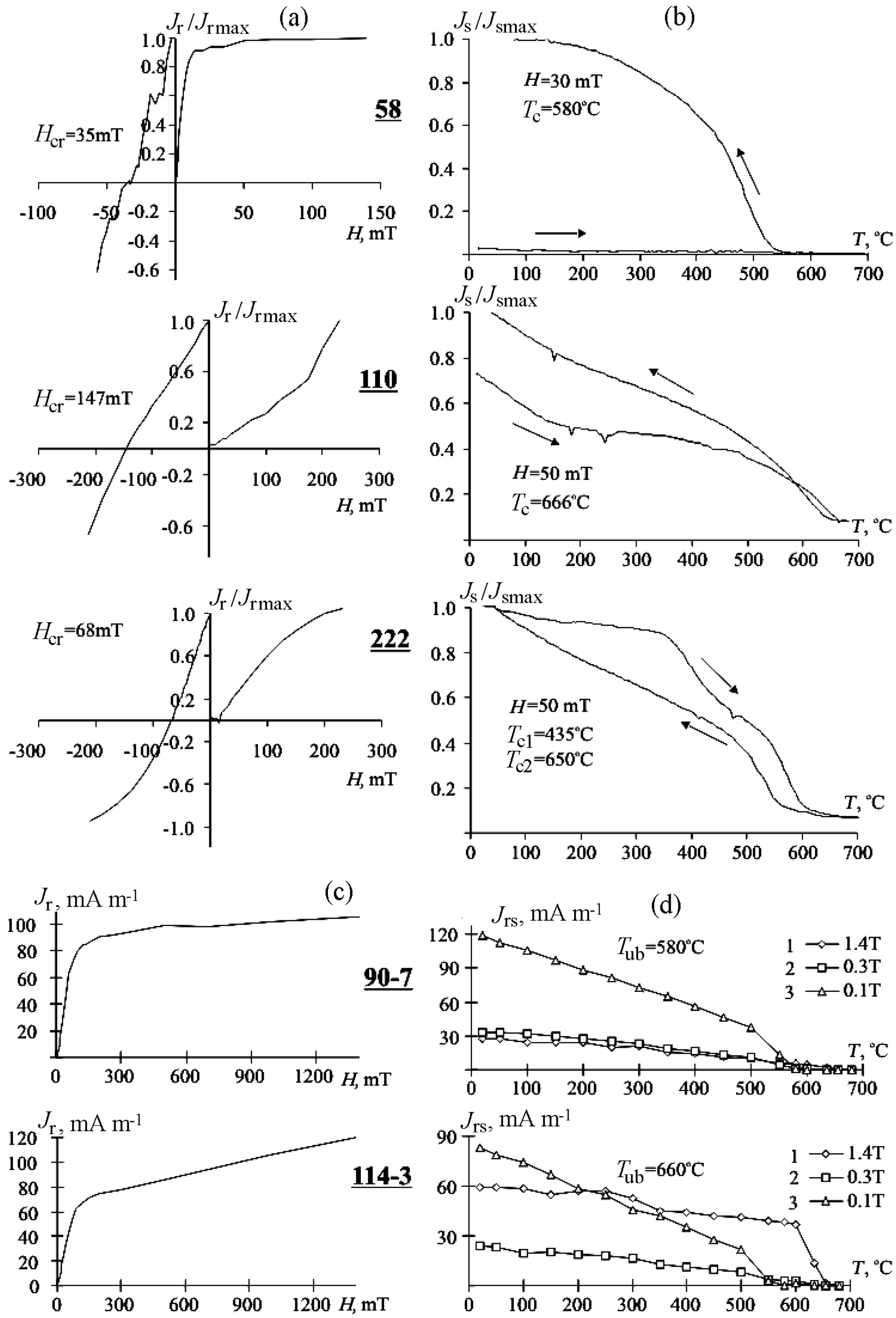

Figure 3. Examples of the thermomagnetic analyses of the Vendian rocks using the VFTB equipment (a and b) and of identifying magnetic minerals using the Lowrie method (c and d): (a) normal magnetization (J_r) curves and the curves of estimating the field of remanence coercivity (H_{cr}); (b) the curves depicting changes in the saturation magnetization (J_s) in the course of heating and cooling (H denoting the saturation field value, T_c denoting the Curie temperature values); (c) isothermal magnetization curves; (d) the curves of the isothermal magnetization breakdown by temperature, the values of the magnetization field being 1 for the X, 2 for the Y, and 3 for the Z axis); T_{ub} is denotes the value of the unblocking temperature.

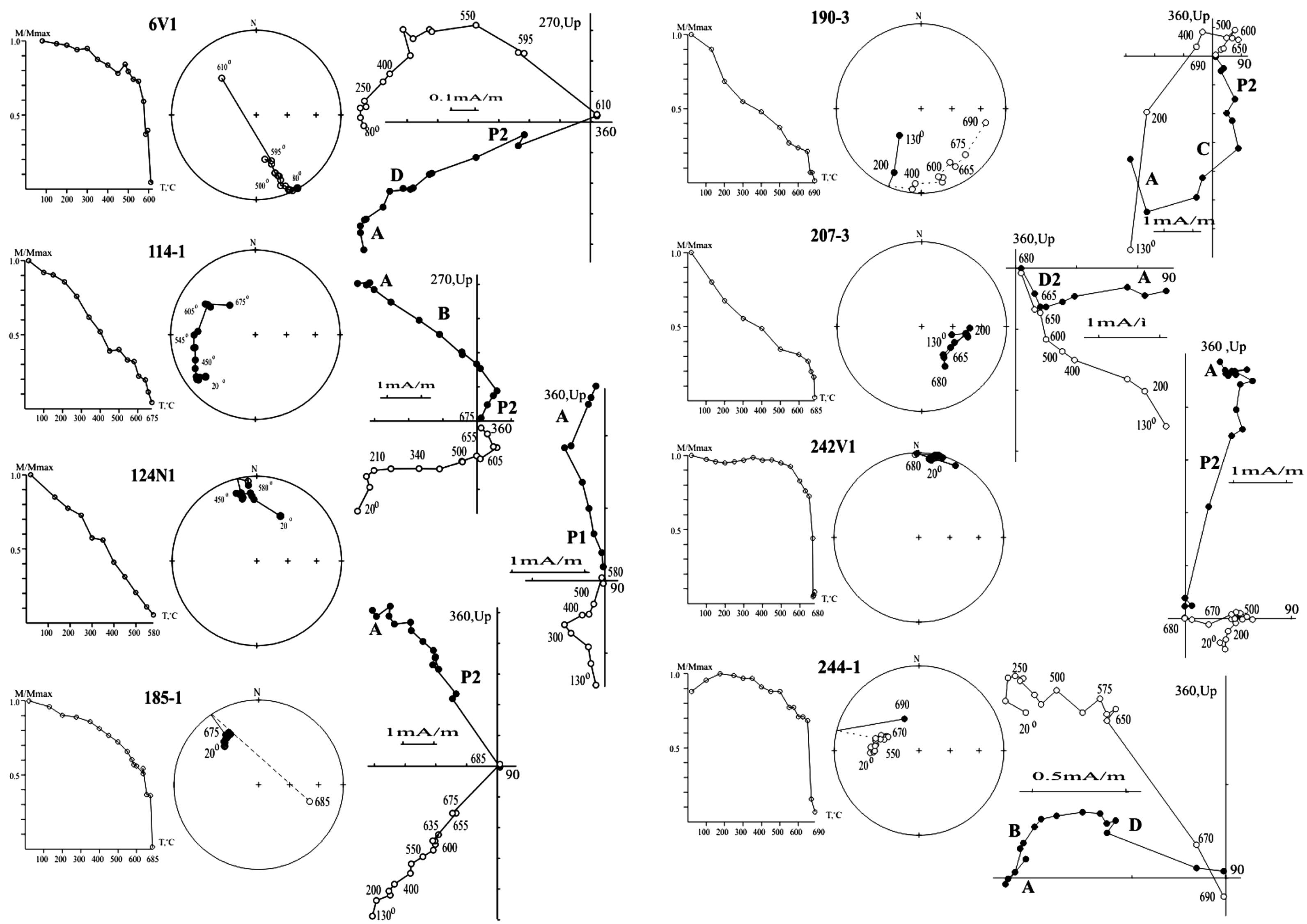

Figure 4. Examples of the thermal demagnetization of Vendian rock samples. Given from left to right are the curves depicting changes in the value of natural remanent magnetization in the course of thermal demagnetization; the stereo-projection of its directions (in the geographical coordinates); the Ziyderveld diagram (in the same coordinates); the empty circles show the projections of the vectors onto the upper hemisphere (the vector projection in the XOZ plane for the Ziyderveld diagrams), the solid circles denote the projections of the vectors onto the lower hemisphere (in the XOY plane for the Ziyderveld diagrams); the numbers near the dots denote the heating temperatures; the letter indices shown in the straight segments of the Ziyderveld diagrams (in accordance with the indices given in Tables 1 and 2) indicate the isolated components.

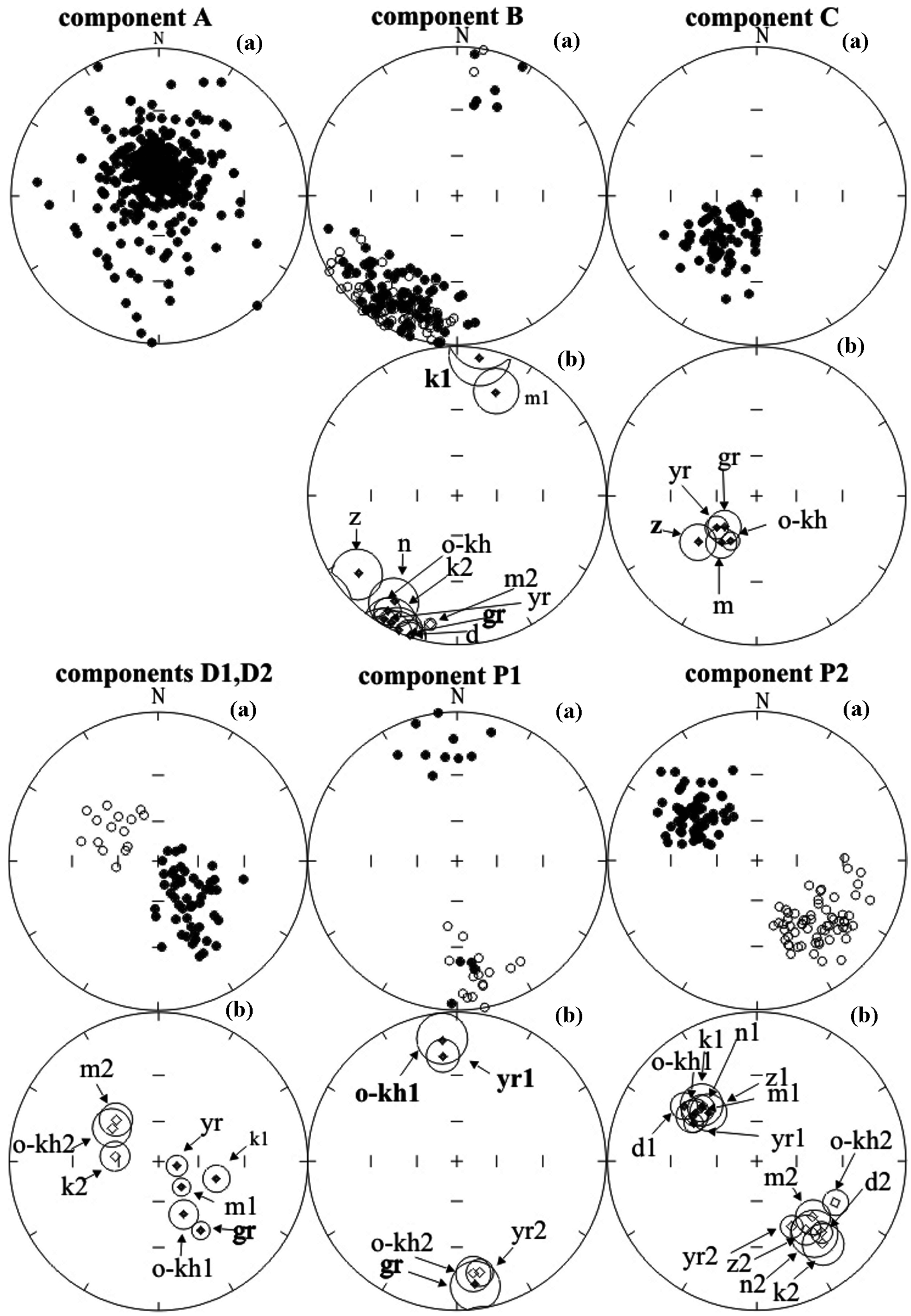

Figure 5. The distribution of the directions of the NRM components identified in the thermal demagnetization experiments. The A, B, C, D1, D2, P1, and P2 indices denote the NRM components in accordance with the indices used in Tables 1 and 2; (a) is the distribution of the NRM directions for the lump samples, (b) is the distribution of the average NRM directions for the rock formations, the notations for which are given in the notes for the Tables 1–3. All data are given in the system of geographical coordinates.

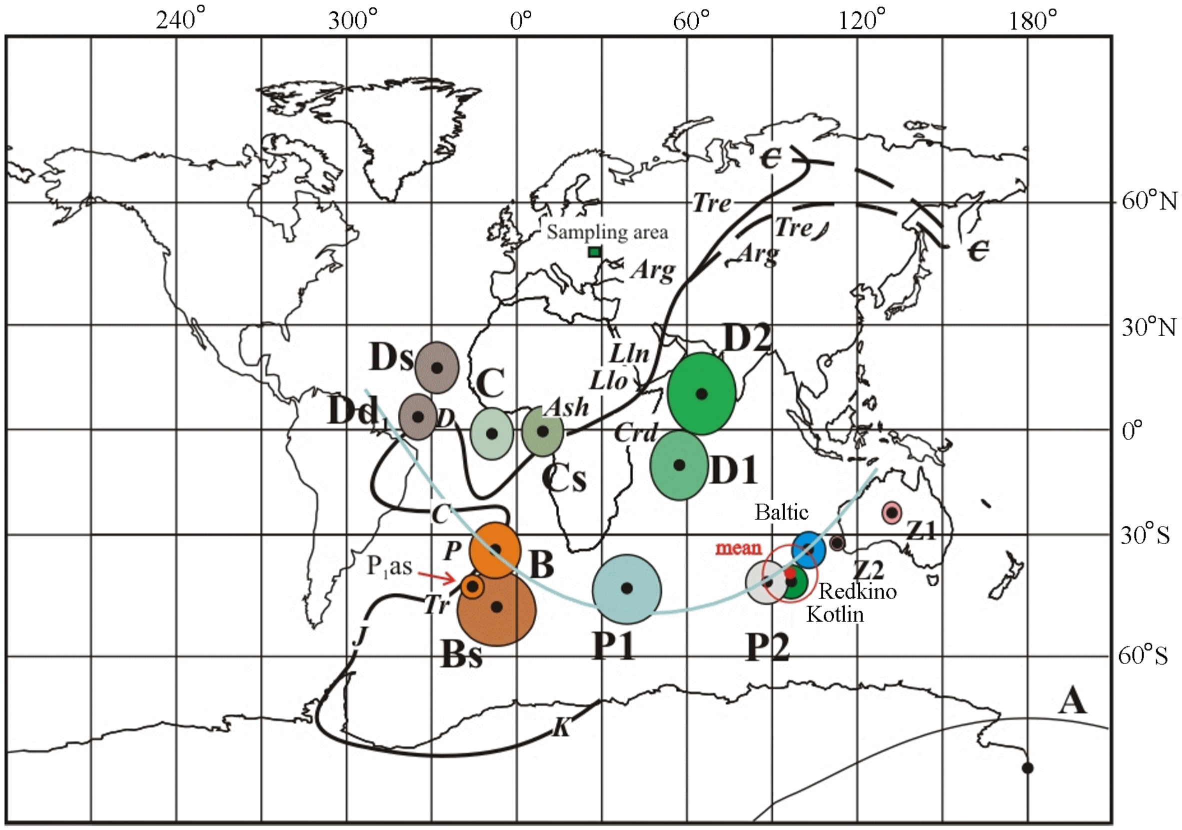

Figure 6. The trajectory of the apparent migration of a paleomagnetic pole for the Baltic region [after *Smethurst et al.,* 1998] and new paleomagnetic poles for the Podolian rocks in the Ukraine region. The indices of the paleomagnetic poles are the same as those used in Tables 1, 2, and 3; the large circle is drawn across the B and P2 poles.

the respective values being 12.0° and 16.4° for the D2 component of the Krushanov rocks. The distribution of the D1 and D2 component directions is shown in Figure 5. The average directions for the rocks in all rock suites are given in Table 1. It should be noted that the C, D1, and D2 components have been identified in the gray rocks. The next two components, P1 and P2, are high-temperature ones, ranging in the temperature intervals of 500–570°C, 600°C and 600–670°C, 690°C. See samples 6V, 114-1, 124N1, 185-1, 190-3, and 244-1 in Figure 4. Most of the rock components are bipolar, show a positive reversal test, and have been ranked as Class C [*McFadden and McElhinny,* 1990]. The distribution pattern of the P1 and P2 components is shown in Figure 5, their average directions being listed in Table 2.

Discussion of Results

The results of this study (Tables 1 and 2) prove that the rocks were subject to the repeated processes of remagnetization, which resulted in the presence of a great number of NRM components. The secondary NRM components were dated using the trajectory of the apparent wandering of the paleomagnetic poles (APWP) for the Baltic region [*Smethurst et al.,* 1998]. It should be noted that since the publication of this paper a significant number of paleomagnetic data were reported in the literature, which call for the revision of this curve for the Carboniferous-Triassic time. One of these papers, where the paleomagnetic poles were revised for the time interval of 300–400 Ma, and a new trajectory was offered for the apparent migration of the paleomagnetic poles for the Baltic region, was a paper by *Torsvik et al.* [2001]. In spite of the fact these authors used mainly the data available only for the western part of the Baltic region, it was proved that some of the APWP poles, namely, the Carboniferous and Permian poles, had been displaced to the higher latitudes. This has been proved by our own investigations of the Permian rocks of the Russian Platform [*Iosifidi and Khramov,* 2002]. In order to estimate the processes of secondary remagnetization, in addition to Vendian rocks, 30 lump samples of the Early Silurian (Llandovery) rocks were collected in outcrop 15 (Kitaigorod Village). The paleomagnetic study of these rocks showed that these rocks had been remagnetized repeatedly [*Iosifidi and Khramov,* 2004]. Figure 6 shows the positions of the paleomagnetic poles obtained using the Vendian rocks of the Arkhangelsk region of Russia [*Popov,* 2001; *Popov et al.,* 2002, 2004, submitted], the Early Silurian rocks of Podolia, the Permian rocks of the Donbass region, and the paleomagnetic pole for

Table 2. The mean paleomagnetic directions and poles for the Vendian rocks of Podolia (Ukraine)

No	Age of the NRM-component	Component index, formation	Statistics of the NRM-component: N/n	D°	I°	K	α°_{95}	Statistics of the pole positions: Φ,°N	Λ,°E	dp,°	dm,°	Test
1		P1, gr	4/5	171.6	10.4	31.2	13.9	-34.1	37.1	7.1	14.1	
2		P1, yr1	3/7	352.4	19.3	91.4	13.0					
3		P1, y2	3/7	168.3	-15.5	148.8	10.1	Angle=5.5°, critical angle=13.7°				
4	V?	P1, yr, (2+3)	6/14	170.3	−17.4	118.6	6.2	−49.5	42.4	3.3	6.4	R+, C
5		P1, o-kh1	7/7	353.1	12.2	20.2	13.8					
6		P1, o-kh2	12/12	171.4	−15.8	22.2	9.4	Angle=4.0°, critical angle=16.0°				
7		P1, o-kh, (5+6)	19/19	172.2	−14.5	22.5	7.2	−48.1	38.1	3.8	7.4	R+, C
8	V?	P1	M=3					−44.0	39.0	A_{95} = 7.5		
9		P2, m1	9/9	305.4	34.3	23.7	10.8					
10		P2, m2	8/8	135.0	-34.3	22.4	12.0	Angle=7.9°, critical angle=15.4°				
11		P2, m, (9+10)	17/17	129.9	−34.4	23.2	7.6	−40.1	99.4	5.0	8.7	R+, C
12		P2, yr	18/41	300.9	37.6	31.2	6.3	−35.9	108.9	4.4	7.4	
13	V	P2, yr	9/18	151.9	−36.8	37.8	8.5	−54.0	76.3	5.8	9.9	
14		P2, yr−	27/59	131.2	−38.3	20.1	6.3	−42.9	100.4	4.4	7.5	R−
15		P2, n1	5/7	312.5	36.5	58.3	10.1					
16		P2, n2	5/5	141.1	−27.8	22.5	16.5	Angle=11.3°, critical angle=17.3°				
17		P2, n, (15+16)	10/12	137.0	−32.3	30.6	8.9	−43.3	90.7	5.7	10.0	R+, C
18	V, Redkino	P2	M=3					−42.2	96.9	A_{95} = 7.5		
19		P2, d1	7/16	308.2	28.6	48.4	8.8					
20		P2, d2	12/29	138.4	−23.7	47.8	6.3	Angle=10.4°, critical angle=10.5°				
21		P2, d, (19+20)	19/45	134.7	−25.6	42.3	5.2	−38.7	89.5	3.0	5.6	R+, C
22		P2, z1	6/11	313.9	41.8	23.4	14.1					
23	V	P2, z2	3/3	144.6	-31.0	86.7	13.3	Angle=13.8°, critical angle=17.1°				
24		P2, z, (22+23)	9/14	137.9	−38.2	27.2	10.0	−46.9	93.0	7.0	11.8	R+, C
25		P2, k1	3/3	316.0	35.7	40.0	19.7					
26		P2, k2	7/7	141.8	-19.5	25.0	12.3	Angle=17.0°, critical angle=18.8°				
27		P2, k, (25+26)	10/10	140.2	−24.4	23.7	10.1	−41.4	83.4	5.8	10.8	R+, C
28	V, Kotlin		M=3					−42.4	88.5	A_{95} = 7.5		
29	V	P2, o-kh1	14/17	308.3	34.6	20.6	9.0					
30		P2, o-kh2	17/21	117.9	-28.6	21.7	7.8	Angle=10.7°, critical angle=11.7°				
31	Baltic series	P2, o-kh, (29+30)	31/38	122.4	−31.4	20.1	5.9	−33.9	103.1	3.7	6.6	R+, C
32	V_{mean} (18+28+31)	P2	M=3					−40.0	96.5	A_{95} = 7.5		

Note. The term "angle" means the angle between the directions of the normal and reversed polarities (NRM); the critical angle is the angle between the directions of the NRM normal and reversed components for a given set of vectors after [*McFadden and McElhinny,* 1990]. See the note for Table 1 for the remaining notations.

Table 3. Some paleomagnetic poles for the Paleozoic rocks of the Ukraine and for the Vendian rocks of the northern Baltic plate

No	Age of rocks	Age of NRM	Φ,°N	Λ,°E	dp°	dm°	Index on Figure 6	Index on Figure 7	Result No, Reference
1	P1as	P_1	−43	344	2	3	P1as		7231
2	D_1	D_1	4	326	2	3	Dd1		5561
3	S_1	Kz	−78	187	8	9			
4	S_1	P-T	−49	353	5	10	Bs		[*Iosifidi and Khamov,* 2004]
5	S_1	D_1(NR)	−18	332	6	9	Ds		
6	S_1	S_1	−0.5	10	6	9	Cs		
7	V	V	−25	132	2	4	Z1	Z1	7218
8	V	V	−32	113	2	3	Z2	Z2	[*Popov,* 2001; *Popov et al.,* 2004, submitted]
9	V	V	−1	78	6	11		1	[*Bylund,* 1994]
10	V	V	−8	92	5	9		2	1328; [*Piper,* 1981]
11	V	V	-26	129	8	12		3	[*Bylund,* 1994]

Note. The term "result number" means the number of a given paleomagnetic determination in the Global Paleomagnetic Data Base (GPMDB) [*McElhinny and Lock,* 1996], Version 4.5; the index NR is used to denote a bipolar component.

the Early Devonian rocks of Podolia reported by *Smethurst and Khramov* [1992]. All of these poles are listed in Table 3. The Ds component, producing a pole close to the Devonian Dd1 pole [*Smethurst and Khramov,* 1992], is bipolar, its reversal test is positive (the angle between the trends of the direct and reversed components is 2.6° (the critical angle being 15.4°) and belongs to the C class [*McFadden and McElhinny,* 1990].

As seen in Figure 6, some of the NRM components, obtained for the Vendian rocks (A, B, C), agree well with the APWP of the Baltic region [*Smethurst et al.,* 1998]. The proximity of the paleomagnetic pole of the B component (Vendian rocks) and of the Bs component (Early Silurian rocks) to the Early Permian P1as pole (Donbass), Table 3 and Figure 6, shows that these rocks were remagnetized during the Kiaman epoch. This is characteristic of most of the Paleozoic-Vendian rocks of the Russian Platform. The paleomagnetic poles of the Permian and Triassic age were also obtained by *Glevasskaya et al.* [2000] for the sedimentary rocks of the Grushka and Yaryshev Formations, and also by *Bakhmutov et al.* [2001] who investigated the Silurian deposits of Podolia. The B component was identified in all of the examined rock suites. Judging by the position of its paleomagnetic pole relative to the Baltic APWP and to the paleomagnetic poles of the Dd1, Ds, and Cs components (Table 3), the C component seems to be produced by the superposition of the results of secondary remagnetization during the Silurian and Early Devonian. The same has been suggested by *Glevasskaya et al.* [2000] using the sedimentary rocks of the Mogilev-Podolian Series and the basalts of the Volynian Series. The paleomagnetic poles obtained for the D1 and D2 components have been located east of the Ordovician APWP segment and are hard to be dated. The next paleomagnetic poles obtained in this study using the Vendian rocks cluster into two groups, P1 and P2 (Table 2 and Figure 6). As follows from Table 2 and Figure 6, the P2 group of poles occupies the position close to the paleomagnetic poles obtained earlier for the Vendian deposits of the White Sea Zimnii Bereg area and in the Zolotitsa River Valley (Arkhangelsk region, Russia), see Table 3 and Figure 6. As seen in Table 2 and Figure 6, the paleomagnetic poles obtained by way of averaging the Redkino Horizon, the Kotlin Horizon, and the Baltic Series are close to one another. The paleomagnetic poles for the Redkino and Kotlin horizons coincide with one another, the pole obtained for the rocks of the Baltic Series differ insignificantly from them. The average paleomagnetic pole ($\Phi = 40°$S, $\Lambda = 97°$E) is close to the pole of the Z2 component [*Popov,* 2001; *Popov et al.,* 2004, submitted]. The P1 component was identified using the rocks of the Grushka and Yaryshev Formations and of the Baltic Series, that is, using the oldest and youngest rocks. This suggests this component to be a secondary one. As seen in Figure 6, the P1 paleomagnetic pole rests on the arc of the large circle drawn across the pole of the B component between the P2 group and the Permian APWP segment of the Baltic region. This component may be a superposition of the Permian and P2 components. It should be noted that the attempts of identifying the Dd1 Early Devonian component using demagnetization circles [*Smethurst and Khramov,* 1992] failed, this suggesting it to be a primary component. The paleomagnetic poles of the D1 and D2 components occupy the position between the Ordovician APWP segment and a group of Late Vendian paleomagnetic poles (P1, P2 and Z1, Z2 groups), being possibly the results of the remag-

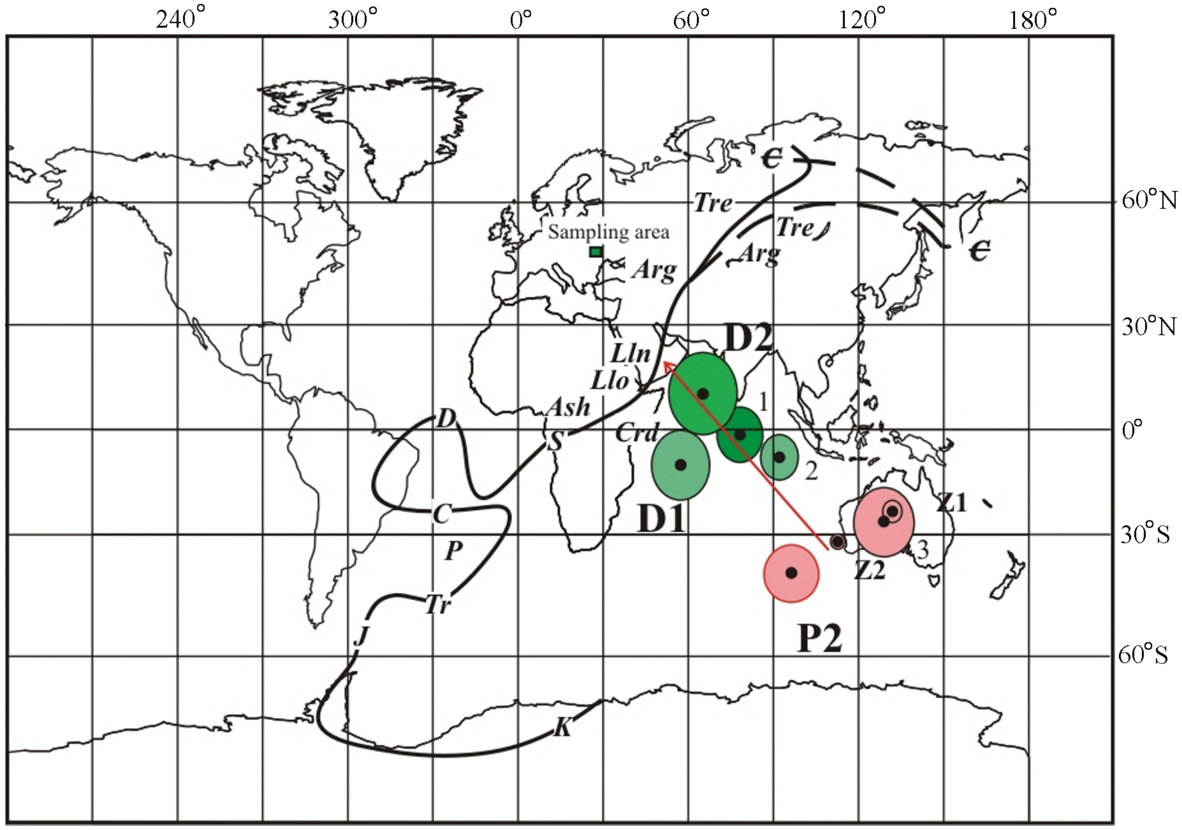

Figure 7. The apparent migration path of a paleomagnetic pole for the Baltic region [after *Smethurst et al.,* 1998] and a group of paleomagnetic poles for the Vendian rocks of the East European Platform. The indices of the paleomagnetic poles are the same as those used in Tables 1, 2, and 3; the arrow shows a potential APWP version for the Vendian-Cambrian time.

netization of these rocks during the Cambrian time. The P1, P2 and Z1, Z2 groups of poles mark a region which is displaced significantly relative to the trajectory of the apparent migration of poles in the Baltic region [*Smethurst et al.,* 1998] and allow one to propose an alternative version of a curve for the Vendian-Ordovician time interval. Listed in Table 3 are the paleomagnetic poles reported by *Piper* [1981] and *Bylund* [1994], which form, together with the poles for the D1 and D2 components, a group of poles transitional from the Vendian to the Ordovician. Figure 7 shows a potential version for the Vendian-Cambrian time.

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