RUSSIAN JOURNAL OF EARTH SCIENCES, VOL. 7, NO. 2, PAGES 1–29, APRIL 2005

Palaeomagnetism, magnetic stratigraphy, and petromagnetism of the Upper Vendian sedimentary rocks in the sections of the Zolotitsa River and in the Verkhotina Hole, Winter Coast of the White Sea, Russia

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Abstract. Palaeomagnetic and petromagnetic studies were carried out in two sections of the Late Vendian–Early Cambrian rocks in the southeastern White Sea region. Ninety meters of the Zolotitsa River section (350 oriented lump samples from the outcrops) and 420 m of core samples from the Verkhotina Hole (443 samples) were studied. Two absolute age values are available for the lower part of the Zolotitsa River section: 550±4.6 Ma and 550±5.3 Ma. These ages were determined using zircons from the volcanic rock interlayers. The rocks investigated in this study are characterized by the low anisotropy of magnetic susceptibility, by the absence of any predominant directions of the half-axes of the ellipsoids of anisotropy, and by the planar type of the latter. The main carrier of natural remanent magnetization (NRM) is hematite in all rocks, magnetite being found occasionally in gray rocks. The detailed stepwise thermal demagnetization of the samples proved the multicomponent composition of the rocks. The low- and medium-temperature components resulted from the demagnetization of the rocks during various interval of geologic time. The high-temperature component is characterized by the positive tests of folding, reversal, and correlation, hence being a primary one. Variations of its direction along the rock sequence were used in this study to identify 27 zones of direct and 28 zones of reversed polarity for the total amount of the rocks investigated in this study. The most reliable results were used to plot the alternative trajectory of the Baltic palaeomagnetic pole migration for the Vendian time and to reconstruct the palaeogeographic Baltic position for that time. A new method was offered and tested for orienting borehole samples in space. Its application was found to produce the high convergence of the results, both in the case of the natural outcrops and borehole samples.

Paper number TJE05167.
ISSN: 1681–1208 (online)

The online version of this paper was published 31 March 2005.
URL: http://rjes.wdcb.ru/v07/tje05167/tje05167.htm

Introduction

The Late Neoproterozoic palaeogeography attracted the attention of many researchers in connection with the hypothesis of the Rhodinia supercontinet which had begun to break up about 725 million years ago. The views on the sub-

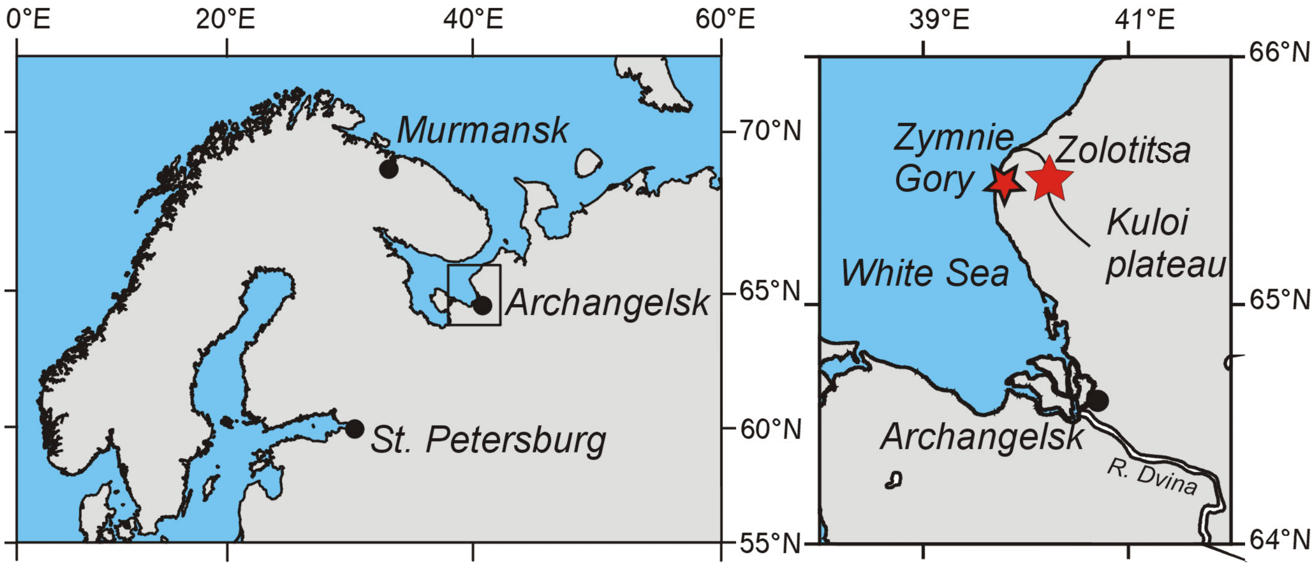


Figure 1. Area of study.

sequent events, such as, the unusually rapid drifting of the continents, their low-latitude positions during the glaciation epochs, and their connection to form the Palaeozoic Pangea, were based mainly on palaeomagnetic data which were extremely scarce for all of these continents. For instance, some authors [*Torsvik et al.,* 1996] used merely five palaeomagnetic poles for the Baltic Vendian rocks, which satisfied the modern criteria of reliability [*Van der Voo,* 1990]. It is clear that these data are absolutely insufficient for choosing any of the competing models available for the movements of the Baltic continent which occupies the central key position in the modern global reconstructions for the Vendian time. As follows from the data reported in [*Torsvik et al.,* 1996], the southern palaeomagnetic pole of the Baltic region had been located in the Vendian time at high northern latitudes. These data suggest that during the Late Vendian time the Baltic region had resided in the region of 60°S. The new palaeomagnetic datings obtained recently for the Vendian rocks of the Russian Platform [*Popov,* 2001; *Popov and Khramov,* 2002; *Popov et al.,* 2002; *Iglesias et al.,* 2004], as well as the results of this study, suggest a new version for the palaeogeographic position of the Baltic Continent during Vendian time.

Geology and Collection of Samples

The Vendian rocks of the region outcrop along the eastern margin of the Baltic Schield in the river valleys of the Onega Range, in the western segment of the Dvina scarp, and in the west of the White-Sea Kuloi scarp, as well as in the scarps of the Onega, Letnii, and Zimnii shores of the White Sea. The Vendian rocks rest almost horizontally on the crystalline basement of the platform and the Upper Riphean rocks. The Late Vendian rocks of the southeastern White Sea region are known to show the best rock sequence in the Russian Platform [*Stankovski et al.,* 1985]. The Ediacarian fossils, unique in their number, variety, and preservation [*Fedonkin,* 1981, 1985; *Grazhdankin,* 2000; *Grazhdankin and Bronnikov,* 1997], as well as the absolute age determinations using zircons [*Iglesias et al.,* 2004; *Martin et al.,* 2000; *Shchukin et al.,* 2002], date very precisely the various parts of the rock sequence, the total thickness of which is greater than 500 m.

Samples for palaeomagnetic studies were collected along the middle course of the Zolotitsa River (Figure 1), where the rocks of the Padun and Remsha formations are exposed and from the Verkhotina Hole drilled near the Zolotitsa River at the Winter Coast of the White Sea (courtesy of E. M. Verichev and T. A. Rumyantseva, Arkhangelsk Geological Survey). This hole exposed also the lower stratigraphic units up to the top of the Ust-Pinezha Formation. Exposed in the upper part of this rock sequence are thick (up to 30 m) members of equally layered sandstone with occasional and thin interbeds of red and gray siltstones and clays, known as the Zolotitsa Beds. These sandstone members extend from a few hundred of meters to a few dozens of kilometers. The lower boundary of these rocks, with conglomerates at the base, corresponds to the lower boundary of the Zolotitsa Beds in the Padun Formation [*Stankovski et al.,* 1985]. The rocks of the Padun Formation were not dated, though some geologists date it (or at least part of it) Early Cambrian [*Grazhdankin,* 2000; *Shchukin et al.,* 2002]. The lower, Late Vendian, part of this rock sequence (Mel, Erga, and Vaisitsa beds) is composed mainly (75%) of red clay and siltstone with occasional thin interbeds of blue clay and siltstone, as well as of red and gray sandstones [*Stankovski et al.,* 1985]. All of these rocks are unmetamorphozed and are poorly lithified. Sediments had accumulated under the slightly brackish and fresh-water conditions of a sea prodelta and a flat plain, remote from the sea shore. The rock sequence shows some cyclicity of the delta, schlieren, and molasse rocks [*Grazhdankin,* 2000]. The zircons found in two volcanic rock layers in the lower part of the Zolotitsa River section were used to determine the absolute age of the rocks [*Iglesias et al.,* 2004]. The resulting ages (550±4.6 Ma and 550±5.3 Ma) agree well with the absolute age determinations carried out earlier [*Martin et al.,* 2000] for the older rocks exposed at the Zimnii Shore in the area of the Medvezhii Creek, which were dated 555±0.3 Ma.

The samples were collected from 10 outcrops, partially overlapping one another, in the middle course of the Zolotitsa River (from 65°20′ N and 40°00′ E to 65°40′ N and 40°30′ E, Figure 1) and from the vertically oriented cores collected from a borehole. The total study interval included 90 meters of the Zolotitsa River section with a sampling interval ranging from 5 cm to 100 cm (350 oriented lump samples) and 420 m of holes cores collected with a sampling interval of 40 cm to 100 cm (443 samples). Where the rocks were studied in the outcrops, they showed subhorizontal bedding with dip angles smaller than 10°. Only the lower sequence of rocks exposed by the Zolotitsa River showed two anticlinal folds with the maximum dip angles of 70°. The folds are believed to have been produced by recent glacial dislocations. The oriented lump samples collected from the Zolotitsa River site were sawed into cubes with the edges of 2 cm (880 cubes); the core samples were used to collect cubic samples with a side of 2 cm or cylinders, 22 mm long and 25 mm in diameter, collecting one sample from each stratigraphic level.

Laboratory Measurements

The palaeomagnetic and petromagnetic studies of the samples were carried out in the VNIGRI Department for Palaeomagnetic Reconstructions (St. Petersburg) and in the Department for Earth and Environmental sciences, Geophysical Section, Ludwig-Maximilian University (Munich, Germany). The NRM of the samples was measured using JR-4 and JR-5 spinner magnetometers (St. Petersburg) and a 2G cryogenic magnetometer (Munich). The samples were subject to detailed cleaning using an alternating magnetic field and to thermal cleaning. The cleaning by the alternating magnetic field did not give any satisfactory results; most of the samples experienced thermal demagnetization. Cleaning was performed in Saint Petersburg using stoves of the VNIGRI construction and TD-48 stoves (USA) and in Munich (Germany) using TSD-1 stoves (Schonstedt production) and TD-48 (USA). The results of magnetic cleaning were analyzed using Ziyderveld diagrams [*Zijderveld,* 1967] and stereoprojections. The linear segments corresponding to NRM components were located on the demagnetization curve in agreement with the technique of a principal component analysis [*Kirschvink,* 1980]. The average directions of the resulting magnetization components were computed using the Fisher Statistics [*Fisher,* 1953]. Where several samples, sawed from the same bulk sample, were used, the directions of their components were averaged, that is, all statistical data reported in this paper are given at the level of lump samples. The computer processing of the results was accomplished using the programs [*Enkin,* 1994]. To control the chemical variations of NRM carrying minerals the magnetic susceptibility of the samples was measured using a KLY-2 Kappa bridge. The cleaning of the samples was terminated, where their magnetic susceptibility increased 5 or more times, or where the value and direction of the residual vector showed chaotic changes at several cleaning steps. These changes are typical of gray rocks and were observed occasionally in red sandstones.

The compositions of magnetic minerals (NRM carriers) were identified in Munich using a thermomagnetic analysis and hysteresis characteristics obtained using a VFTB (Variable Field Translation Balance) equipment, and also in Saint Petersburg using the curves recording changes in magnetic susceptibility as a function of temperature, recorded by a KLY-3 Kappa bridge and a CS-3 thermal attachment (Spinning Specimen Magnetic Susceptibility Anisotropy Meter). This instrument was also used to study the anisotropy of the magnetic susceptibility of the samples collected from the Zolotitsa River cross section.

Petromagnetic Results

The magnetic properties of the rocks studied in the upper (supposedly Early Cambrian) and in the lower (Late Vendian) intervals of the rock sequence both in the Verkhotina Hole and in the Zolotitsa River outcrops differ significantly. The upper part of the rock sequence is distinguished by the low values of magnetic susceptibility (κ) and by the high values (up to 100) of the Koenigsberger factor (Q), see Figures 2 and 3. These Q values, abnormally high for sedimentary rocks seem to be associated with the presence of diamagnetic carbonate admixtures, which lower the κ values. Figure 4 shows the curves of Q variations for the rock sequences examined in the cross-sections concerned, and smoothed using a techniques of a sliding mean. This figure shows that the maximum Q values reside above the inferred Vendian-Cambrian boundary in both sections. The fact that the Q peaks are observed in the hole and in the natural outcrops at different distances, in terms of thickness, from the boundary between the Zolotitsa and Mel layers, seems to be associated with the different thicknesses of the sandy rock units. The fairly gentle variations of the κ and Q values in the boundary layers, with the absence of any abrupt κ and Q changes at the boundary itself, suggest that changes in the feeding province and in the sedimentary basin itself had taken place at the Vendian-Cambrian boundary. In particular, the decline of the magnetic susceptibility and the Q growth were controlled by the diminishing concentration of hematite and oxidized magnetite in the sediments and by the growing content of diamagnetic carbonate. The latter resulted in the lower κ values and, accordingly, in the Q values abnormally high for the sedimentary rocks. The Q values, as high as 100 and larger, are more characteristic of oceanic carbonate sediments (see Initial ODP Reports, for example, Holes 750a, 758a, and 1135a).

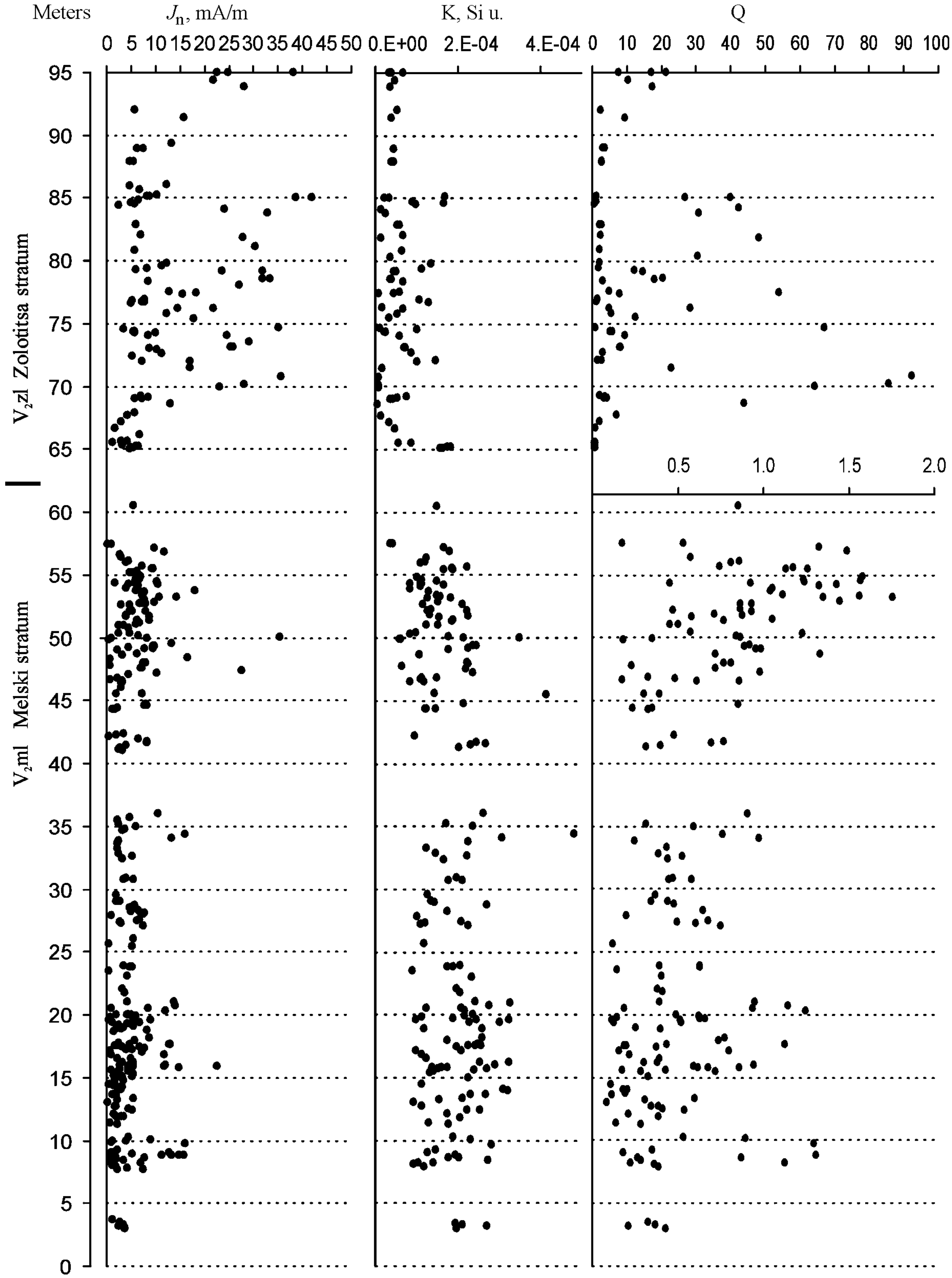


Figure 2. Variations of J_n, magnetic susceptibility (κ), and Koenigsberger factor (Q) along the Zolotitsa River section. The Q plot shows a 50-time difference between the horizontal scales of the upper (65–95 m) and lower (0–65 m) parts of the rock sequence.

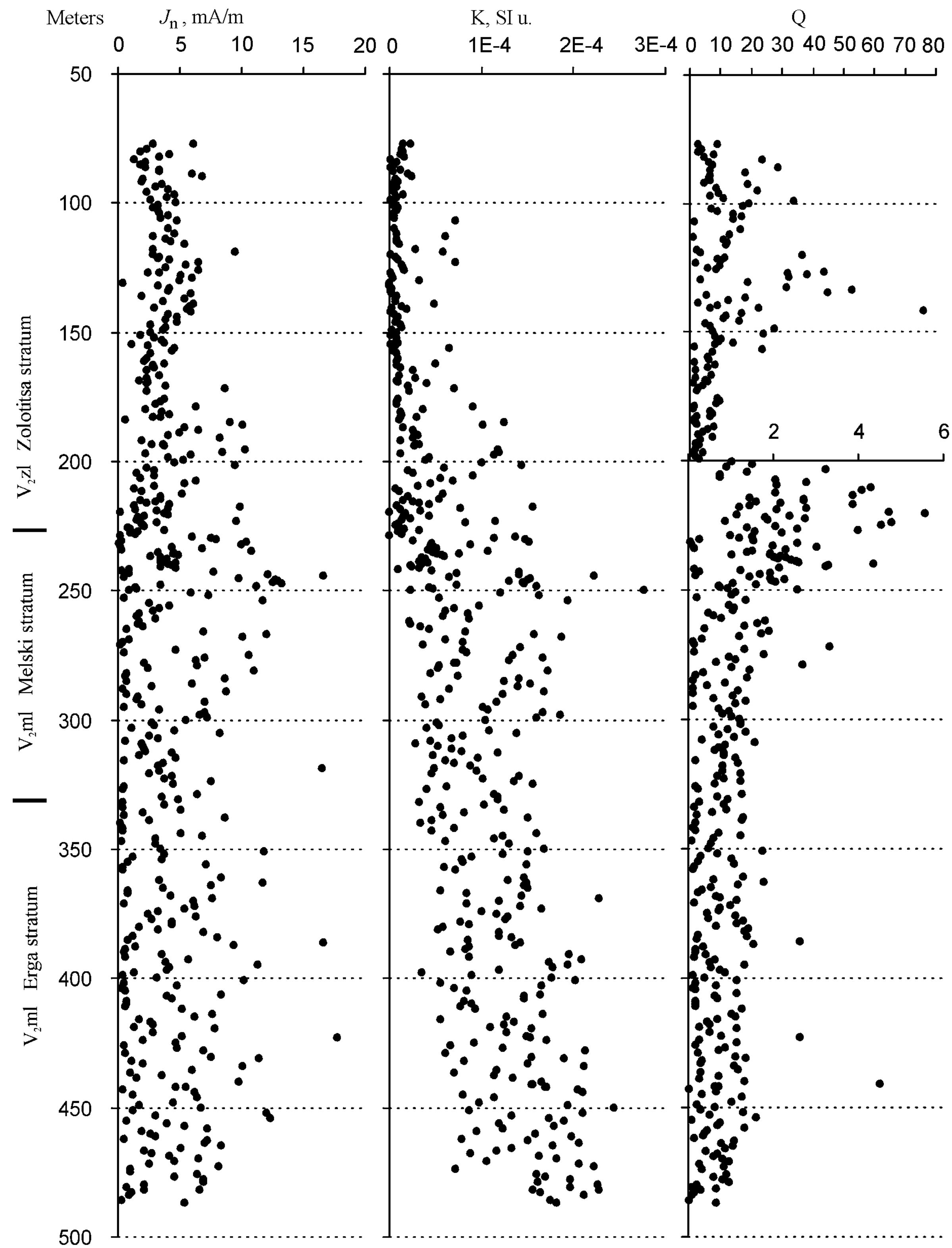


Figure 3. Variations of J_n, magnetic susceptibility (κ), and the Koenigsberger factor (Q) along the hole section. As to the Q plot, the horizontal scales of the upper (0–200 m) and lower (200-500 m) parts of the rock sequence differ by a factor of 13.

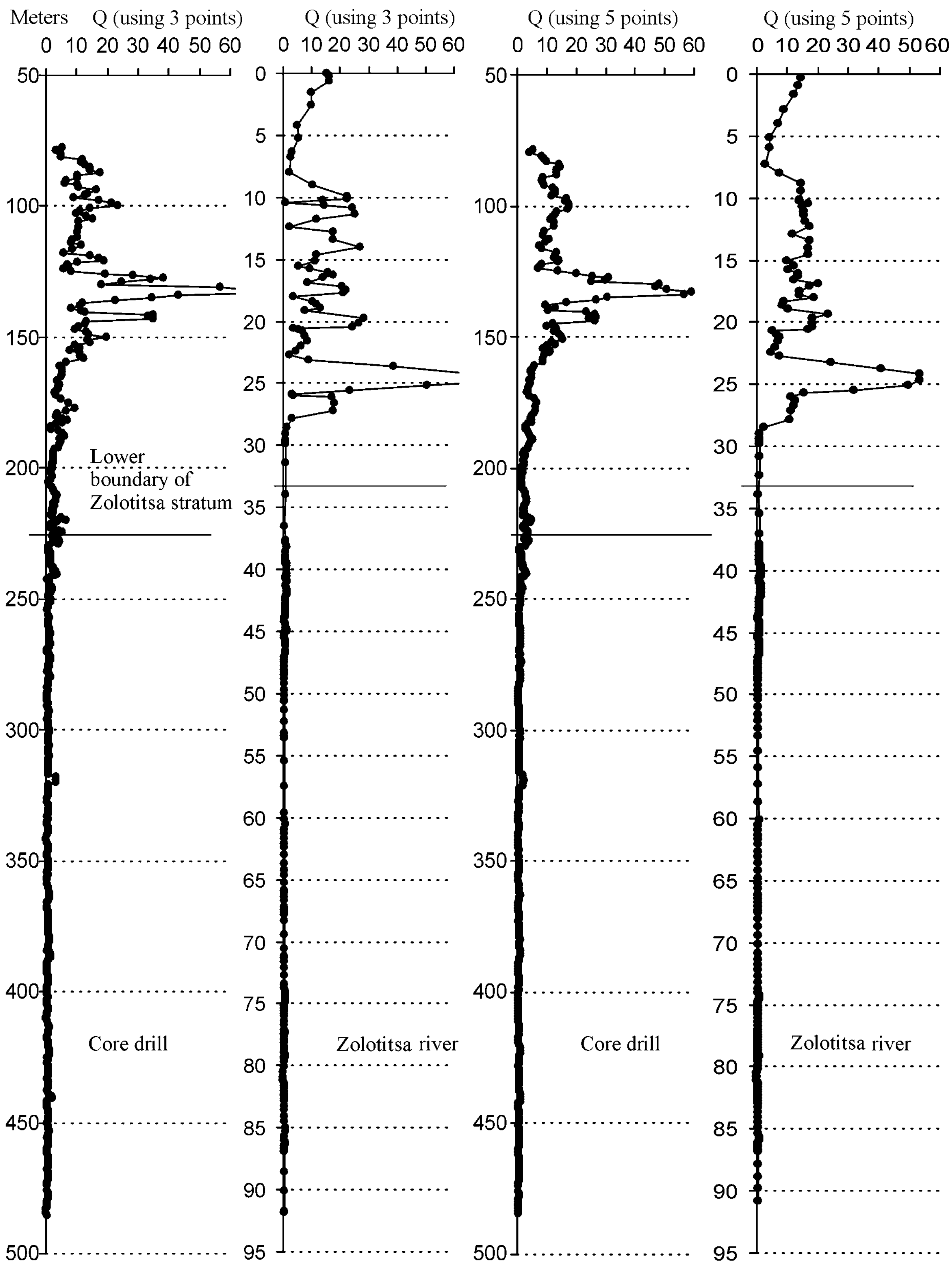


Figure 4. Variation of the Koenigsberger factor (Q) along the hole section and along that of the Zolotitsa River, obtained using a moving average for three and five sites.

The anisotropy of magnetic susceptibility (AMS) was measured using a collection of samples from the Zolotitsa River area. All samples showed low AMS values (Figures 5 and 6). For instance, the Pj parameter characterizing the degree of anisotropy [*Tarling and Hrouda,* 1993] showed a value below 1.06 for most of the samples, except for three sandstone and four clay samples which showed the Pj values ranging between 1.06 and 1.1 (Figure 6a, and 6c). The maximum values of the AMS parameters of the rocks are not associated with their stratigraphic positions relative to the inferred boundary (Figures 5a, 5b, 6a, 6b, and 6c). The $L(F)$ and $T(Pj)$ parameter relationships suggest the planar type of the ellipsoid [*Tarling and Hrouda,* 1993] for most of the samples collected from the clay-siltstone portion of the rock sequence (Figures 5 and 6). Some sandstone samples showed an elongated ellipsoid (Figure 6a), the anisotropy coefficients being low in this case.

The distributions of the maximum and intermediate AMS ellipsoid axes did not show any predominant directions for all types of the study rocks (Figure 7a and 7B), except for the greater scatter of the directions recorded for the sandstone samples. The minimum axes showed an average vertical direction (Figures 7c and 7d) and a positive fold test [*McFadden and Jones,* 1981; *Watson and Enkin,* 1993] with a probability of 99% for claystones and siltstones. In the case of sandstones this test yielded an indefinite solution, because their samples had been collected from the subhorizontal portion of the rock sequence. The results obtained for the magnetic anisotropy of the rocks suggest the detrital origin of the magnetic susceptibility carriers and the poor compaction of the sediments.

The results of the thermomagnetic analysis of the samples collected from the Zolotitsa River rock sequence showed that they consisted of hematite alone or the latter was obviously a predominant mineral. The content of magnetite (or, to be more exact, of oxidized magnetite, because none of the samples showed $T_c = 580°C$) was higher in the sandstones of the lower (Vendian) rock sequence. In most cases the magnetization of the samples grew notably in the course of their heating, beginning from the temperature of about 200°C and showing the maximum values at ∼400°C. The $J(T)$ peaks in the upper part of the rock sequence were recorded in all samples, except for those from the Vendian interval where the peaks diminish with some samples showing a reversed $J(T)$ curve pattern. A similar effect is often observed in experimental $J(T)$ curves, measured in the absence of any saturation field, especially in the case of hematite-bearing rocks [e.g., *Duff,* 1979]. The theoretical substantiation of the peaks in the thermal magnetization and susceptibility curves observed for a great number of compounds was offered by I. Y. Korenblit and E. F. Shender [1989], and this phenomenon was referred to as "spin glass". Later, the model of the spin glass behavior was applied to a system of interacting single-domain particles disseminated in a nonmagnetic matrix resembling a natural rock material [*Belokon and Nefedov,* 2001; *Duff,* 1979]. The presence of a peak in the $J(T)$ curve can be explained in the following way. In the case of disorded hematite ("spin glass"), and in the case where the field in which the thermomagnetic analysis was performed was not a saturation field (the thermomagnetic analysis was performed in the field of 100 mT, the saturation field being higher than 250 mT), the magnetic material was ordered during the heating, following the ordering of the spin glass type, leading to the growth of magnetization which was preserved during the cooling in the field, producing an irreversible $J(T)$ curve. As to the samples with the notable contents of magnetite, oxidized magnetite, and some magnetically "soft" material, the value of 100 mT denotes a saturation field and suggests these minerals to be magnetically ordered and showing no effect concerned. Moreover, since these minerals are more magnetic than hematite, the effect of hematite is masked. The ubiquitous presence of $J(T)$ peaks suggests the predominance of more rigid hematite with a disorded magnetic structure in the upper part of the rock sequence. All of the studied samples showed their second heating and cooling $J(T)$ curves, almost coinciding with the first cooling curve, confirming the explanation of the $J(T)$ behavior offered in this paper.

The $\kappa(T)$ variation curves also prove the presence of hematite in the study rocks. The curves obtained for the first and second heating showed substantial differences in many cases (Figure 8). The data obtained for thermal NRM demagnetization confirm the petromagnetic data, namely, the fact that the carrier of its high-temperature component in the rocks is hematite alone.

The predominance of hematite in the rocks of the whole sequence is proved by the high magnetic rigidity of the rock samples: magnetic saturation is not achieved in the field of up to 250 mT, H_{cr} = 110–170 mT. As to the Vendian rocks, only some samples of gray sandstone showed $H_{cr} < 50$ mT (e.g., only one sample (no. 200) showed $H_{cr} = 30$ mT. Its $J(T)$ curve showed $T_c = 610°C$ and 680°C, suggesting the presence of single-phase oxidized magnetite and hematite). There are also indications of maghemite (a J peak in the vicinity of 200°C in red claystone sample no. 343). The sandstone samples collected from the top of the rock sequence, showing the lowest κ values and the highest Q values, are distinguished by a broad, flattening hysteresis loop, the irreversible J growth during the heating, a significant difference between the J values before and after the heating, and a segment with negative J values in the $J(T)$ curve (Figure 9a). The claystone and siltstone samples collected from the lower part of the rock sequence, distinguished by the lowest κ and highest Q values, showed a more narrow hysteresis loop, the absence of any segments with negative J values in the $J(T)$ curve, a lower $J(T)$ peak, and the lower difference between the J values before and after the heating (Figure 9b). These data suggest that this interval of the rock sequence is composed mostly of coarse-grained hematite which is accompanied by some magnetite. The presence of oxidized magnetite and maghemite in the Vendian rocks, even in small amounts, can explain the low Q values in these rocks, compared to the Cambrian "purely hematitic" sediments, apart from the role of diamagnetic carbonate rocks.

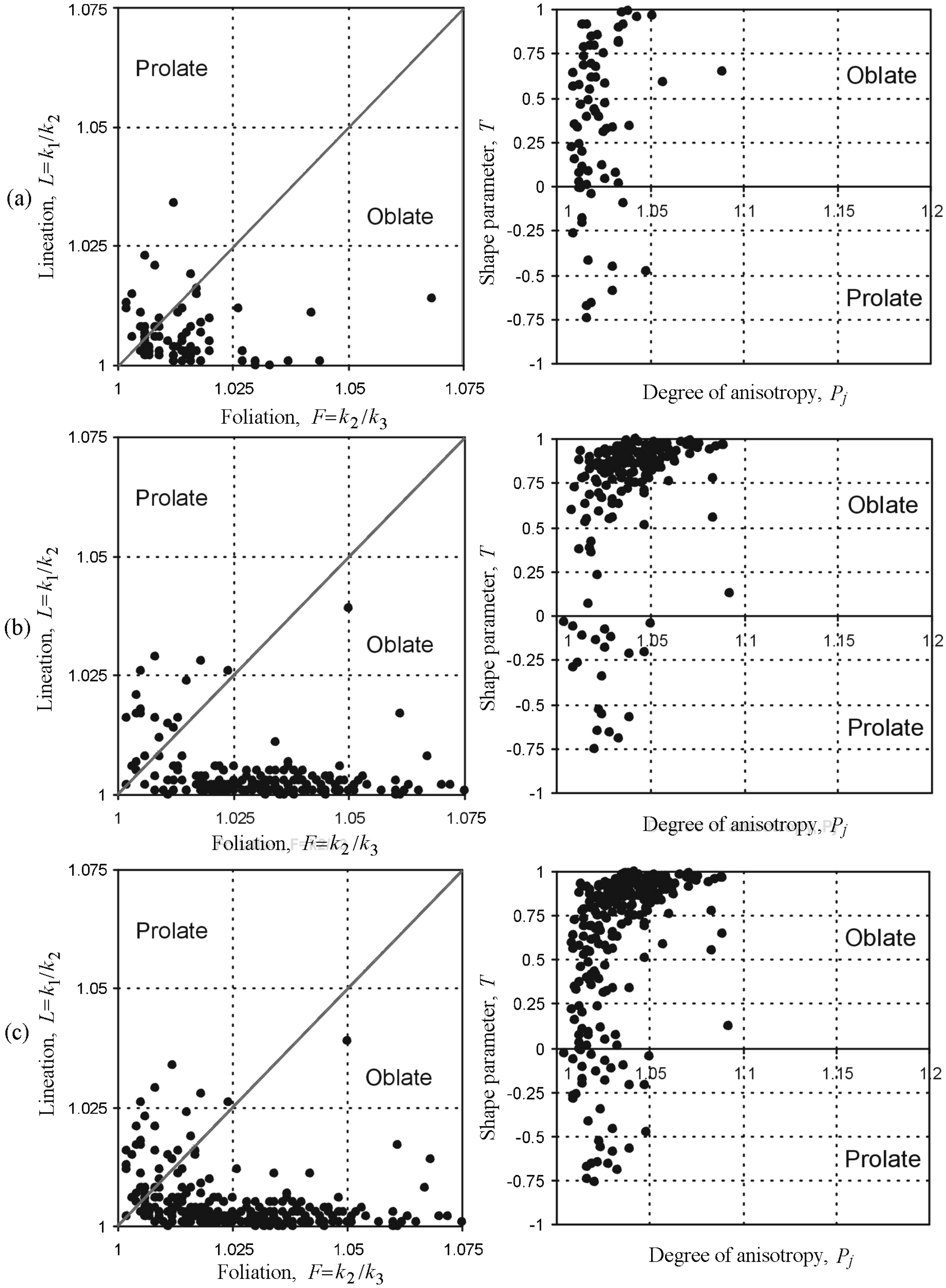


Figure 5. Variations of the parameters of the magnetic susceptibility anisotropy $L(F)$ in the left and $T(Pj)$ in the right. (A) the upper 0–30 m and (B) the lower 30–95 m of the rocks; (C) the total Zolotitsa River rock sequence.

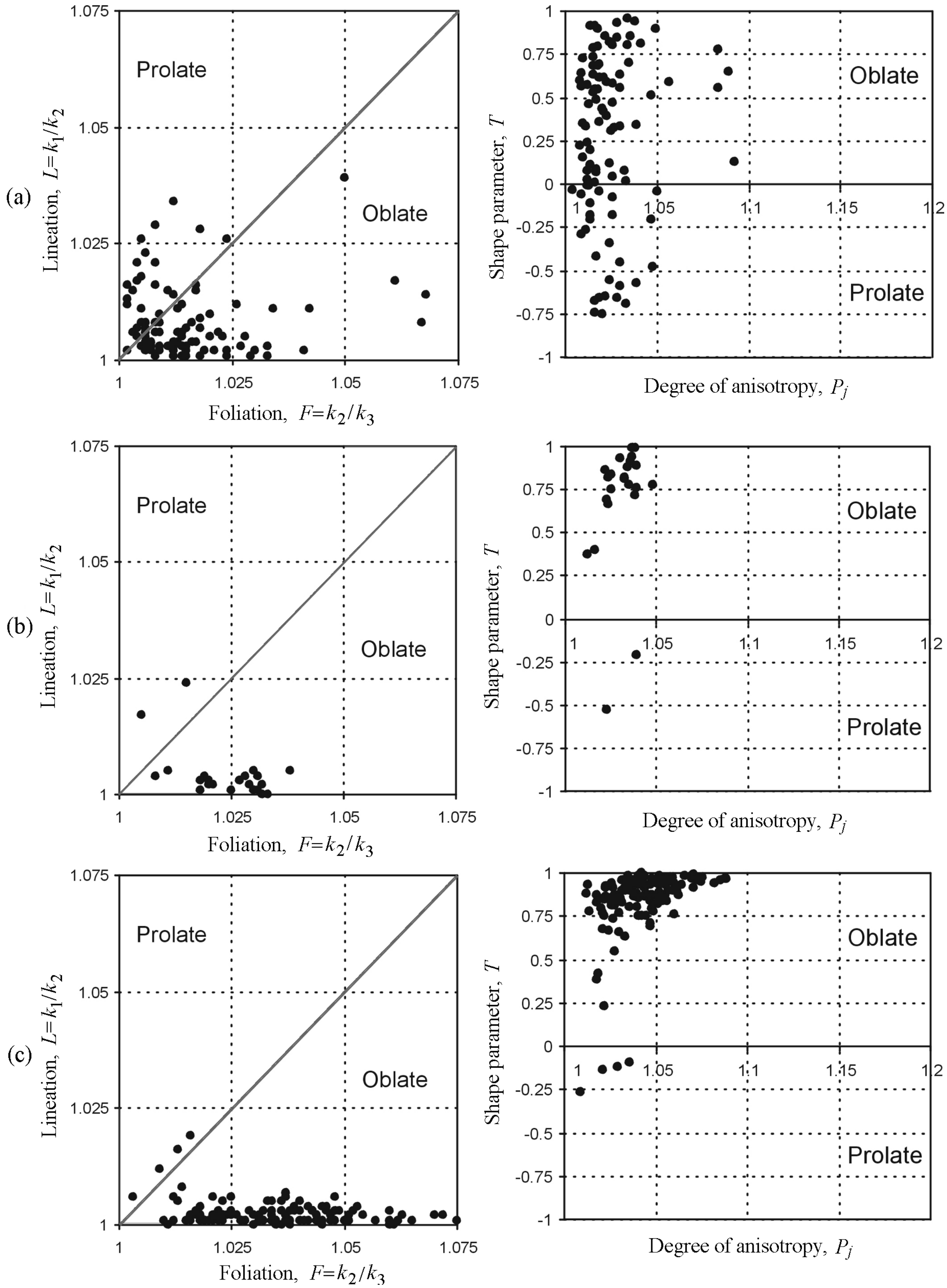


Figure 6. Variations of the parameters of the magnetic susceptibility anisotropy $L(F)$ in the left and $T(Pj)$ in the right. (A) sandstone, (B) siltstone, and (C) clay of the Zolotitsa River section.

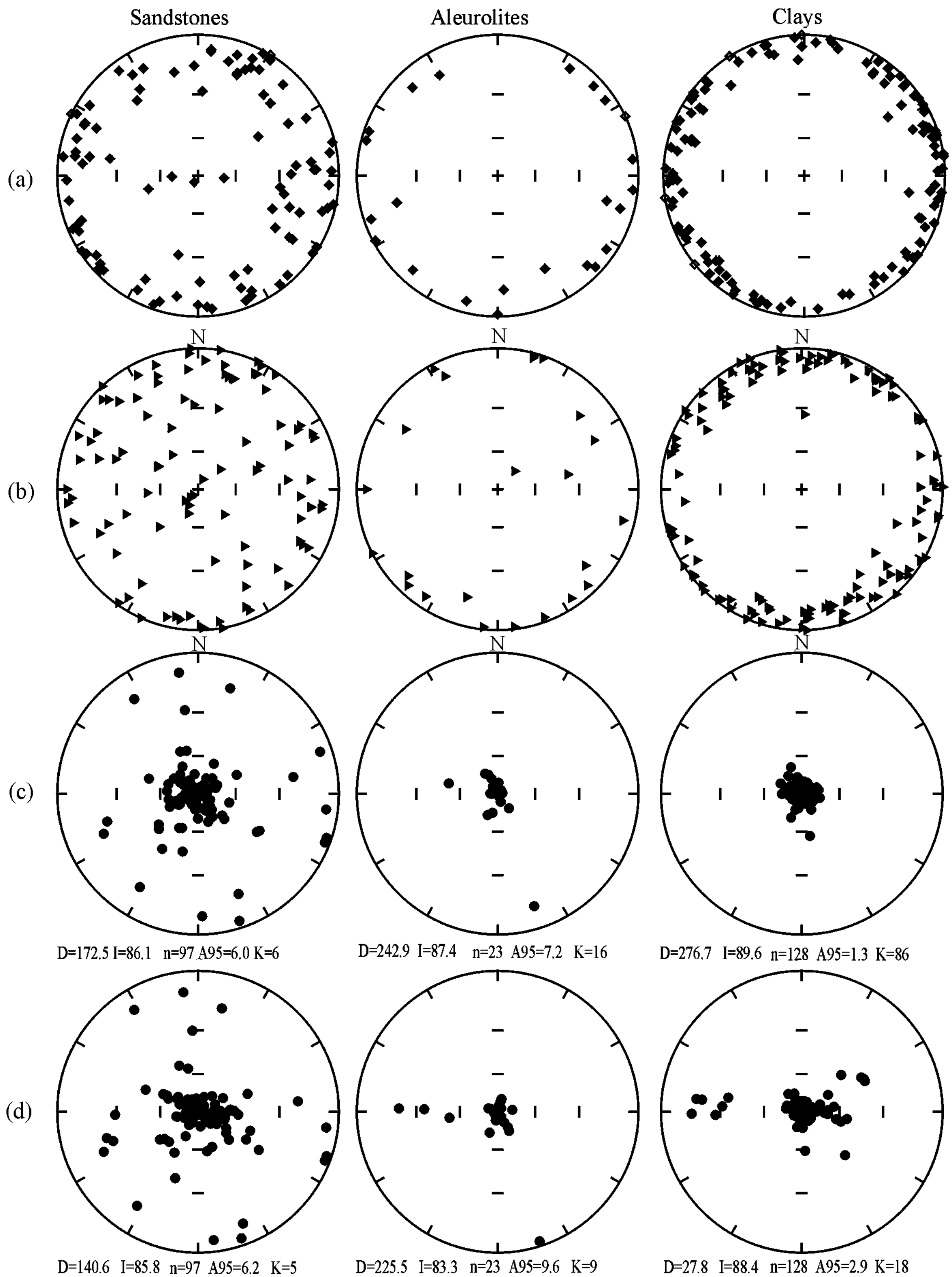


Figure 7. Distribution of the axes directions of the magnetic susceptibility anisotropy ellipsoids: (A) maximal, (B) intermediate, and (C) minimal axes in the stratigraphic system of coordinates; (D) distribution of the minimal axes in the geographical system of coordinates.

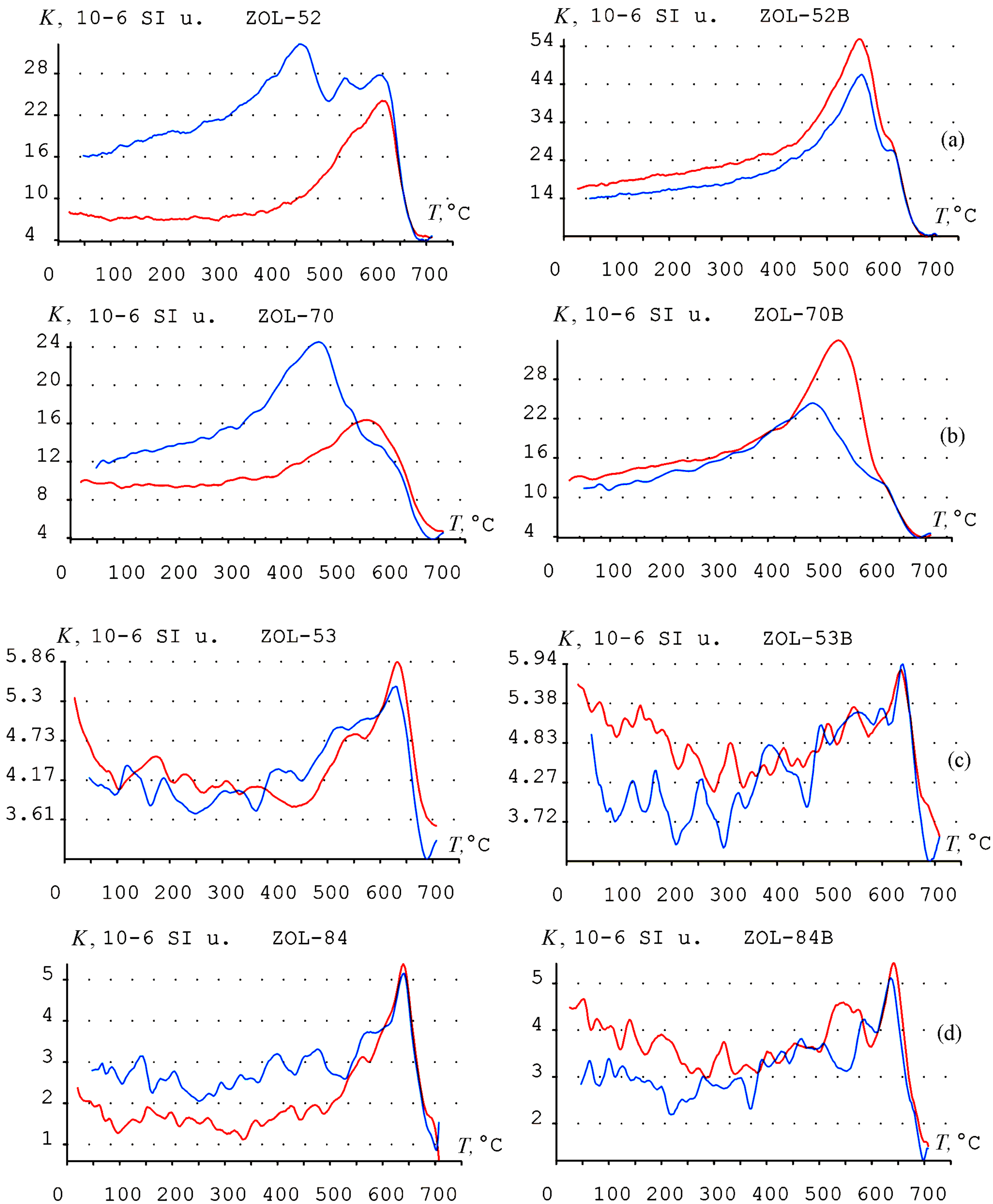


Figure 8. Magnetic susceptibly variations vs. temperature for the rock samples from the Zolotitsa River rock sequence. The curves shown in the left are for the first, and those in the right, for the second heating. The A and B curves were obtained for the claystone and C and D, for the sandstone.

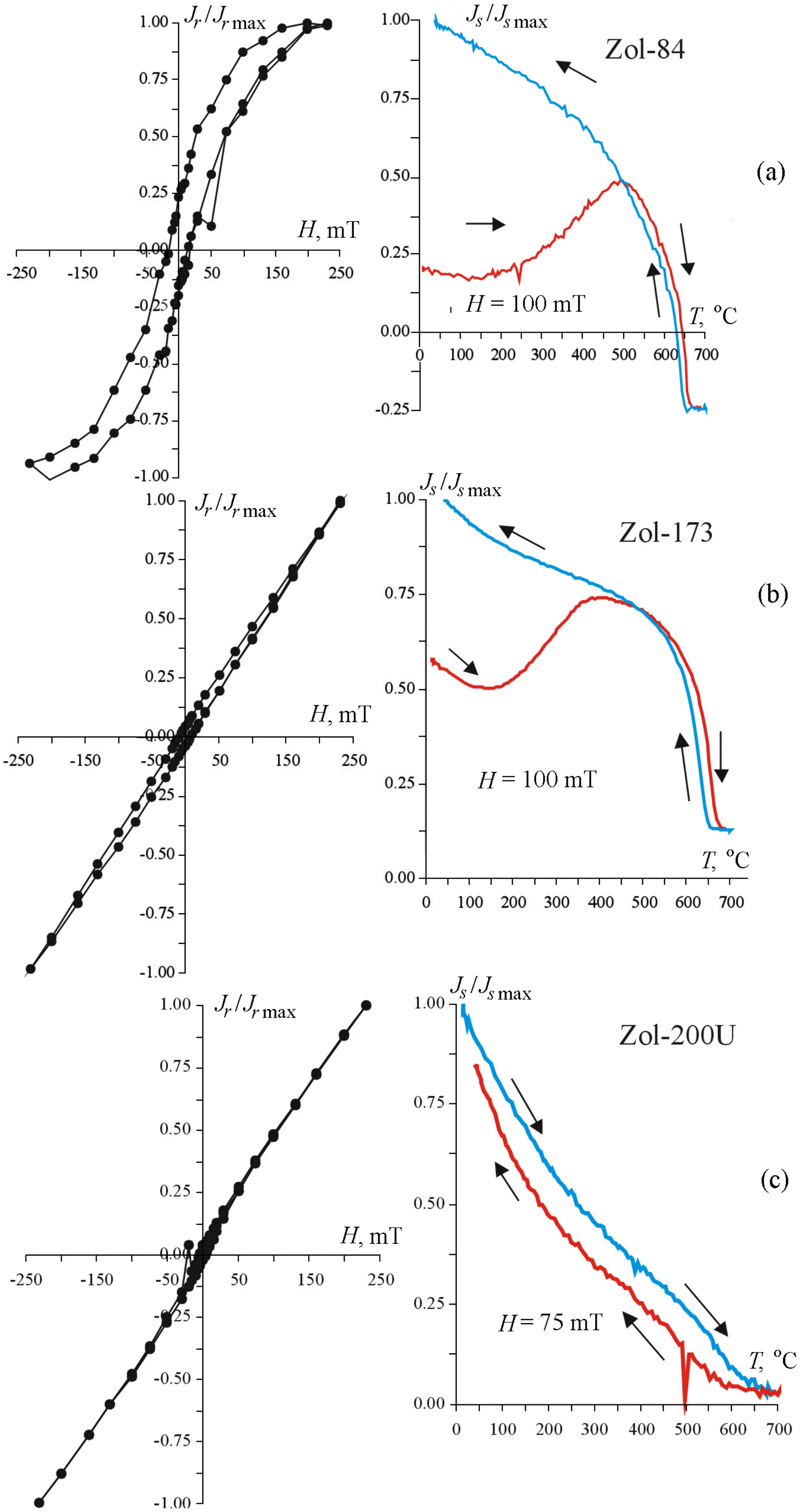


Figure 9. The results of the VFTB analysis of rock samples from the Zolotitsa River section: (A) red sandstone, (B) red claystone, and (C) gray claystone.

Table 1. Mean palaeomagnetic directions from Upper Vendian rocks of Zolotitsa River section

Component	N	Dg	Dsin	Ds	Ig	Jsin	Js	Kg	Ksin	Ks	α_{95}g	α_{95}sin	α_{95}s	Test
A	299	21.7	2.8	348.2	82.6	84.0	84.1	25.2	32.2	27.3	1.7	1.4	1.6	55%
B	286	172.5	174.4	178.3	67.4	67.4	66.5	17.8	19.9	16.4	2.0	1.8	2.1	40%
C	39	212.0		215.2	−32.1		−35.3	8.6		17.8	8.3		5.6	F+(98%)
Z(N)	138	301.8		298.5	39.5		40.2	8.9		18.8	4.3		2.8	F+(99%)
Z(R)	96	120.5		119.5	−35.2		−36.5	10.6		16.3	4.6		3.7	F+(99%)
Z = Z(N) + Z(R)	234	301.2		298.9	37.7		38.8	9.5		17.6	3.1		2.3	F+(99%), R+(B)

A/B/C/Z – name of component in the text, (N)/(R) – normal/reversed polarity, N – number of levels included in statistics, D/I – mean declination/inclination, K/α_{95} – precision parameter/percent confidence circle (g – *in situ*, sin – sintilting, s – after bedding correction), F+ – positive fold test, R+ – positive reversal test.

NRM Component Composition of the Study Rocks

Zolotitsa River Section

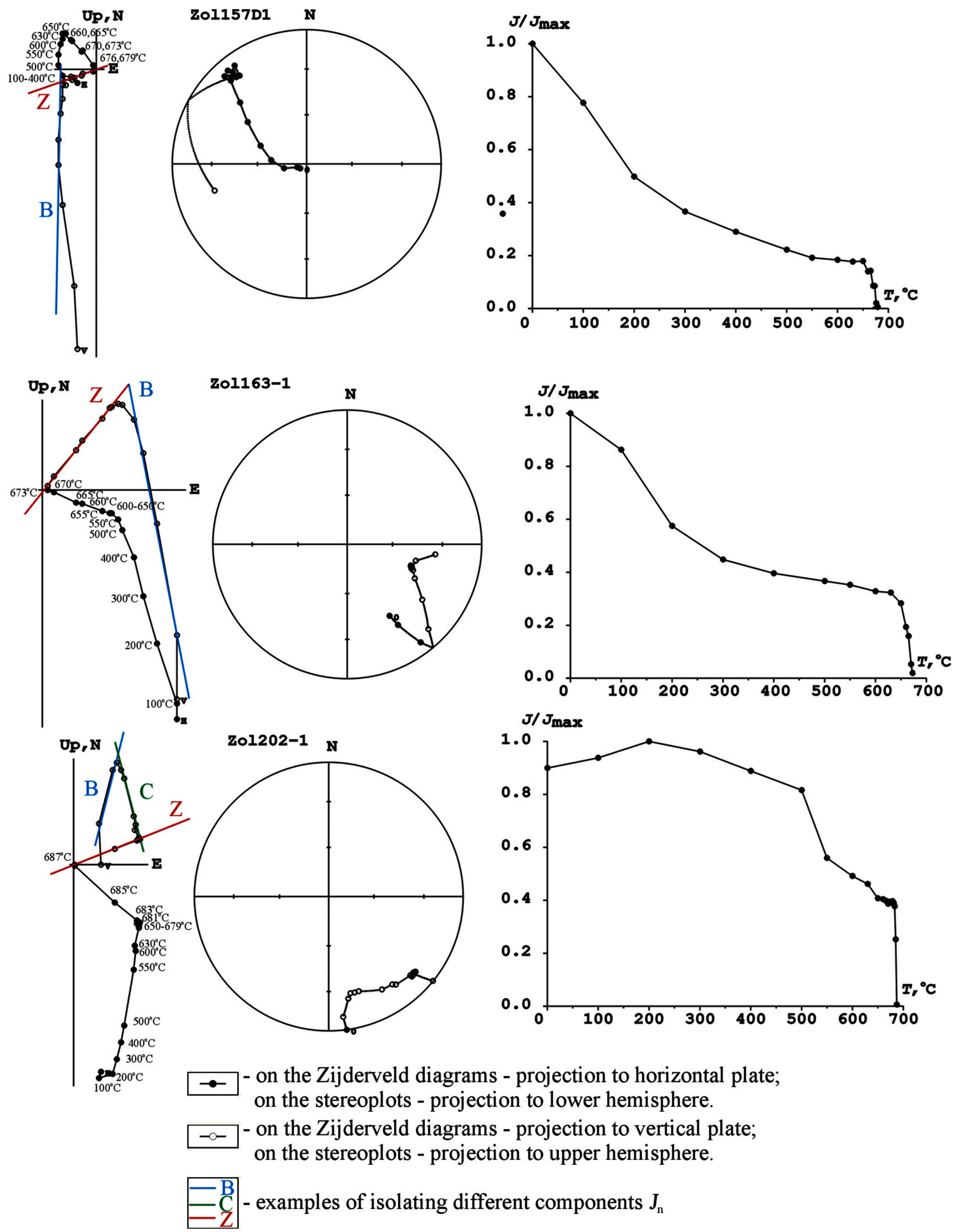
The thermal demagnetization of the rocks allowed us to distinguish four NRM components: the A low-temperature component, two B and C medium-temperature components, and the Z high-temperature bipolar component (Figure 10, Table 1).

The A component was found to disintegrate in the narrow temperature range of 20–250°C (Figure 10) and in many cases in the temperature range of 20–150°C (Figure 10) and was identified in all rock samples. This component showed the best statistics where a progressive fold test was used (with 55% rectification) [*McFadden and Jones,* 1981; *Watson and Enkin,* 1993] and yielded a mean direction which almost coincided with the direction of the present-day geomagnetic field at the sampling site (Figure 11a, and Table 1). It appears that this component is the product of modern (partially, laboratory) remagnetization.

The mean-temperature B component showed blocking temperatures, varying from sample to sample. In some cases it was destroyed at a temperature range of 100–300°C, in other cases it remained to be stable at the temperatures as high as 680°C (Figure 10). This component was recorded in all rock samples and showed the best statistical values, both where a progressive fold test was used, and where the whole collection of samples was used (40% rectification) [*McFadden and Jones,* 1981; *Watson and Enkin,* 1993], and where we only used the samples where the rocks had substantially different dips and strikes (50% rectification). The palaeomagnetic pole obtained in the latter case had the following coordinates: $\Phi = 25.8°$N, $\Lambda = 44.2°$E, dp = 2.5°, and dm = 3.0° (Figure 11b, Table 1).

The medium-temperature C component was identified in a small number of samples, namely, in 39 samples out of the studied 350 lump samples. All of these samples had been collected in the lower segment of the Zolotitsa River section, where the rocks had been folded, and also below this zone. This component was located in a temperature range of 400–670°C and always showed higher blocking temperatures, compared to the those of the B component (Figure 10). The C component also showed the best distribution in the stratigraphic system of the coordinates and a positive fold test with a probability of 98% [*McFadden and Jones,* 1981; *Watson and Enkin,* 1993] (Figure 11c, and Table 1). The palaeomagnetic pole ($\Phi = 38.5°$S, $\Lambda = 356.2°$E, dp = 3.7°, and dm = 6.5°) corresponding to this component is located in the vicinity of the Permian pole for the Russian Platform [*Iosifidi and Khramov,* 2002; *Smethurst et al.,* 1998; *Torsvik et al.,* 1996].

The Z high-temperature component was identified in many of the study samples (234 lump samples). It was destroyed in the narrow temperature range of 660–690°C and occasionally in the range of 680–695°C (Figure 10). In most cases the recording of this component called for diminishing the interval of the temperature cleaning at the last steps down to 5°C, 3°C, and 2°C, up to 20–50% of NRM being often destroyed at the last ten degrees of cleaning (Figure 10). The Z component distinguished in this way showed two polarities. Its polarity was not controlled by the lithology of the samples (being most reliably detected in the red and mottled clays) or by the component composition of a particular sample (in the presence of all components or of merely A, B, or Z), but was controlled only by the positions of the samples in the rock sequence. The Z component showed a positive reversal test of the B class (its difference from the antiparallel pattern of the direct and reverse mean directions being 4.1° with the critical angle of 6.7°) [*McFadden and McElhinny,* 1990]. The fold test was also found to be positive with a probability of 99% [*McFadden and Jones,* 1981; *Watson and Enkin,* 1993] for the components of direct polarity, reversed polarity, and for all population of the vectors (Figure 11d, and Table 1). The palaeomagnetic pole ($\Phi = 31.7°$S, $\Lambda = 112.9°$E, dp = 1.6°, dm = 2.7°), calculated from the mean direction of the Z component resides far from the trajectory of the apparent migration of the palaeomagnetic pole of the Russian Platform [*Smethurst et al.,* 1998; *Torsvik et al.,* 1996] and is close to the pole which was obtained earlier using the Zimnegorsk outcrops at the Winter Coast of the White Sea [*Popov et al.,* 2002]. All of the above data allow us to rank the Z component as the old and primary component, synchronous to the sediments accumulation.


Zol157D1
Up,N
E
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Zol163-1
Zol202-1
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Z
- on the Zijderveld diagrams - projection to horizontal plate;
on the stereoplots - projection to lower hemisphere.
- on the Zijderveld diagrams - projection to vertical plate;
on the stereoplots - projection to upper hemisphere.
- examples of isolating different components J_n

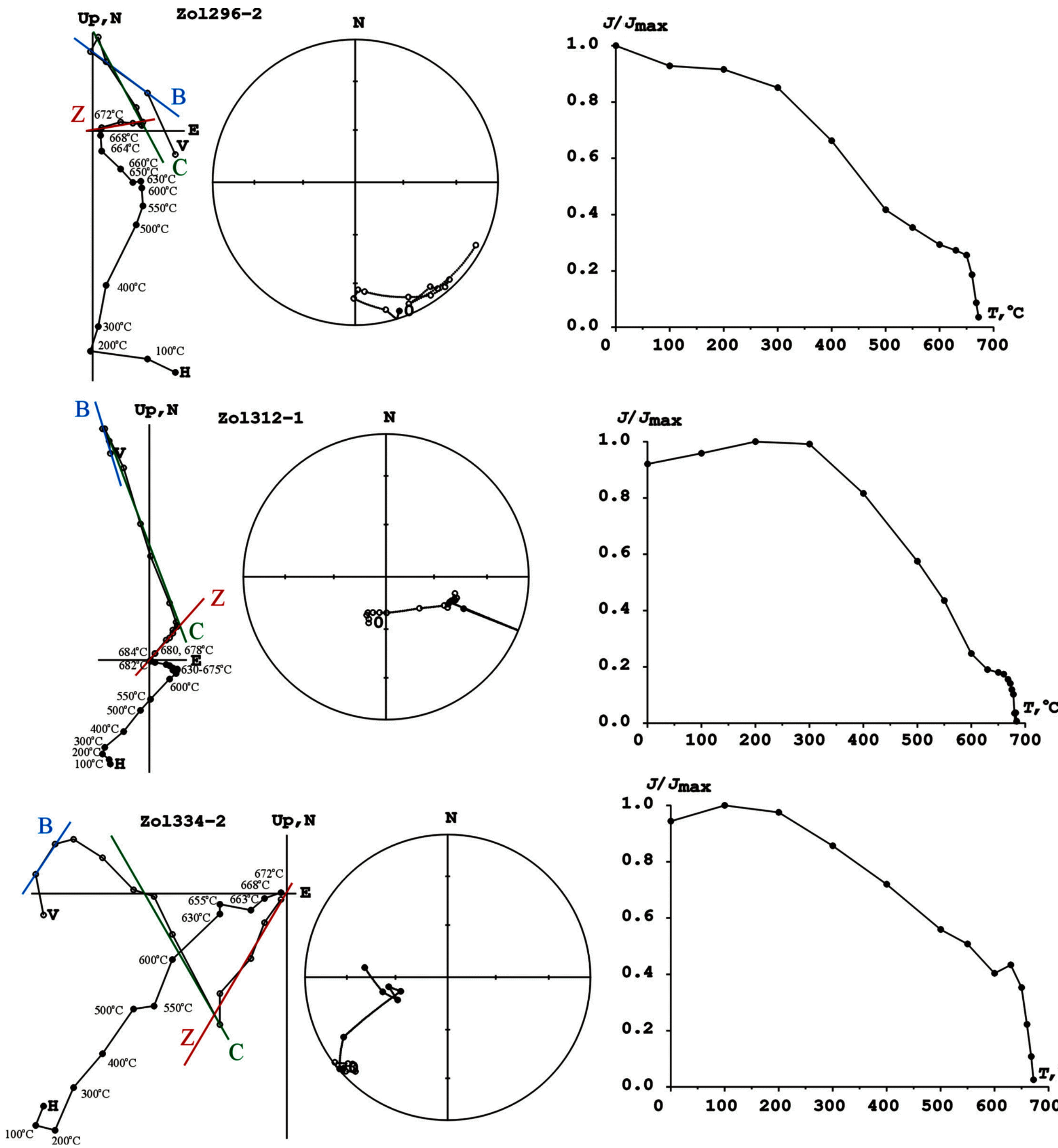

Figure 10. The results of the temperature cleaning of the samples from the Zolotitsa River rock sequence in the stratigraphic system of the coordinates. Shown in the left is the Ziyderveld diagram, in the middle is the stereogram, and in right is the $J_{\mathrm{n}}(T)$ variation curve.

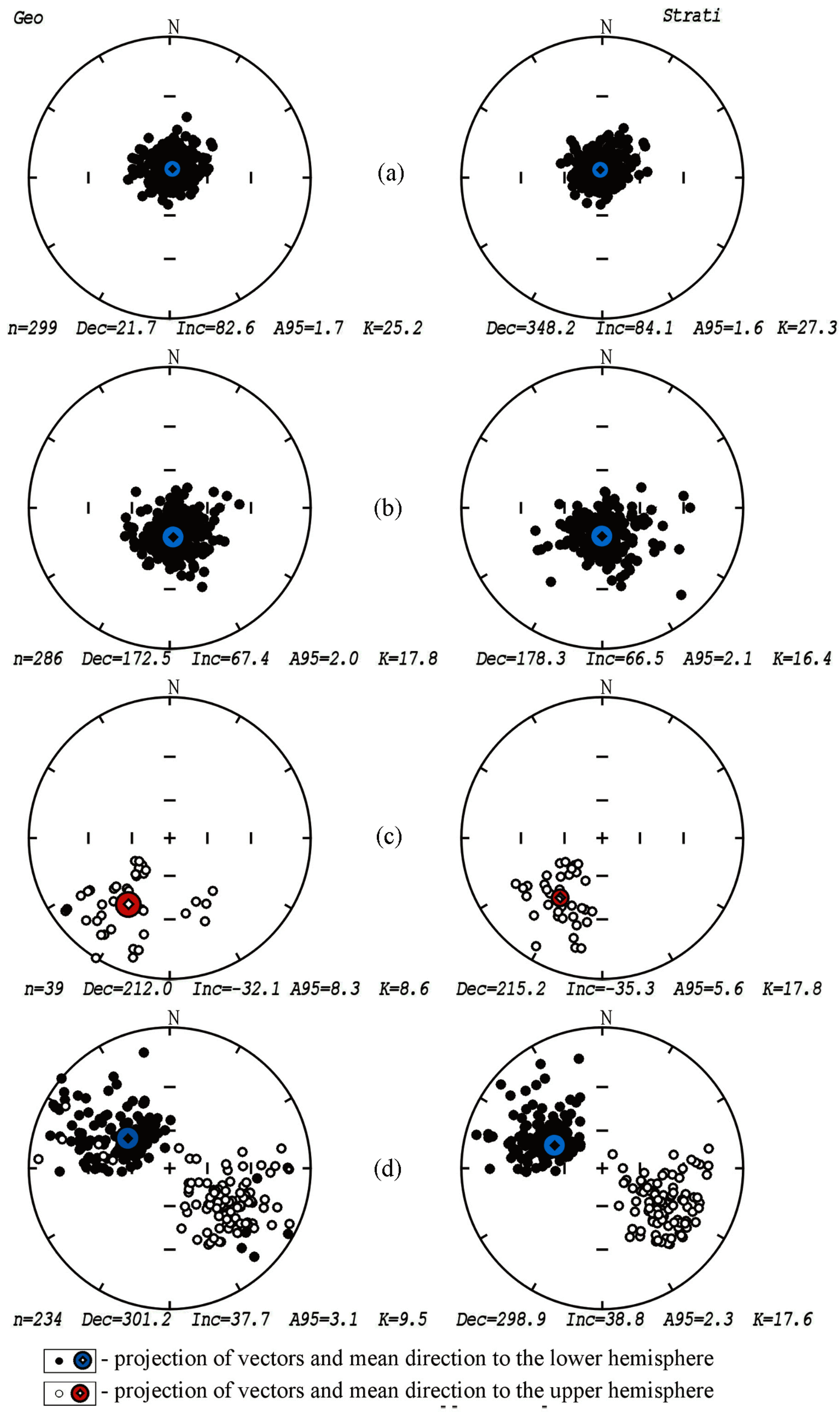

Figure 11. The distribution of the A (a), B (b), C (c), and Z (d) magnetization components identified. Those in the left are shown in the geographical, and those in the right, in the stratigraphic system of coordinates.

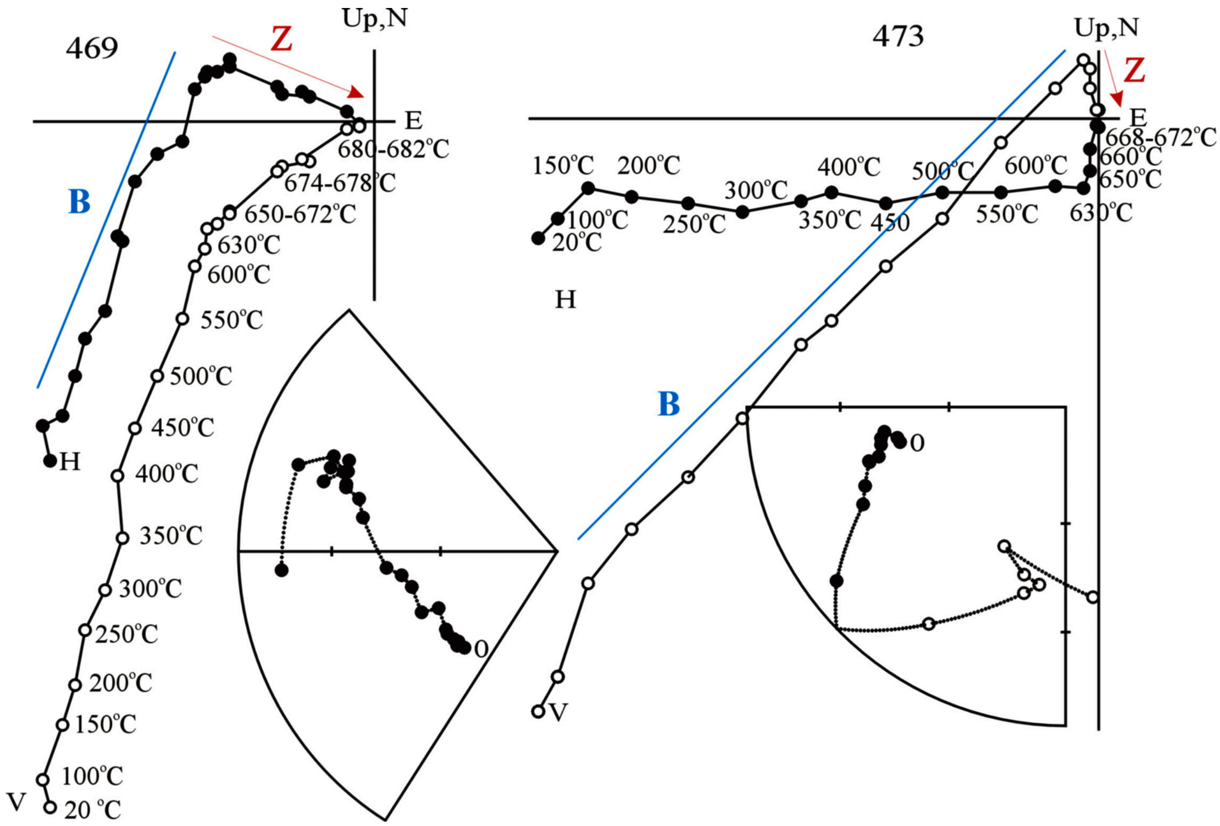

Figure 12. Examples of the Ziyderveld diagrams for the samples collected from the hole cores. The samples were not oriented in the horizontal plane. See Figure 10 for the legend.

The Rocks Exposed by the Verkhotina Hole

These rocks showed four NRM components: the A low-temperature component, two (B and C) medium-temperature components, and the Z high-temperature bipolar component (Figure 12). As follows from the modes of the thermal demagnetization curves, from the blocking temperature spectra, and from the presence of identical magnetic minerals, the resulting NRM curves agree with the similar components found in the samples collected from the natural outcrops exposed by the Zolotitsa River. It should only be noted that the A and C components were identified less reliably in the hole samples: the A component seems to be a "drilling component" or a superposition of a modern and a "drilling" component, while the C component was distinguished only in 20 samples, and often looked as a zone where the blocking temperature spectra of the B and Z components overlapped one another. The Z component was found to have two polarities, and, like in the Zolotitsa River section, its polarity is not controlled by the lithology or by the component composition of the samples, being controlled only by the position of the rocks in the section.

A New Method for Orienting Core Samples in Space

We could not use the low-temperature modern component of magnetization to orient the cores in space using the conventional method for several reasons.

- One of them was associated with the principal limitations for the high latitudes where the inclination of the modern component shows high values. In this case, owing to the natural scatter of magnetization vectors, some of them may have declinations differing from the declinations of the modern geomagnetic field by the angles as high as 180°. The use of the conventional orientation method might lead to errors in detecting the directions of the old magnetization component;
- The other limitation is associated with the fact that in some cases the modern viscous component may be highly contaminated and sometimes wholly destroyed in the course of drilling or laboratory remagnetization;
- Finally, the modern component of many samples has a very narrow spectrum of demagnetizing effects, this precluding its reliable identification.

In the case of this situation we offer a new method for orienting drill cores in space, which allows one to calculate,

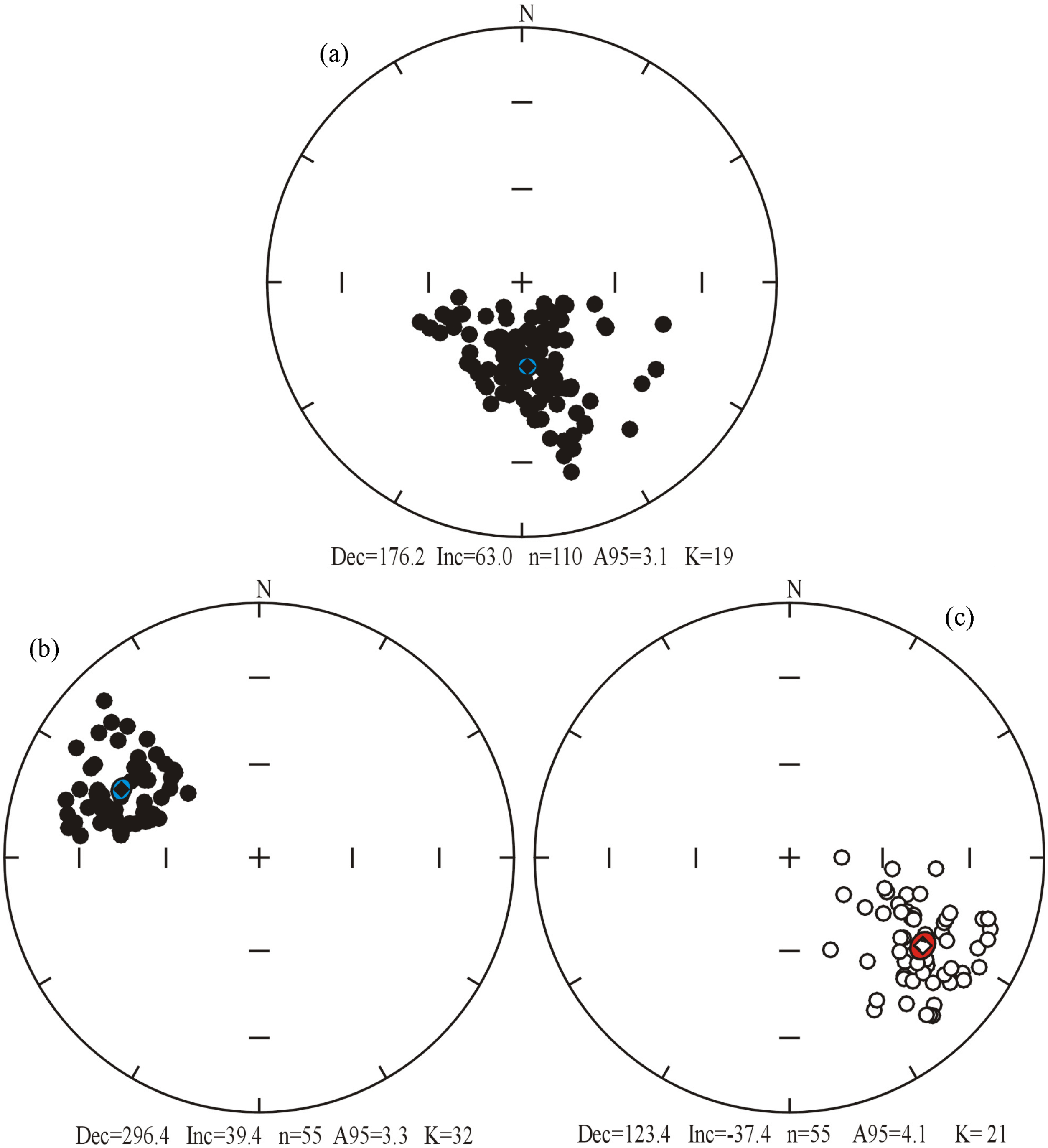

Figure 13. The distribution of the medium- and high-temperature magnetization components in random samples prior to using the new method. See Figure 11 for the legend. (A) is the medium-temperature component, (B) is the high-temperature component, N group, and (C) is the high-temperature component, R group.

adhering to certain conditions, the direction of the modern magnetization component in the cases where the conventional method fails to give a satisfactory result for the reasons mentioned above. The basic condition for using this new method is the availability of the results of the magnetic cleaning of the rocks of the same type and age, collected from natural outcrops and drill cores, and the proved identity of the NRM component composition of these rocks. In this case the cores should be oriented using the directions of the lines normal to the circles drawn via the directions of the old components, rather than the modern viscous component. The procedure of this work is as follows:

(1) chose two most representative magnetization components, found in the predominant number of the samples collected from natural outcrops: A1 and A2;

(2) compute the mean directions of these components: D_{A1}, I_{A1} and D_{A2}, I_{A2};

(3) compute the mean direction of the normal to the large circle drawn via these average D_n and I_n directions;

(4) compute the direction of a normal to the large D_{ni}, I_{ni} circle drawn via the similar $A1_i$ and $A2_i$ components;

(5) compute the inclination difference $\Delta_i = D_n - D_{ni}$ between the average direction of the D_n, I_n normal and the direction of the normal for each ith core sample D_{ni}, I_{ni};

(6) add the computed Δ_i value to the inclinations of all components which have been identified in the ith sample.

This procedure allows one to compare the reconstructed distributions in the drill cores and in the natural outcrops for several magnetization components simultaneously.

The correctness of this method is based on the following statement: if the application of this method for the distributions obtained in natural outcrops does not modify the average directions of the magnetization components within an error, this method can be used for similar components identified in core samples.

In order to verify this statement, a new approach was used to process the data (B and Z components distribution) obtained in the Zolotitsa River area. The processing procedure consisted of the following steps:

1. the computation of the D_n, J_n normal to the large circle drawn via the average directions of the B and Z components (Table 1);

2. the random selection of 55 samples showing the direct polarity of the Z component (N group) and 55 samples showing the inverse polarity (R group), Figure 13;

3. the chosen vector samples were processed using the above technique and the B and Z components, Figure 14;

4. the average directions and statistical parameters of the B and Z components, as well as the angle δ between these average directions, were computed for the N and R groups prior to and after using this method;

5. 5, 10, ... 50 random samples were discarded from the N and R groups, and the computations mentioned in item 4 were repeated (Figure 15);

6. the operations mentioned in items 2 to 6 were repeated tens of times. Figure 15 presents two examples of this operation.

As can be seen in Figure 15, the differences between the average δ directions prior to and after the use of this method for all data samples, up to the diminishing the number of samples to 5 in each group, are not greater than the angle of confidence α_{95} for each data distribution, both for the B and Z components. This proves the correctness of using this new method.

The magnetization components recorded in the borehole section and oriented using this method showed a compact distribution pattern (see Figure 16). The average directions of these components and their statistical values are close to the respective values obtained for the area of the Zolotitsa River (see Figures 11 and 16 and Tables 1 and 2). The bipolar Z component showed a positive reversal test of the B class [*McFadden and McElhinny,* 1990]. The palaeomagnetic poles computed for these two directions also showed a good agreement with the results obtained for the collection of samples from the Zolotitsa River area (Table 3).

Table 2. Mean Palaeomagnetic directions from Upper Vendian rocks of Verkhotina core-drill

Component	N	D	I	K	α_{95}	Test
B	322	164.8	71.5	12.1	2.3	
Z(N)	198	305.4	39.1	14.5	2.8	
Z(R)	124	125.9	−31.4	14.0	3.7	
Z = Z(N) + Z(R)	322	305.0	35.9	13.6	2.2	R+(B)

B/Z – name of component in the text, (N)/(R) – normal/reversed polarity, N – number of samples included in statistics, D/I – mean declination/inclination, K/α_{95} – precision parameter/percent confidence circle, R+ – positive reversal test.

Magnetic Stratigraphy

Variations in the declination and inclination of the Z component along the rock sequences of the Zolotitsa River area and the Verkhotina Hole and the respective magnetic zoning are shown in Figures 17 to 19. The ten outcrops, where samples were collected along the Zolotitsa River, were subdivided conventionally into two parallel profiles (Figure 17). This figure shows that similar magnetic zones can be located in different outcrops situated at significant distances from one another. For instance, the lowest zone of direct polarity was identified in the two limbs of a fold, with a distance of 10 m between them (see Section 7 and Section 7c in Figure 17). In this case it was very easy to determine the exact stratigraphic position of each rock sample, because the marking beds of different colors could be easily traced in the outcrops throughout the strike of the rocks. A similar zone of direct polarity was identified in the upper part of outcrop 10 located at a distance of 5 km from outcrop 7 (see Section 10 in Figure 17). Two zones of inverse and direct polarity were located higher up the rock sequence in three outcrops spaced 2.5 km apart (see Section 7, Sections 8a, 8b, and 8c, and Section 9 in Figure 17). The primary origin of the Z component was also proved by a correlation test [*Opdyke and Channell,* 1994]. The combination of the two parallel profiles for the Zolotitsa River section is shown in Figure 18. The Zolotitsa River rock sequence showed 9 zones of direct, 8 zones of reversed, and 2 zones of alternating polarity. These zones are numbered here using the data obtained for the lower stratigraphic levels in the Zimnegorsk outcrops [*Popov et al.,* 2002].

A similar pattern was observed in the rocks exposed by the Verkhotina Hole, see Figure 19. To sum up, the total

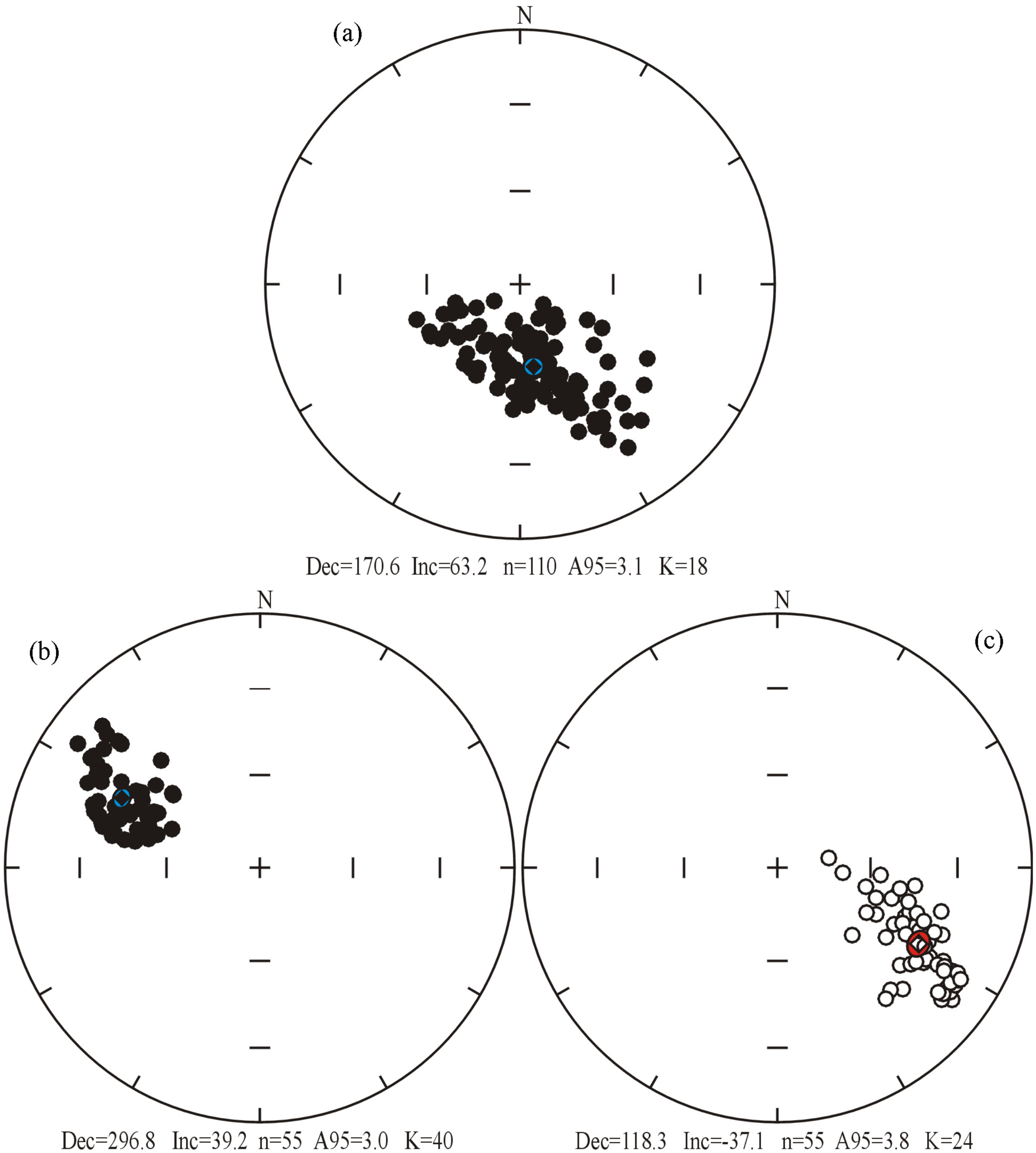

Figure 14. The distribution of the medium- and high-temperature magnetization components in random samples after to using the new method. See Figure 11 for the legend. (A) is the medium-temperature component, (B) is the high-temperature component, N group, and (C) is the high-temperature component, R group.

number of 27 zones of direct polarity and 28 zones of reversed polarity were identified using the Kotlin Horizon of the Upper Vendian to the Lower Cambrian rocks. The intervals of the same age of the polarity scale, plotted using the data obtained from the Zolotitsa River sections and from the hole showed good agreement (Figure 20), this justifying the conclusion that these rocks can be used for the magnetostratigraphic correlation of rock sequences.

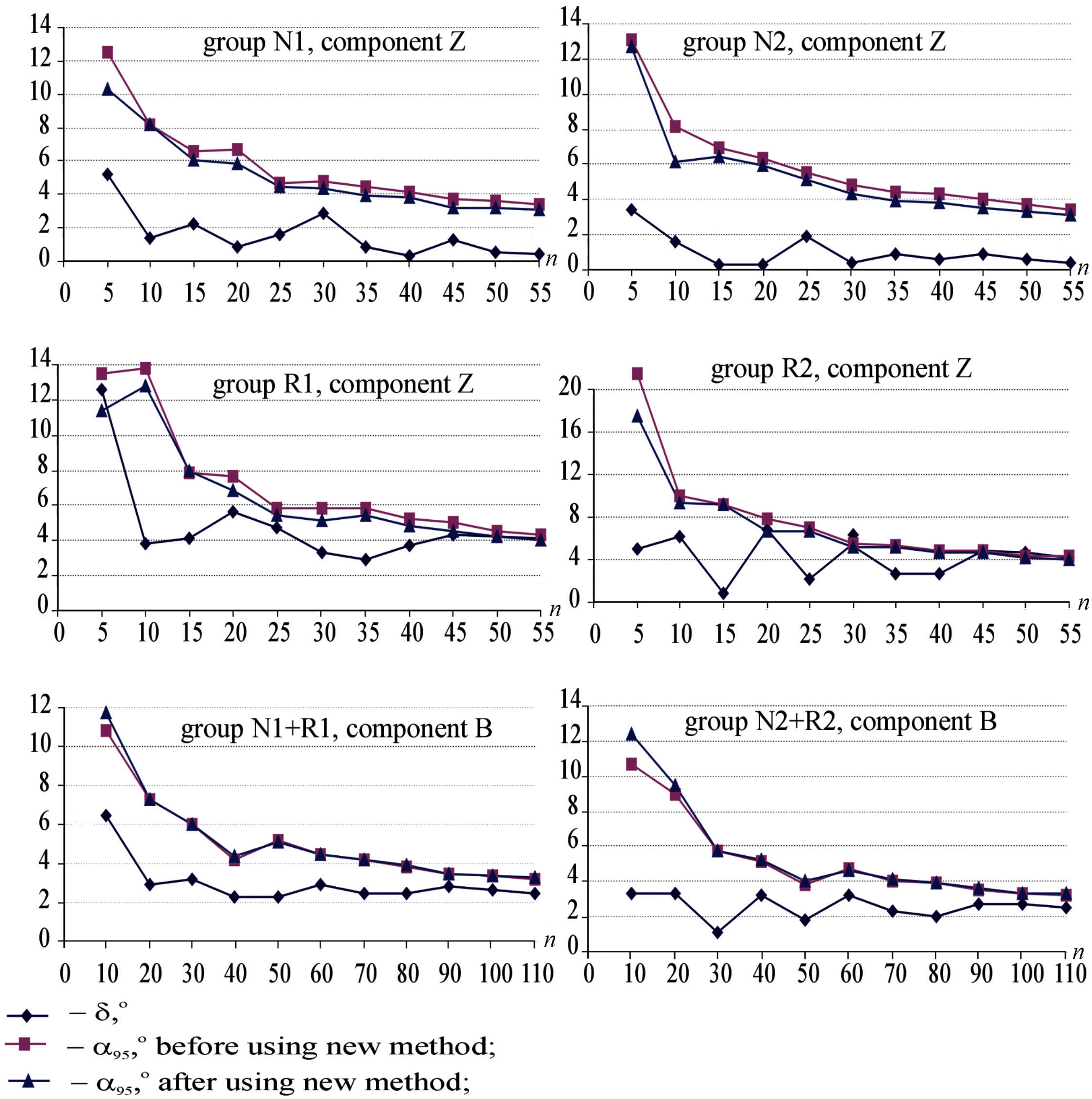

Figure 15. Variation of the δ angle between the average directions of the initial and final data distributions and the radii of the confidence circles (a_{95}) for these distributions as a function of the number (n) of samples in random sample collections. Groups N1 and N2 belong to the normal and R1 and R2, to the reversed polarity.

Discussion of the Results

As a result of studying the Late Vendian–Early Cambrian rocks in the Baltic region, we proved the multicomponent NRM composition (Table 3, Figure 21) and distinguished three main components of the rock magnetization. The palaeomagnetic poles corresponding to the B medium-temperature, synfolding component (poles 2 to 5 in Table 3 and Figure 21) reside in the area of the Baltic Ordovician

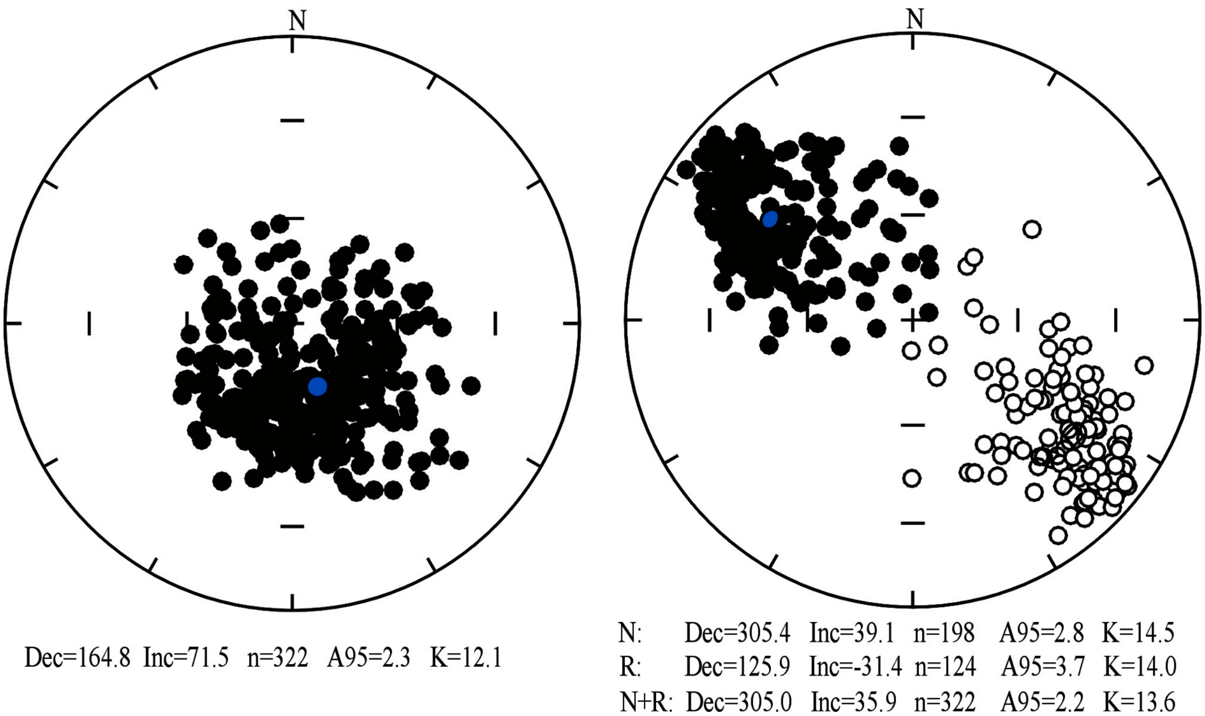

Figure 16. Distribution of medium- and high temperature magnetization components for the hole after the use of the new method. See Figure 11 for the legend.

Table 3. Palaeomagnetic poles for Later Proterozoic–Early Paleozoic rocks from Baltic

no.	Rock unit	Rock age Ma	Pos. Mag age Ma	B	N	Pole position °N	°E	dp°	dm°	References
1	Early Paleozoic (mean pole position)	475	475	4		28.3	51.3	A_{95} = 10.5		[*Claesson,* 1978; *Perroud et al.,* 1992; *Smethurst et al.,* 1998; *Torsvik and Trench,* 1991a, 1991b]
2	Winter Coast seds., B	555.0±0.3	?*		232	40.0	79.0	2.0	2.3	[*Popov et al.,* 2002]
3	Zolotitsa seds., B	550.0±5.3	?*		286	25.8	44.2	2.5	3.0	This study
4	Verkhotina seds., B	550.0±5.3	?*		322	31.1	51.1	3.0	3.5	This study
5	Zolotitsa seds., B	550.0±5.3	?*		575	30.9	55.4	A_{95} = 2.7		[*Iglesias et al.,* 2004]
6	Zolotitsa seds., C	550.0±5.3	290*		39	−38.5	356.2	3.7	6.5	This study
7	Zolotitsa seds., Z	550.0±5.3	550.0±5.3		234	−31.7	112.9	1.6	2.7	This study
8	Zolotitsa seds., Z	550.0±5.3	550.0±5.3		57	−28.3	110.0	A_{95} = 3.8		[*Iglesias et al.,* 2004]
9	Verkhotina seds., Z	550.0±5.3	550.0±5.3		322	−32.2	107.1	1.5	2.6	This study
10	Winter Coast seds., Z	555.0±0.3	553.0±0.3		94	−25.3	132.2	2.3	3.7	[*Popov et al.,* 2002]
11	Alnon Complex	553±6	553±6	21	103	−7.6	92.0	4.7	9.3	[*Piper,* 1981]
12	Fen carbonatites	583±15	208–245*	19	19	63.0	142.0	3.1	4.3	[*Poorter,* 1972]
13	Fen tinguates	583±15	208–245*	20	144	50.1	143.9	4.9	7.9	[*Piper,* 1988]
14	Fen Central Complex	583±15	208–245*	6	55	56.0	150.0	7.0	10.0	[*Meert et al.,* 1998]
15	Later Proterozoic (mean pole position)	750	750	3		−28.1	17.3	A_{95} = 7.6		[*Bylund,* 1994; *Shipunov and Chumakov,* 1991; *Torsvik et al.,* 1995]

Note: Rock ages is done according authors, listed in References, except of entries 4, corrected according new data [*Roberts et al.,* 1997]. B is number of sites or beds sampled, N is number of samples included in statistics, dp, dm are semi-axes of 95% oval of confidence for pole, 11, 12, 13, 14 results taking from Global Palaeomagnetic Database, 1 and 15 additional published results, * – remagnetized.

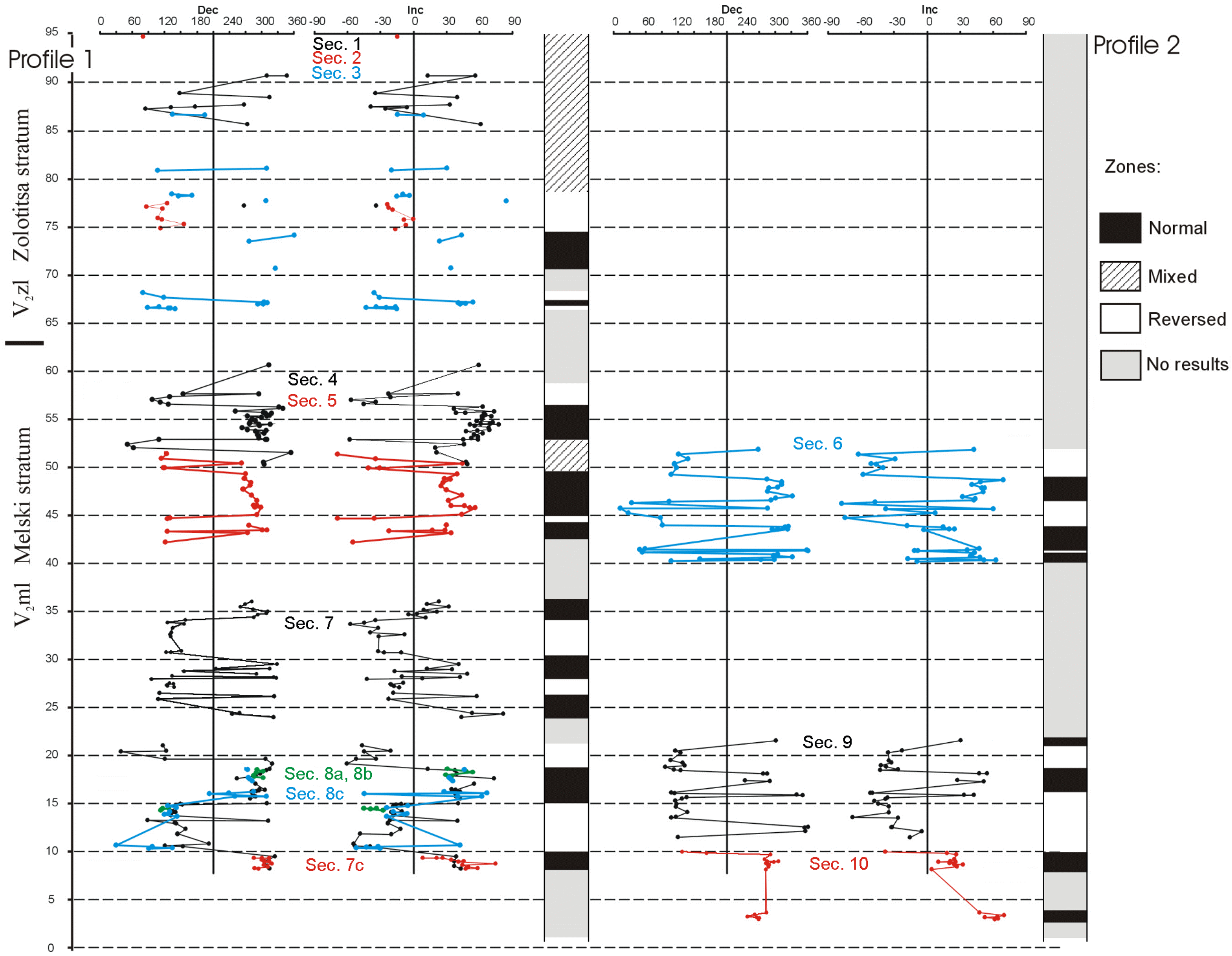

Figure 17. Changes in the declination (Dec) and inclination (Inc) of the Z component in different outcrops of the Zolotitsa River area and the respective magnetic zoning.

poles [*Smethurst et al.,* 1998; *Torsvik et al.,* 1996]. It would be logical to infer the Ordovician remagnetization of the rocks, yet, the age of this component is Cenozoic, as follows from the age of the folding. Moreover, the other medium-temperature component, namely, C, is a pre-folding and, hence, an older one, always showing high blocking temperatures, higher than those of the B component, has a positive fold test (pole 6 in Table 3 and in Figure 21), and shows a palaeomagnetic pole near the Permian segment of the trajectory of the apparent Baltic pole migration [*Iosifidi and Khramov,* 2002; *Smethurst et al.,* 1998; *Torsvik et al.,* 1996]. In this case the association of this component with Permian remagnetization looks fairly well substantiated. The palaeomagnetic poles calculated for the high-temperature prefolding bipolar Z component, which showed a positive reversal test (see poles 7 to 10 in Table 3 and in Figure 21), reside far from the migration path of the Baltic pole for the Phanerozoic, this fact, in turn, being another confirmation of the primary type of this component: it had not been associated with any remagnetization of the rocks. The poles calculated for the Z component place the Baltic region into the area of low to moderate northern latitudes. This position agrees with the palaeontological data available for the rich and variable Ediacarian fauna and with the presence of red rocks in the sequence, thus introducing substantial corrections into the reconstructions offered recently for the Late Vendian [*Torsvik et al.,* 1996, 2001].

Figure 21 shows new palaeomagnetic poles and a trajectory for the apparent migration of the Baltic palaeomagnetic pole [*Smethurst et al.,* 1998]. The polarity of the new de-

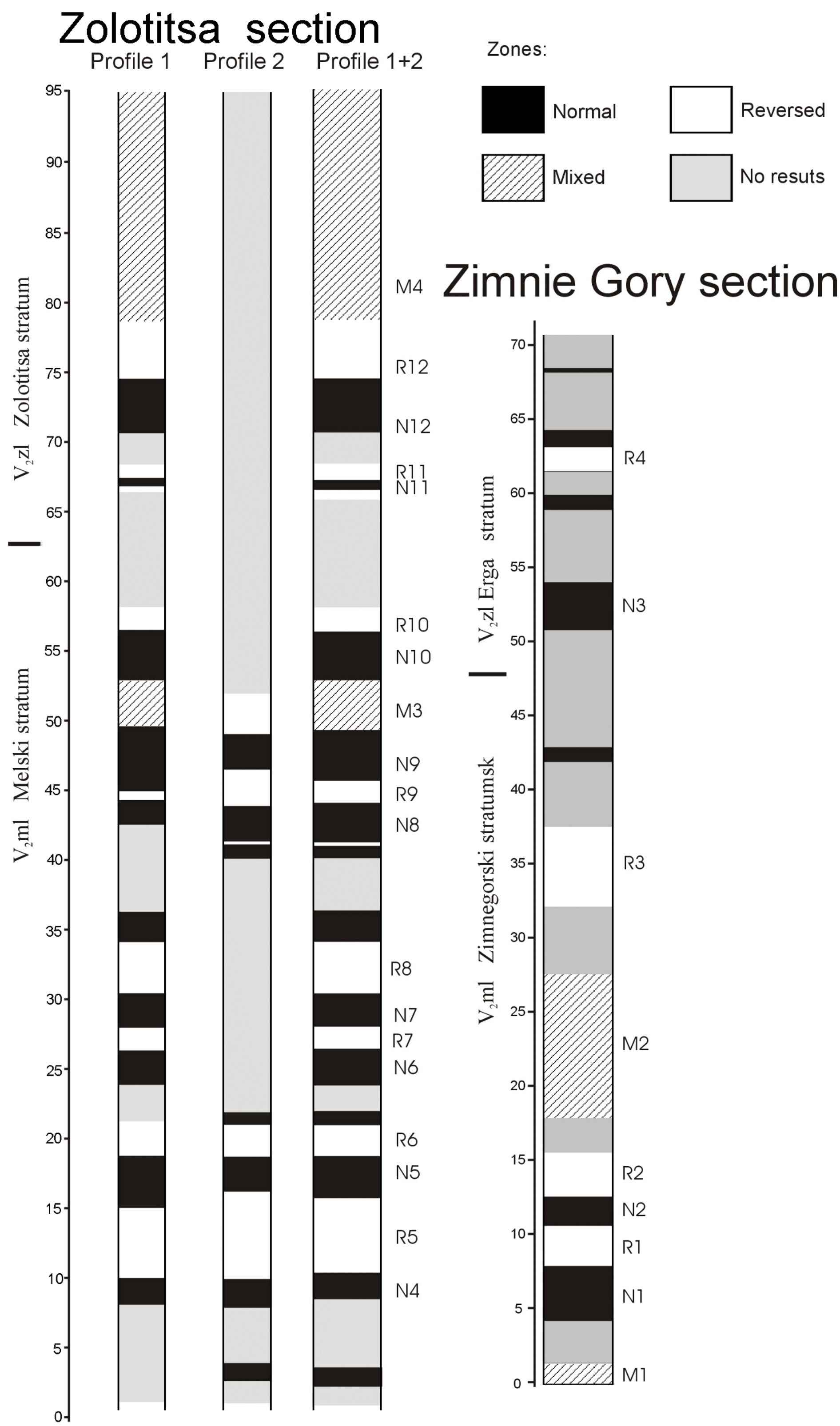

Figure 18. Magnetic zoning in two parallel profiles across the Zolotitsa River and in the Zimnii Gory rock sequence.

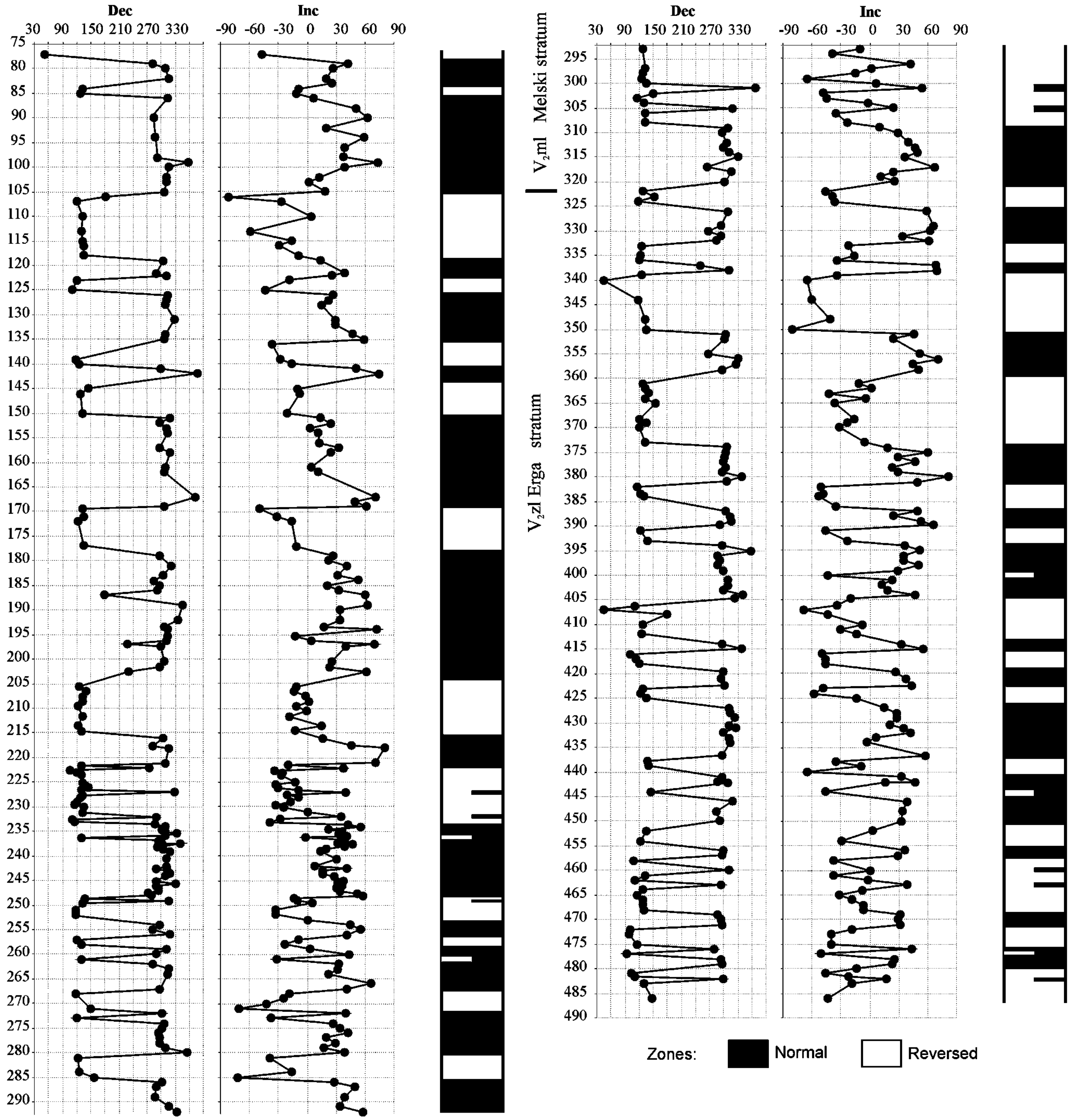

Figure 19. Changes in the declination and inclination of the Z component in the rocks penetrated by the Verkhotina Hole after the application of the new method, and the respective magnetic zoning.

terminations in this case was chosen proceeding from the principle of the minimization of absolute movements. Yet, the fact that the Laurentian northern poles of the same age [*McElhinny and Lock,* 1996, version 4.5; *Meert and Van der Voo,* 1994; *Torsvik et al.,* 1996] reside in the vicinity of a compact group of late Vendian poles for the Baltic region, obtained in our study and reported in [*Bylund,* 1994; *Iglesias et al.,* 2004; *Iosifidi et al.,* 2004], allows us to propose a dif-

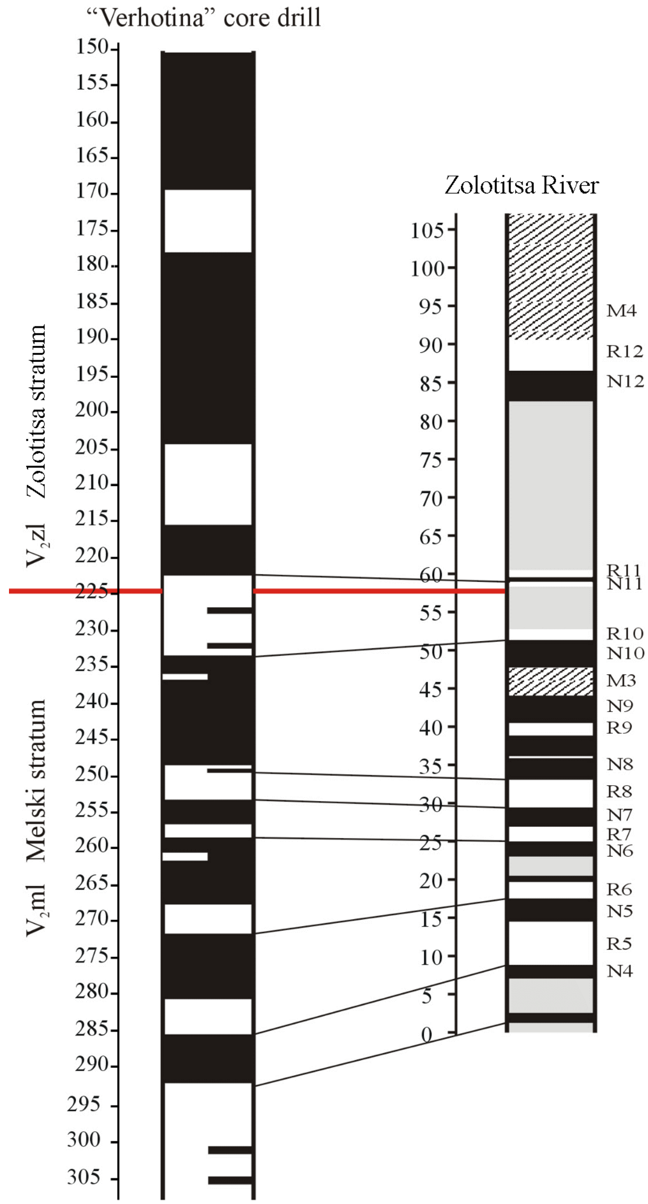

Figure 20. Correlation of the magnetostratigraphic rock sequences penetrated by the Verkhotina Hole and exposed by the Zolotitsa River.

ferent polarity. In this case we can reconstruct the palaeogeographic position of the Baltic region for the time interval concerned. Unfortunately, the data available for the Vendian time in the World Palaeomagnetic Data Base [*McElhinny and Lock,* 1996, version 4.5] are not sufficient for plotting any well-founded spline for the curve of the apparent migration of the Baltic palaeomagnetic pole in the Vendian time. For this reason we superposed the palaeomagnetic poles available for the Baltic Late Vendian rocks [*Torsvik and Smethurst,* 1999] with the respective segment of the curve for Laurentia [*Meert and Van der Voo,* 1994], see Figure 22. This figure shows the superposed Baltic and Laurentia southern poles for the time of 550 million years and the reconstruction of the positions of these two poles relative to one another, performed on the assumption that the palaeomagnetic pole for the Baltic region, $\Phi = 31.7°$S, $\Lambda = 112.9°$E, obtained for

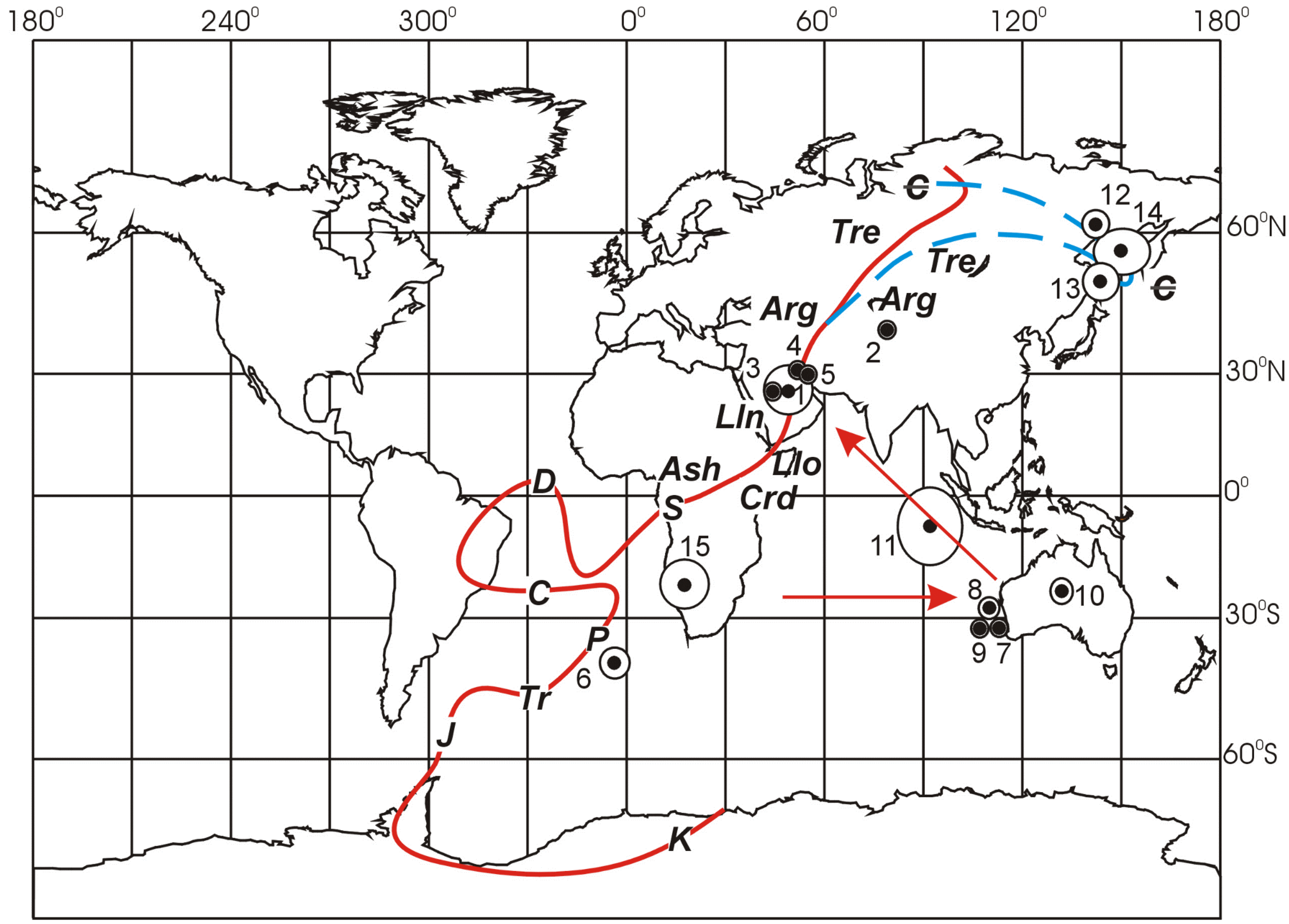

Figure 21. The apparent migration path of the Baltic palaeomagnetic pole after [*Smethurst et al.*, 1998], and the alternative poles for the time interval discussed.

the Zolotitsa River section and for some sections surveyed nearby, are the northern ones. This interpretation of the data available suggested that both plates had been located in the southern hemisphere: the Laurentia plate, between 10°S and 60°S, and the Baltic plate, between the equator and 40°S (Figure 22).

Conclusion

More than 800 samples, collected from natural outcrops and from drill hole cores were subjected to a complete cycle of palaeomagnetic studies. More than 400 m of the classical Late Vendian–Early Cambrian rock sequences were studied in the north of the Russian Platform. The rocks were dated using the Ediacarian fauna found in the Zimnegorsk outcrops and also using zircons found in the lower part of the Zolotitsa River section (550 Ma). The results of our study proved the multicomponent NRM composition. Two medium-temperature components, showing different blocking temperatures, were proved to have been associated with the different-age remagnetization of the rocks. The high-temperature bipolar component showed positive fold, reversal, and correlation tests. Its carrier was found to be hematite. 27 zones of the direct and 28 zones of the reversed polarity were located in the Kotlin Horizon of the Late Vendian–Early Cambrian rocks using the direction of this component. A new technique was offered and tested for orienting borehole cores in space. Its use allowed us to reconstruct the distribution of NRM components in the core samples. The resulting distributions coincided with the distributions obtained for natural outcrops. The high reliability of the resulting data makes it possible to introduce substantial corrections to the potential positions of the apparent migration path of the Baltic palaeomagnetic pole for Vendian-Cambrian time and to reconstruct the palaeogeographic positions of the Baltic and Laurentia for the investigated period of geological time.

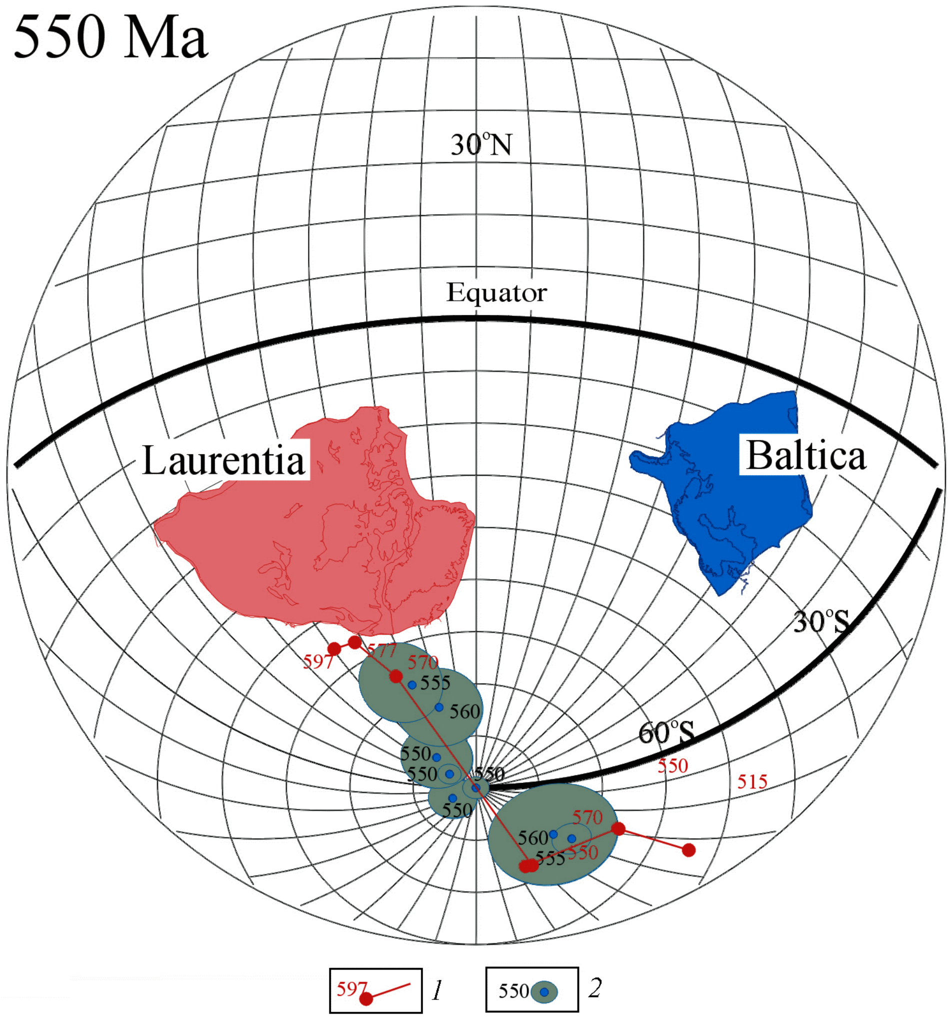

Figure 22. Reconstruction of the palaeogeographic positions of Baltic and Laurentia for the Vendian (550 Ma). See the text for explanations.

Acknowledgments. We are grateful to V. Butikov and E. Golubkova for their help in our field work done in the Zolotitsa River area, to T. Rumyantseva for the collection of core samples from the Verkhotina Hole, to Manuela Wise for performing VFTB experiments, and also to A. Iosifidi and D. Pechersky for his constructive comments and the discussion of this paper. This work was supported by the INTAS Foundation, project no. 97-1204, and by Program no. 5 of the Department of Earth Sciences, Russian Academy.

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(Received 15 March 2005)