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Paleomagnetism of Traps in the Podkamennaya Tunguska and Kotui River Valleys: Implications for the Post-Paleozoic Relative Movements of the Siberian and East European Platforms

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Abstract—New paleomagnetic results contributing substantially to the paleomagnetic database of the Siberian Permian–Triassic traps are obtained; based on these results, the position of the Permian–Triassic pole of the Siberian platform is determined with high accuracy. Comparison of the inferred pole with the apparent polar wander paths of Eastern Europe points to a significant convergence of the Siberian and East European platforms in the post-Paleozoic time, which is inconsistent with the available geological evidence. A more correct comparison with stratigraphically dated poles of "stable Europe" indicates that the available paleomagnetic data yield no evidence of the mutual motion of the Siberian and East European platforms in the post-Paleozoic time. Our results do not preclude possible relative movements of these cratonic blocks but place substantial limitations on their scale.

INTRODUCTION

The Siberian traps have recorded information (in the form of a paleomagnetic signal) on the position of the Siberian continent in the latest Paleozoic–earliest Mesozoic time. At that time, the formation of Pangea was accomplished, Eurasia and the Siberian continent converged, and the formation of Asia was still in progress, with the Tarim, North Chinese, and other structures being attached to the Siberian continent. Comparison between paleomagnetic data from traps of the Siberian platform and similar evidence from other crustal blocks enables the reconstruction of their mutual position at the Paleozoic/Mesozoic boundary and provides constraints on their subsequent movements.

The paleomagnetic study of Siberian traps started immediately after the origination of paleomagnetology. Apparently, the Siberian Permian–Triassic traps surpass all other geological formations of Siberia in the amount of paleomagnetic determinations. These investigations were most extensive in the late 1960s and early 1970s, when paleomagnetic results were obtained from traps of the Taimyr and Maimecha–Kotui regions [Gusev *et al.*, 1967; Gusev, 1968], the Norilsk region [Davydov and Kravchinsky, 1965; Lind, 1973], the Nizhnyaya Tunguska and Podkamennaya Tunguska regions [Davydov and Kravchinsky, 1971], the southern and western Siberian platform [Davydov, 1964; Fainberg and Lind, 1965; Fainberg and Dashkevich, 1960; Fainberg, 1960; Gusev *et al.*, 1967], and other regions.

In those years, sample collections were not subjected to treatment by the methods and techniques that are presently regarded as obligatory (extensive cleanings of collections, complete and detailed demagnetization of samples, the use of PC analysis [Kirschvink, 1980] in the identification of magnetization components, and others).

The significant modifications in instrumentation and paleomagnetic methods that took place in the 1980s–1990s, as well as more stringent requirements on the quality of paleomagnetic determinations, made it relevant to refine, substantiate, and partially revise results obtained previously.

Presently, a large amount of recent data has been accumulated from the majority of continental blocks defining the present tectonic structure of Asia. These data are of great importance for understanding the tectonic evolution of the Eurasian continent, and their adequate interpretation is critically dependent on the availability of a reliable Permian–Triassic paleomagnetic pole of Siberia, which relies on an up-to-date methodological and instrumental base.

The goal of this work is precisely the localization of the Permian–Triassic paleomagnetic pole of the Siberian platform with high accuracy in accordance with current paleomagnetic criteria.

This work is the third in the series of our papers devoted to the creation of a modern paleomagnetic database related to Permian–Triassic subvolcanic bodies and, in part, flows outcropping within the Tunguska

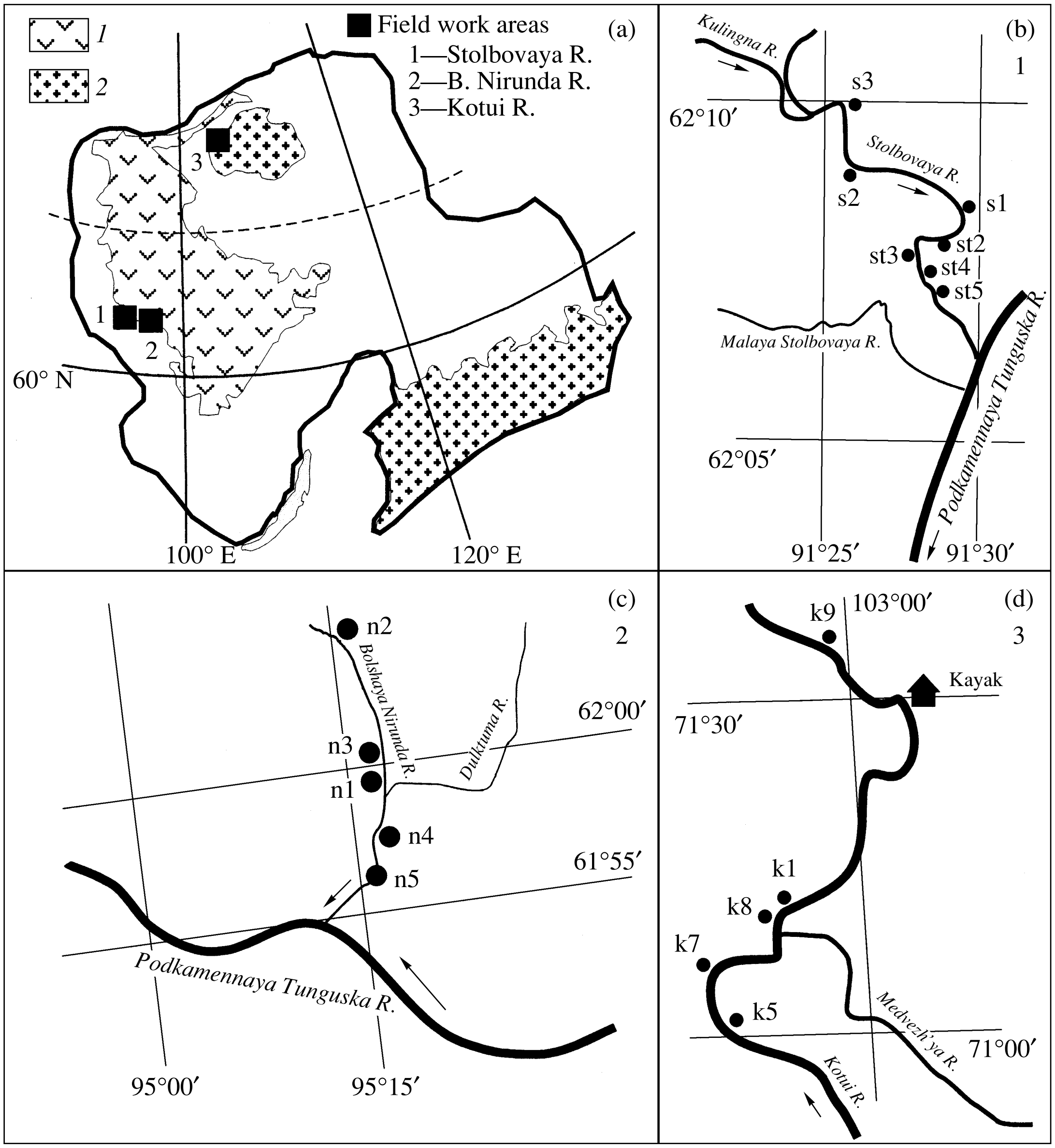

Fig. 1. Geographical position of the (a) field work region and (b–d) sampling sites (magmatic bodies and outcrops): (*1*) main occurrence area of Permian–Triassic trap formation rocks of the Siberian platform; (*2*) main outcrops of the Early Proterozoic– Archean basement of the Siberian platform.

syneclise and its adjacent areas. This paper presents results of paleomagnetic studies of traps in the lower Kotui River valley (adjacent to the Anabar Plateau in the west), as well as traps and sedimentary rocks magnetized by them on the southern and southwestern slopes of the Tunguska syneclise that were sampled in the valleys of the Bolshaya (B.) Nirunda and Stolbovaya rivers (tributaries of the Podkamennaya Tunguska River).

Previously, we presented results of trap studies in the Moiero River valley (bordering the Anabar Plateau to the south) [Kamenshchikov *et al.*, 1996] and in the western Norilsk region [Pavlov *et al.*, 2001]. Kravchinsky *et al.* [2002] reported similar data on rocks of the eastern periphery of the Siberian trap occurrence area. Results from the volcanic–sedimentary trap sequence composing the Putorana Plateau will be published by Gurevich *et al.* [in press]. Synthesis of these data will make it possible to localize the Permian–Triassic paleomagnetic pole of the Siberian platform with high accuracy, determine the position of Siberia in the system of paleogeographical and paleotectonic reconstructions at the Paleozoic/Mesozoic boundary, and gain new constraints on the development history of the Eurasian continent.

ROCKS STUDIED

In our field work of 2000, we sampled nine trap sills and flows outcropping over 50 km along the lower Kotui River valley (Fig. 1d). Similarly to the majority of other trap formations of the Siberian platform, the bodies sampled are composed of basic rocks (basalts, gabbroids, and dolerites). Their primary bedding is in places disturbed by vertical movement of blocks that occurred here after the trap intrusion. Their attitude elements were determined from the bedding of host rocks, and in the case of flows they were measured on the flow surfaces. In the latter case, the attitude determination accuracy was no better than 8°–12° due to significant irregularities of the flow surfaces. Taking into account the low quality of the paleomagnetic signal in these flows and the obviously nonsystematic differences between determinations in the stratigraphic and geographic coordinates, we eliminated these rocks from our paleomagnetic analysis.

In the summer of 2001, we conducted magnetostratigraphic studies of Middle–Upper Ordovician reference sections in the valleys of the B. Nirunda and Stolbovaya rivers; these sections are composed mostly of greenish gray carbonate–clay rocks. The position of the study outcrops is shown in Figs. 1b and 1c. They were sampled upward along the section at a step of 0.5–1 m. At the same time, in order to assess the influence of potential bodies capable of overprinting the primary paleomagnetic signal in the Ordovician rocks, we examined large (a few kilometers in diameter) hypabyssal doleritic intrusions outcropping in the mouth areas of these rivers. The Nirunda intrusion was sampled at a single point, and the Stolbovaya intrusion, at four points a few hundred meters apart. Eight to twelve oriented samples were taken at each point. Laboratory studies of the sedimentary rocks composing the Ordovician section of the B. Nirunda and Stolbovaya rivers showed that all these rocks have been completely remagnetized by traps. We used the trap magnetization component identified in these rocks for calculating average Permian–Triassic paleomagnetic directions. The sedimentary rocks of the Stolbovaya River valley occur nearly horizontally. The generally subhorizontal occurrence of the B. Nirunda sediments is somewhat disturbed in the outcrops studied: beds dip there at small angles (up to 10°–12°) in various directions. Silurian and Early Devonian rocks conformably overlie Ordovician beds, and younger (except for Late Cenozoic) rocks are absent in the region. Thus, based on the available data, the folding age cannot be determined more accurately than as the Early Devonian.

PALEOMAGNETIC ANALYSIS

Method

Paleomagnetic laboratory studies and data preprocessing were carried out at paleomagnetic laboratories of the UIPE (Moscow) and the IPGP CNRS (Paris) using conventional methods [Zijderveld, 1967; Khramov, 1982; Shipunov, 1999; Collinson, 1980; Kirschvink, 1980; McFadden, 1988; McFadden and McElhinny, 1990; Enkin, 1994; Torsvik *et al.*, 1990].

All samples were subjected to detailed thermal demagnetization, as a rule, to temperatures of 580–600°C. The number of demagnetization steps was typically no less than 10–11 and occasionally larger. Special nonmagnetic furnaces with an uncompensated field of no more than 5–10 nT were used for the demagnetization of the samples. The remanent magnetization was measured with a 2G Enterprises cryogenic magnetometer and a JR-4 torque magnetometer. Magnetization was measured in a space screened from the external magnetic field. The measured data were processed with the use of Enkin's software [Enkin, 1994] implementing the PCA method for identifying magnetization components [Kirschvink, 1980].

Identification of Magnetization Components

Kotui River. Overall, the quality of the paleomagnetic record in the trap bodies studied in the lower Kotui River valley is poor. The temperature demagnetization of many samples yields a very noisy or chaotically varying signal that precludes the identification of the existing magnetization components and the determination of their directions. Fortunately, this relates primarily to the bodies whose attitude elements could not be determined with the required accuracy (see above). For this reason, we eliminated these data from the further analysis.

The remaining five bodies yielded evidence that characteristic magnetization components of normal (samples k1, k7, and k8) and reversed (k5 and k9) polarities are present. These are the most stable (often single) components destroyed in the interval 300–600°C (Figs. 2a–2d). Sometimes, a low-temperature component removed at 200–400°C is observed; probably, it is a superposition of the natural recent and laboratory viscous components of magnetization. The presence of normal and reversed polarity vectors enables the application of the reversal test. Unfortunately, due to a limited number of bodies, we could not apply this test at the level of their averages; however, a qualitatively reasonable result can be obtained by comparing the distributions of individual vectors of normal and reversed polarities. The distribution of these vectors obtained from five bodies is shown in Fig. 2j. Although confidence ovals of the averages overlap after their reduction to a single polarity (D = 296.2°, I = –69.0°, N = 17, K = 53.3, α_{95} = 4.9° and D = 105.7°, I = 78.2°, N = 10, K = 69.5, α_{95} = 5.8°), the test of McFadden and McElhinny [1990] indicates that the inferred directions are statistically (at a 95% confidence level) different. The angle between these directions is 9.6°, whereas its critical value is 7.6°. However, the average directions of the normal and reversed polarities are nearly antipodal, and the negative result of the reversal test is most natu-

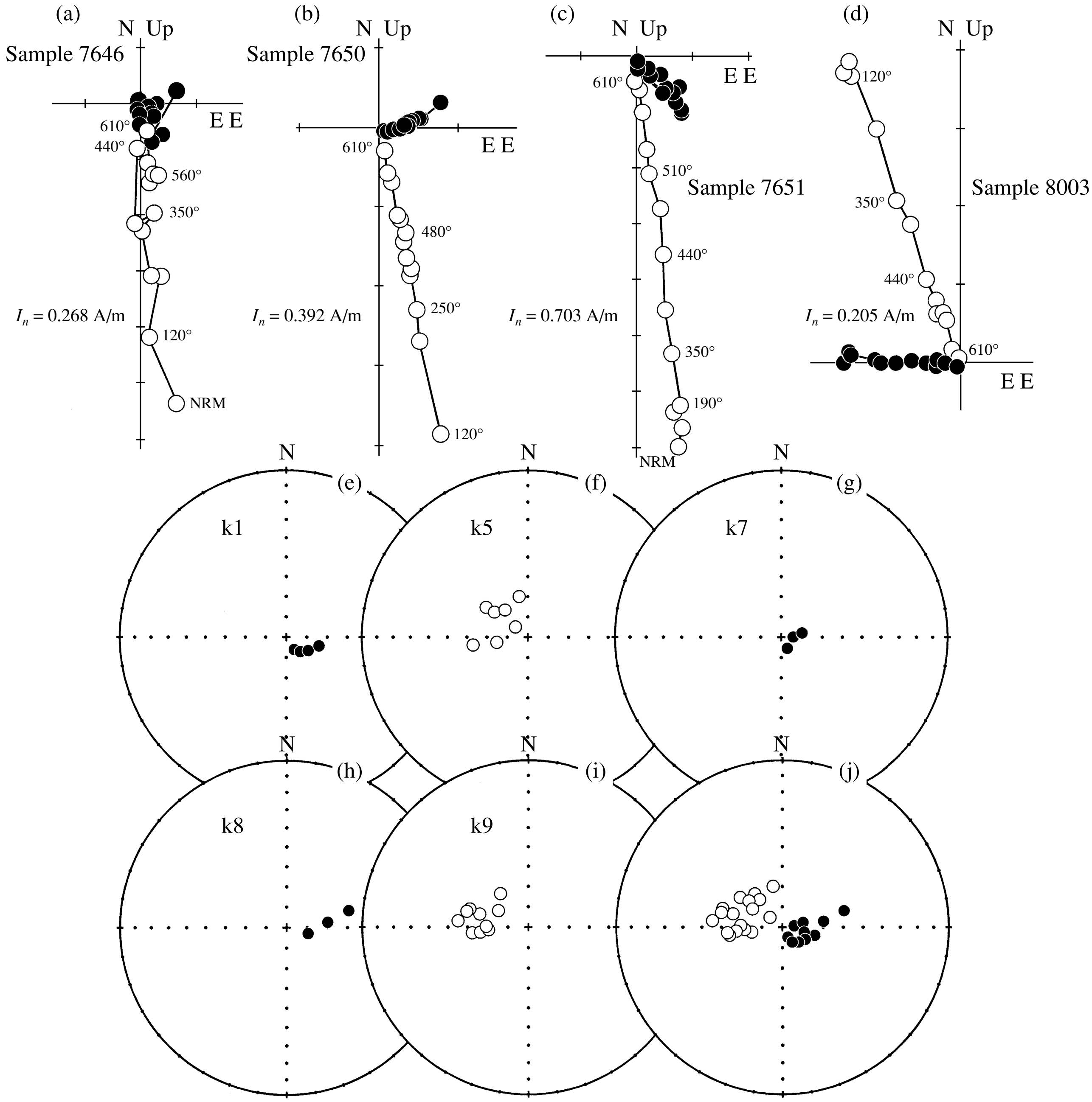

Fig. 2. Rocks studied in the Kotui River valley: (a–d) Zijderveld diagrams demonstrating the NRM variation patterns in samples during their thermal demagnetization; (e–i) stereograms showing the distributions of characteristic magnetization vectors in the rocks studied; (j) stereogram summarizing the distributions of characteristic magnetization vectors in the rocks studied. The solid and open circles in the Zijderveld diagrams (stereograms) are, respectively, vector projections onto the horizontal plane (lower hemisphere) and the vertical plane (upper hemisphere).

rally accounted for by the incomplete removal of the recent magnetization component by the demagnetization procedure. Since the difference between average directions reduced to one polarity is small, we may expect that the average direction obtained by averaging data over samples magnetized normally and reversely will differ from the actual direction by no more than 1°–3°.

Stolbovaya River. *Magmatic body.* The thermal demagnetization of samples revealed the presence of a distinct paleomagnetic signal produced by superposition of two (Fig. 3c), three (Figs. 3a, 3b, and 3d), or four (Figs. 3e and 3f) magnetization components. The first, least stable component is destroyed upon heating to 200–250°C or earlier and is a combination of the natural recent and laboratory viscous overprints, as is evi-

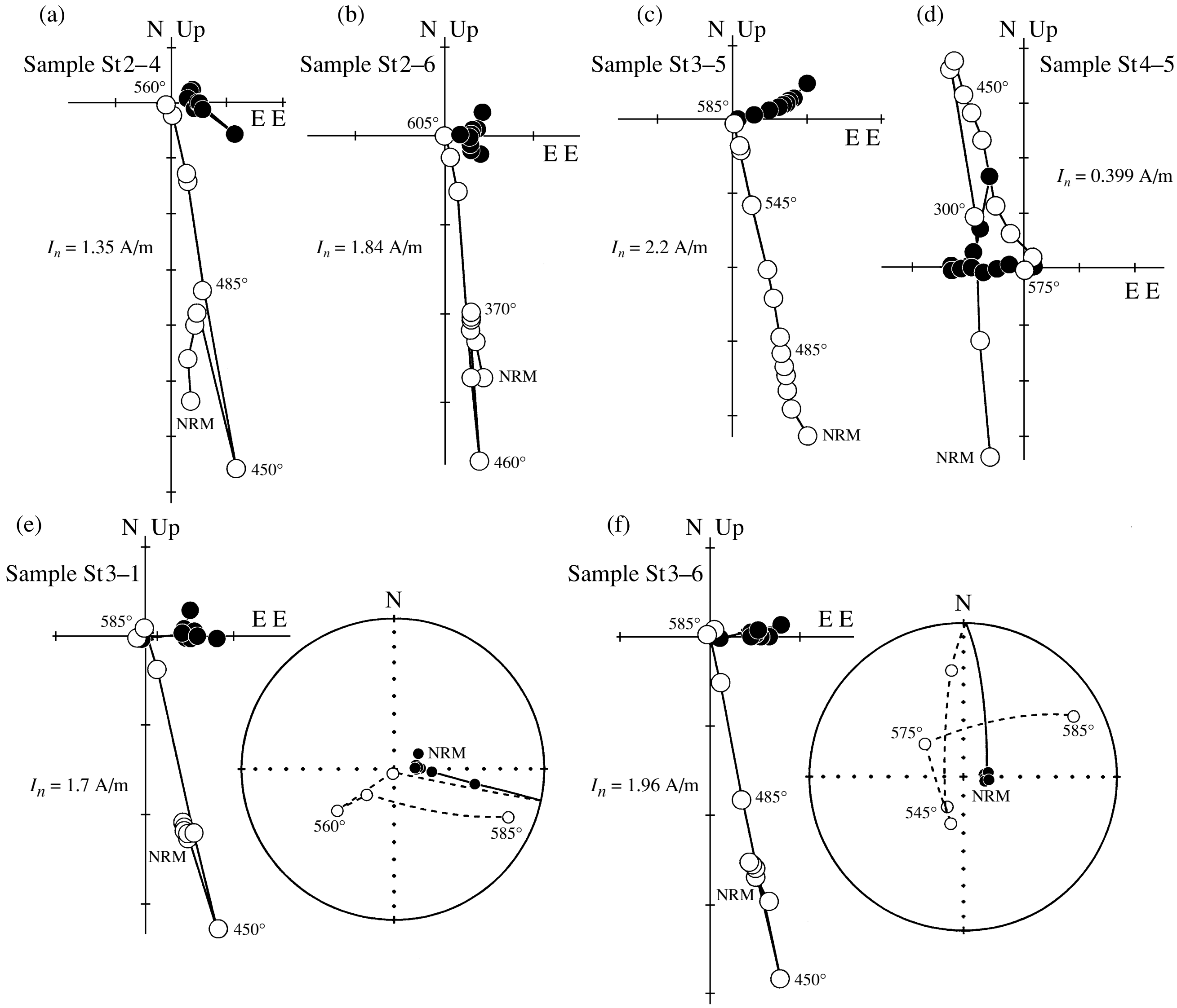

Fig. 3. Zijderveld diagrams and stereograms from a trap body in the Stolbovaya River mouth. The symbols are explained in Fig. 2.

dent from the stereographic vector distribution of this component. This distribution is characterized by a large scatter of vectors, with an average direction close to the direction of the present dipole field (D = 25.9°, I = 76.7°, K = 14.9, α_{95} = 7.3°, N = 28). This component is virtually unrecognizable in several samples, in which cases the two-component Zijderveld diagrams degenerate into one-component diagrams.

The second, medium-temperature component (MTC) has in various samples either normal (Fig. 3d) or reversed (Figs. 3a, 3b, 3e, and 3f) polarity. This component is removed in the interval 300–450°C, although it is traceable in the Zijderveld diagrams of some samples from outcrop st5 as a small loop in the interval 150–300°C.

The third, high-temperature component (HTC1) also can have either normal (Figs. 3a, 3b, 3e, and 3f) or reversed (Fig. 3d) polarity. Its interval of unblocking temperatures is 450–580°C.

Finally, several samples show traces of the fourth, likewise high-temperature, component (HTC2; see Figs. 3e and 3f). This component has the reversed polarity and is removed in the interval 540–580°C.

Examination of the Zijderveld diagrams gives an impression of closeness between all inferred components (except for the low-temperature one). This is supported by comparison of average directions calculated for each of the components (Fig. 4f). Such closeness implies that the components in question are of nearly the same age. This conclusion is confirmed by comparing the average directions of the normal and reversed polarity vectors (Fig. 4e) calculated for all stable components (D = 102.2°, I = 81.8°, K = 343.1, α_{95} = 5.0°, N = 4 and D = 280.7°, I = –74.4°, K = 143.8, α_{95} = 7.7°,

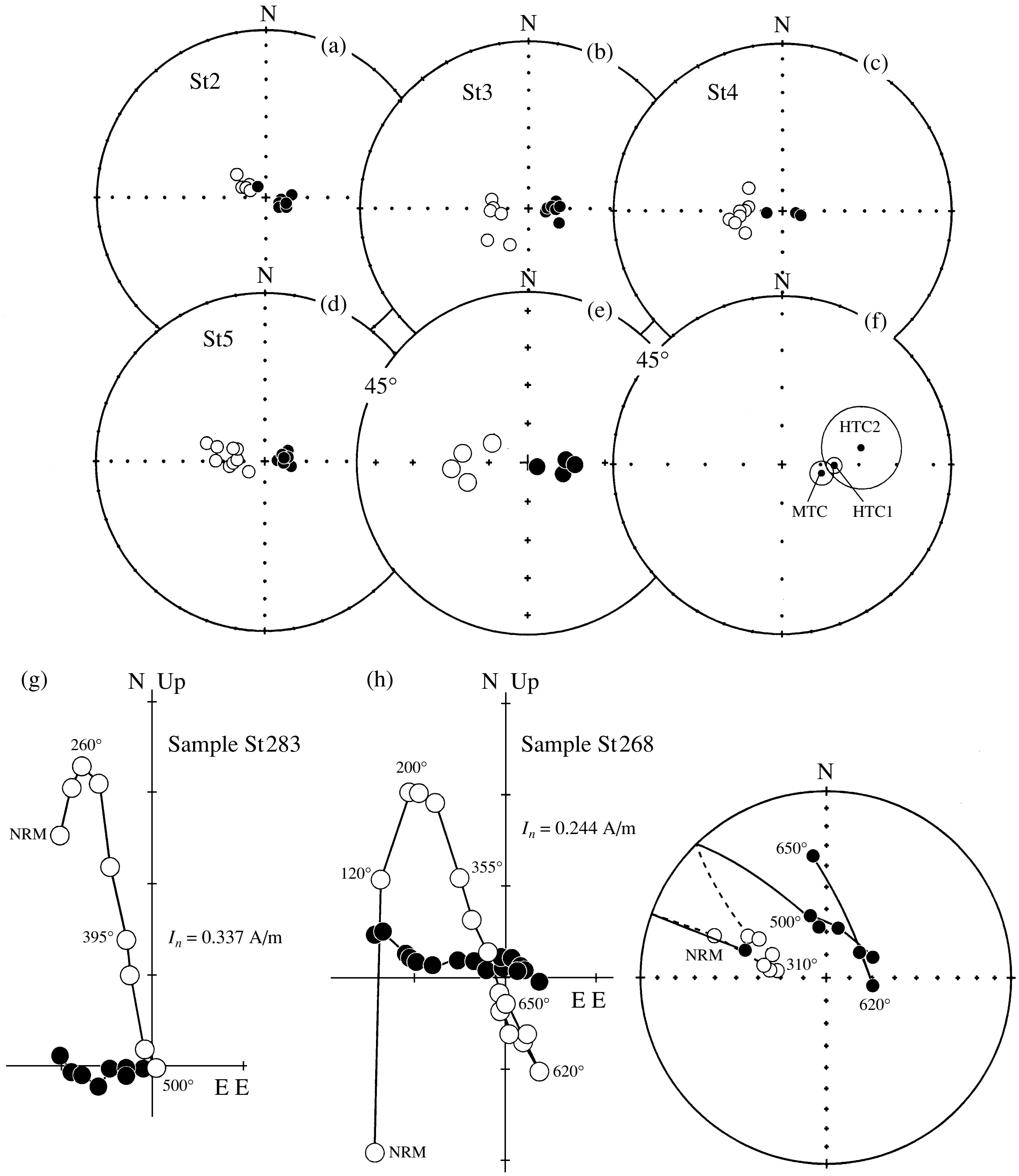

Fig. 4. A trap body in the Stolbovaya River mouth: (a–d) stereograms demonstrating the distributions of the characteristic component vectors at the sampling points studied; (e) distribution of the high- and medium-temperature magnetization components calculated for each sampling point separately; (f) comparison of average directions of the MTC, HTC1, and HTC2 components (the averaging was performed over the entire trap body studied). (g, h) Zijderveld diagrams and a stereogram from sedimentary rocks of the Stolbovaya River valley. The symbols are explained in Fig. 2.

N = 4). Upon the reduction to a single polarity, the difference between these averages becomes statistically insignificant (γ/γ_c = 7.4°/8.0°). Calculating the average directions, we used the most stable magnetization components from the outcrop studies (see the discussion below). Moreover, the vector calculated from all stable components is virtually indistinguishable from the vector obtained with the use of the most stable component.

Sedimentary rocks. With the exception of redbeds of the Kirenskii–Kudrinskii horizon, which yield evidence of an Ordovician magnetization component, all the other study sediments of the Stolbovaya section either record an irregular or chaotic signal or are completely remagnetized. In the latter case, their natural remanent magnetization (NRM) typically consists of two magnetization components, less stable (recent) and

Table 1. Paleomagnetic directions

Sampling site	N	Geographic coordinates				Stratigraphic coordinates			
		D, deg	I, deg	K	α_{95}, deg	D, deg	I, deg	K	α_{95}, deg
B. Nirunda River (sedimentary rocks, overprinting component)									
n1	61	276.0	–73.7	29.5	3.4	262.2	–77.9	55.0	2.5
n2	17	271.4	–63.9	90.4	3.8	260.7	–83.4	80.1	4.0
n4	9	257.1	–43.6	73.0	6.1	261.4	–70.0	81.9	5.7
Average	**3**	**265.1**	**–60.7**	**25.4**	**25.0**	**261.5**	**–77.1**	**144.8**	**10.3**
B. Nirunda River (magmatic body)									
n5	9	271.5	–72.6	225.2	3.4	271.5	–72.6	225.2	3.4
B. Nirunda average (sedimentary rocks+magmatic body)	**4**	**266.2**	**–63.7**	**31.2**	**16.6**	**264.6**	**–76.0**	**177.7**	**6.9**
Stolbovaya River (sedimentary rocks, overprinting component)									
s1	6	267.3	–70.5	215.9	4.6	267.3	–70.5	215.9	4.6
s2	6	247.4	–70.7	97.5	6.8	247.4	–70.7	97.5	6.8
s3	30	245.8	–74.0	59.0	3.4	245.8	–74.0	59.0	3.4
Average	**3**	**254.0**	**–72.0**	**362.1**	**6.5**	**254.0**	**–72.0**	**362.1**	**6.5**
Stolbovaya River (magmatic body)									
St 2	6	97.8	79.9	775.1	2.4	97.8	79.9	775.1	2.4
St 3	8	89.4	78.4	485.7	2.5	89.4	78.4	485.7	2.5
St 4	5	263.3	–71.0	275.5	4.6	263.3	–71.0	275.5	4.6
St 5	8	86.5	80.2	539.6	2.4	86.5	80.2	539.6	2.4
Average	**4**	**88.2**	**77.4**	**320.8**	**5.1**	**88.2**	**77.4**	**320.8**	**5.1**
Stolbovaya average (sedimentary rocks+magmatic body)	**4**	**76.7**	**74.1**	**201.8**	**6.5**	**76.7**	**74.1**	**201.8**	**6.5**
Kotui River traps									
k1	4	129.3	78.8	254.9	5.8	129.3	78.8	254.9	5.8
k5	7	309.4	–73.0	46.4	9.0	309.4	–73.0	46.4	9.0
k7	3	102.3	83.8	238.0	8.0	102.3	83.8	238.0	8.0
k8	3	167.1	49.5	51.7	17.3	89.6	69.5	51.9	17.3
k9	10	289.7	–65.8	81.7	5.4	289.7	–65.8	81.7	5.4
Average	**5**	**137.4**	**72.0**	**25.2**	**15.5**	**111.0**	**74.7**	**88.9**	**8.2**

more stable (characteristic) ones (Fig. 4g). The less stable component is destroyed at temperatures of up to 250–340°C, whereas the maximum unblocking temperatures of the characteristic component typically lie within the interval 500–530°C but can occasionally approach the T_c values of magnetite and hematite. The average direction of the characteristic component is close to the paleomagnetic directions obtained from trap bodies (see Table 1) and is absolutely dissimilar to the expected Ordovician direction [Pavlov and Gallet, 1998; Smethurst *et al.*, 1998], unambiguously indicating that the recorded characteristic component is coeval with the trap intrusion. It is interesting to note that two stable components of opposite polarities and similar directions (Fig. 4h) are obtained from outcrop s1, which is closest to the trap body studied in the Stolbovaya River valley.

Bolshaya Nirunda River. *Magmatic body.* The NRM of the samples studied includes two components (Fig. 5a). The first component is close in direction to the present field and is destroyed in the interval 100–250°C; the second, characteristic component has the reversed polarity, and its unblocking temperatures lie in the T_c interval of magnetite. The vectors corresponding to this component in the stereogram group in the high-inclination area (Fig. 5h).

Sedimentary rocks. The NRM of the sedimentary rocks sampled in the B. Nirunda River valley is similar in its behavior during the thermal demagnetization to the NRM of sedimentary rocks from the Stolbovaya section. The majority of the study samples yielded evidence indicating the presence of two magnetization components, recent (low-temperature) and characteristic; the latter has a high negative inclination and is

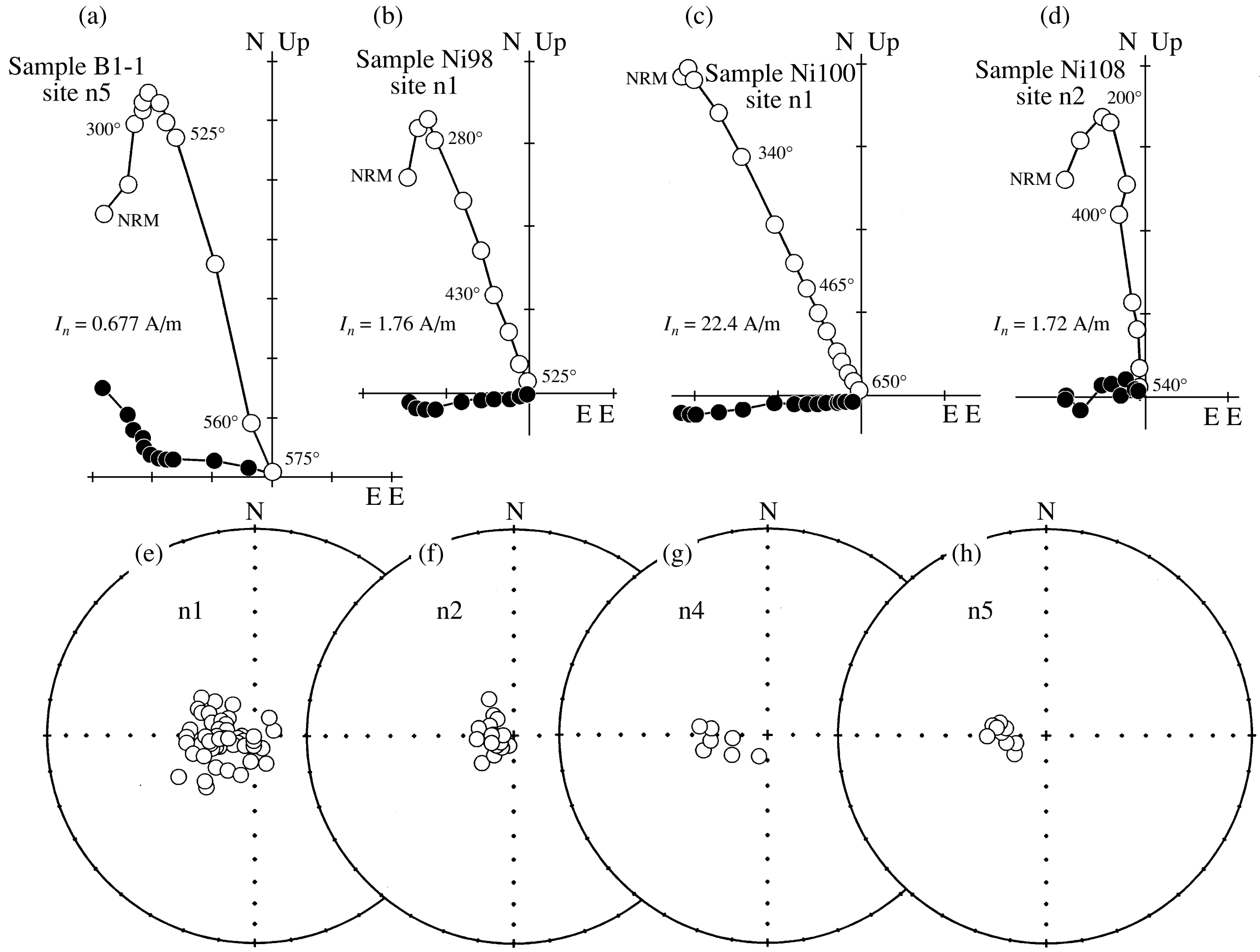

Fig. 5. Rocks studied in the B. Nirunda River valley. The Zijderveld diagrams demonstrate the NRM variation patterns during thermal demagnetization in samples of the (a) trap body and (b)–(d) sedimentary rocks. The stereograms show the distribution of characteristic magnetization vectors in the study samples of (e)–(g) outcropping sedimentary rocks and (h) the trap body. The symbols are explained in Fig. 2.

nearly completely destroyed in the interval 500–550°C (Figs. 5b and 6d). The characteristic component in redbed samples has the same direction as in other sediments, but the spectrum of its unblocking temperatures extends to 650°C (Fig. 5c). In some samples, the NRM varies during the thermal demagnetization irregularly or chaotically. The distribution of the directions from B. Nirunda outcrops is shown in Figs. 5e–5h and is reflected in Table 1.

AGE OF THE INFERRED MAGNETIZATION COMPONENTS

Comparison of the average directions of the stable magnetization components derived from the bodies studied indicates with a high degree of confidence that these components are virtually coeval. The average directions inferred from various bodies are similar (typically differing by no more than 10°), which is readily explained in terms of the statistical scatter in the magnetization directions naturally arising during the magnetization acquisition, the secular variations, a somewhat inadequate interpretation of local tectonic conditions, and so on.

The geological situation in the field work areas precludes the application of the so-called field methods in estimating the age of the inferred magnetization components. The pebble test is inapplicable because no breccias and conglomerates containing fragments of the study rocks are present in the sections; the contact method is irrelevant to the situation when the magmatic bodies under study are a source of regional remagnetization; and the fold test cannot be used because the uncertainty in the folding age determination is too large. Under these conditions, we propose the following arguments in favor of the Permian–Triassic age of the inferred components.

The paleomagnetic poles calculated from the direction of the inferred components are close to those previously determined from other Permian–Triassic sec-

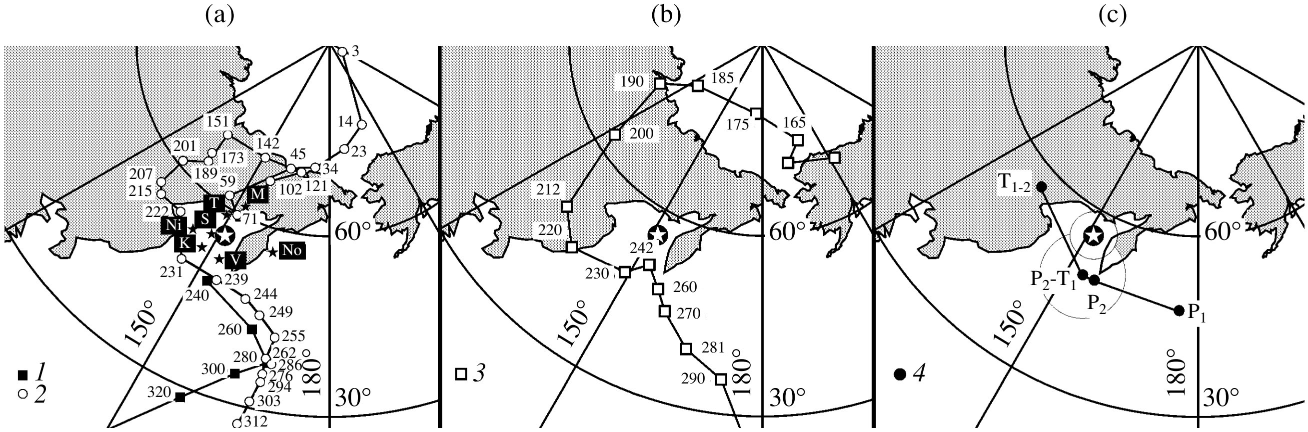

Fig. 6. Comparison of trap paleomagnetic poles with the East European platform APW paths. The solid stars are trap poles: No, western Norilsk area [Pavlov *et al.*, 2001]; M, Moiero River valley [Kamenshchikov *et al.*, 1996]; T, western Taimyr [Gurevich *et al.*, 1995]; V, Vilyui [Kravchinsky *et al.*, 2002]; Ni, B. Nirunda; K, Kotui; S, Stolbovaya. The open circle is the average pole (Table 2). European APW path segments: (*1*) [Pechersky and Didenko, 1995]; (*2*) [Molostovsky and Khramov, 1997]; (*3*) [Smethurst *et al.*, 1998]; (*4*) sequence of average "stratigraphic" European poles. The shaded areas around poles in Fig. 6c are their confidence circles.

tions of the Siberian platform (Table 2) but appreciably differ from the Late Mesozoic and Cenozoic poles of Eurasia and Siberia [Besse and Courtillot, 1991; Molostovsky and Khramov, 1997].

Examination of sedimentary rocks in the Podkamennaya Tunguska River valley indicates the presence of intense regional overprinting. The paleomagnetic directions of the overprinting component in the sedimentary rocks virtually coincide with those in the trap intrusions studied. This is possible in two cases: if sedimentary rocks were remagnetized under the effect of trap magmatism or if the sedimentary rocks and the traps were completely remagnetized due to an intense tectonic or magmatic event of a younger age. Any traces of the latter being absent in the geological history of the region, the first explanation appears to be the only possible one.

In our laboratory studies, we discovered virtually antipodal components of normal and reversed polarities. Their presence is believed to be a fairly strong argument in favor of the primary nature of the magnetization [Van der Voo, 1993]. Although there are known cases when the remagnetization process gives rise to components of opposite polarities, research experience points to a markedly higher probability of the one-component remagnetization. Thus, we conclude that the presence of components of normal and reversed polarities differing by an angle close to 180° supports our suggestion on the Permian–Triassic age of the inferred components.

The presence of two and occasionally three antipodal (or nearly antipodal) components in the Stolbovaya dolerite samples deserves a special discussion. This fact cannot be accounted for by slow cooling of the intrusion, because samples differing in the record pattern are encountered within one sampling site (i.e., separated by a few meters). We believe that a multicomponent magnetization can be interpreted in terms of repeated magma emplacements during the formation of the Stolbovaya intrusion and/or self-reversal during the thermoremanent magnetization acquisition by the rocks. In both cases, the oldest is the component with the highest unblocking temperatures. Based precisely on these considerations, we calculated the average directions in the outcrops studied (sampling sites). The possibility of a self-reversal in rocks of the Stolbovaya intrusion is presently being studied by petromagnetic methods.

Comparison of the geographical and stratigraphic vector distributions of the stable component derived from the Middle–Late Ordovician rocks of the B. Nirunda River valley (Table 1) unambiguously indicates a prefolding age of this component. Its direction differs appreciably from the Early–Middle Paleozoic directions calculated from the related poles of the Siberian platform but nearly coincides with the paleomagnetic direction from the nearby trap intrusion (Table 1). The record of this component has virtually the same pattern as the record of the overprinting component in coeval or lithologically similar rocks of the Stolbovaya section. All of the aforesaid clearly points to the trap (Permian–Triassic) age of this component. Thus, it is clear that the folding of sedimentary sequences in this region postdated the trap emplacement and its age may be determined as post-Paleozoic. The disjunctive deformations of the sedimentary sequences might be related to the intrusion of traps, possibly followed by regional or local tectonic movements.

DISCUSSION

A fairly large amount of data presently accumulated [Bogdanov *et al.*, 1998] indicate that the Permian–Tri-

Table 2. Paleomagnetic poles

Sampling site	Sampling point coordinates		Pole coordinates		d_p/d_m (α_{95})
	φ, deg	λ, deg	φ, deg	λ, deg	
B. Nirunda River (sedimentary rocks, overprinting component)					
n1	62.0	95.3	56.8	140.7	4.4/4.7
n2	62.0	95.3	61.4	122.9	7.7/7.8
n4	62.0	95.3	49.0	157.8	8.1/9.8
Average:	N = 3; φ = 56.6; Λ = 142.3; α_{95} = 17.7°; K = 49.4				
B. Nirunda River (magmatic body)					
n5	62.0	95.3	47.8	147.5	5.4/6.0
B. Nirunda average: N = 4; φ = 54.4; Λ = 143.8; α_{95} = 12.0°; K = 59.6					
Stolbovaya River (sedimentary rocks, overprinting component)					
s1	62.1	91.5	47.2	149.7	6.9/8.0
s2	62.2	91.4	55.8	161.9	10.2/11.8
s3	62.2	91.4	59.6	155.1	5.5/6.1
Average:	N = 3; φ = 54.3; Λ = 155.2; α_{95} = 11.2°; K = 122.3				
Stolbovaya River (magmatic body)					
s4 St 2	62.1	91.5	54.2	126.1	4.4/4.6
St 3	62.1	91.5	55.0	133.0	4.5/4.7
St 4	62.1	91.5	57.4	123.2	4.7/4.8
St 5	62.1	91.5	57.7	129.0	4.4/4.6
St 2	Average:	N = 4; φ = 56.1; Λ = 127.9; α_{95} = 3.3°; K = 774			
Stolbovaya average: N = 4; φ = 55.3; Λ = 148.7; α_{95} = 11.2°; K = 68.3					
Kotui River (lava flows)					
k1	73.0	102.4	55.2	132.3	10.4/11.0
k5	73.0	102.4	46.0	137.9	14.3/16.1
k7	73.0	102.4	67.1	134.6	15.5/15.7
k8	73.0	102.4	50.1	171.4	25.3/29.6
k9	73.0	102.4	40.2	157.9	7.2/88
Kotui average: N = 5; φ = 52.7; Λ = 148.4; α_{95} = 13.9°; K = 31.1					
	N	φ, deg	Λ, deg	α_{95}, deg	K
Western Taimyr pole[1]	29	59.0	149.7	15.7	16.0
Moiero River Valley pole[2]	12	61.7	153.4	7.3	36.0
Norilsk pole[3]	10	56.4	165.3	10.0	24.3
B. Nirunda River pole[4]	4	54.4	143.8	12.0	59.6
Stolbovaya River pole[4]	4	55.3	148.7	11.2	68.3
Kotui River pole[4]	5	52.7	148.4	13.9	31.1
Vilyui River pole[5]	5	52.5	153.3	17.5	20.0
Average pole	**7**	**56.2**	**151.7**	**3.8**	**255.4**

[1] [Gurevich *et al.*, 1995].
[2] [Kamenshchikov *et al.*, 1996].
[3] [Pavlov *et al.*, 2001].
[4] This work.
[5] [Kravchinsky *et al.*, 2002].

assic magmatism lasted for no more than 10–15 Myr, with the majority of trap formation rocks being formed in the interval from 255–253 to 248–244 Ma [Zolotukhin *et al.*, 1996]. Some researchers [Gurevich *et al.*, 1995; Renne *et al.*, 1995] note that the most active stage of the trap volcanism, which transported a huge mass of basalts onto the surface, could span a geologically very short time interval, and this could be responsible for the mass extinctions of organisms and dramatic changes in biocenoses that took place 250 Ma at the Paleozoic/Mesozoic boundary. Thus, the age of the study rocks (and, accordingly, of the inferred paleomagnetic poles) lies in the interval of 255–244 Ma and, with a high probability, can be considered as close to 250 Ma.

The problem of possible relative movements of the Siberian and East European platforms has repeatedly been discussed in the domestic literature. Khramov *et al.* [1982], based on the then-available data, suggested that the northern edge of the Siberian platform moves away from the East European platform. Following Gusev [1974], these authors suppose that the Yenisei–Khatanga trough formed due to the movement of the Taimyr block away from the Siberian platform. Proceeding from the paleomagnetic reliability criteria, Bazhenov and Mossakovsky [1986] carefully selected the Siberian and East European data and established an appreciable distinction between the positions of the related Early Triassic poles. This distinction was interpreted as evidence for a clockwise rotation of the Precambrian Siberian continental block relative to the East European block through an angle of about 10° (assuming that the rotation pole lies in the northern Kazakhstan region). This conclusion was seemingly supported by analysis of the distribution of Early Mesozoic structures of compression and extension on the periphery of the Siberian platform [Bazhenov and Mossakovsky, 1986].

After new paleomagnetic poles had been obtained from traps on the basis of up-to-date methods in the mid- to late 1990s, the problem of possible post-Paleozoic relative movements of the Siberian and East European platforms was tackled again in [Kamenshchikov *et al.*, 1996; Pavlov *et al.*, 2001]. Comparison of the new paleomagnetic poles with the East European apparent polar wander (APW) paths reported in [Pechersky and Didenko, 1995; Molostovsky and Khramov, 1997] indicates a significant distinction between the average trap pole and the corresponding segments of the East European APW paths. However, in contrast to [Bazhenov and Mossakovsky, 1986; Khramov *et al.*, 1982], their present mutual position can only be accounted for by the movement of the northern Siberian platform toward the East European platform accompanied by rotation opposite to that suggested in these papers. This interpretation appears to be paradoxical from the geological standpoint, because it implies the presence of large-scale compressional structures in Western Siberia, whereas, on the contrary, Early Mesozoic grabens widespread in this region are evidence of widely developed processes of extension.

Results obtained in our work and data reported by Kravchinsky *et al.* [2002] appreciably enlarge the paleomagnetic database of Siberian traps, providing the basis for a more rigorous approach to the problem of possible post-Paleozoic mutual movements of the Siberian and East European platforms.

The average paleomagnetic poles calculated for the sections in the valleys of the Kotui, B. Nirunda, and Stolbovaya rivers are presented in Table 2. First of all, note that, along with the Siberian trap poles determined previously (we discuss only the data obtained by modern methods (see the discussion in [Kravchinsky *et al.*, 2002])), they form a very compact group. The very fact that the concentration of poles forming this group amounts to 250 is remarkable.

Such a value of the precision parameter could be expected in the case of a virtually instantaneous (on a geological time scale) magmatic event resulting in the formation of Siberian traps, i.e., an event lasting a few hundred to a few thousand years. However, based on general considerations, the hypothesis of a virtually instantaneous formation of Siberian platform traps appears to be implausible. Incidentally, in future, it can be tested by comparing the inferred average trap pole with the paleomagnetic pole from a section of a similar age belonging to the same plate and developing for a sufficiently long time (a few hundred to a few million years). In this work, we reject this hypothesis as an unlikely one.

Another interpretation of the high concentration of trap poles requires the validity of the following conditions: (1) the formation of the study bodies was fairly rapid (compared to the plate motion rates); (2) the geomagnetic field in this time coincided with the dipole field (at least, within the Siberian platform); (3) the effect of the secular variations in the study sections can be minimized by adequate averaging; and (4) the primary paleomagnetic signal is identified with a high degree of reliability.

Another important property of the poles under consideration is the fact that they deviate from the East European platform APW path not randomly but rather systematically, in one direction (Fig. 7), and this is consistent with a counterclockwise rotation of the Siberian platform relative to the East European platform. This fact was already noted in [Pavlov *et al.*, 2001] in relation to the three poles known at that time. Presently, it is confirmed on the basis of much more representative statistical data.

To assess the statistical significance of this deviation, we use the APW paths obtained in [Pechersky and Didenko, 1995; Molostovsky and Khramov, 1997]. Unfortunately, the APW path proposed by Smethurst *et al.* [1998] is given in a form precluding its use for a rigorous comparison of poles.

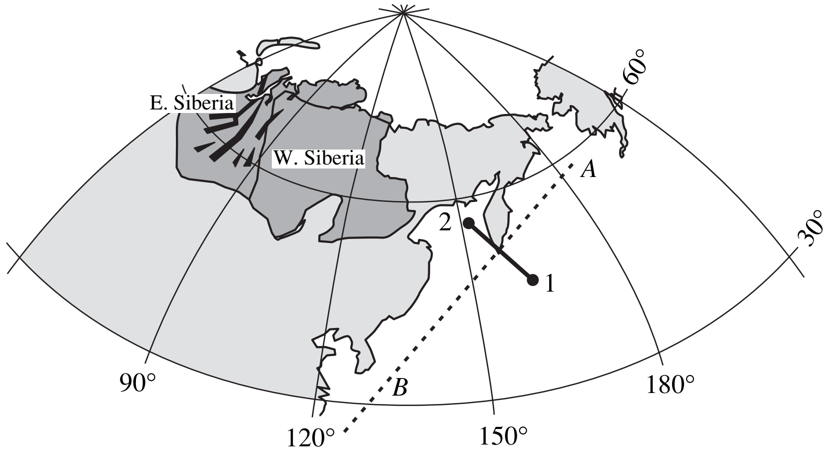

Fig. 7. Position of the great circle AB representing the locus of possible rotation poles of the Siberian platform relative to the East European platform: (*1*) average European pole at 250 Ma (calculated by averaging the poles given in [Pechersky and Didenko, 1995; Molostovsky and Khramov, 1997]; (*2*) average trap pole calculated in our work (see Table 2). Thick lines west of the Siberian platform show symbolically grabens of Western Siberia.

Table 3 presents angular distances between the calculated average trap pole and the East European APW segments of similar age. As before, a statistically significant difference is observed for poles from the interval 262–244 Ma. The new data also indicate the convergence of the average trap pole with the segments of the East European APW path corresponding to 239 and 222 Ma. Thus, the new data seem to confirm (with certain adjustments) the previously drawn conclusion that, if the trap age does exceed 240 Ma, the post-Paleozoic movement of the Siberian platform relative to the East European platform actually took place. In order to bring into coincidence the trap pole of the Siberian platform with the 250-Ma point of the East European APW path and to reconstruct the mutual position of the continental blocks in question at this time, the Siberian platform should be rotated about an Euler pole located on the great circle passing through and perpendicular to the midpoint of the small circle connecting the pole and this point. In terms of this reconstruction, if the Euler pole lies west of the center of this circle (but not farther than by 180°), Siberia should be brought from its present position into the Permian–Triassic position through a counterclockwise rotation and, if the pole lies to the east of the center (but not farther than by 180°), through a clockwise rotation.

As seen from Fig. 8, the rotation pole should lie outside the Siberian platform, sufficiently far from its geometric center. This implies that the relative movement of the Siberian and East European platforms in the post-Paleozoic time cannot be a simple slip motion, as was supposed by Bazhenov and Mossakovsky [1986], but should involve their considerable convergence (see Fig. 8). Thus, the paleolatitude of the present-day Igarka area of the Siberian platform margin (68° N, 88° E) calculated from the average trap pole differs from its 250-Ma value calculated according to the East European pole path by more than 10° (see Fig. 8a). If the poles are authentic, the available APW paths reflect the East European platform movements adequately, and the Earth's magnetic field had a dipole pattern in the time considered, this means that the Siberian and East European platforms converged by more than 1000 km in the post-Paleozoic time.

However, all available geological data are in conflict with this conclusion. As noted above, extensional structures represented by grabens of Early Mesozoic age are widespread in Western Siberia. The Triassic and Early Jurassic deposits filling these grabens are often folded [Bochkarev, 1973], indicating the existence of a compression episode in this region in the Middle Mesozoic. However, the scale of real compressive deformations is at least two orders of magnitude smaller compared to deformations complying with the amount of convergence of the Siberian and East European platforms derived above.

The above induces us to examine more carefully the method of calculating relative movements. We have no grounds for doubting the quality of the paleomagnetic poles used. The dipole pattern of the geomagnetic field in the epoch under consideration is well substantiated [Kent and Smethurst, 1998]. Our data (see above) are likewise well consistent with the dipole hypothesis of the geomagnetic field. The remaining question is whether the inferred pole and the APW path are correctly compared or, in other words, whether the APW paths are reliable and correctly dated. We believe that the problem stems from here.

In the last decade, numerical age values have been ascribed to the poles composing APW paths, whereas previously these were stratigraphic ages (e.g., see [Khramov, 1991]). Numerical age values are taken from the geochronological scales that are available at the time of constructing the APW paths (or the data-

Table 3. Comparison of the average Siberian trap pole with East European platform poles of similar ages

Age, Ma	Angular distance γ, deg	Critical angular distance [McFadden and McElhinny, 1990], γ_c, deg
APW path from [Molostovsky and Khramov, 1997]		
222	7.8	7.8
231	8.3	7.2
239	7.3	8.4
244	10.0	5.0
249	13.1	3.9
255	17.2	4.7
262	20.3	6.6
APW path from [Pechersky and Didenko, 1995]		
240	8.3	5.0
260	16.1	5.0
World database [McElhinny and Lock, 1996] result nos.: 1419, 1813, 2779, 168 (Early Permian); 2421, 652, 165-1, 1408, 2744, 2779-1, 2779-2, 3161 (Late Permian); 1832, 1123, 3188, 158, 3199, 1028 (Late Permian–Early Triassic); 2622-1, 2622-2, 2411, 3253 (Early–Middle Triassic, 270–230 Ma)		
Early Permian–Middle Triassic $\Phi = 51.4°$; $\Lambda = 156.1°$; $N = 23$; $K = 35.7$; $\alpha_{95} = 5.1°$.	5.5	9.5
Early Permian $\Phi = 48.3°$; $\Lambda = 175.5°$; $N = 4$; $K = 19.5$; $\alpha_{95} = 21.3°$.	16.5	13.7
Late Permian $\Phi = 49.7°$; $\Lambda = 157.9°$; $N = 9$; $K = 110.6$; $\alpha_{95} = 4.9°$.	7.5	6.2
Late Permian (Late Permian–Early Triassic) $\Phi = 49.7°$; $\Lambda = 156.1°$; $N = 15$; $K = 81.1$; $\alpha_{95} = 4.3°$.	7.0	6.6
Late Permian–Early Triassic $\Phi = 49.7°$; $\Lambda = 153.3°$; $N = 6$; $K = 52.4$; $\alpha_{95} = 9.3°$.	6.6	8.8
Early–Middle Triassic $\Phi = 57.0°$; $\Lambda = 132.6°$; $N = 4$; $K = 51.8$; $\alpha_{95} = 12.9°$.	10.5	9.2

bases used for their construction), and these scales are often updated. There are known examples when numerical age estimates of stratigraphic units changed by tens of millions of years over one decade. For the Mesozoic, such changes are not overly large, but they are significant enough to affect the results of tectonic interpretations of paleomagnetic data. For example, the Permian/Triassic boundary in the time scale of Harland *et al.* [1988] is 5 Myr younger than the same boundary in more recent schemes [Menning, 1995]. On the other hand, stratigraphic age estimates are more conservative and their revisions are very rare (we mean here rocks of continental blocks, where stratigraphic and paleontological characteristics and geological relationships are established, as a rule, very reliably). Moreover, the construction of APW paths often involves either arbitrary or poorly substantiated ordering of poles according to numerical ages within individual stratigraphic units. A striking example of this is the APW path obtained by Smethurst *et al.* [1998]: its poles, obtained from rocks whose age is known with no better accuracy than the Late Ordovician, are ordered in an interval of no more than 20 Myr. This drawback is often characteristic of other APW paths as well.

Proceeding from the above, we compared the average trap pole with the Permian and Triassic poles of Europe selected from the world database [McElhinny and Lock, 1996] on the condition that their "magnetic age" lay within the interval 270–230 Ma and the parameter DC, characterizing the quality of laboratory processing of a collection, was no less than 3. The position of the sequence of Early Permian–Middle Triassic poles is shown in Fig. 6c and is characterized in Table 3. As seen from the table, the average trap pole differs on a significant level from the Early Permian, Late Permian, and Early–Middle Triassic poles of Europe and is very close to the pole obtained by averaging the poles dated in the database as Late Permian and Late Permian–Early Triassic; in fact, the latter are statistically indistinguishable from the average trap pole. Hence, the comparison of paleomagnetic poles using the stratigraphic approach, which is apparently more correct than the geochronological one, leads to the conclusion

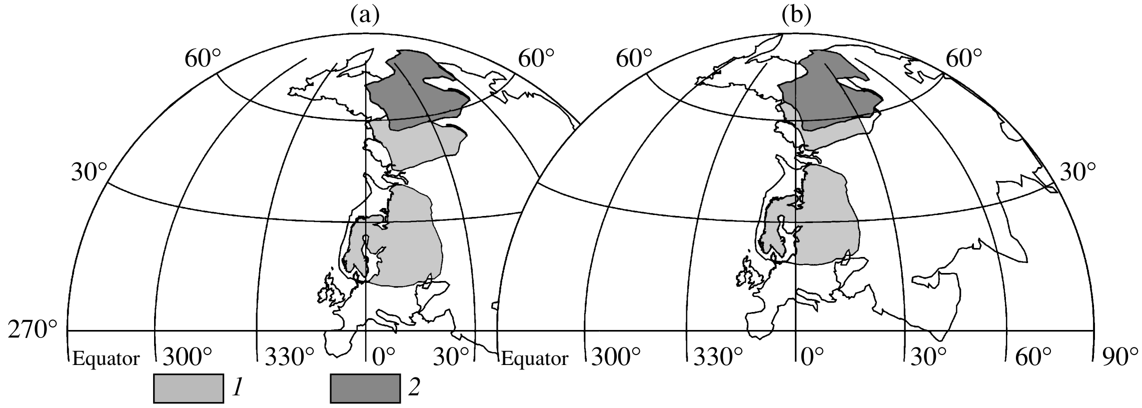

Fig. 8. Reconstruction of the mutual position of the Siberian and East European platforms if the latter is constrained by (a) the 250-Ma pole from the APW paths presented in [Pechersky and Didenko, 1995; Molostovsky and Khramov, 1997] and (b) the average "stratigraphic" pole of the Late Permian–Early Triassic: (*1*) mutual position of the East European and Siberian platforms, provided that they were rigidly connected at least from the Late Permian; (*2*) position of the Siberian platform calculated from the average trap pole.

that the available data yield no evidence of a mutual movement of the Siberian and East European platforms in the post-Paleozoic time.

It is important to emphasize that this inference does not mean that such movements were completely absent but only that the scale of these movements, if they did exist, was restricted to a value consistent with the angular difference between the Siberian and East European poles, amounting to 6°–7°.

Thus, our data do not discard altogether the possibility of relative movements of the Siberian and East European platforms, but significantly limit their possible scale. The next step in solving this problem should consist in gaining more accurate determinations of the Permian–Triassic poles of Europe and Siberia. This is particularly important for the European pole, because the determination accuracy of the Siberian pole is presently at the limit of the potential of the paleomagnetic method.

Finally, we consider the implications of the inferred paleomagnetic data for the formation of the system of Early Mesozoic West Siberian grabens due to the rotation of the Siberian platform relative to the North Eurasian territories lying to the west of the platform. As distinct from the viewpoint of Bazhenov and Mossakovsky [1986], the present data indicate that the West Siberian rift structures degenerate northward, as is evident from their deep geophysical indicators, which become fewer and less pronounced in this direction. In particular [Bogdanov *et al.*, 1998] the lateral sizes of the Koltogorsk–Urengoi rift in the drilling area of the Tyumen overdeep hole TSG-6 amount to 120–130 km, whereas the amplitude of its rift valley is on the order of 1.5 km. Above the polar circle, the rift valley is no wider than 50–70 km, and the trough depth decreases to a few hundred meters. Farther to the north, the rift continues attenuating and completely disappears near the Kara Sea. Similar data are available on the Khudoseiskii rift. A similar geometry of the system of grabens points to their possible formation due to the counterclockwise rotation of Siberia through an angle of about 4°–6° around a pole located near the western coast of West Siberia. Such a possibility does not contradict the paleomagnetic data. The position of the average trap pole northeast of the presently available Permian–Triassic trend of European poles can be regarded as evidence for a counterclockwise rotation of Siberia. In this case, if the future, more accurate Permian–Triassic European paleomagnetic pole will be somewhat displaced relative to its present position toward the Permian–Triassic pole, this will be a fairly strong argument in favor of the Siberian Euler pole position near the West Siberian coast of the Arctic Ocean. Settling this problem requires new, highly accurate paleomagnetic data on Late Permian–Early Triassic Europe.

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