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Paleomagnetism of the Upper Riphean Lakhandinskaya Group in the Uchuro-Maiskii Area and the Hypothesis of the Late Proterozoic Supercontinent

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Abstract—The results of paleomagnetic studies on rocks of the Neryuenskaya and Ignikanskaya Formations of the Late Riphean Lakhandinskaya Group (the Uchuro-Maiskii Riphean hypostratotype, southeastern Siberian Platform) are presented. The direction of the inferred characteristic component of magnetization is independent of magnetic mineralogy and persists over at least a few tens of kilometers but varies, on a significant level, from the bottom to top of the section. The data obtained indicate a prefolding age of the characteristic component. The paleomagnetic poles from the study rocks clearly differ from younger poles of the Siberian Platform. All these data point to the fact that the inferred characteristic component was acquired at the time of or shortly after the deposition of the Lakhandinskaya Group. Taking into account recent paleomagnetic data on the Middle Riphean Malginskaya Formation, results of this current work suggest, depending on the choice of the paleomagnetic direction polarity, two possible scenarios for relative movements of the Siberian Platform and Laurentia in a 1100–1000-Ma interval. One of these scenarios contradicts the hypothesis on Siberia as a part of the Rodinia supercontinent. The second scenario, which implies a variation in the generally accepted polarity for one of the cratonic blocks considered, is in a good agreement with this hypothesis but requires a coincidence of northern Laurentia with south-southeastern Siberia, rather than with its northern part, as is assumed in most reconstructions.

INTRODUCTION

Previously, we have shown [Pavlov and Gallet, 1999] that the paleomagnetic data from Siberia and Laurentia for a period of 1100–1050 Ma can be fitted in terms of the hypothesis of a coherent supercontinent only if the generally adopted polarity pattern of Late Proterozoic Laurentia paleomagnetic directions are revised, as was proposed by Park [1994]. Our paleomagnetic results for the Middle Riphean Malginskaya Formation confirmed that the Siberian craton could have been located in the vicinity of the contemporary northern and northeastern boundaries of Laurentia, as it was supposed in [Hoffman, 1991; Condie and Rosen, 1994; Pelechaty, 1996]. Nevertheless, unlike the reconstructions proposed by these authors, our data required that Siberia be rotated so as to juxtapose its south-southeastern part and the northern and northeastern parts of Laurentia.

In order to verify the validity of the model proposed, it was necessary to compare the paleomagnetic poles of Siberia and Laurentia for other time levels. If both cratons also had consistent paleolatitudes at some other time level and, in addition, experienced consistent movements during the pertinent time period, our model would be considerably supported.

The paleomagnetic poles obtained for the Late Riphean Neryuenskaya and Ignikanskaya Formations of Lakhandinskaya Group in the Uchuro-Maiskii area during the time period from the 1960s through the 1980s [Sidorova, 1965; Komissarova and Osipova, 1986; Pavlov, 1994] need revision and improvement due to imperfections of the methods used at that time. In 1998 and 1999, using up-to-date instrumentation and techniques, we carried out special studies that made it possible to assess the reliability of the previous results and, in part, to refine them. These estimates are presented in the first part of this paper. In its second part, the data obtained are used to test the hypothesis that Siberia and Laurentia were parts of a general supercontinent during the late Meso- and early Neoproterozoic periods.

GEOLOGY AND AGE

The Lakhandinskaya Group is an important structural element of the Riphean Uchuro-Maiskii Hypostratotype located in the southeast of the Siberian platform. The sampled exposures are located at a considerable distance (tens of kilometers) from each other. Their geographical position is shown in Fig. 1. Resting unconformably on the Kerpyl'skaya Group, rocks of the Lakhandinskaya Group compose the lowermost

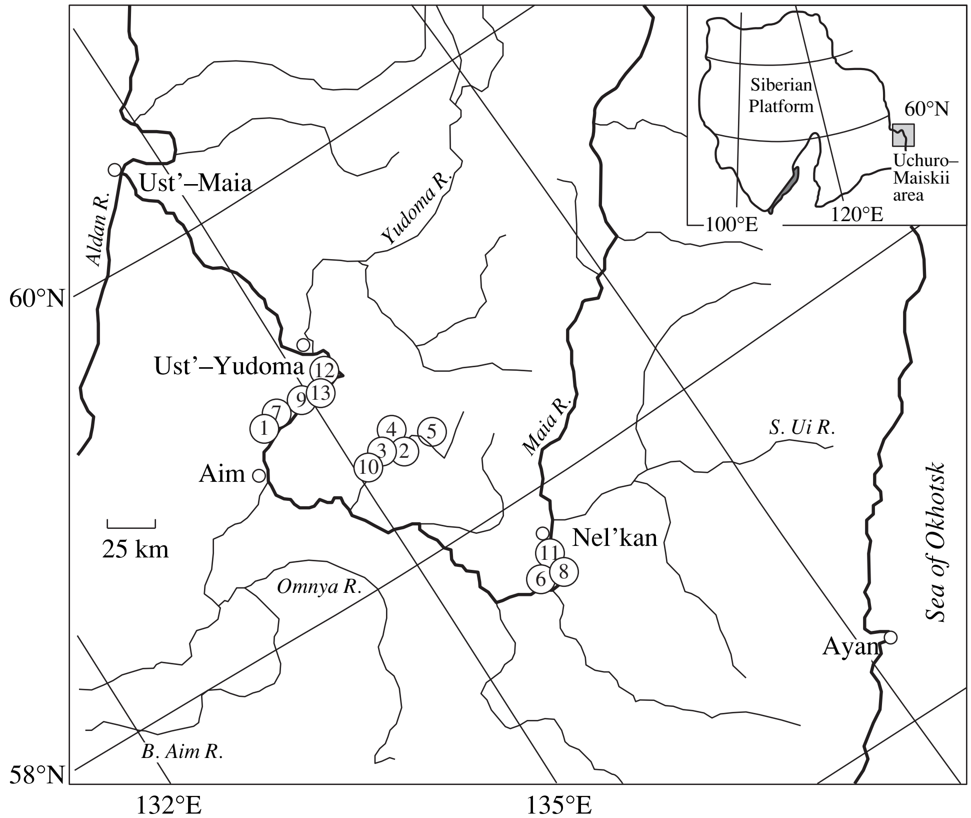

Fig. 1. Geographical position of the study area and exposures. The circles with numbers inside are the exposures studied: Kumakhinskaya Formation (1) Neryuen, (2) Ingili 2, (3) Khandy-Makit; Mil'konskaya Formation: (4) Ingili 3, (5) Tastakh, (6) Nel'kan 1, (7) Ytyrynda; Nel'kanskaya Formation: (8) Nel'kan, (9) Lakhanda; Ignikanskaya Formation: (10) Ingili 4, (11) Lakes Chuiskie, (12) Red Cliffs, (13) Emelekeen.

unit of the Upper Riphean part of the section and are usually subdivided into the Neryuenskaya and Ignikanskaya Formations (Fig. 2) [Semikhatov, 1983]. Within the Maia basin, the Neryuenskaya Formation has a distinct three-unit structure and can be reliably subdivided into predominantly argillaceous Kumakhinskaya and Nel'kanskaya Subformations, separated by the carbonaceous Mil'konskaya Subformation. Since the sections studied in this paper are located exactly in this part of the Uchuro-Maiskii area, we carried out paleomagnetic studies separately for each of the stratigraphic levels mentioned above.

The Kumakhinskaya Subformation is represented by variegated foliated argillites giving place to argillaceous–silty and sometimes stromatolithic dolomites in the upper part of the section.

The Mil'konskaya Subformation is composed solely of carbonaceous rocks, namely, of phytogenic and chemogenic limestones that sometimes have a reddish and greenish color.

Similar to the Kumakhinskaya Subformation, the Nel'kanskaya Subformation has a terrigenous–carbonaceous composition. However, it is distinguished by a greater amount of siltstones and stromatolithic dolomites, including reddish and greenish varieties.

The total thickness of the Neryuenskaya Formation within the Maia basin varies from 200 to 300 m. The rocks of this formation, except its middle part, are poorly exposed and their *in situ* study is only possible on very rare exposures.

The Neryuenskaya sediments are conformably overlain by limestones and dolomites of the Ignikanskaya Formation, which is 160–200 m thick within the study area of the Uchuro-Maiskii region. Red-colored limestones and dolomites dominate in the lower part of the formation and are overlain by gray and brownish, often bituminous, dolomites.

Preliminary studies [Petrova, *et al.*, 1987; Pavlov, 1986] showed that the presence of a paleomagnetic signal in rocks of the study area is clearly related to their color. For this reason, mostly reddish and greenish varieties were selected for our paleomagnetic studies. Within exposures, samples were taken consecutively from the bottom to top of the section in order to ensure the averaging of secular variations. Depending on the exposure conditions, the sampling interval varied from a few tens of centimeters to a few meters.

The study rocks occur everywhere nearly horizontally, with dip angles rarely reaching 5°–6°. However, a few exposures studied in this paper are located near the

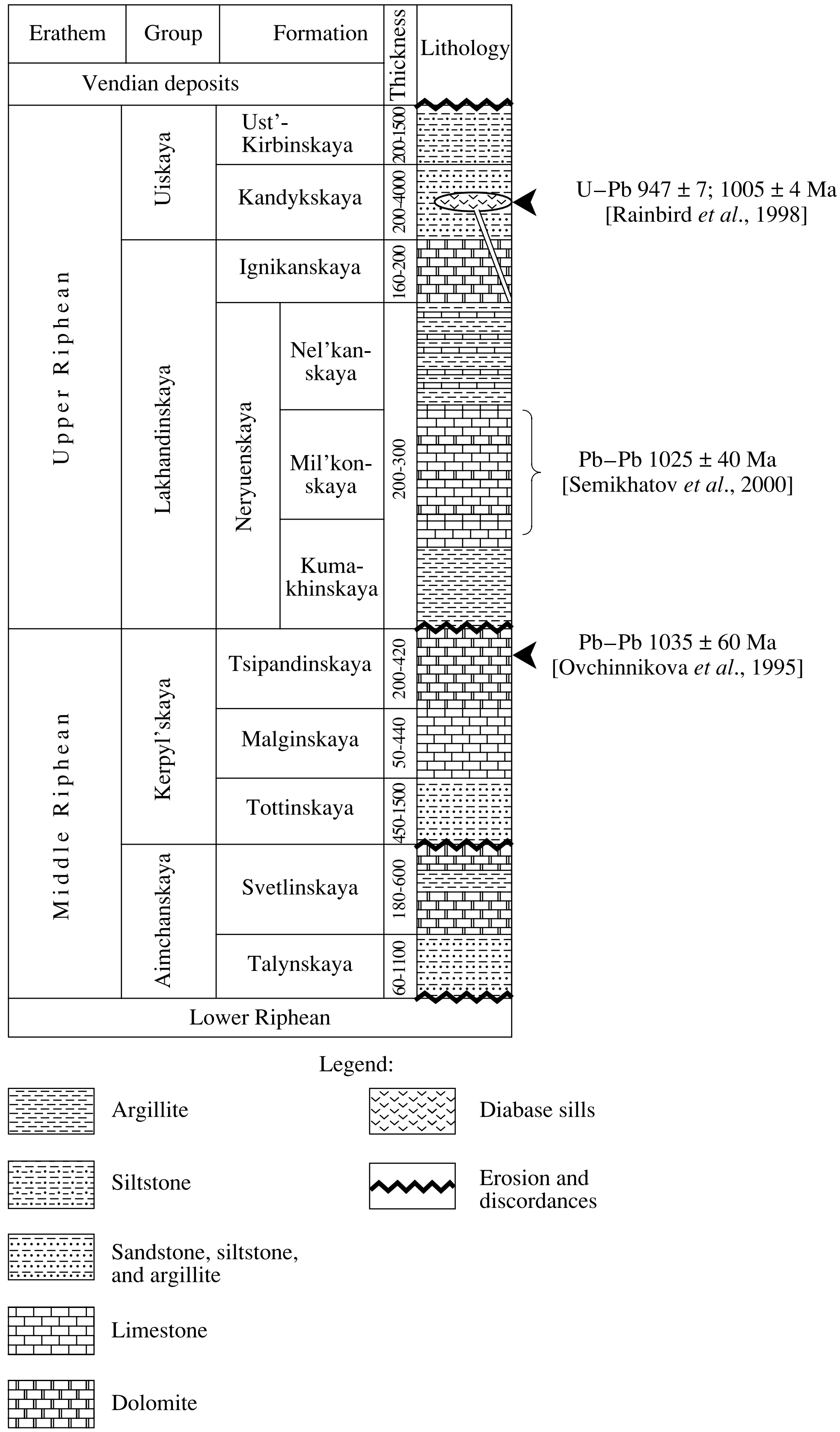

Fig. 2. Lithostratigraphic column.

Ingiliiskaya ring structure, formed as a result of the emplacement of a large-scale ultrabasic alkaline massif 640–740 Myr ago [Semikhatov, 1983]. In these exposures, dip angles of the sequences are as high as 20°–25°.

Rocks of the Lakhandinskaya Group are characterized by the presence of complexes of abundant stromatolites, oncolites, and catagraphites, which make it possible to reliably attribute the sediments under consideration to lower horizons of the Upper Riphean [Semikhatov, 1983]. Recent isotopic datings necessitate a substantial revision of the previously existing concepts concerning the age of the Lakhandinskaya Group, which appears to have been underestimated. Thus, Rainbird *et al.* [1998] obtained U–Pb baddeleyite ages of 974 ± 7 and 1005 ± 4 Ma for basic sills cutting the rocks of the Lakhandinskaya Group. These ages indicate that the upper age boundary of the Lakhandinskaya Group cannot be younger than 1000 Ma. On the other hand, Ovchinnikova *et al.* [1995] obtained an age of 1035 ± 60 Ma for the Riphean Sukhaya Tunguska Formation, which is the age analogue of the Tsipandinskaya Formation underlying the Neryuenskaya deposits, and this value thereby provides a lower age boundary of the Lakhandinskaya Group.

Along with an age 1025 ± 40 Ma recently determined by Semikhatov *et al.* [2000] for rocks from the middle horizons of the Neryuenskaya Formation, these data are reliable evidence that the Lakhandinskaya Group was deposited within a 1030–1000-Ma interval.

PALEOMAGNETIC ANALYSIS

Procedure and technique. In the second half of the 1980s, we gathered collections from Lakhandinskaya Group exposures which were treated, at that time, in the following way. A pilot collection (usually 25%–30% of the total number of samples) was randomly selected for each exposure. The pilot collection was subjected to detailed thermal demagnetization, and its results were used to choose an optimum regime of demagnetization, i.e., the temperature at which, supposedly, only the characteristic component remained in the sample. Special experiments designed to compare the results of thermal and alternating magnetic field demagnetizations showed a low efficiency of the latter. The entire collection was then demagnetized using the chosen optimum regime. The inferred results were used, upon rejection of a certain number of samples, for calculating paleomagnetic directions and poles. The following rejection criteria were employed: small signal values comparable with the instrumentation noise, the closeness of vector directions to the direction of the present geomagnetic field, or a strong deviation of directions in particular samples from the mean direction, around which most vectors concentrated. At that time, the choice of this technique was dictated by a lack of efficient high-sensitivity instruments, the low quality of the demagnetization apparatus, a limited access to computers, and a lack of software implementing up-to-date methods of the component analysis.

Obviously, the instrumentation and techniques of that time could give reliable results only in the case of very homogeneous collections with a simple composition of magnetization and rather low blocking temperatures of superimposed components. The detailed demagnetization results from the pilot samples implied that, on the whole, the conditions mentioned above are fulfilled, but this evidence was obviously inadequate in order to state this with confidence. Moreover, only a part of the pilot collection, which did not experience considerable temperature-induced alterations and remagnetization during heating, could be used for the component analysis of magnetization. Thus, the representativeness of the detailed demagnetization results was considerably reduced.

In recent years, thanks to cooperation with western paleomagnetic laboratories, we have had the possibility to study a part of the old collections at a much higher level and to estimate the reliability of previous results in line with the up-to-date requirements.

Laboratory paleomagnetic studies and preprocessing of the results were carried out in the Paleomagnetic Laboratories of the Institute of General and Applied Geophysics (Munich, Germany) and at the Institute of Earth Physics (Paris, France) using standard techniques [Molostovskii and Khramov, 1997; Butler, 1992; Enkin, 1994; Kirschvink, 1980; Collinson, 1980].

All samples were subjected to detailed thermal demagnetization, mostly to temperatures of 685–690°C. The number of temperature steps was 15 and, in some cases, greater. Special nonmagnetic TSD-2 (Shonstedt) kilns with a value of the uncompensated field of no more than 3–6 nT were used for the sample demagnetization. The remanent magnetization was measured on cryogenic magnetometers manufactured by 2G Enterprises and CTF. All laboratory procedures were conducted in a room screened from the external magnetic field. The measured data were processed with the help of the program package developed by Enkin [1994], which uses the PCA method [Kirschvink, 1980] for the identification of magnetization components.

The natural remanent magnetization (NRM) of the study rocks varies from 0.5×10^{-3} to 3×10^{-3} A/m. The magnetic susceptibility is usually $10–30 \times 10^{-6}$ SI units.

Thermal demagnetization. The results of the detailed thermal demagnetization clearly demonstrate (Fig. 3) that most of the studied samples of the Lakhandinskaya Group contain two NRM components: a less stable component close in direction to the present geomagnetic field and the ancient, characteristic component. Judging from the values of the maximal blocking temperatures, the carriers of the characteristic magnetization component in the study rocks studied are magnetite (Figs. 3c and 3e) and hematite (Figs. 3b, 3d, 3f, and

3g), and the direction of the characteristic magnetization is independent of its carrier.

Detailed examination of each sample shows that, in a number of cases, the present magnetization component can persist at higher temperatures than was previously assumed from the pilot collection data [Pavlov, 1994]. Although the old collections were demagnetized at temperatures at which the contribution of the present component to the total vector was quite insignificant, the disregard of this circumstance could introduce a systematic error into the determination of the paleomagnetic direction. This error can be estimated from the comparison of previous results with our data on the magnetization components identified and calculated with the use of detailed thermal demagnetization and PCA method [Kirschvink, 1980].

The detailed demagnetization considerably improved our knowledge of the relation between the magnetization components in the Ignikanskaya Formation rocks from the Lakes Chuiskie exposure. Previously, based on a limited amount of data, the conclusion was drawn that, in addition to the present component, some samples from this exposure carry the primary component, whereas other samples carry a metachronous component (presumably, of the Kandykskii age), and there are samples in which these components completely overlap, forming intermediate directions. Based on this pattern, analysis of the entire set of vectors obtained after the heating of samples to T = 600°C (Fig. 4) distinguished a cluster, supposedly representing the primary component. The data from this cluster were used for calculating the paleomagnetic pole of the Ignikanskaya Formation. The laboratory studies of this work showed that many samples from the Lakes Chuiskie exposure contain both the tentatively primary component and the metachronous one, whose blocking temperature spectra are different but largely overlap one another. The metachronous component could not be removed even at the highest temperatures near the Curie point of hematite (Fig. 3a). Thus, at the present level of studies, the data obtained from the Lakes Chuiskie exposure cannot be used for the calculation of the paleomagnetic pole.

Table 1 presents the paleomagnetic directions previously derived by the authors of this work from the thermal demagnetizations of the collections in the predetermined optimal regime and the new data calculated with the PCA method from the results of the detailed thermal demagnetizations. The comparison of the "old" and "new" data for all revisited exposures, using the method of MacFadden and McElhinny [1990], showed that they do not differ on a significant level.

However, due to a limited number of samples being used, the γ_c value, which is a measure of the accuracy of such a comparison, points to the class C, i.e., to the roughest acceptable accuracy [MacFadden and McElhinny, 1990]. More stringent constraints on our data can be gained from the comparison between the virtual geomagnetic poles obtained for each time level of all exposures studied. As seen from Table 2, this test actually improves the accuracy, and γ_c values fall into the interval 5°–10°, which corresponds to the higher accuracy class B according to MacFadden and McElhinny [1990].

Due to a limited number of the available samples, we could reexamine the data from only 8 of 13 Lakhandinskaya Group exposures studied previously. Nevertheless, the revised results indicate convincingly that, on a statistically significant level, our previous estimates of the characteristic magnetization directions from the rocks studied do not differ from the determinations obtained with the use of up-to-date methods and instruments and can therefore be used in further paleomagnetic studies.

The arguments supporting the validity of the inferred magnetization components are as follows.

1. The fold test is applicable to the Mil'konskaya Subformation, represented by four exposures in the collection studied (its application to a smaller number of the compared mean vectors appears to be invalid). This test (in the modification of Enkin [1994]) gives a positive result; in combination with a noticeably better concentration of the mean directions in the stratigraphic coordinates system, as derived from other time levels, this result suggests that the characteristic magnetization components in the Lakhandinskaya Group rocks were acquired before the emplacement of the Ingiliiskaya Intrusion, i.e., they are at least as old as the Late Riphean.

2. Whereas coeval rocks from various outcrops, which are sometimes separated by tens of kilometers, give statistically indistinguishable results, mean directions for any two neighboring time levels differ on a statistically significant level. Together with the fact that the related paleomagnetic poles appreciably differ from the younger poles of the Siberian Platform [Pavlov, 1994; Khramov *et al.*, 1982], these data can be considered as evidence that the rocks were not remagnetized.

3. The characteristic magnetization direction is independent of the carrier mineral; together with other arguments, this is an additional argument in favor of the primary origin of the components in question.

Thus, the available data point to the fact that the inferred characteristic component formed during or soon after the deposition of the rocks studied.

DISCUSSION

The sequence of the individual paleomagnetic poles derived from the Lakhandinskaya rocks can provide detailed constraints on the movement of the Siberian craton in the earliest Late Riphean. However, within the framework of this work, mean paleomagnetic poles obtained for a relatively long time interval should apparently be used for solving the problem of the relative position of Siberia and Laurentia. Such an

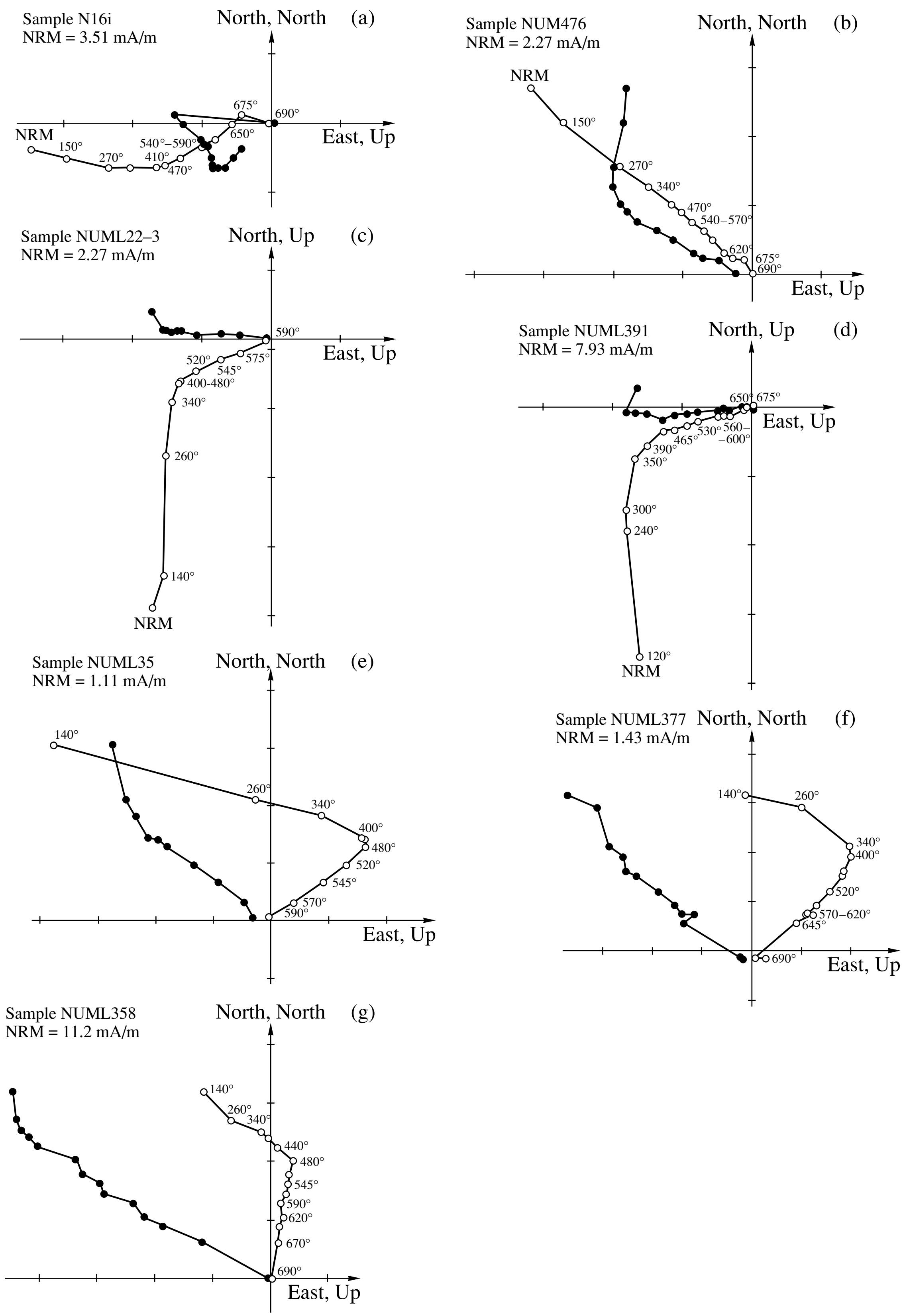

Fig. 3. Typical Zijderveld diagrams (in stratigraphic coordinates): (a), (b) Ignikanskaya Formation; (c), (d) Nel'kanskaya Subformation; (e), (f) Mil'konskaya Subformation; (g) Kumakhinskaya Subformation. The solid and open circles are projections of NRM vectors onto the horizontal vertical planes, respectively.

Table 1. Paleomagnetic directions

Formation/Subformation	Exposure/coordinates	Treatment	N	Geographic coordinate system				Stratigraphic coordinate system				γ/γ_c
				D	I	K	α_{95}	D	I	K	α_{95}	
Ignikanskaya	Ingili 4	I	11	295.5	1.3	12.8	13.3	297.9	6.6	12.8	13.3	5.7/25.2
	$\lambda = 135.3$ $\varphi = 58.5$	II	4	302.8	–2.0	12.3	27.3	303.6	6.8	13.0	26.5	
	Red Cliffs	I	26	301.8	6.9	15.1	7.5	301.8	6.9	15.1	7.5	6.6/12.8
	$\lambda = 135.1$ $\varphi = 58.9$	II	11	295.6	3.7	14.5	12.4	296.4	3.2	15.6	11.9	
	Emelekeen	I	17	297.3	6.8	11.5	11.0	297.3	6.8	11.5	11.0	
	$\lambda = 135.1$ $\varphi = 58.9$	II	Lacking data									
	Lakes Chuiskie	I	17	292.9	7.8	16.0	8.5	293.5	2.9	16.0	8.5	
	$\lambda = 136.3$ $\varphi = 57.6$	II	Characteristic component was not recognized									
	Average	I	3	298.2	5.0	317.1	6.9	299.0	6.8	1111.4	3.7	
Neryuenskaya/Nel'kanskaya	Nel'kan 2	I	18	287.6	12.8	12.6	10.1	287.4	11.6	13.1	9.9	6.6/15.3
	$\lambda = 136.3$ $\varphi = 57.6$	II	12	281.1	22.6	13.3	12.3	283.6	17.1	13.4	12.3	
	Bol'shaya Lakhanda	I	6	285.8	6.0	28.1	12.8	283.1	9.8	44.9	10.1	4.2/15.3
	$\lambda = 134.9$ $\varphi = 58.9$	II	4	283.4	14.0	41.9	14.4	283.4	14.0	41.9	14.4	
	Average	I	2	286.6	9.4	268.2	15.3	285.2	10.7	622.7	10.0	
Neryuenskaya/Mil'konskaya	Ytyrynda	I	21	307.7	–16.6	18.8	7.5	307.7	–16.6	18.8	7.5	8.4/11.2
	$\lambda = 134.8$ $\varphi = 58.7$	II	12	299.0	–16.1	35.1	7.4	299.1	–16.0	36.8	7.3	
	Nel'kan 1	I	23	297.6	–16.8	13.3	8.6	297.6	–16.8	13.3	8.6	4.1/11.4
	$\lambda = 136.3$ $\varphi = 57.6$	II	21	298.9	–19.2	18.0	7.7	298.2	–20.9	18.2	7.7	
	Tastakh	I	5	302.0	–18.8	15.8	19.9	299.5	–9.1	15.7	19.9	
	$\lambda = 135.6$ $\varphi = 58.5$	II	Lacking data									
	Ingili 3	I	12	302.3	–10.1	22.3	9.4	301.7	–7.8	22.3	9.4	
	$\lambda = 135.4$ $\varphi = 58.5$	II	Lacking data									
	Average	I	4	302.9	–9.5	35.3	15.7	301.2	–12.9	168.1	7.1	
Neryuenskaya/Kumakhinskaya	Neryuen	I	17	299.0	2.2	47.3	5.2	298.9	2.4	45.3	5.4	2.5/8.9
	$\lambda = 135.1$ $\varphi = 58.9$	II	13	297.3	0.4	27.8	8.0	297.2	3.9	29.1	7.8	
	Khandy-Makit	I	11	290.4	14.9	29.2	8.6	290.7	–6.9	29.6	8.5	
	$\lambda = 135.3$ $\varphi = 58.5$	II	Lacking data									
	Ingili 2	I	6	295.1	–4.0	47.2	9.9	295.1	–4.0	47.2	9.9	
	$\lambda = 135.4$ $\varphi = 58.5$	II	Lacking data									
	Average	I	3	295.6	13.0	57.3	16.4	294.9	–2.9	169.5	9.5	

Note: N is the number of samples from an exposure and the number of exposures used for the calculation of the average direction. D, I, K, and α_{95} are the characteristics of the Fisher distribution. γ and γ_c are the angular distance between averages and the critical angle (according to [McFadden and McElhinny, 1990]). Treatment: (I) demagnetization through heating to a temperature chosen from results of the detailed demagnetization of the pilot collection; (II) detailed thermal demagnetization of each sample with the subsequent calculation of the components using the PCA method [Kirschvink, 1980].

approach is capable, to an extent, of reducing the possibility of errors associated with inaccurate determination of the age and position of individual paleomagnetic poles. Therefore, in our further discussion, we will use the pole obtained from the averaging of the poles calculated for all four age levels of the Lakhandinskaya Group (Table 2) under the assumption that its age lies within the time interval 1030–1000 Ma.

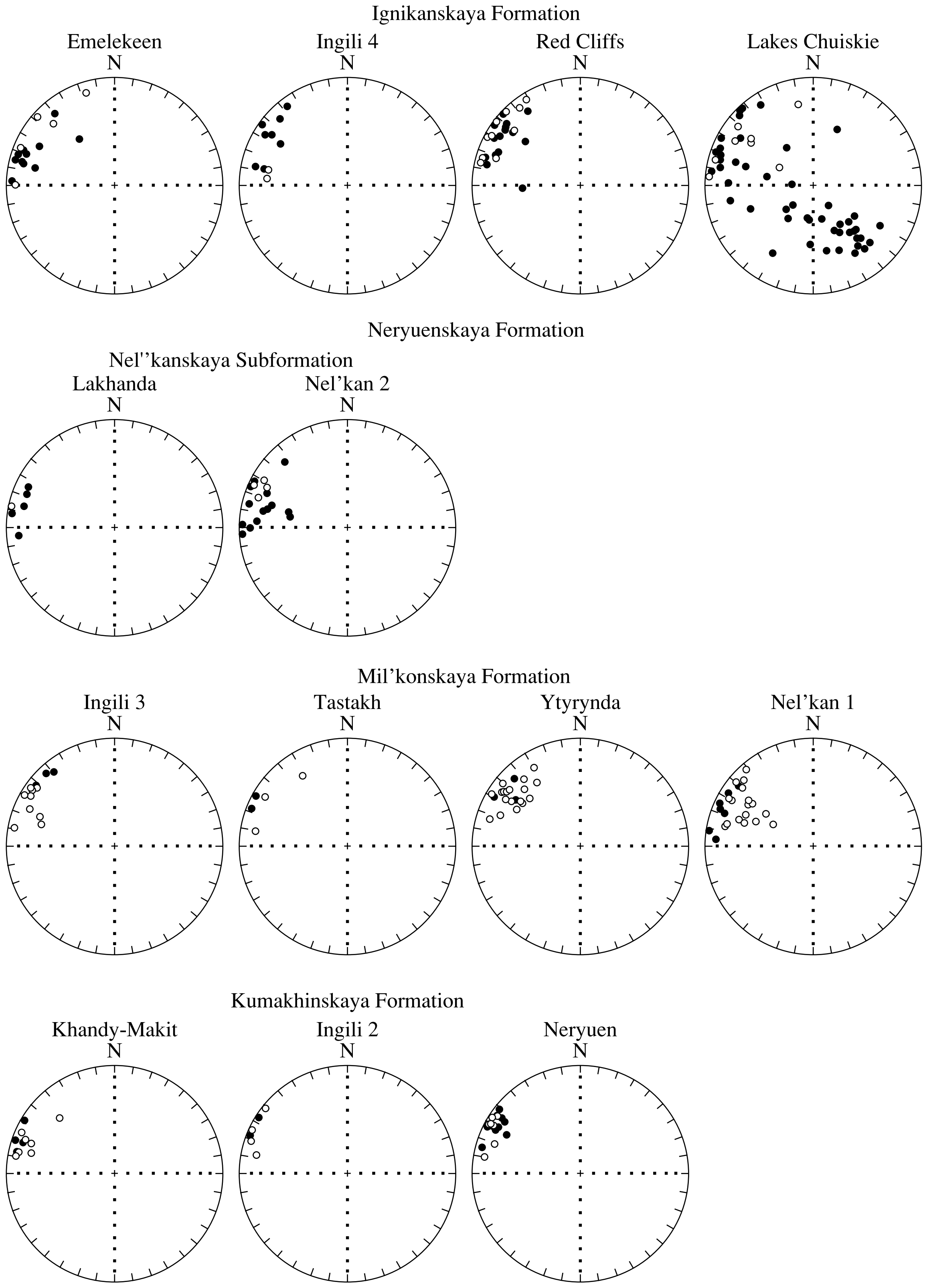

Fig. 4. Stereograms (in the stratigraphic coordinates). The solid and open circles are vector projections of the characteristic component onto the lower and upper hemispheres, respectively.

Table 2. Paleomagnetism of the Upper Riphean Lakhandinskaya Group

Formation/Subformation	Treatment	*N*	Φ	Λ	A_{95}	*K*	γ/γ_c
Ignikanskaya	I	54	–18.0	201.1	4.4	20.4	2.0/9.1
	II	15	–16.0	201.4	7.4	27.9	
Neryuenskaya/Nel'kanskaya	I	24	–13.8	215.2	5.5	29.9	3.8/8.3
	II	16	–14.4	219.1	6.3	35.3	
Neryuenskaya/Mil'konskaya	I	61	–8.8	194.2	3.5	28.1	3.6/5.5
	II	33	–5.6	195.9	3.8	43.7	
Neryuenskaya/Kumakhinskaya	I	34	–12.2	202.4	3.2	59.3	2.1/6.6
	II	13	–13.9	201.2	7.0	36.4	
Average	I	4	–13.3	203.2	10.7	75.2	

Note: *N* is the number of VGPs (samples) used for the calculation of the mean pole. Φ and Λ are the latitude and longitude of the mean paleomagnetic pole. A_{95} is the confidence radius. *K* is the precision parameter. γ and γ_c are the angular distance between the mean poles and the critical angle (according to [McFadden and McElhinny, 1990]).

The polarity of the inferred paleomagnetic directions was chosen on the basis of the apparent polar wander (APW) curve proposed and substantiated by Smethurst *et al.* [1998]. According to this curve, the mean pole characterized in Table 2 should be considered as the north pole. Hence, at the Lakhandinskaya time, the Siberian Platform was located near the equator and rotated so that its east-southeastern part faced north, the equator was either near the Uchuro–Maiskii area or crossed it, and the major part of the Siberian Platform was in the Southern Hemisphere.

Like in our previous work [Pavlov and Gallet, 1999], we emphasize that the polarity problem of the Late Proterozoic directions from Siberia remains unsolved because reliable paleomagnetic data on the Upper Riphean and Low Vendian of Siberia are presently unavailable. The polarity option consistent with the APW curve of Smethurst and coauthors can be considered as the most convincing and substantiated one. Nevertheless, one cannot exclude that novel data on the time intervals mentioned above would require a drastic revision of this inference.

A set of the Meso–Neoproterozoic poles of Laurentia, presented by Weil *et al.* [1998], makes it possible to determine the mean paleomagnetic pole for this craton in the time interval 1020–1000 Ma. The coordinates of this pole are $\Phi = 9.2°$, $\Lambda = 164.6°$ with a confidence radius of $A_{95} = 16.1°$; six poles were used in the determination. The polarity problem for the Late Proterozoic paleomagnetic directions of Laurentia also remains unsolved. Moreover, recent new data [Meert *et al.*, 1994; Clark, 1997; Schmidt and Clark, 1997] support the opinion of Park [1994], who suggested the polarity option other than what has been accepted until recently [e.g., Weil *et al.*, 1998].

Thus, in order to solve the problem of the relative position of Siberia and Laurentia in the Late Proterozoic from paleomagnetic data, one should consider four possible variants of the solution (reconstructions) following from the polarity choice for the paleomagnetic directions of Siberia and Laurentia. Since these four variants are represented by two pairs of solutions symmetrical with respect to the equator, it is sufficient to consider only two variants (see Figs. 5a and 5b) in order to determine the relative position of Siberia and Laurentia.

The first of these variants is based on the traditional choice of the polarity for the Late Precambrian directions from Siberia (e.g., see, [Smethurst *et al.*, 1998]) and Laurentia (e.g., [Weil *et al.*, 1998]). The second variant proceeds from the opposite polarity choice for Laurentia [Park, 1994], with the Siberia polarity remaining unchanged. Taking into account the data which we have previously obtained for the Malginskaya Formation, the first variant suggests the following scenario for the mutual evolution of the Siberian platform and Laurentia.

At the time 1100–1050 Ma, Siberia was situated at moderate and subtropical latitudes of the Southern Hemisphere, and its presently eastern side faced north (Fig. 5a). Laurentia was situated in the Northern Hemisphere at that time and no less than 3000 km from Siberia (Fig. 5a). Hence, it is clear that Siberia and Laurentia could not belong to a coherent cratonic block, as is suggested in all main paleoreconstructions of Rodinia [Hoffmann, 1991; Dalziel, 1991; Torsvik *et al.*, 1996]. In other words, using the polarity options that are currently widely applied in Siberia and Laurentia studies, the inferred paleomagnetic data conflict with the hypothesis according to which Siberia was connected with Laurentia and was a part of Rodinia at the time 1100–1050 Ma.

Later, Siberia and Laurentia moved from the opposite Hemispheres toward a near-equatorial area and slightly rotated counterclockwise with respect to the meridian. By 1020–1000 Ma, Siberia and south-southeastern Laurentia were brought to proximate latitudes, but the present northern and northeastern parts of Lau-

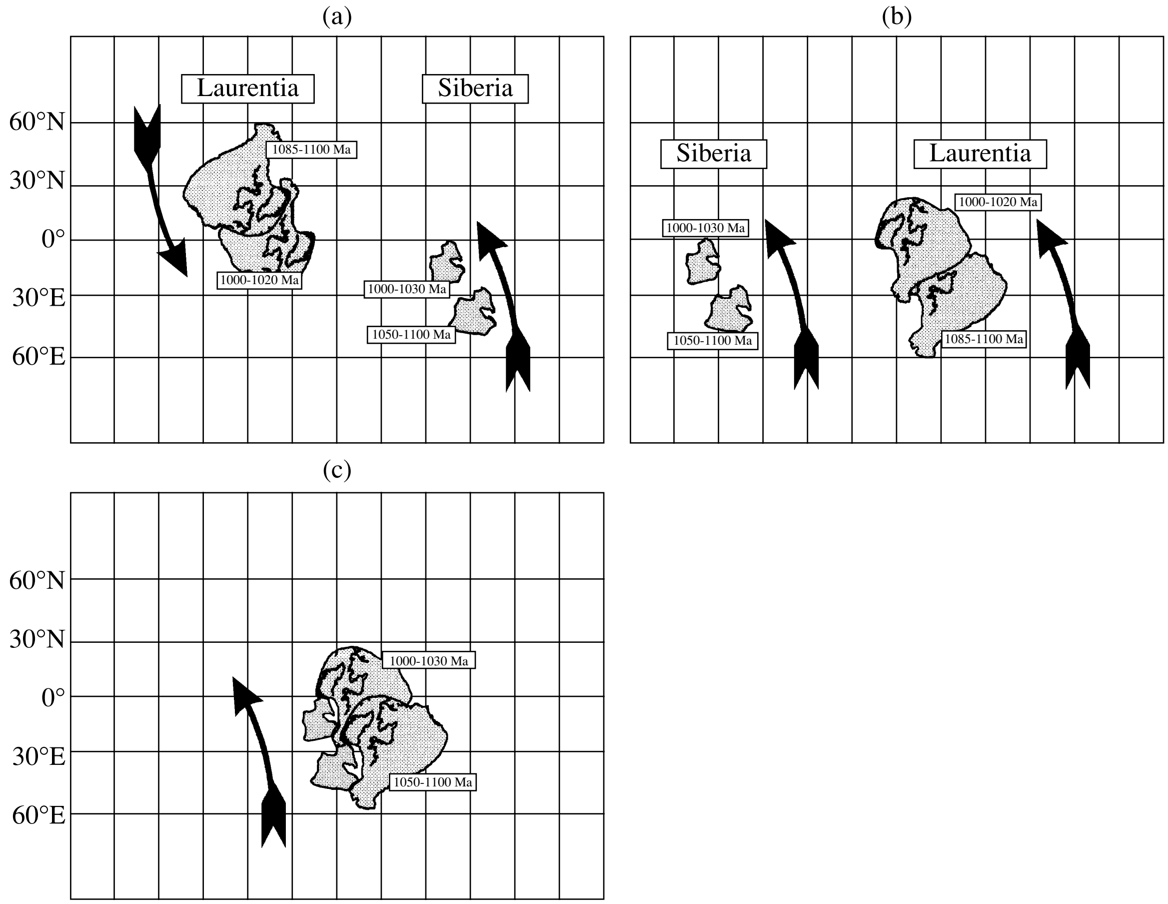

Fig. 5. Variants of the relative position of Siberia and Laurentia 1100–1000 Ma: (a) traditional choice of the polarity [Smethurst *et al.*, 1998; Weil *et al.*, 1998]; (b) polarity of the Proterozoic paleomagnetic directions chosen according to Park [1994]; (c) reconstruction of the relative position of Siberia and Laurentia. The paleogeographical position of Laurentia was determined on the basis of the paleomagnetic poles calculated from the data of Weil *et al.* [1998]: $\Phi = 32.9°$, $\Lambda = 179.7°$, $A_{95} = 7.4°$, 1100–1085 Ma; $\Phi = 24.3°$, $\Lambda = 176.8°$, $A_{95} = 12.0°$, 1100–1050 Ma; and $\Phi = 9.2°$, $\Lambda = 164.6°$. $A_{95} = 16.1°$, 1020–1000 Ma. The paleogeographical position of Siberia for the 1100–1050-Ma interval was determined using the paleomagnetic pole of the Malginskaya Formation with the following parameters from [Pavlov and Gallet, 1999]: $\Phi = -25.5°$, $\Lambda = 230.4°$, $A_{95} = 2.5°$. The data of this paper (Table 2) were used for the 1030–1000-Ma interval.

rentia, where the Siberian craton is usually placed in the reconstructions of Rodinia, were at a considerable distance to the north from Siberia (Fig. 5a). Our paleomagnetic data do not contradict the fact that Siberia could be joined to the present western or eastern parts of Laurentia. However, these assumptions are in evident contradiction, on the one hand, to the geological and paleomagnetic evidence indicating that the East Gondwana cratonic blocks were contiguous to Laurentia in the west [Hoffman, 1991; Dalziel, 1991] and, on the other hand, to the paleomagnetic data indicating that the Baltic block was located east of Laurentia by that time [Torsvik *et al.*, 1996]. Thus, the reconstruction based on the first variant involves appreciable difficulties because it is impossible to incorporate both the Siberian craton and Laurentia to the Rodinia supercontinent without a cardinal revision of its configuration.

The paleomagnetic direction polarity choice consistent with the second variant (Fig. 5b) leads to an essentially different interpretation of paleomagnetic data. In this case, at a time of 1100–1050 Ma, both Siberia and the northern part of Laurentia were located at moderate and subtropical latitudes of the Southern Hemisphere. By the time 1030–1000 Ma, both Siberia and the northern part of Laurentia moved back from the south into the near-equatorial area and slightly rotated counterclockwise with respect to the meridian. In this variant, in agreement with paleomagnetic data, the Siberian craton can easily be brought into coincidence with the northern part of Laurentia, as is suggested in most reconstructions of Rodinia [Hoffman, 1991; Dalziel, 1991; Torsvik *et al.*, 1996]. However, this involves an essential modification: our results indicate that the south-southeastern part of the Siberian platform, rather than its northern part, as is supposed in the works mentioned above, should have joined to North Laurentia (Fig. 5c). This conclusion is in a perfect agreement with the reconstruction of Rainbird *et al.* [1998], based on new isotopic data recently obtained for the Upper Riphean rocks from the Uchuro–Maiskii.

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