Late Mesoproterozoic magnetostratigraphic results from Siberia: Paleogeographic implications and magnetic field behavior

Yves Gallet, Vladimir E. Pavlov, Mikhail A. Semikhatov, Peter Yu. Petrov

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. B7, PAGES 16,481-16,499, JULY 10, 2000

Late Mesoproterozoic magnetostratigraphic results from Siberia: Paleogeographic implications and magnetic field behavior

Yves Gallet

Laboratoire de Paléomagnétisme, UMR CNRS 7577, Institut de Physique du Globe de Paris

Vladimir E. Pavlov

Department of Geomagnetism and Paleomagnetism, Institute of Physics of the Earth, Moscow

Mikhail A. Semikhatov and Peter Yu. Petrov

Geological Institute, Russian Academy of Sciences, Moscow

Abstract. We present a magnetostratigraphic study of the late Mesoproterozoic Malgina and Linok Formations, located along the southeastern (Uchur-Maya region) and northwestern (Turukhansk region) margins of the Siberian craton, respectively. Biostratigraphic, radiometric, and chemostratigraphic data indicate that these formations are likely coeval between 1050 and 1100 Ma. Paleomagnetic analyses reveal a high-temperature component carried by magnetite and/or hematite. This component yields positive fold and reversal tests, together with a positive conglomerate test for the Malgina Formation, which indicates that the magnetization was acquired during or soon after sediment deposition. The mean paleomagnetic direction obtained from the Uchur-Maya region, which is unambiguously representative of the Siberian craton, indicates that it could not have been part of Rodinia at that time if Siberia was located in the Southern Hemisphere and if we assume that Laurentia and Siberia were connected along their present northern shorelines. We emphasize that Siberia could have been part of Rodinia during the late Mesoproterozoic if southern Siberia was joined to the northern part of Laurentia as recently proposed by *Rainbird et al.* [1998]. If true, placing the Siberian craton in the Southern Hemisphere implies that the magnetic polarity of the ~1000 Ma Laurentian paleomagnetic poles must be switched. Our data also show the occurrence of at least 15 symmetric geomagnetic field reversals, indicating that the paleomagnetic results from the late Mesoproterozoic Keweenawan lavas do not reflect a worldwide and persistent asymmetric field during the Proterozoic.

1. Introduction

Recent paleomagnetic analyses of the Brunhes and Matuyama chrons show that no statistical difference exists between the normal and reversed time-averaged geomagnetic fields [e.g., *McElhinny et al.*, 1996]. In both polarity states, the time-averaged field closely conforms to a geocentric axial dipole (GAD) with a minor (a few percent) contribution from an axial quadrupole [e.g., *Carlut and Courtillot*, 1998]. The dipolar nature of the field has likely held during the whole Cenozoic and the Mesozoic, although the contribution from the axial quadrupole may have varied slightly during those periods [*Coupland and Van der Voo*, 1980; *Livermore et al.*, 1984; see also *Kent and Smethurst*, 1998].

For much older periods, such as the Proterozoic, the characteristics of the Earth's magnetic field are still very poorly constrained from paleomagnetic data. A major reason for this is the difficulty in finding nonremagnetized Proterozoic rocks. Another problem is the large uncertainties on Proterozoic plate reconstructions despite recent progress made in defining the assembly and the breakup of the Rodinia supercontinent at the end of the Proterozoic (between ~1100 Ma and 750 Ma [e.g., *Hoffman*, 1991; *Powell et al.*, 1993]). In principle, paleomagnetic data can test the dipolar nature of the geomagnetic field by comparing coeval paleomagnetic poles obtained from a large undeformed block. *Evans* [1976] proposed a more general method based on the analysis of the probability distribution of paleomagnetic inclinations over a time interval long enough to ensure that an unbiased random sampling distribution is considered. When applied to the Precambrian, the Evans method reveals an anomalous inclination distribution which may indicate a significant contribution of multipolar sources [*Kent and Smethurst*, 1998]. Although not excluding a bias in their analysis due to a particular low-latitude geographical distribution of the plates, *Kent and Smethurst* [1998] propose that the nondipole field was of higher amplitude during the Proterozoic, with possibly a zonal octupolar field of intensity up to 25% of the GAD.

Interestingly, several paleomagnetic studies of Proterozoic rocks have suggested the occurrence of asymmetrical polarity reversals, which may indicate the presence of a significant long-standing and nonreversing field. The best case for the existence of asymmetrical reversals comes from the Keweenawan rocks of the Lake Superior region dated at 1110-1080 Ma [*Pesonen and Nevanlinna*, 1981; *Nevanlinna*

Paper number 1999JB900354.
0148-0227/00/1999JB900354$09.00

and Pesonen, 1983; *Cannon and Nicholson*, 1996]. In these volcanic rocks a ~25° difference in inclination was observed between the normal and reversed directions, whereas the declinations were roughly 180° apart. *Pesonen and Nevanlinna* [1981], and *Nevanlinna and Pesonen* [1983] considered that this asymmetry reflects a persistent worldwide geomagnetic feature during this period and proposed a two-dipole field configuration model to fit the data. In this simplistic model, one dipole sporadically changes its polarity whereas the other does not (or more rarely), thus introducing the nonantiparallel normal and reversed directions. Alternatively, a high-amplitude nondipole field would also permit a model in which the reversing dipolar field and the nondipole field behaved differently [*Kent and Smethurst*, 1998]. Whatever their origin, the field asymmetry and/or a high-amplitude nondipole field during the Proterezoic would question paleomagnetism's ability to make paleogeographic reconstructions for this period.

Magnetostratigraphy may help address the question of a Proterozoic asymmetric geomagnetic field. For this reason, we studied the magnetostratigraphy of two late Mesoproterozoic sedimentary formations in Siberia. These data also provide new constraints on the paleoposition of Siberia with respect to the Rodinian supercontinent. In particular, the possibility for a Laurentia - Siberia connection during this period is presently poorly constrained by paleomagnetic data, and the paleogeographic reconstructions based on geological data are contradictory.

2. Geologic Setting, Lithology, and Sampling of the Malgina and Linok Formations

The Malgina and Linok Formations are two distinct, but lithologically very similar members of the Riphean successions exposed in the Uchur-Maya and Turukhansk regions,

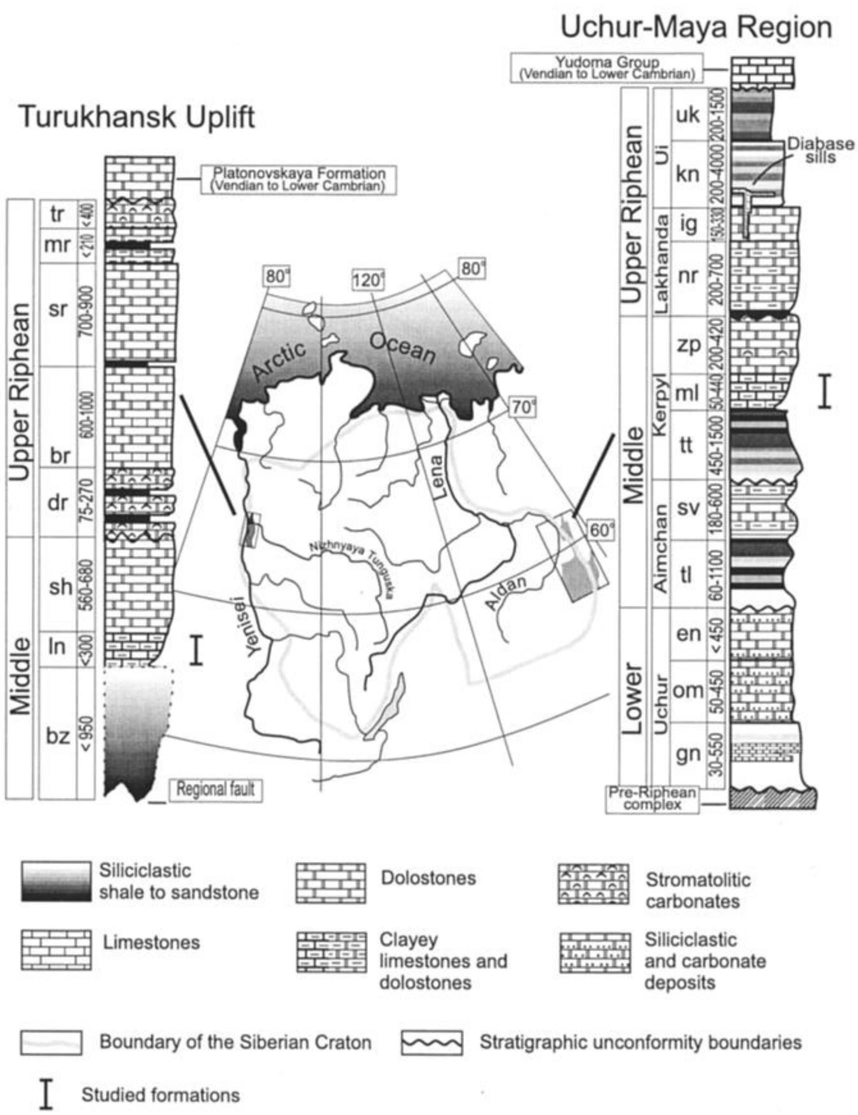

Figure 1. Locality map of the Uchur-Maya and Turukhansk regions and simplified description of the Riphean successions in both regions. Names of the geologic formations in the Uchur-Maya region are as follows: gn, Gonam; om, Omakhta; en, Enna; tl, Talyn; sv, Svetla; tt, Totta; ml, Malgina; zp, Tsipanda; nr, Neryuen; ig, Ignikan; kn, Kandyk; uk, Ust'kirba. Names of the formations in the Turukhansk region are as follows: bz, Bezymyannyi; ln, Linok; sh, Sukhaya Tunguska; dr, Derevnya; br, Burovaya; sr, Shorikha; mr, Miroyedikha; tr, Turukhansk.

2400 km apart, along the southeastern and northwestern margins of the Siberian craton, respectively (Figure 1).

2.1. Malgina Formation

The Uchur-Maya region comprises a vast exposure of Riphean deposits that rest unconformably on Archean crystalline basement and late Paleoproterozoic rocks and that are unconformably overlain by upper Vendian to Middle Cambrian sediments. Two tectonic structures separated by an eastward dipping thrust are located within the area: the Uchur-Maya undeformed zone in the southwest and the north-south trending Yudoma-Maya fold belt in the east [*Semikhatov and Serebryakov*, 1983]. Our samples were collected from four sections located 50-120 km apart in the middle part of the Maya river basin, along the eastern margin of the first structure (Figure 2). The strata at three of the sections (Haahar, Emelekeen, and Selia) are flat lying, with dips not exceeding 2°-3°. The rocks of the fourth Ingili section are locally deformed, with dips up to 65°-90°, by the emplacement of an alkaline ultrabasic pre-Vendian intrusion (~640-660 Ma [e.g., *Semikhatov and Serebryakov*, 1983]).

The Uchur-Maya Riphean succession is subdivided into five unconformity-bounded groups: Uchur (lower Riphean), Aimchan and Kerpyl' (middle Riphean), and Lakhanda and Ui groups (upper Riphean [*Semikhatov and Serebryakov*, 1983; *Semikhatov*, 1991]). The most widespread Riphean unit in the Uchur-Maya region is the Kerpyl' group, which consists from bottom to top of the siliclastic Totta, the limy Malgina, and the dolomitic Tsipanda Formations (Figure 1).

In the studied sections the Malgina Formation is a 40-140 m-thick unit dominated by variegated (green, gray, and buff and subordinate yellow, pale, and red) horizontally or hummocky cross-laminated micritic limestone. These limestones grade upward into an extensive discontinuous unit, up to 28-30 m thick, of alternating black carbonaceous shales and limestones. Subordinate lithologies include microbially laminated limestones, dolomites, and occasionaly silty and stro-

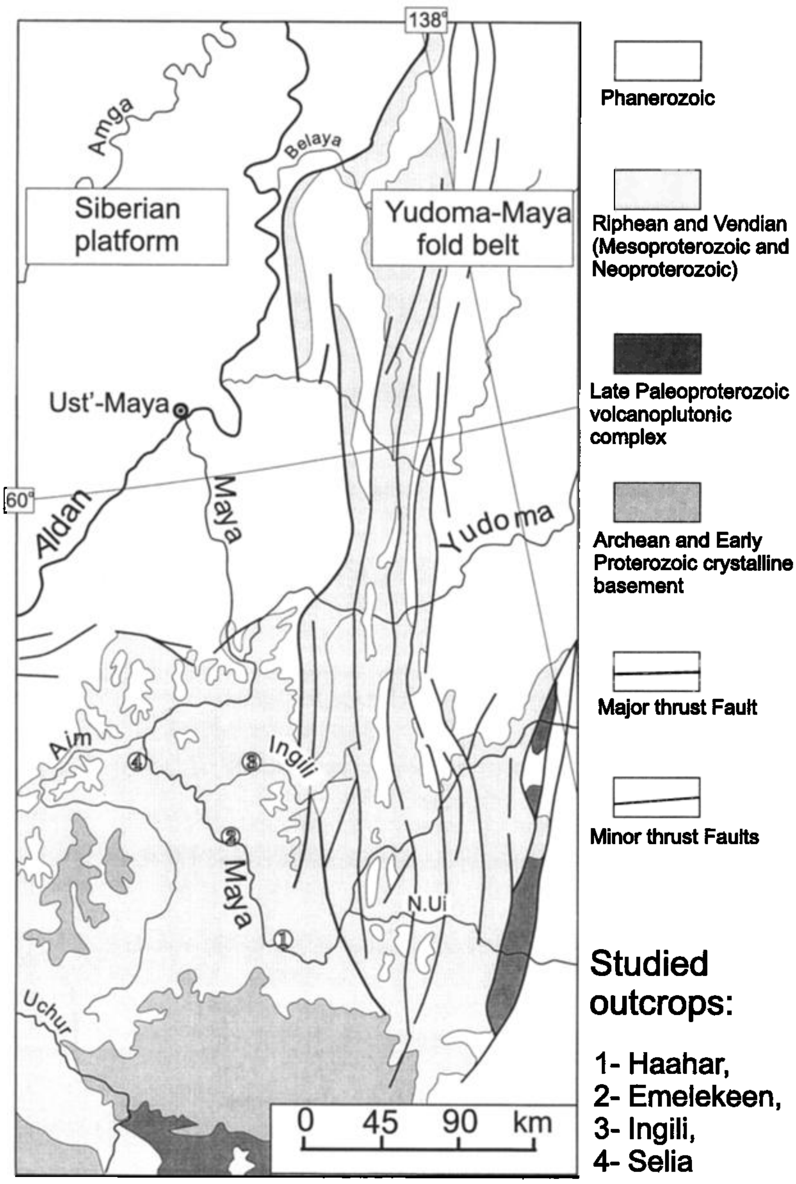

Figure 2. Simplified geological map of the eastern part of the location of the Uchur-Maya region (modified from *Semikhatov and Serebryakov* [1983]) and location of the studied sections.

matolitic limestones. Lenses and beds of flakestones occur in the lower and middle parts of the formation. This lithology indicates that the Malgina Formation, which thickens and deepens eastward, was accumulated in an open marine environment below and near the storm wave base.

2.2. Linok Formation

The Turukhansk region corresponds to a marginal uplift along the north-western edge of the Siberian craton. Within the uplift, Riphean deposits define three north-south trending, east transported, thrust-bounded blocks. In each block these deposits form either gentle (15°-35°) westward dipping homoclines or an asymmetrical syncline. Late Vendian to Upper Cambrian sediments lie subhorizontally and are separated from Riphean rocks by a gentle unconformity (2°-5°), which locally may reach up to 80°-90° [*Semikhatov and Serebryakov*, 1983]. Paleomagnetic samples were collected from six outcrops located several tens of kilometers apart in two different blocks (Figure 3).

The oldest succession exposed within the Turukhansk uplift belongs to the late middle Riphean and comprises three units, the Bezymyannyi, the Linok, and the Sukhaya Tunguska Formations (Figure 1), the latter being separated from the overlying late Riphean Derevnya Formation by an important erosional surface. Our study is focused on the Linok Formation, which is subdivided into three units [*Petrov*, 1993]. The lower unit, which in our sections is 20-46 m-thick and from which most of the paleomagnetic samples were collected, consists of greenish-gray, partly red-colored platy and horizontally laminated micritic limestones with subordinate marls, calcareous shales, and rare siltstones at the base. The middle unit (42-70 m thick) contains black carbonaceous shales and gray micritic limestones. The upper unit (95-140 m thick) is dominated by light gray and greenish-gray finely laminated and hummocky cross-laminated micritic limestones. The lower two units were deposited in relatively deep-water marine settings while the upper one reflects a gradual decrease of the paleodepth [*Petrov*, 1993; *Veis and Petrov*, 1994].

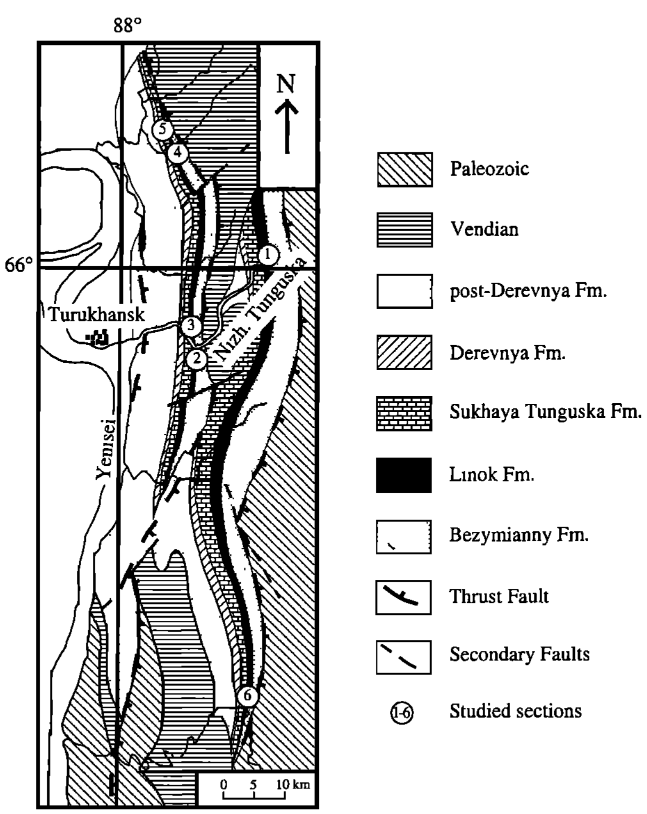

Figure 3. Simplified geological map of the Turukhansk uplift [after *Pavlov and Petrov*, 1996] and location of the sampled outcrops.

3. Age of the Studied Formations

The lithologies of the Kerpyl' and the Lakhanda groups from the Uchur-Maya region and the Bezymyannyi through the Derevnya Formations from the Turukhansk region are strikingly similar. This similarity was originally used as evidence for their correlation, which is further supported by paleontological (stromatolites and organic walled microfossils), geochronological, and chemostratigraphic data.

Stromatolite assemblages within the Riphean Uchur-Maya and Turukhansk sections undergo important changes in their taxonomic compositions at the base of the Lakhanda group and Derevnya Formation, respectively. Assemblages confined to the upper Kerpyl' and to the Sukhaya Tunguska deposits are dominated by endemic form species of the long-ranging middle Riphean to late Riphean form genera and contain several forms known to occur in the upper middle-lower upper Riphean interval. In the Lakhanda group and Derevnya Formation the stromatolite assemblages are replaced by diverse and remarkable ones which contain abundant middle-upper Riphean form species of long-ranged form genera, together with quantitatively subordinate but stratigraphically important taxa (*Baicalia lacera Semikhatov*, *Inzeria tjomusi Krylov*, and *Jurusania cylindrica Krylov*) which appear in the lower upper Riphean of the Ural Mountains, of northern Africa and elsewhere [*Krylov*, 1975; *Semikhatov and Raabens*, 1994, 1996; *Knoll and Semikhatov*, 1998].

The stromatolite-based constraints on the stratigraphic age of the Uchur-Maya and Turukhansk Riphean successions are corroborated by microfossils [*Herman*, 1990; *Petrov and Veis*, 1995; *Veis and Petrov*, 1995]. Organic walled microfossils display distinct changes in taxonomic composition at the base of the Lakhanda and Derevnya strata. The shales of the Totta and Bezymyannyi Formations contain very similar microfossil assemblages yielding, along with very long ranging, small simple forms, several distinctive taxa, for example, large Chuaria, broad sheaths of Rectina, Rugosoopsis, and Polytrichoids, and branching thalii of Ulophyton and Majaphyton, which are representative of the Mesoproterozoic (for discussion see *Sergeev et al.* [1995] and *Semikhatov* [1995]). The Lakhanda and Derevnya assemblages are notable for the appearance and wide distribution of a number of spectacular upper Riphean morphotypes, for example, acantamorphic acritarchs, tufted sheats, cylindrical spirals, and fungi. The appearance of these taxa, and particularly of the acantomorphic *Trachyhystrichospharea aimika* and *Trachyhystrichospharea stricta*, marks an important change in the Proterozoic microbiota observed across the middle-upper Riphean boundary [*Knoll and Sergeev*, 1995; *Semikhatov*, 1995].

The paleontological data therefore indicate that (1) the middle-upper Riphean boundary should be placed between the

Kerpyl' and Lakhanda groups of the Uchur-Maya succession and between the Sukhaya Tunguska and the Derevnya Formations in the Turukhansk region, and (α2) the Malgina and Linok Formations belong to the late middle Riphean (late Mesoproterozoic).

The maximum age of the Uchur-Maya Riphean succession is constrained by U-Pb dates of 1703±18 and 1727±11 Ma on zircon and monazite from the youngest pre-Uchur group magmatic rocks [*Neymark et al.*, 1992; *Larin et al.*, 1997]. Numerous K-Ar determinations on globular glauconite from the Riphean succession, which have been interpreted to record depositional ages, show an upsection pattern of decreasing age. Ages of 1520-1360 and 1200-1230 Ma were obtained for the Uchur and middle Aimchan groups, respectively, while glauconite collected in the Totta Formation produced ages of 1170-1070 Ma for the lower and middle parts of the unit and 1020-970 Ma for its upper part [*Semikhatov and Serebryakov*, 1983, and references therein]. Glauconite-illite minerals from the overlying Neryuen, Ignikan (Lakhanda group), and lowermost Ui deposits yielded K-Ar ages of 950±30, 840±40, and 760-700 Ma, respectively. However, several of these data appear to be at odds with recent U-Pb baddeleyite dates of 1004±5 and 947±7 Ma from mafic sills cutting the lower part of the Ui group and the upper part of the Lakhanda group [*Semikhatov and Serebryakov*, 1983; *Rainbird et al.*, 1998]. A Sm-Nd isochron also produced a 948±18 Ma date for the sills [*Pavlov et al.*, 1992]. Furthermore, a maximum age of 1300±5 Ma for the Kerpyl' group, which includes the studied Malgina Formation, was recently obtained by U-Pb dating on detrital zircon in the Totta Formation [*Khudoley et al.*, 1999]. These isotopic dates constrain the age of the Malgina Formation to be surely younger than 1300±5 Ma, most likely younger than 1150 Ma, and older than 1004±15 Ma.

Age constraints on the Turukhansk Riphean succession are more limited [e.g., *Knoll et al.*, 1995]. A recent 16-point Pb-Pb isochron on carbonates from the middle Sukhaya Tunguska Formation yields an age of 1035 ± 60 Ma [*Ovchinnikova et al.*, 1995]. K-Ar determinations on globular glauconite-illite minerals from different levels within the succession are considered to reflect resetting of the K-Ar clock ~850-900 Myr ago [*Semikhatov and Serebryakov*, 1983; *Knoll et al.*, 1995], while that from the counterparts of the Bezymyannyi and Derevnya Formations exposed in the Yenisei Ridge (south of the Turukhansk region) give ages of ~1100 and 1007±15 - 924 Ma, respectively [*Shenfil'*, 1991, and references therein]. The age of the Linok Formation therefore lies within the ~1035±60 -1100 Ma time interval [*Gorokhov et al.*, 1995].

Hence available paleontological and radiometric data are mutually consistent and define a late middle Riphean (late Mesoproterozoic) age for both the Kerpyl group and the Bezymyannyi-Sukhaya Tunguska succession, whereas radiometric data indicate that these rock units fall within the same, rather narrow time interval (according to Precambrian standards). It is probable that the lithologically similar middle members of the above units, the Linok and Malgina Formations, are coeval deposits older than 1000 Ma, likely around 1050-1100 Ma. Recent strontium and carbon chemostratigraphic data obtained from both formations strongly support this correlation [*Gorokhov et al.*, 1995; *Vinogradov et al.*, 1998; *Bartley et al.*, 2000].

4. Paleomagnetic Analyses

The magnetic measurement of the samples from the Linok Formation was carried out with a CTF three-axis cryogenic magnetometer in the magnetically shielded laboratory at the Institut de Physique du Globe de Paris. Analyses of samples from the Malgina Formation were conducted using a 2G three-axis cryogenic magnetometer in the paleomagnetic laboratory at the Institutt für Allgemeine und Angewandte Geophysik of München (Germany).

4.1. The Malgina Formation

The magnetization of ~120 hand samples was analyzed. The samples were thermally demagnetized in 12-20 steps (Figure 4). A low unblocking temperature component (LTC) is isolated below 300°-340°C (Figures 4a and 4d). The LTC directions are roughly parallel to the present geomagnetic field direction in the studied area. At higher temperatures another component directed towards the origin of the orthogonal diagrams is isolated up to 570°-590°C or 680°C, depending on the samples. These unblocking temperatures indicate that hematite (Figures 4a and 4b) and/or magnetite (Figures 4c and 4d) carry the remanence. Sometimes, both magnetic minerals are present in the same sample (Figures 4e and 4f). Note that in any case, the directions are similar. This magnetic mineralogy is confirmed by isothermal remanent magnetization (IRM) experiments (Figure 5a). In some cases, the magnetization is saturated in low fields (~0.3 T), whereas for other samples often of redish color, the magnetization is still not saturated at 1.2 T.

The high unblocking temperature component (HTC) clearly contains two magnetic polarity states (Figures 4a, 4c, and 4e for one polarity and Figures 4b, 4d, and 4f for the other). The HTC directions are shown in Figure 6, both in equal area projections and in magnetostratigraphic sequences. In the declinations and inclinations versus depth diagrams (right plots in Figure 6), the results obtained in this study are shown by circles, and only these data will be considered for mean computations. The squares indicate directions previously obtained from an old collection of samples demagnetized in Moscow at 450°C, which are only used to better constrain the magnetic polarity sequences (note that for the Selia section, all the new data lack a stratigraphic control). The magnetic polarity patterns obtained from the four sections are roughly similar, and a composite magnetostratigraphic sequence can be proposed (Figure 7a), although several magnetic polarity intervals are defined by only one sample. Numerous reversals are present in the lower and middle parts of the sections, whereas a predominant reversed polarity is observed in their upper parts (if we assume that Siberia was located in the Southern Hemisphere during this period; see section 5).

The mean HTC directions from the four sections are shown in Figure 8. For the four sections, a positive reversal test is obtained (Table 1 and Figures 8a and 8b) [*McFadden and McElhinny*, 1990]. The mean directions calculated at the site level yield a positive fold test at the 99% level (Figures 8c and 8d) [*McElhinny*, 1964]. We also report the paleomagnetic directions isolated from 22 pebbles sampled in a conglomerate intercalated in the lower part of the Selia section (Figure 9). These pebbles exhibit demagnetization behaviors similar to that observed in the lower part of the Selia section,

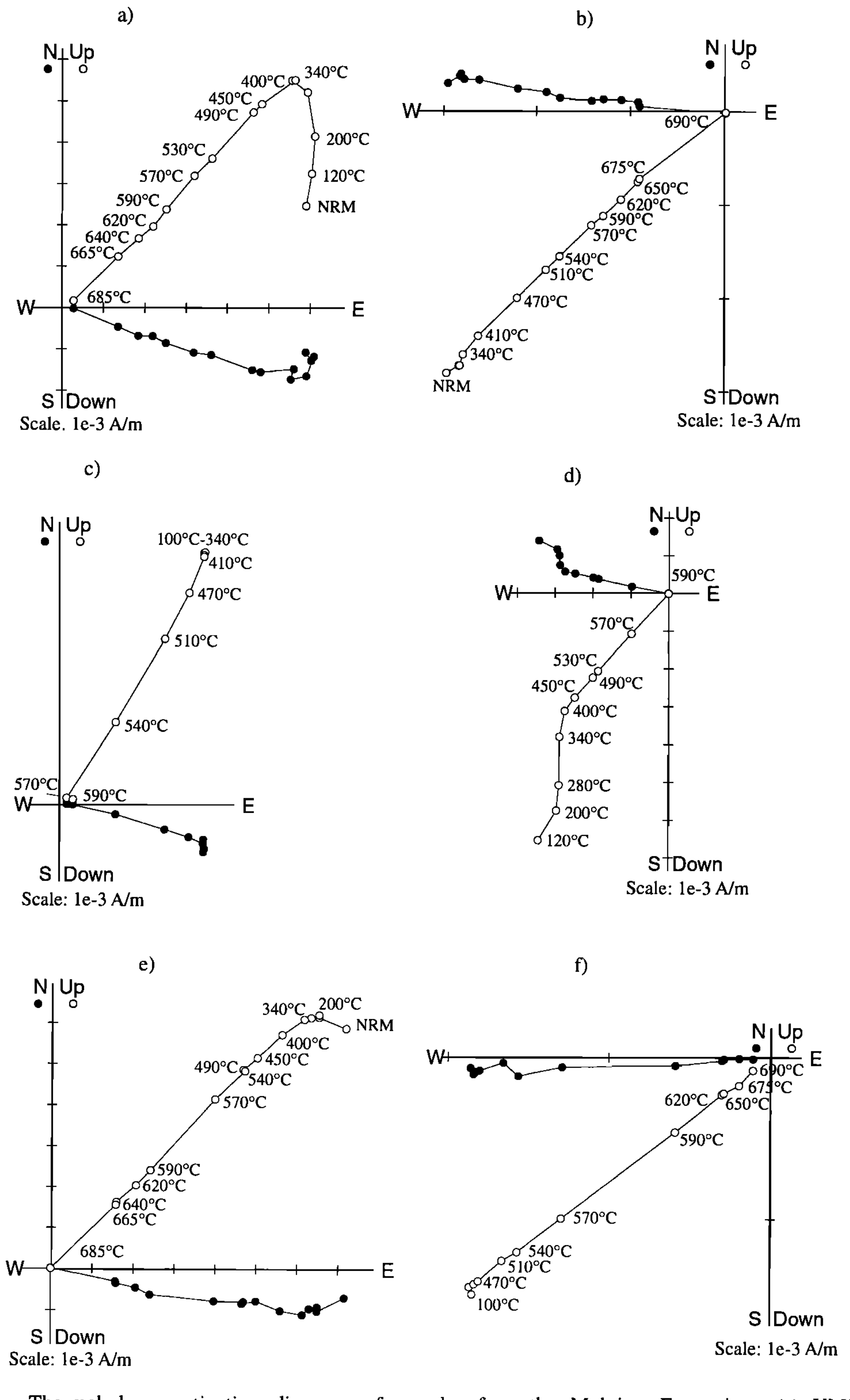

Figure 4. Thermal demagnetization diagrams of samples from the Malgina Formation: (a) UM26, (b) UM259, (c) UM76, (d) UM5, (e) UM241, and (f) UM73. Solid circles are in the horizontal plane, and open circles are in the vertical plane. All diagrams are in stratigraphic coordinates. NRM, natural remanent magnetization.

where the magnetization is carried by magnetite and hematite (Figures 9a and 9b). The directions of their HTC component are clearly randomly distributed and therefore yield a positive conglomerate test. Altogether, the paleomagnetic tests indicate that the magnetization of the four studied sections was acquired during or very soon after sediment deposition.

4.2. The Linok Formation

The thermal treatment shows clear demagnetization paths in ~160 from 230 samples collected from the Linok Formation (Figure 10). A soft component, which has roughly the direction of the present geomagnetic field, is isolated in

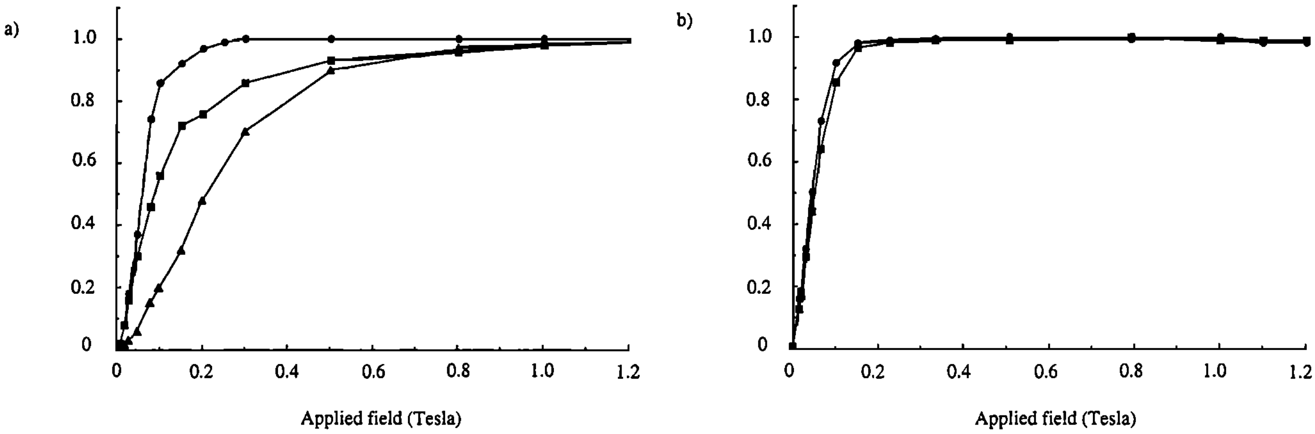

Figure 5. Isothermal remanent magnetization (IRM) experiments up to 1.2 T carried out on samples from the (a) Malgina Formation and the (b) Linok Formation. Read 1e-3 as 1×10^{-3}.

the first demagnetization steps until ~200°-300°C. An intermediate component is then isolated between ~300° and 420°C. Although this component is obvious in many samples (Figures 10a and 10b), its direction cannot be precisely determined because of overlapping with the other components. In contrast, a clear HTC temperature component is obtained between 450° and 560-580°C. This latter component, which after bedding correction points either toward south with positive inclinations (Figures 10a and 10b) or toward the north with negative inclinations (Figures 10c and 10d) and thus clearly has the two magnetic polarity states.

In contrast with the data from the Uchur-Maya sections, the magnetization of the Linok Formation is homogeneously carried by a mineral of the magnetite family. This is obvious

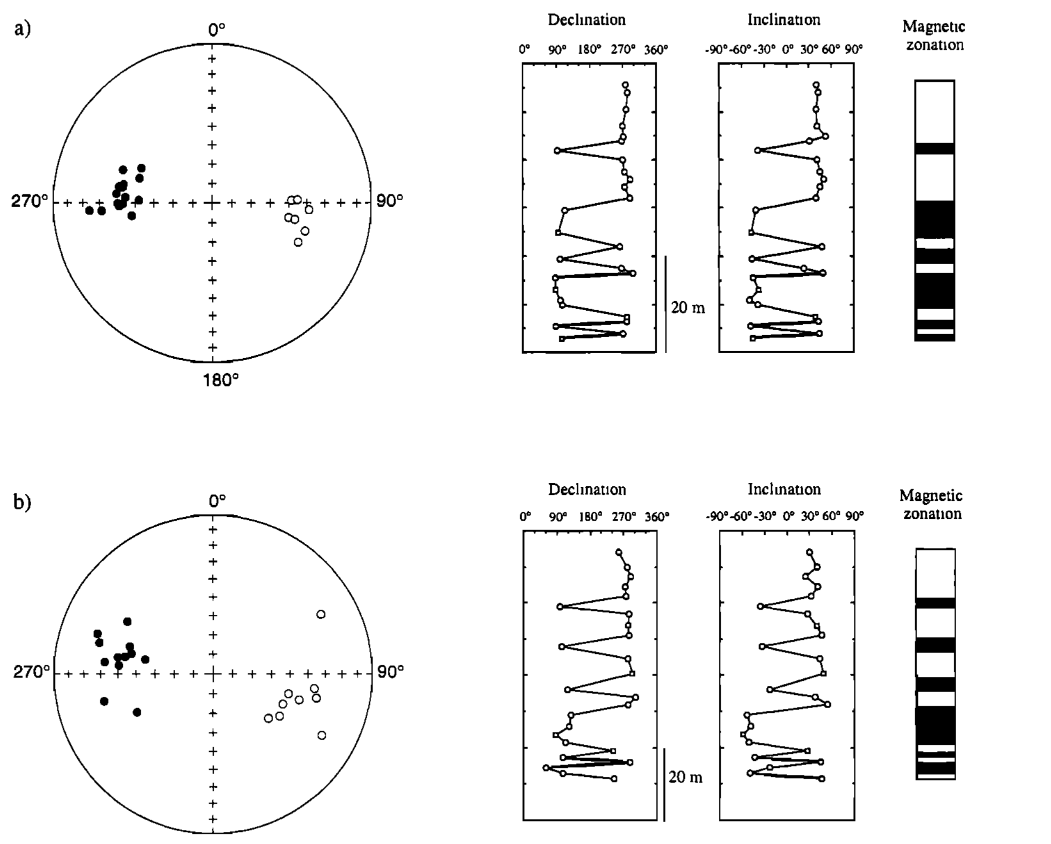

Figure 6. Directions in stratigraphic coordinates of the high unblocking temperature component obtained in four sections from the Malgina Formation (a) Emelekeen section, (b) Haahar section, (c) Ingili section, and (d) Selia section. The corresponding magnetostratigraphic sequences are shown in the right plots assuming that Siberia was located in the Southern Hemisphere. The circles show the data obtained in this study and considered for mean computations. The squares indicate results previously obtained from an old collection of samples, which are only used to constrain the magnetostratigraphic sequences.

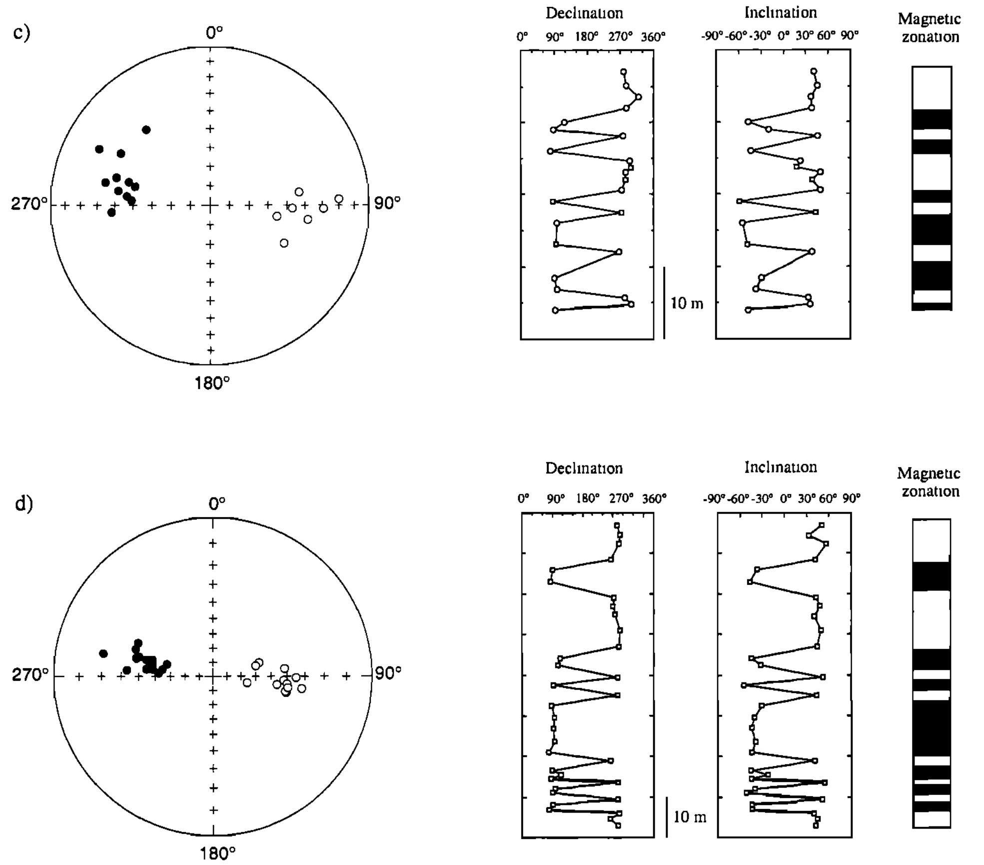

Figure 6. (continued)

from thermal demagnetization achieved at 560°-580°C, and this is confirmed by IRM experiments which show that all the magnetization is saturated in a ~0.2 T field (Figure 5b). In some samples the demagnetization behavior is relatively scattered in the high-temperature range (above 400°C), which may be owing to the transformation of iron sulfides during the thermal treatment. These transformations are also detected from measurements of the bulk susceptibility after each demagnetization step, indicating an increase of the value with increasing temperature.

Five sections show HTC directions of both magnetic polarities (Figure 11). Although the magnetic polarity sequences are relatively fragmentary, they indicate the occurrence of several magnetic reversals during the lower and middle parts of the Linok Formation and a predominant reversed polarity during its upper part (Figure 7b; again assuming that Siberia was located in the Southern Hemisphere). These characteristics are similar to those previously observed from the Malgina Formation (Figure 7a). In all sections showing magnetic reversals the HTC directions yield a positive reversal test (Figures 12a and 12b and Table 2). Moreover, the mean direction estimated for the six sections yields a positive fold test at the 99% level (Figures 12c and 12d). These characteristics indicate that the magnetization of the Linok Formation was likely acquired during the sedimentation process.

5. Discussion

5.1. Paleoposition of Siberia

The paleomagnetic study of the Malgina and Linok Formations provides two well-defined mean directions (Tables 1 and 2). The corresponding geomagnetic poles are statistically different, which indicates that a relative motion took place between the northwestern and southeastern parts of Siberia. This is in agreement with the suggestion of *Gurevich* [1984] and *Pavlov and Petrov* [1996], who proposed that the opening of the Viluy rift and the formation of the Viluy graben during the Paleozoic generated a relative rotation between these two parts of Siberia. From the available Proterozoic and Paleozoic paleomagnetic data, *Smethurst et al.* [1998] have recently estimated this rotation to be of the order of 20° with a rotation pole located in the western end of the Viluy graben at 60°N, 100°E (northwest Siberia rotating anticlockwise relative to southeast Siberia). Using this Euler pole, we observe that a rotation of ~25°-30° would be necessary to reconcile our two paleomagnetic poles, roughly similar to the value estimated by *Smethurst et al.* A second tectonic possibility may, however, also contribute to this difference. Indeed, whereas the Uchur-Maya region is unambiguously representative of the Siberian craton, the Turukhansk region belongs to a disturbed margin of the cra-

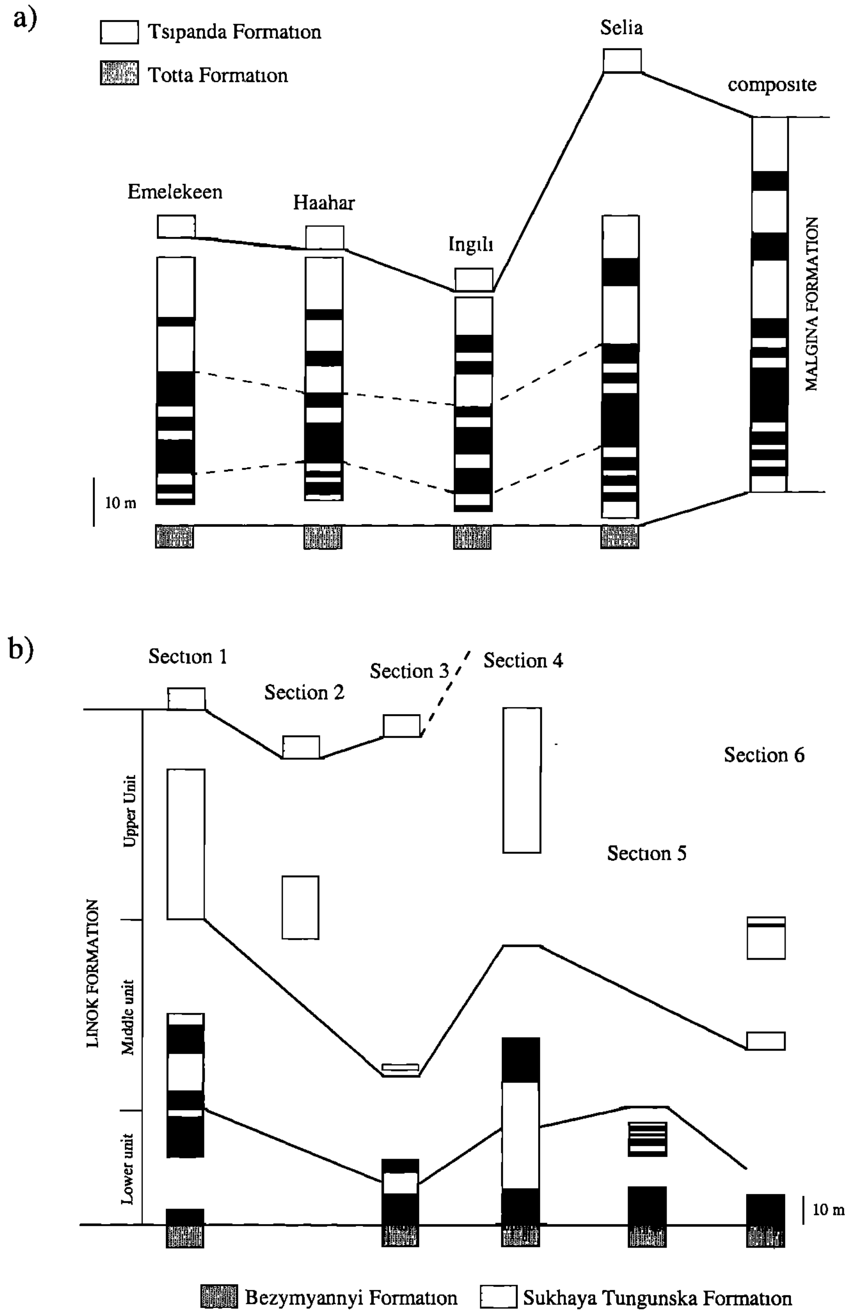

Figure 7. Comparison between the different magnetostratigraphic sequences obtained from the (a) Malgina Formation and the (b) Linok Formation.

ton where relative rotations may have occurred during thrusting. However, the lack of statistically meaningful differences in paleomagnetic pole positions calculated for the Linok deposits exposed in two different thrust-bounded blocks and the absence of large-scale transverse slip faults in the regional structure render this suggestion unlikely. A final possibility would be that the discordance in paleomagnetic poles reflects an age difference between the Malgina and Linok Formations. However, again, the stratigraphic, biostratigraphic, and chemostratigraphic data contradict this alternative. It seems, therefore, reasonable to suggest that the opening of the Viluy rift is responsible for all the difference between our results. However, in order to meet the rigidity requirement for paleomagnetic reconstruction, we will use in this study only the paleomagnetic pole obtained from the Uchur-Maya region to constrain the paleoposition of Siberia.

A major problem is the assignment of magnetic polarities to the observed directions, which is linked to the hemispheric position of Siberia during the Proterozoic. *Smethurst et al.* [1998] have recently discussed this issue. They propose that Siberia remained in the Southern Hemisphere from 1100 to ~470 Ma (from the late Mesoproterozoic to the Ordovician), with only a brief incursion in the Northern

Table 1. Paleomagnetic Results Obtained From the Uchur-Maya Region

	N	Geographic Coordinates				Stratigraphic Coordinates				Reversal Test		Paleomagnetic Poles		
		D, deg	I, deg	K	α_{95}, deg	D, deg	I, deg	K	α_{95}, deg	γ, deg	γ_c, deg	Lat., deg	Long., deg	dp/dm, deg
Emelekeen (58.3°N, 135.0°E)														
Normal polarity	7	99.3°	-44.3°	92.8	6.3°	99.3°	-44.3°	92.8	6.3°					
Reversed polarity	16	275.5°	42.3°	66.7	4.5°	275.5°	42 3°	66.7	4.5°					
General	23	96.6°	-42.9°	73.9	3.5°	96.6°	-42.9°	73.9	3.5°	3.4°	7.8°	-24.4°	233.4°	2.7°/4.3°
Haahar (57.6°N, 135.4°E)														
Normal polarity	9	104.2°	-42.0°	17.1	12.8°	105.0°	-41.8°	17.8	12.6°					
Reversed polarity	12	278.7°	39.4°	30.7	8.0°	278.8°	39.4°	30.4	8.0°					
General	21	101.0°	-40.5°	23.7	6.7°	101.4°	-40.5°	24.0	6.6°	5.3°	13.7°	-25.4°	229.0°	4.7°/7.3°
Selia (58.7°N, 134.1°E)														
Normal polarity	12	93.4°	-44.8°	44.3	6.6°	93.4°	-44.8	44.3	6.6°					
Reversed polarity	15	282.1°	42.6°	62.1	4.9°	282.1°	42.6°	62.1	4.9°					
General	27	98.7°	-43.3°	62.0	3.6°	98.3°	-43.7°	50.2	4.0°	6.7°	7.8°	-25.9°	231.3°	3.1°/5.0°
Ingili (58.5°N, 135.5°E)														
Normal polarity	7	191.6°	-61.1°	39.9	9.7°	94.6°	-40.2	31.1	11.0°					
Reversed polarity	11	8.5°	52 1°	33.5	8.0°	287.0°	40.8°	34.4	7.9°					
General	18	189.5°	-52.6°	33.9	6.0°	102.2°	-40.7°	31.5	6.3°	9.4°	12.6°	-26.0°	228.1°	4.6°/7.6°
Mean 1	4	114.1°	-50.8°	8.1	34.5°	99.7°	-42.0°	1032.9	2.9°	2.6°	5.9°	-25.4°	230.5°	A_{95}=2.6°
Mean 2	89	109.5°	-49.8°	10.1	5.0°	99.4°	-42.2°	39.1	2.4°	2.5°	5.0°	-25.4°	230.8°	1.8°/3.0°

N is number of samples or sites averaged; D and I are declination and inclination of mean paleomagnetic directions; K is concentration parameter [*Fisher*, 1953]; α_{95} is radius of 95%; γ and γ_c are angular distances [*McFadden and McElhinny*, 1990]; Lat. and Long. are north latitude and east longitude of paleomagnetic poles.

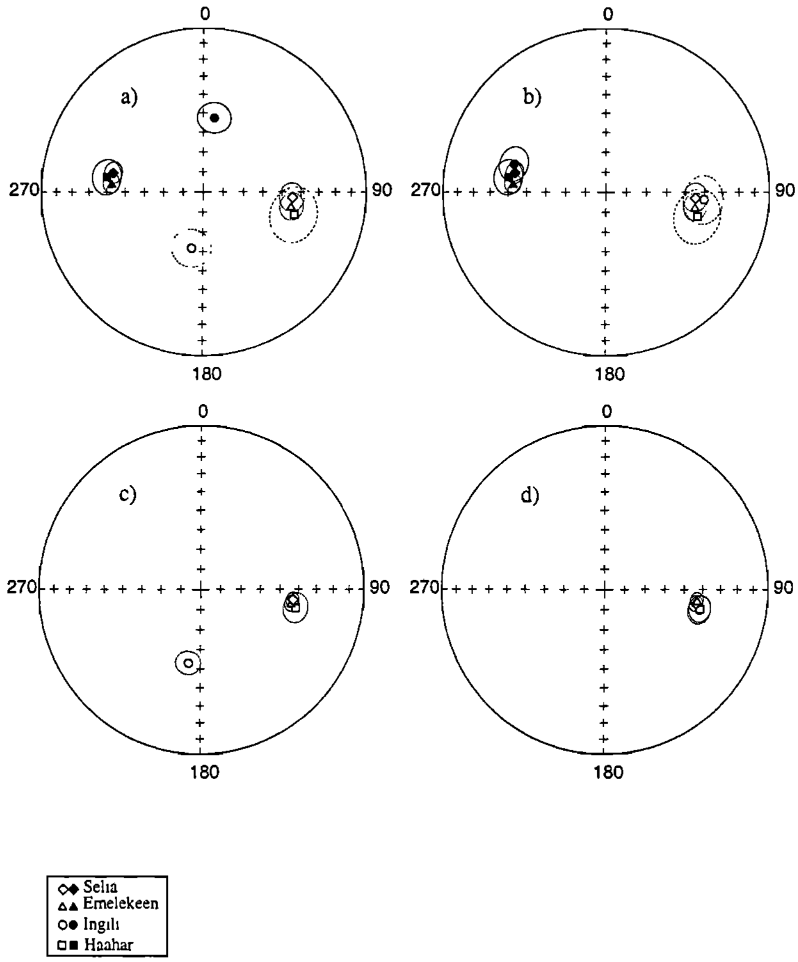

Figure 8. Mean high unblocking temperature component (HTC) directions obtained from the Malgina Formation: (a) mean directions of normal and reversed magnetic polarities obtained from the four sections before bedding correction, (b) mean directions of normal and reversed magnetic polarities obtained from the four section after bedding correction, (c) mean directions combining both polarities from the different sections before bedding correction, and (d) mean directions combining both polarities from the different sections after bedding correction.

Hemisphere around 730 Ma. Under this assumption, our results indicate that the present-day northern shoreline of Siberia was roughly facing to the west around 1050-1100 Myr ago, in agreement with the paleoposition suggested by *Smethurst et al.* However, a definitive answer for the Southern Hemisphere option will be obtained by studying Vendian and Lower Cambrian Siberian deposits, two periods for which paleomagnetic data are presently either missing (Vendian) or contradictory (e.g., Lower Cambrian [*Kirschvink and Rozanov*, 1984; *Pisarevsky et al.*, 1997]).

It is also of interest to compare the paleoposition of the Siberian craton with respect to Rodinia. Following several authors [e.g., *Hoffman*, 1991; *Powell et al.*, 1993; *Dalziel*, 1997], the ~1100 Ma period corresponds to the beginning of the amalgamation of Rodinia along the Grenvillian orogenic belts. This supercontinent would have existed until ~725-750 Ma. Around 1050-1100 Ma the paleoposition of Laurentia is constrained by several paleomagnetic poles [e.g., *Powell et al.*, 1993; *Costanzo-Alvarez et al.*, 1993; *Weil et al.*, 1998]. Here we consider three paleomagnetic poles with ages likely coeval to the Malgina and Linok Formations: (1) paleomagnetic pole 1, age range 1050-1060 Ma, λ=5.8°, φ=178.0° (also considered by *Powell et al.* [1993]; Table 3); (2) paleomagnetic pole 2, age range 1060-1075 Ma, λ=29.0°, φ=176.7°, A_{95}=8.5°, N=3 (estimated from the list of results given by *Weil et al.* [1998]; Table 3); and (3) paleomagnetic pole 3, age range 1080-1100 Ma, λ=33.6°, φ=181.9°, A_{95}=6.6°, N=4 (estimated from the list of results given by *Weil et al.* [1998]; Table 3). Using these paleomagnetic poles, our data indicate that Siberia could not be part of the Rodinian supercontinent at that time if we assume the classical configuration showing the Laurentia and Siberia connected along their present northern shorelines (Figure 13a) [*Condie and Rosen*, 1994; *Pelechaty*, 1996; *Smethurst et al.*, 1998]. However, this connection is geologically and paleomagnetically poorly substantiated [see also *Piper*, 1982, 1987]. In particular, it has been recently discussed and challenged by *Rainbird et al.* [1998]. From new U-Pb geochronologic data obtained from southeast Siberia (Uchur-Maya region), these authors propose a connection between southern Siberia and northwest Laurentia during the middle and late Riphean. Following this configuration, our paleomagnetic results would indicate that the northern part of Laurentia was facing west (Figure 13b), exactly opposite to the position considered in most studies. This solution is similar to the paleoposition of Laurentia derived if the polarity

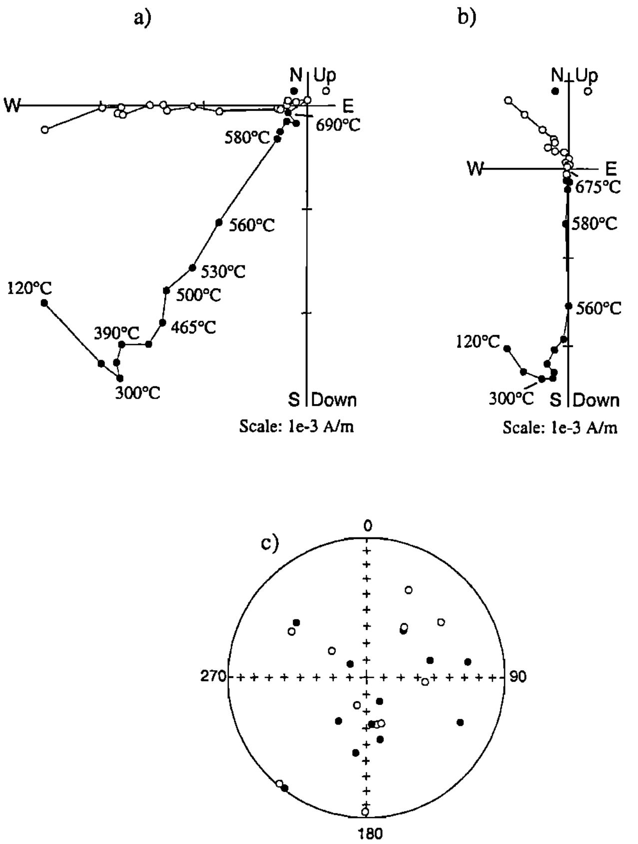

Figure 9. Data obtained from a conglomerate located in the lower part of the Selia section from the Malgina Formation: (a) thermal demagnetization diagram in stratigraphic coordinates (same convention as in Figure 4) for sample G4, (b) thermal demagnetization diagram in stratigraphic coordinates for sample G14, and (c) HTC directions obtained from 27 pebbles.

option for the Laurentian poles is switched as was previously suggested by *Park* [1994; see also *Schmidt and Morris*, 1977; *Schmidt and Clark*, 1997]. By inverting the three mean paleomagnetic poles previously considered for Laurentia, we indeed obtain a paleoposition which allows a connection between Laurentia and Siberia (Figure 13b). In this way, Siberia would belong to the Rodinian supercontinent. It is worth noting that a tight fit is obtained between Siberia and Laurentia when paleomagnetic pole 2 is considered for Laurentia (Figure 13b), which is in very good agreement with the geologically based connection proposed by *Rainbird et al.* As noted by *Powell et al.* [1993] and *Schmidt and Clark* [1997], this solution would have important consequences for the Rodinian configuration and on the Late Precambrian-lower Paleozoic paleogeographic reconstructions between Laurentia and Siberia on one hand and the Gondwanian blocks on the other one. However, we mention that the Laurentia-Siberia connection proposed by *Rainbird et al.* would also be compatible with the conventional polarity option for the Laurentian poles if Siberia was located in the Northern Hemisphere. This clearly underlines the broad interest in better defining the apparent polar wander path of Siberia during the Neoproterozoic.

5.2. On the Behavior of the Earth's Magnetic Field

The uncertainties on the Rodinian configuration around 1050-1100 Ma are not critical for discussing the Earth's magnetic field behavior during the Proterozoic. The antiparallel and consistent paleomagnetic directions (after closure of the Viluy aulacogen) observed in two coeval formations from two sites located several thousands of kilometers apart suggest that the prevailing geomagnetic field was strongly dipolar. This would be more evident if the reconstruction proposed in Figure 13b was confirmed. However, it remains premature to discern if this dipole was aligned with the Earth's spin axis [e.g.,*Williams*, 1993].

The magnetostratigraphic results obtained from the Malgina and Linok Formations show a relatively large number of magnetic polarity intervals, but a magnetic reversal frequency cannot be estimated. It has been suggested that field reversals were less frequent during the Proterozoic than during the Phanerozoic [e.g., *Roberts and Piper*, 1989]. Such a characteristic does not seem to be confirmed by our study, at least during a part of the Proterozoic. This may indicate that large changes in magnetic reversal frequency have existed during the Proterozoic similar to those observed during

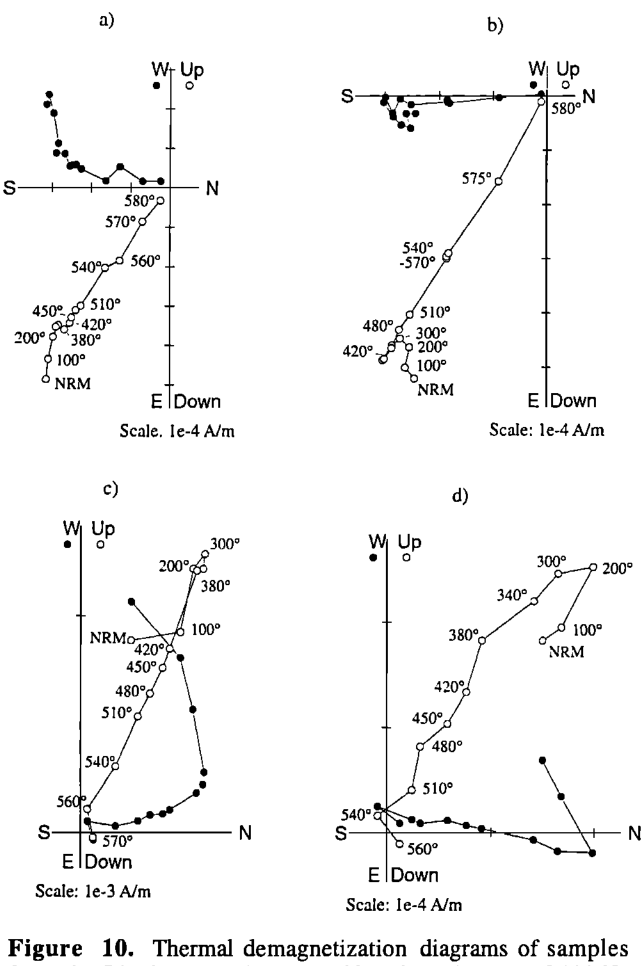

Figure 10. Thermal demagnetization diagrams of samples from the Linok Formation (Turukhansk region): (a) M4169, (b) M4376, (c) M4153, and (d) M4322. Convention is the same as that in Figure 4.

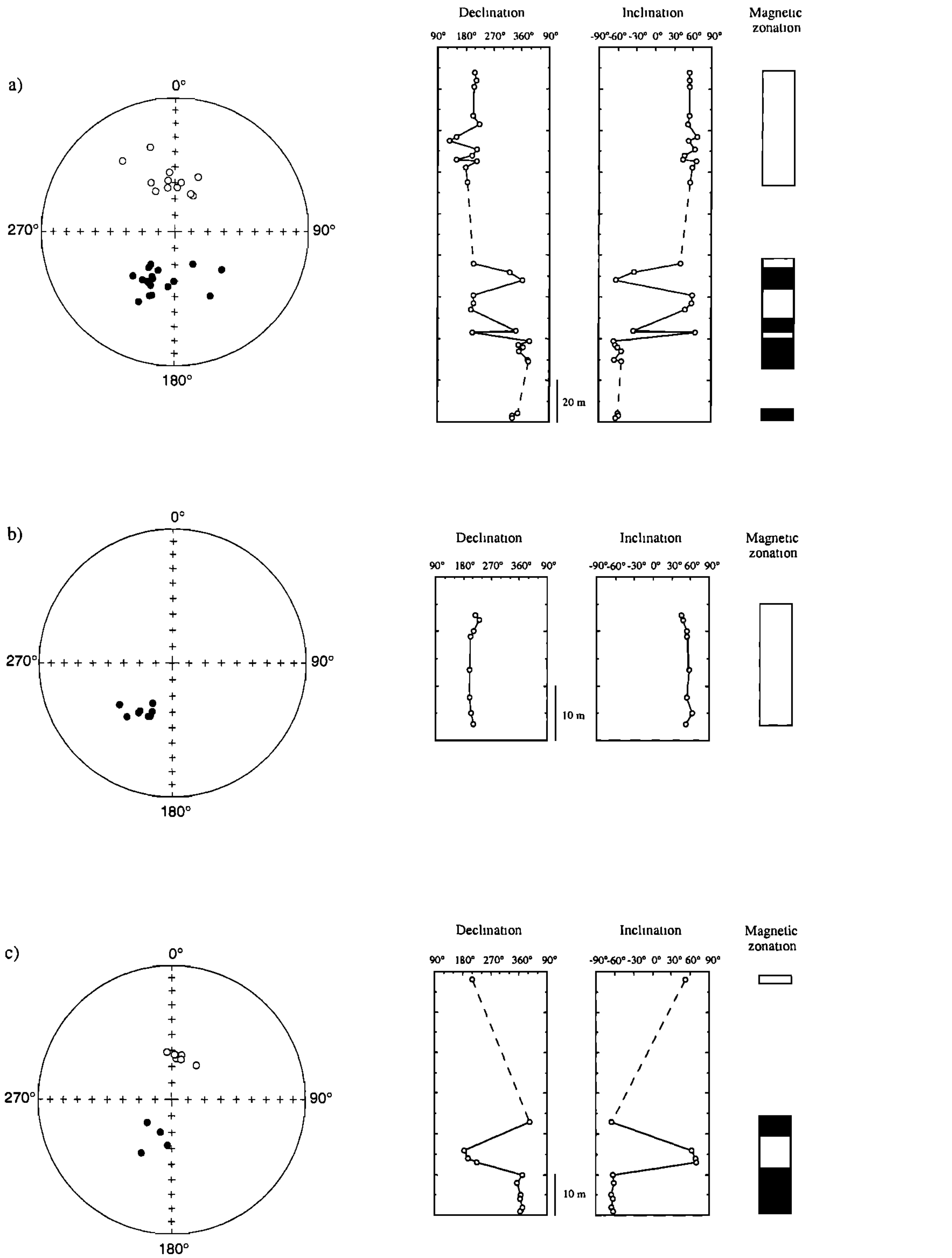

Figure 11. Directions in stratigraphic coordinates of the high-temperature component isolated in six sections from the Linok Formation: (a) section 1, (b) section 2, (c) section 3, (d) section 4, (e) section 5, and (f) section 6. The corresponding magnetostratigraphic sequences are shown in the right plots. The magnetic zonation is established considering that Siberia was located in the Southern Hemisphere.

the Phanerozoic [e.g., *Gallet et al.*, 1992]. Another possibility would be that the magnetic reversals were more frequent during the Precambrian because of the fact that the solid inner core, which may act on the stability of the geodynamo, was likely smaller than it is at present [e.g., *Hollerbach and Jones*, 1993; *Gubbins*, 1999]. Unfortunately, it will be very difficult to constrain this important issue which may help to constrain the influence of the growing inner core during the

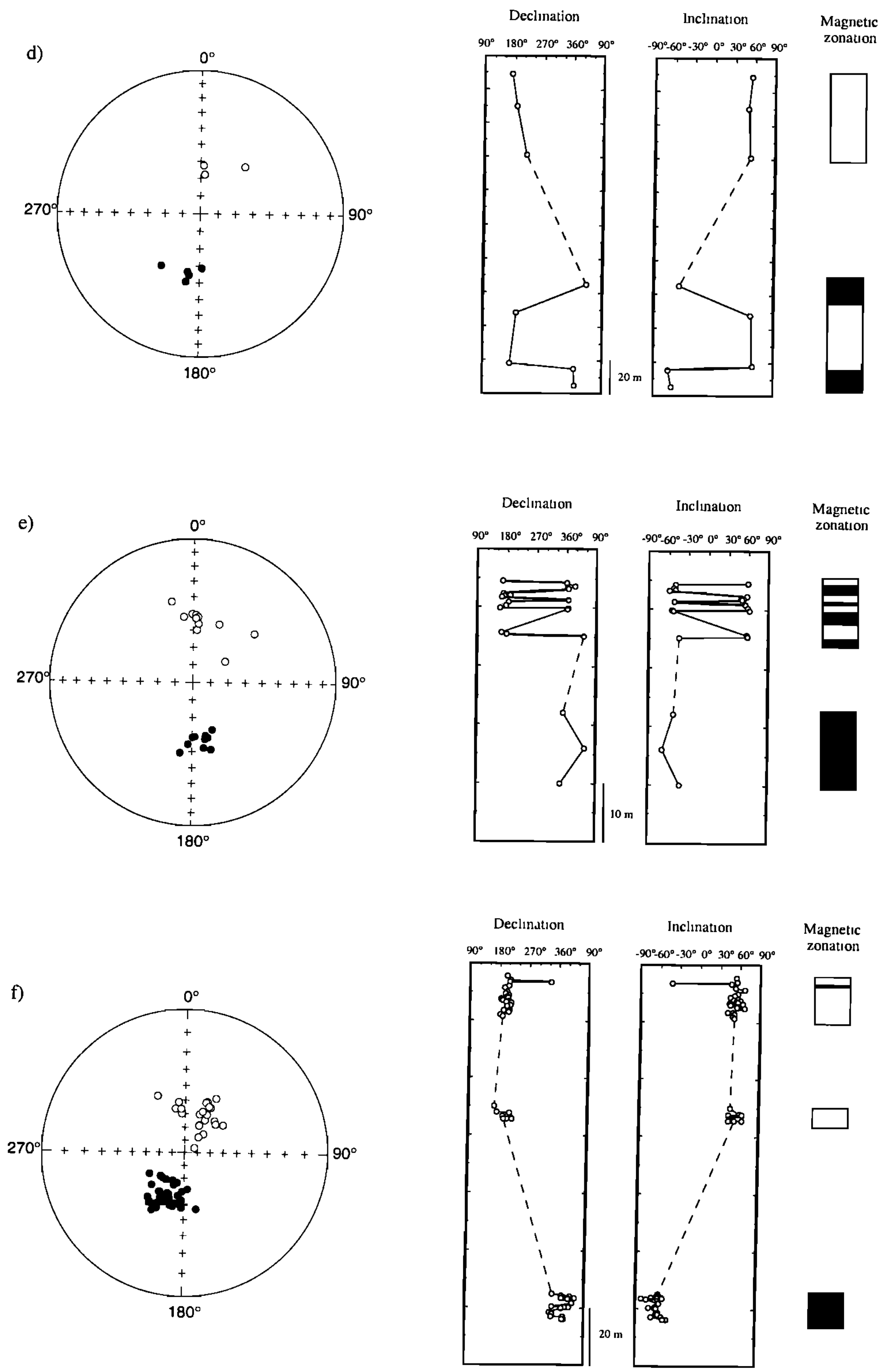

Figure 11. (continued)

Precambrian, owing in particular to the lack of strong age constraints and biases in the second resulting from a small number of paleomagnetically well-preserved Precambrian sedimentary sections.

Our magnetostratigraphic results also show no evidence for asymmetric reversals during a period roughly similar to the age of the emplacement of the Keweenawan lavas [*Pesonen and Nevanlinna*, 1981; *Nevanlinna and Pesonen*, 1983]. *Pesonen and Nevanlinna* [1981] noted several paleomagnetic studies that favor the worldwide occurrence and persistence of an asymmetric geomagnetic field during the Proterozoic. One study concerns sedimentary sections from

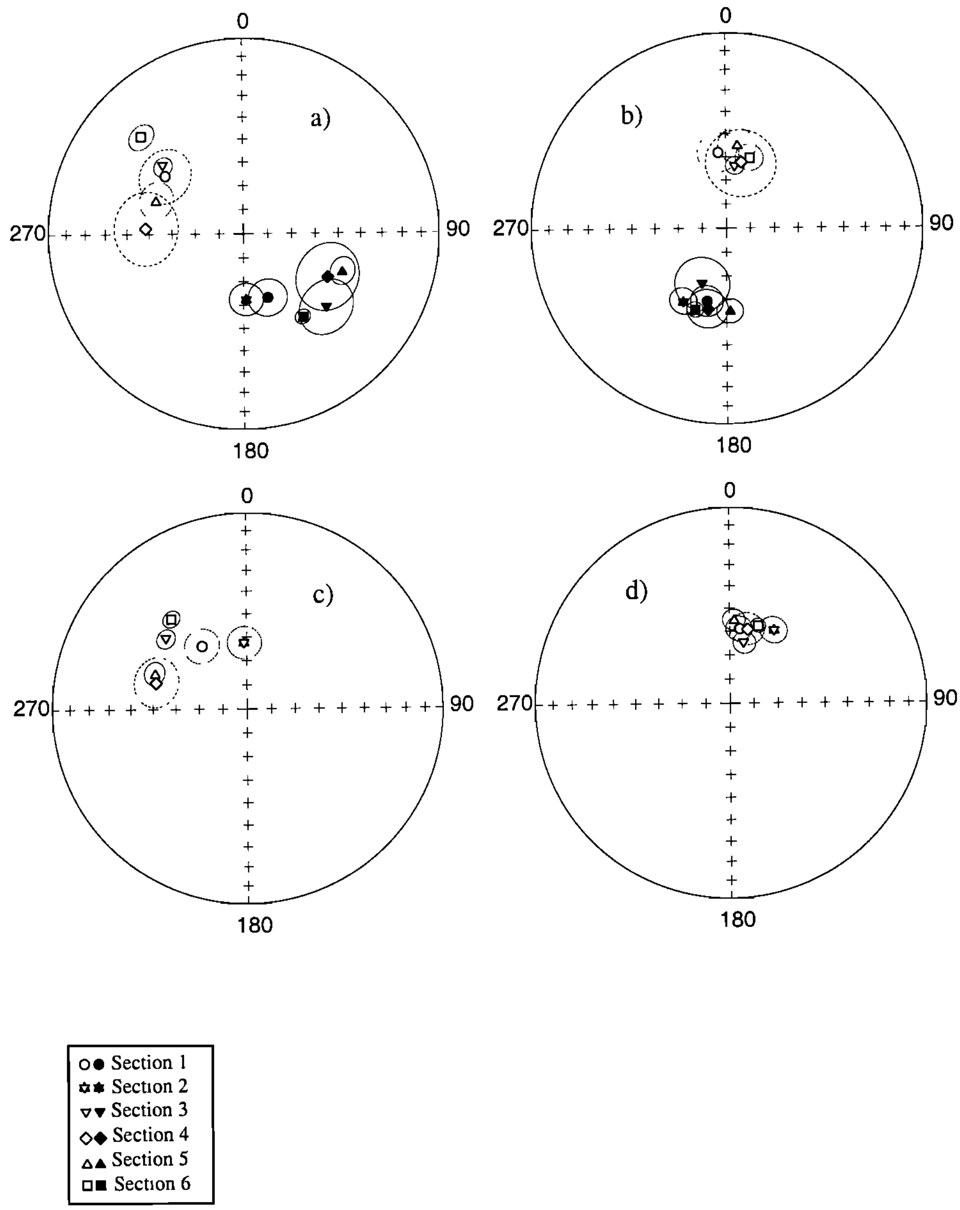

Figure 12. Mean HTC directions obtained from the Linok Formation: (a) mean directions of normal and reversed polarity obtained from the six sections before bedding correction, (b) mean directions of normal and reversed polarity obtained from the six sections after bedding correction, (c) mean directions combining both polarity directions from the different sections before bedding correction, and (d) mean directions combining both polarity directions from the different sections after bedding correction.

the Yenisei Ridge region, where asymmetrical reversals were observed by *Vlasov and Popova* [1968]. Our data, in particular those from the Turukhansk region, do not confirm this characteristic. The lack of standard demagnetization treatment in the study of *Vlasov and Popova* likely explains this difference. A second data set cited by *Pesonen and Nevanlinna* was obtained by *Piper and Stearn* [1977] in the Gardar Province from southern Greenland. In this latter study, the asymmetry is opposite to the one observed in Keweenawan, although the distance between southern Greenland and the Lake Superior region at that time was likely closer than the one between the Uchur-Maya and Turukhansk regions (note that the connection between North America and Greenland seems unambiguous). These results therefore contradict the two-dipole model suggested by *Pesonen and Nevanlinna* and *Nevanlinna and Pesonen* [1983]. In order to explain their data, *Piper and Stearns* suggested that a transitional-like behavior of the field persisted over several million years. Such a possibility is not supported by our magnetostratigraphic results. More recent paleomagnetic data obtained by *Lewchuk and Symons* [1990a, b], *Costanzo-Alvarez et al.* [1993], and *Symons* [1994] from eastern Canada (Coldwell, Shenango, Nemegosenda, Chipman Lake, and Seabrook Lake alkaline and carbonatite complexes) are also important for testing the regional consistency of the Keweenawan asymmetrical reversals. These data, which have the same age as the lavas studied by *Nevanlinna and Pesonen*, show several magnetic polarity in-

Table 2. Paleomagnetic Results Obtained From the Turukhansk Region

	N	Geographic Coordinates				Stratigraphic Coordinates				Reversal Test		Paleomagnetic Poles		
		D, deg	*I, deg*	*K*	α_{95}, *deg*	*D, deg*	*I, deg*	*K*	α_{95}, *deg*	γ, *deg*	γc, *deg*	*Lat., deg*	*Long., deg*	*dp/dm, deg*
					Section 1 (66.0°N, 88.6°E)									
Normal polarity	12	306.5°	-48.8°	16.3	11.1°	354.2°	-58.0°	27.8	8.4°					
Reversed polarity	18	157.6°	61.4°	18.3	8.3°	194.0°	58.4°	25.7	6.9°					
General	30	322.8°	-57.3°	14.0	7.3°	6.0°	-58 6°	24.8	5.4°	10.4°	10.6°	-15 4°	263.8°	6.0°/ 8.0°
					Section 2 (65.8°N, 88.3°E)									
Normal polarity														
Reversed polarity	8	177.6°	62.4°	64.6	6.9°	211.1°	54.3°	98.1	5.6°					
General	8	357.6°	-62.4°	64.6	6.9°	31.1°	-54.3°	98.1	5.6°			-13.5°	242 5°	5.5°/ 7.9°
					Section 3 (65.8°N, 88.3°E)									
Normal polarity	7	310 0°	-45.6°	246 5	3.9°	8 2°	-63.6°	250.9	3 8°					
Reversed polarity	4	132 0°	42 6°	67.1	11 3°	203 7°	64.4°	49.8	13.2°					
General	11	310.8°	-44.5°	136 4	3 9°	13.7°	-64.1°	98.1	4.6°	6.8°	9.3°	-22.1°	258.0°	5.9°/ 7.3°
					Section 4 (66.1°N, 88 2°E)									
Normal polarity	3	273.2°	-50.8°	33.5	21.6°	20.4°	-62.3°	36.4	20.7°					
Reversed polarity	5	117.6°	49.8°	32.8	13 6°	193.6°	55 0°	86.2	8.3°					
General	8	288.6°	-50.8°	28.1	10.6°	25.8°	-57.7°	58.3	7.3°	8.1°	15.3°	-15.2°	255.4°	7.9°/10.7°
					Section 5 (66.1°N, 88 2°E)									
Normal polarity	11	291.1°	-50.6°	39.0	7.4°	7.6°	-54.9°	37.4	7.6°					
Reversed polarity	10	111.1°	45 0°	76 9	5.5°	177.8°	55.0°	84.5	5.3°					
General	21	291.1°	-47.9°	50.2	4.5°	2 9°	-55.0°	50.2	4.5°	5.6°	9.0°	-11.7°	265.8°	4.5°/ 6.4°
					Section 6 (65.2°N, 88.5°E)									
Normal polarity	24	313.7°	-28.9°	33.5	5.2°	18.4°	-58.8°	29.0	5.6°					
Reversed polarity	37	144.9°	46 7°	60.2	3.1°	201.4°	53.2°	50.8	3.3°					
General	61	319.9°	-39.9°	28 1	3.5°	20.3°	-55.4°	38.1	3.0°	5.8°	6.0°	-12.4°	251.8°	3.0°/ 4.3°
Mean 1	6	312.6 °	-52.4°	23.8	14.0°	15.2°	-57.9°	147.7	5.5°	4.7°	8.1°	-15.2°	256.2°	A_{95}= 7.5°
Mean 2	139	315 0°	-48 0°	16.7	3.0°	14 8°	-57.3°	34.7	2.1°	5.3°	4.1°	-14.3°	256 4°	2.2°/ 3.1°

N is number of samples or sites averaged; D and I are declination and inclination of mean paleomagnetic directions; K is concentration parameter [*Fisher*, 1953]; α_{95} is radius of 95%; γ and γ_c are angular distances [*McFadden and McElhinny*, 1990]; Lat and Long. are north latitude and east longitude of paleomagnetic poles.

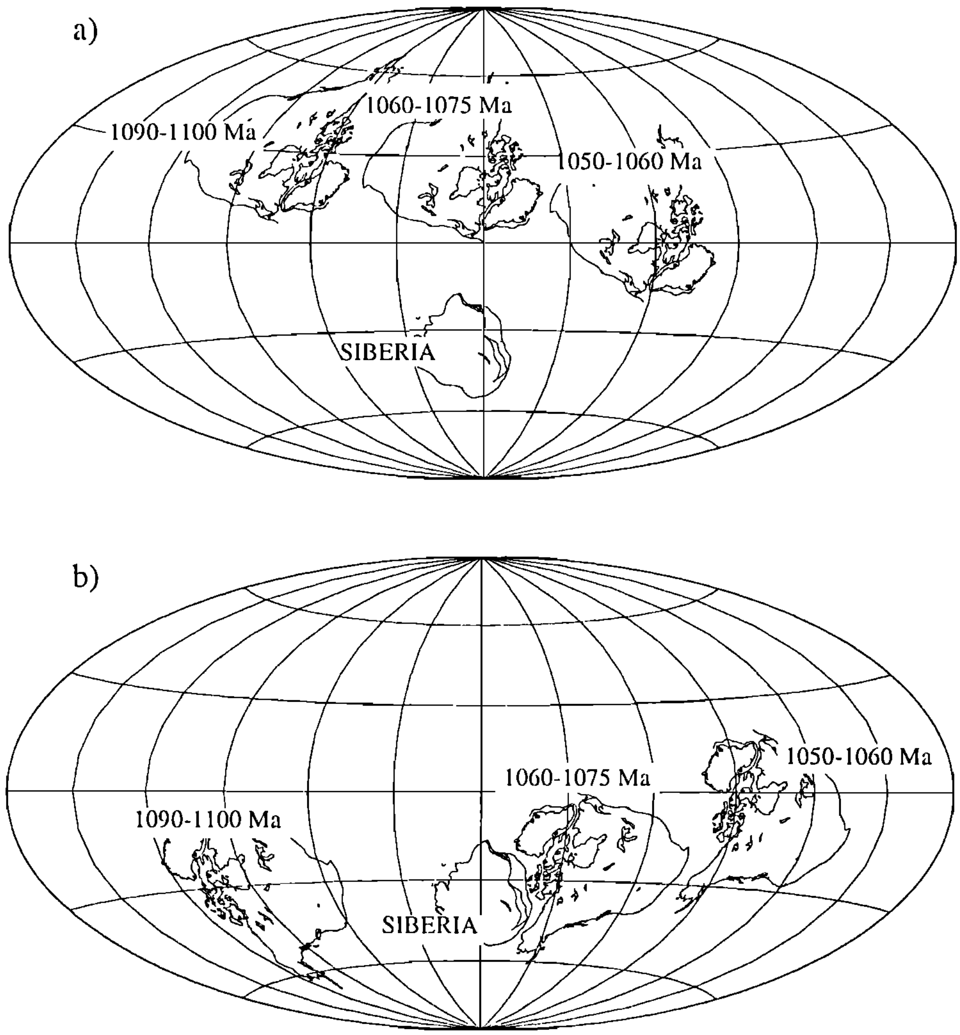

Figure 13. Tentative paleogeographic reconstructions of the Laurentian and Siberian cratons between 1050 and 1100 Ma: (a) reconstructions obtained considering the southern option for the Laurentian poles, and (b) reconstructions obtained considering the northern option for the Laurentian poles [e.g., *Park*, 1994].

tervals with no evidence for an asymmetric geomagnetic field. Taking into account the previous observations, it is therefore reasonable to consider that the asymmetrical reversals observed in the Keweenawan region do not reflect a wide and persistent characteristic of the Earth's magnetic field around 1110-1080 Ma. A simple and satisfactory solution would be that the asymmetrical reversals observed by *Pesonen and Nevanlinna* are an effect of nonaveraged secular variation [see also *Costanzo-Alvarez et al.*, 1993].

The possibility for an asymmetric field has been suggested for several other periods during the Proterozoic and the Phanerozoic. For instance, *Schmidt and Williams* [1995] have observed a large difference in inclination of ~20° between normal and reversed mean directions from late Neoproterozoic (650-600 Ma) sediments from Australia. Nonantiparallel directions were also reported by *Torsvik et al.* [1995] from lower Paleozoic Scandinavian sediments. However, no case exists where several results obtained from coeval formations sampled in widespread regions show the occurrence of an asymmetric field. For this reason, for the studies mentioned above, we cannot exclude a possible bias due to a remagnetization component which may not have been completely erased by demagnetization treatment. Such a bias is sometimes observed in magnetostratigraphic studies of much more recent sediments, even those showing an apparently clear demagnetization behavior (e.g., *Muttoni et al.* [1996] for Triassic sediments). It should be remembered that an asymmetric field was suggested by *Schneider and Kent* [1988] for the last few million years, which they attributed to different contributions of a zonal quadrupolar field between the normal and reversed polarity states. However, this was subsequently disproved by the statistical analysis of a large compilation of paleomagnetic directions [*McElhinny et al.*, 1996]. This point illustrates the difficulty of identifying such a geomagnetic characteristic, although numerous well-dated paleomagnetic data of good quality are available. We therefore think that there is at present no strong evidence supporting the existence of a long-standing asymmetric geomagnetic field over at least the last billion years.

Table 3. Mean Paleomagnetic Poles Used to Constrain the Paleoposition of Laurentia Between 1100 and 1050 Ma

	Age range, Ma	*N*	Latitute,deg	Longitude, deg	A_{95}, deg	Sources
Paleomagnetic pole 1	1050-1060	2	5.8°	178.0°	-	Nonesuch Shale [*Henry et al.*, 1977] Freda sandstone [*Henry et al.*, 1977]
Paleomagnetic pole 2	1060-1075	3	29.0°	176.7°	8.5°	Clay-Howells Carbonatite complex [*Lewchuk and Symons*, 1990b] Michipicoten Island volcanics [*Palmer and Davis*, 1987] Copper Harbor conglomerate [*Halls and Palmer*, 1981]
Paleomagnetic pole 3	1080-1100	4	33.6°	181.9°	6.6°	Logan dikes [*Halls and Pesonen*, 1982] Upper Osler Group [*Halls*, 1974] Portage lake volcanics [*Books*, 1972] Mamainse Point volcanics [*Palmer and Davis*, 1987]

Acknowledgments. We thank S. Gilder and M. Lewchuk for very constructive comments. This work was partially funded by the CNRS-INSU program Terre Profonde. This is INSU contribution 226 and IPGP contribution 1664. V. Pavlov was financed by the Russian Science Foundation grant 98-05-65082. M. Semikhatov and P. Petrov were financed by the Russian Science Foundation grant 99-05-64054

References

Bartley, J., A. Kaufman, M. Semikhatov, M. Pope, A. Knoll, and S. Jacobsen, Global events across the Mesoproterozoic-Neoproterozoic boundary: C and Sr isotopic evidence from Siberia, *Precambrian Res.*, in press, 2000.

Books, K., Paleomagnetism of some Lake Superior Keweenawan rocks, *U.S. Geol. Surv. Prof. Pap.*, *550-d*, 117-124, 1972.

Cannon, W., and S. Nicholson, Middle Proterozoic midcontinent rift system, *U.S Geol. Surv. Prof. Pap.*, *1556*, 60-67, 1996.

Carlut, J., and V. Courtillot, How complex is the time-averaged geomagnetic field over the last 5 Myr?, *Geophys. J. Int.*, *134*, 527-544, 1998.

Condie, K., and O. Rosen, Laurentia-Siberia connection revisited, *Geology*, *22*, 168-170, 1994.

Costanzo-Alvarez, V., D. Dunlop, and L. Pesonen, Paleomagnetism of alkaline complexes and remagnetization in the Kapuskasing structural zone, Ontario, Canada, *J. Geophys. Res.*, *98*, 4063-4079, 1993.

Coupland, D., and R. Van der Voo, Long-term nondipole components in the geomagnetic field during the last 130 M.Y., *J. Geophys. Res.*, *85*, 3529-3548, 1980.

Dalziel, I., Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation, *GSA Bull.*, *109*, 16-42, 1997.

Evans, M., Test of the dipolar nature of the geomagnetic field throughout Phanerozoic time, *Nature*, *262*, 676-677, 1976.

Fisher, R. A., Dispersion on a sphere, *Proc.R. Soc. London A*, *217*, 295-305, 1953

Gallet, Y., J. Besse, L. Krystyn, J. Marcoux, and H. Théveniaut, Magnetostratigraphy of the Late Triassic Bolücektaı Tepe section (southwestern Turkey): Implications for changes in magnetic reversal frequency, *Phys. Earth Planet. Inter.*, *73*, 85-108, 1992.

Gorokhov, I., M Semikhatov, A. Baskakov, E. Kutyavin, N. Melnikov, A. Sochava, and T. Turchenko, Sr isotopic composition in Riphean, Vendian and Lower Cambrian carbonates from Siberia, *Stratigr. Geol. Correl.*, *3*, 1-28, 1995.

Gubbins, D., The distinction between geomagnetic excursions and reversals, *Geophys. J. Int.*, *137*, F1-F3, 1999.

Gurevich, E., Paleomagnetism of the Ordovician deposits of the Moyero river sequence (in russian), in *Paleomagnetic Methods in Stratigraphy*, pp. 35-41, All-Russ. Pet. Sci. Res Geol. Explor. Inst., St. Petersburg, Russia, 1984.

Halls, H., A paleomagnetic reversal in the Osler volcanic group, Northern Lake Superior, *Can. J Earth Sci*, *11*, 1200-1207, 1974.

Halls, H., and H. Palmer, Remagnetization in Keweenawan rocks, part II, Lava flows within the Copper Harbor conglomerate, Michigan, *Can. J. Earth Sci.*, *18*, 1395-1408, 1981.

Halls, H., and L Pesonen, Paleomagnetism of Keweenawan rocks, *Mem. Geol. Soc. Am.*, *156*, 173-201, 1982.

Henry, S., F. Mauk, and R Van der Voo, Paleomagnetism of the upper Keweenawan sediments: the Nonesuch Shales and Freda Sandstones, *Can. J. Earth Sci*, *14*, 1128-1138, 1977

Herman, T., *Organic World a Billion Years Ago*, 49 pp. Nauka, Leningrad, Russia, 1990

Hoffman, P., Did the breakout of Laurentia turn Gondwana inside out?, *Science*, *252*, 1409-1412, 1991.

Hollerbach, R., and C Jones, Influence of the Earth's inner core on geomagnetic fluctuations and reversals, *Nature*, *365*, 541-543, 1993.

Kent, D., and M Smethurst, Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian, *Earth Planet. Sci. Lett.*, *160*, 391-402, 1998.

Khudoley, A., R. Rainbird, R. Stern, A. Kropachev, L. Heaman, A. Zanin, V. Podkovyrov, and V. Sukhorukov, New data on the Riphean tectogenese in the north-eastern Russia: Tectonics, geodynamics and processes of magmatism and metamorphism, paper presented at 32nd Tectonic Meeting, Russian Fund for Basic Research, Moscow, 1999.

Kirschvink, J., and A. Rozanov, Magnetostratigraphy of Lower Cambrian strata from the Siberian platform: A paleomagnetic pole and a preliminary polarity time-scale, *Geol. Mag.*, *121*, 189-203, 1984.

Knoll, A., and M. Semikhatov, The genesis and time distribution of two distinctive Proterozoic stromatolite microstructures, *Palaios*, *13*, 407-421, 1998.

Knoll, A., and V. Sergeev, Taphonomic and evolutionary changes across the Mesoproterozoic-Neoproterozoic transition, *Neues Jahrb. Geol. Palaeontol Abh.*, *195*, 289-302, 1995.

Knoll, A., A. Kaufman, and M. Semikhatov, The carbon-isotopic composition of Proterozoic carbonates. Riphean successions from Northwestern Siberia (Anabar massif, Turukhansk uplift), *Am. J. Sci.*, *295*, 823-850, 1995.

Krylov, I., Stromatolites of the USSR Riphean and Vendian (in Russian), *Tr. Akad Nauk SSSR*, *Geol. Inst.*, *274*, 243 pp., 1975.

Larin, A , Y. Amelin, L. Neymark, and R. Krimsky, The origin of the 1.72-1.73 Ga anorogenic Ulkan volcano-plutonic complex, Siberian Platform, Russia: Inference from geochronological, geochemical and Nd-Sr-Pb isotopic data, *An. Acad. Bras. Cienc.*, *63*, 295-312, 1997.

Lewchuk, M., and D. Symons, Paleomagnetism of the Clay-Howells carbonatite complex: Constraints on Proterozoic motion in the Kapuskasing structural zone, Superior Province, Canada, *Tectonophysics*, *172*, 67-75, 1990a

Lewchuk, M , and D. Symons, Paleomagnetism of the Late Precambrian Coldwell complex, Ontaria, Canada, *Tectonophysics*, *14*, 73-86, 1990b.

Livermore, R., F. Vine, and A. Smith, Plate motions and the geomagnetic field, II, Jurassic to Tertiary, *Geophys. J. R. Astron. Soc.*, *79*, 939-961, 1984.

McElhinny, M., Statistical significance of the fold test in paleomagnetism, *Geophys. J. R. Astron. Soc.*, *8*, 338-340, 1964.

McElhinny, M., P. McFadden, and R. Merrill, The time-averaged paleomagnetic field 0-5 Ma, *J. Geophys. Res.*, *101*, 25,007-25,028, 1996.

McFadden, P., and M. McElhinny, Classification of the reversal test in palaeomagnetism, *Geophys. J. Int.*, *103*, 725-729, 1990.

Muttoni, G., D. Kent, S. Meço, A. Nicora, M. Gaetani, M. Balini, D. Germani, and R. Rettori, Magneto-biostratigraphy of the Spathian to Anisian (Lower to Middle Triassic) Kçira section, Albania, *Geophys. J. Int.*, *127*, 503-514, 1996.

Nevanlinna, H., and L. Pesonen, Late Precambrian Keweenawan asymmetric polarities as analyzed by axial offset dipole geomagnetic models, *J. Geophys. Res.*, *88*, 645-658, 1983.

Neymark, L., A. Larin, Y. Yakovleva, and B. Gorokhosky, Uranium-lead age of igneous rocks in the Ulkan graben in the southeastern part of the Aldan shield (in Russian), *Dokl. Akad. Nauk SSSR*, *324*, 92-96, 1992.

Ovchinnikova, G , M. Semikhatov, I. Gorokhov, B. Belyatskii, I. Vasilieva, and L. Levskii, U-Pb systematics of Pre-Cambrian carbonates: The Riphean Sukhaya Tunguska Formation in the Turukhansk uplift, Siberia, *Lithol. Miner. Resour.*, *Engl. Transl*, *30*, 477-487, 1995.

Palmer, H., and D. Davis, Paleomagnetism and U-Pb geochronology of volcanic rocks from Michipicoten Island, Lake Superior, Canada: Precise calibration of the Keweenawan polar wander track, *Precambrian Res.*, *37*, 157-171, 1987.

Park, J., Palaeomagnetic constraints on the position of Laurentia from middle Neoproterozoic to Early Cambrian times, *Precambrian Res.*, *69*, 95-112, 1994.

Pavlov, V., and P. Petrov, Paleomagnetic study of Riphean deposits in the Turukhansk area, *Izv Acad. Sci. USSR Phys. Solid Earth, Engl. Transl.*, *3*, 239-249, 1996.

Pavlov, V., K. Burakov, V. Tsel'movich, and D. Zhuravlev, Paleomagnetism of sills from the Uchur-Maya region and estimation of geomagnetic field intensity during the Late Riphean (in Russian), *Izv. Acad. Sci. USSR Phys. Solid Earth*, *1*, 72-79, 1992.

Pelechaty, S., Stratigraphic evidence for the Siberia-Laurentia connection and Early Cambrian rifting, *Geology*, *24*, 719-722, 1996.

Pesonen, L., and H. Nevanlinna, Late Precambrian Keweenawan asymmetric reversals, *Nature*, *294*, 436-439, 1981.

Petrov, P., Depositional environments of the lower formations of the Riphean sequence, northern part of the Turukhansk uplift, Siberia, *Stratigr. Geol. Correl.*, *1*, 181-191, 1993.

Petrov, P., and A. Veis, Facial-ecological structure of the Derevnya Formation microbiota, Upper Riphean, Turukhansk Uplift, Siberia, *Stratigr. Geol. Correl.*, *5*, 435-460, 1995.

Piper, J., The Precambrian palaeomagnetic record. The case for the Proterozoic supercontinent, *Earth Planet. Sci. Lett.*, *46*, 443-461, 1982.

Piper, J., *Palaeomagnetism and the Continental Crust*, John Wiley, New York, 434 pp., 1987.

Piper, J., and J. Stearn, Palaeomagnetism of the dyke swarms of the Gardar igneous province, South Greeland, *Earth Planet. Sci. Lett.*, *14*, 345-358, 1977.

Pisarevsky, S., E. Gurevich, and A. Khramov, Paleomagnetism of the Lower Cambrian sediments from the Olenek river section (northern Siberia): Paleopoles and the problem of the magnetic polarity in the Early Cambrian, *Geophys. J. Int.*, *130*, 746-756, 1997.

Powell, C., M. McElhinny, J. Meert, and J. Park, Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana, *Geology*, *21*, 889-892, 1993.

Rainbird, R., R. Stern, A. Khudoley, A. Kropachev, L. Heaman, and V. Sukhorukov, U-Pb geochronology of Riphean sandstone and gabbro from southeast Siberia and its bearing on the Laurentia-Siberia connection, *Earth Planet. Sci. Lett.*, *164*, 409-420, 1998.

Roberts, N., and J. Piper, A description of the behaviour of the Earth's magnetic field, in *Geomagnetism*, vol. 3, edited by J. Jacob, pp. 163-260, Academic, San Diego, Calif., 1989.

Schmidt, P., and D. Clark, Late Proterozoic and Late Palaeozoic reconstructions: Rodinia to Pangaea, paper presented at 8th Meeting, Int. Assoc. of Geomagn. and Aeron., Uppsala, Sweden, 1997.

Schmidt, P., and W. Morris, An alternative view of the Gondwana Paleozoic apparent polar wander path, *Can. J. Earth Sci.*, *14*, 2674-2678, 1977.

Schmidt, P., and G. Williams, The Neoproterozoic climatic paradox: Equatorial palaeolatitude for Marinoan glaciation near sea level in South Australia, *Earth Planet. Sci. Lett*, *134*, 107-124, 1995.

Schneider, D., and D. Kent, The paleomagnetic field from equatorial deep-sea sediments: Axial symmetry and polarity asymmetry, *Science*, *24*, 252-256, 1988.

Semikhatov, M., (General problems of Proterozoic stratigraphy in the USSR: Scientific review), *Sov. Sci. Rev. Sect. G.*, *Geol. Rev.*, *19*, 48-92, Harwood, New York, 1991.

Semikhatov, M., Methodic principles of the Riphean stratigraphy, *Stratigr. Geol. Correl.*, *3*, 559-574, 1995.

Semikhatov, M., and S. Serebryakov, The Siberian hypostratotype of the Riphean (in Russian), *Tr. Akad. Nauk. SSSR Geol. Inst.*, *367*, 152-224, 1983.

Semikhatov, M., and M. Raabens, Dynamics of the global diversity of Proterozoic stromatolites, 1, Northern Eurasia, China and India, *Stratigr. Geol. Correl.*, *2*, 492-513, 1994.

Semikhatov, M., and M. Raabens, Dynamics of the global diversity of Proterozoic stromatolites, 2, Africa, Australia, North America, and general synthesis, *Stratigr. Geol. Correl.*, *4*, 24-50, 1996.

Sergeev, V., A. Knoll, and J. Grotzinger, Paleobiology of the Mesoproterozoic Billyakh Group, Anabar Uplift, Northern Siberia, *J. Paleontol.*, *69*, 1-37, 1995.

Shenfil', V., *The Late Pre-Cambrian of the Siberian Platform*, Nauka, Moscow, 184 pp., 1991.

Smethurst, M., A. Khramov, and T. Torsvik, The Neoproterozoic and Palaeomagnetic data for the Siberian platform: From Rodiania to Pangea, *Earth Sci. Rev.*, *43*, 1-24, 1998.

Symons, D., Paleomagnetism of the Keweenawan Chipman lake and Seabrook lake carbonatite complexes, Ontario, *Can. J. Earth Sci.*, *29*, 1215-1223, 1994.

Torsvik, T. H., A. Trench, K. C. Lohmann, and S. Dunn, Lower Ordovician reversal asymmetry: An artifact of remagnetization or nondipole field disturbance?, *J. Geophys. Res.*, *100*, 17,885-17,898, 1995.

Veis, A., and P. Petrov, The peculiarities of the environmental distribution of microfossils in the Riphean basins of Siberia, *Stratigr. Geol. Correl.*, *2*, 397-425, 1994.

Veis, A., and P. Petrov, Dependence of the Riphean organic walled microfossil systematic diversity on conditions of their environment in Siberia, in *Ecosystem Restructures and the Evolution of the Biosphere*, vol. 1, pp. 32-42, Nedra, Moscow, 1995.

Vinogradov, V., B. Pokrovskii, D. Golovin, M. Buyakaite, V. Muraviev, and A. Veis, Isotopic evidence of epigenetic transformations and the problem of age of Riphean rocks in the Uchur Maya region, Eastern Siberia, *Lithol. Miner. Resour.*, *Engl. Transl.*, *6*, 875-885, 1998.

Vlasov, A., and A. Popova, Paleomagnetism of Enisey Ridge Precambrian deposits, *Izv. Akad. Nauk. SSSR Fiz. Zemli*, *2*, 63-70, 1968.

Weil, A., R. Van der Voo, C. Mac Niocaill, and J. Meert, The Proterozoic supercontinent Rodinia: Paleomagnetically derived reconstructions for 1100 to 800 Ma, *Earth Planet. Sci. Lett.*, *154*, 13-24, 1998.

Williams, G., History of the Earth's obliquity, *Earth Sci. Rev.*, *34*, 1-45, 1993.

Y. Gallet, Laboratoire de Paléomagnétisme, UMR CNRS 7577, Institut de Physique du Globe de Paris, Tour 14-24, 1er étage, 4 Place Jussieu, 75252 Paris Cedex 05, France. (gallet@ipgp.jussieu.fr)

V.E. Pavlov, Department of Geomagnetism and Paleomagnetism, Institute of Physics of the Earth, 123810 Moscow, Russia.

P.Y. Petrov and M.A. Semikhatov, Geological Institute, Russian Academy of Sciences, 109017 Moscow, Russia.

(Received January 27, 1999; revised September 2, 1999; accepted October 4, 1999.)