Variations in geomagnetic reversal frequency during the Earth's middle age

Vladimir Pavlov, Yves Gallet

Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 11, Number 1
21 January 2010
Q01Z10, doi:10.1029/2009GC002583
ISSN: 1525-2027

Click Here for Full Article

Variations in geomagnetic reversal frequency during the Earth's middle age

Vladimir Pavlov
Institute of Physics of the Earth, Bol'shaya Gruzinskaya 10, Moscow 123995, Russia (pavlov-home@rambler.ru)

Yves Gallet
Equipe de Paléomagnétisme, Institut de Physique du Globe de Paris, UMR 7154, CNRS, 4 Place Jussieu, F-75252 Paris CEDEX 05, France (gallet@ipgp.fr)

[1] We have obtained new magnetostratigraphic results from two Precambrian sedimentary sections from eastern Siberia and the southern Urals dated between ~1100 Ma and ~800 Ma. Sample magnetizations from the uppermost Mesoproterozoic Talakh-Khaya section in the Siberian Uchur-Maya region appear to be mostly carried by a mixture of magnetite and hematite. A sequence of 33 magnetic polarity intervals is recorded within the section. All reversals occur in the first ~24 m, while the upper ~160 m are characterized by a single magnetic interval of normal polarity assuming a Northern Hemisphere position of Siberia around 1000 Ma. The Lower Neoproterozoic Uralian Minyar section also possesses an ancient magnetization carried by magnetite and hematite. The high-temperature magnetization component obtained from the Minyar section establishes a sequence of 43 magnetic polarity intervals. Positive reversal tests obtained from the data sets presented here and from other previously analyzed Proterozoic sections provide no convincing evidence for a long-standing asymmetric geomagnetic field during the Proterozoic that would make the Precambrian field markedly less dipolar than during the Phanerozoic. The new data further reveal the occurrence of sharp transitions and alternations between long periods without any reversal (one superchron is observed from the Talakh-Khaya section) and periods with high reversal frequencies, possibly larger than 5–10 reversals per Myr. This characteristic may well be an important property of the Precambrian field, although rather sudden transitions between reversing and nonreversing states of the geodynamo may not be unique to this period.

Components: 11,197 words, 14 figures, 3 tables.

Keywords: magnetostratigraphy; Proterozoic; magnetic polarity reversal frequency; superchron.

Index Terms: 1520 Geomagnetism and Paleomagnetism: Magnetostratigraphy; 1535 Geomagnetism and Paleomagnetism: Reversals: process, timescale, magnetostratigraphy; 9622 Information Related to Geologic Time: Proterozoic.

Received 23 April 2009; **Revised** 9 September 2009; **Accepted** 5 October 2009; **Published** 21 January 2010.

Pavlov, V., and Y. Gallet (2010), Variations in geomagnetic reversal frequency during the Earth's middle age, *Geochem. Geophys. Geosyst.*, *11*, Q01Z10, doi:10.1029/2009GC002583.

Theme: Magnetism From Atomic to Planetary Scales: Physical Principles and Interdisciplinary Applications in Geoscience
Guest Editors: J. Feinberg, F. Florindo, B. Moskowitz, and A. P. Roberts

1. Introduction

[2] Reversals in the Earth's magnetic field over the past 150 Myr are well known due in large part to the analysis of the oceanic magnetic anomalies and to many magnetostratigraphic studies carried out over the last 40 years. For older periods of the Phanerozoic, magnetostratigraphic data obtained from biostratigraphically well-dated sedimentary sections are less abundant and have provided so far only fragments of the entire geomagnetic polarity reversal history. Nevertheless, the available data show that the geomagnetic reversal frequency has significantly varied over time, from a zero value during long periods without any reversal (the so-called superchrons) to periods characterized by frequent reversals, such as during the Middle Cambrian, the Middle Jurassic and during the Miocene (see, e.g., *Pavlov and Gallet* [2005, Figure 9] or *Algeo* [1996] and *Opdyke and Channell* [1996]). At present, three superchrons, each one lasting several tens of Myr, were detected during the Phanerozoic, one during the Early Paleozoic [e.g., *Gallet and Pavlov*, 1996; *Pavlov and Gallet*, 1998], another at the end of the Paleozoic and the most recent during the Cretaceous [e.g., *Opdyke and Channell*, 1996]. These geomagnetic features are often considered as exceptional phenomena in Earth history and are likely related to major volcanic and biological events [e.g., *Courtillot and Olson*, 2007, and references therein]. The dominant theory on their origin, which is supported by 3-D geodynamo simulations [e.g., *Glatzmaier et al.*, 1999], is that they result from long- or medium-term (on the 10 Myr time scale) changes in core-mantle boundary conditions [e.g., *McFadden and Merrill*, 1984, 2000]. *Hulot and Gallet* [2003], however, underlined the sharp transition between the reversing and nonreversing states of the geodynamo during the Lower Cretaceous. They suggest that this transition might principally reflect the nonlinear nature of the magnetohydrodynamical processes acting in Earth's core. If confirmed, such a possibility would challenge the assumption of some dominant mantle-induced effects on the reversal rate variations. Gathering a more precise description of the magnetic polarity time scale at the limits of the other superchrons would thus be of particular interest. We will show below that studying the geomagnetic field behavior during the Proterozoic, i.e., during the ''Earth's middle age'' as termed by A. Knoll (personal communication, 2008), may also provide valuable constraints on this topic.

[3] Only very few continuous magnetostratigraphic sequences can presently be considered to constrain the geomagnetic field behavior during the Precambrian. However, several differences between the Precambrian and Phanerozoic field have been tentatively proposed, including a higher contribution of nondipole components [*Kent and Smethurst*, 1998], the occurrence of asymmetric magnetic reversals (perhaps a consequence of a less dipolar field) [*Pesonen and Nevanlinna*, 1981; *Nevanlinna and Pesonen*, 1983] or, on average, less frequent geomagnetic polarity reversals [e.g., *Roberts and Piper*, 1989]. On the other hand, *Smirnov and Tarduno* [2004] and *Biggin et al.* [2008] have argued for a dominantly dipolar field in the early Earth's history from an analysis of the geomagnetic secular variation at the Late Archean and Early Proterozoic. But, each of the characteristics above clearly requires further investigation and close scrutiny of any potential effect that might be related to the late growth of the inner core [e.g., *Coe and Glatzmaier*, 2006; *Lay et al.*, 2008; *Biggin et al.*, 2009]. In this respect, the Proterozoic appears as a vast and promising domain of research. We report magnetostratigraphic results obtained from two Proterozoic sedimentary sections from Siberia and southern Urals dated between ~1100 Ma and ~800 Ma.

2. Geological Setting, Lithology, and Age of the Studied Sections

2.1. Malgina and Tsipanda Formations From the Uchur-Maya Region

[4] The Uchur-Maya region is located to the southeast of the Siberian platform (Figure 1). It comprises two adjacent tectonic structures separated by the north/northeast oriented Nelkan-Kyllakh thrust system. Situated to the west of this thrust system, the first structure, referred to as the Uchur-Maya undeformed zone, belongs to the Siberian platform in a strict sense. In this zone, multiple sections of nonmetamorphosed, flat-lying Riphean rocks are exposed. To the eastern side, the second structure, the so-called Judoma-Maya fold-thrust belt, represents the disturbed margin of the Siberian platform.

[5] We sampled the Malgina and Tsipanda formations in the Uchur-Maya undeformed zone. According to paleontological evidence [e.g., *Semikhatov and Serebrjakov*, 1983; *Bartley et al.*, 2001], these two upper members of the Kerpyl group date to the uppermost Mesoproterozoic (Figure 2). These formations were deposited in shallow water environments in rift-related intracraton basins [*Khudoley et al.*, 2001]. They are well exposed over several

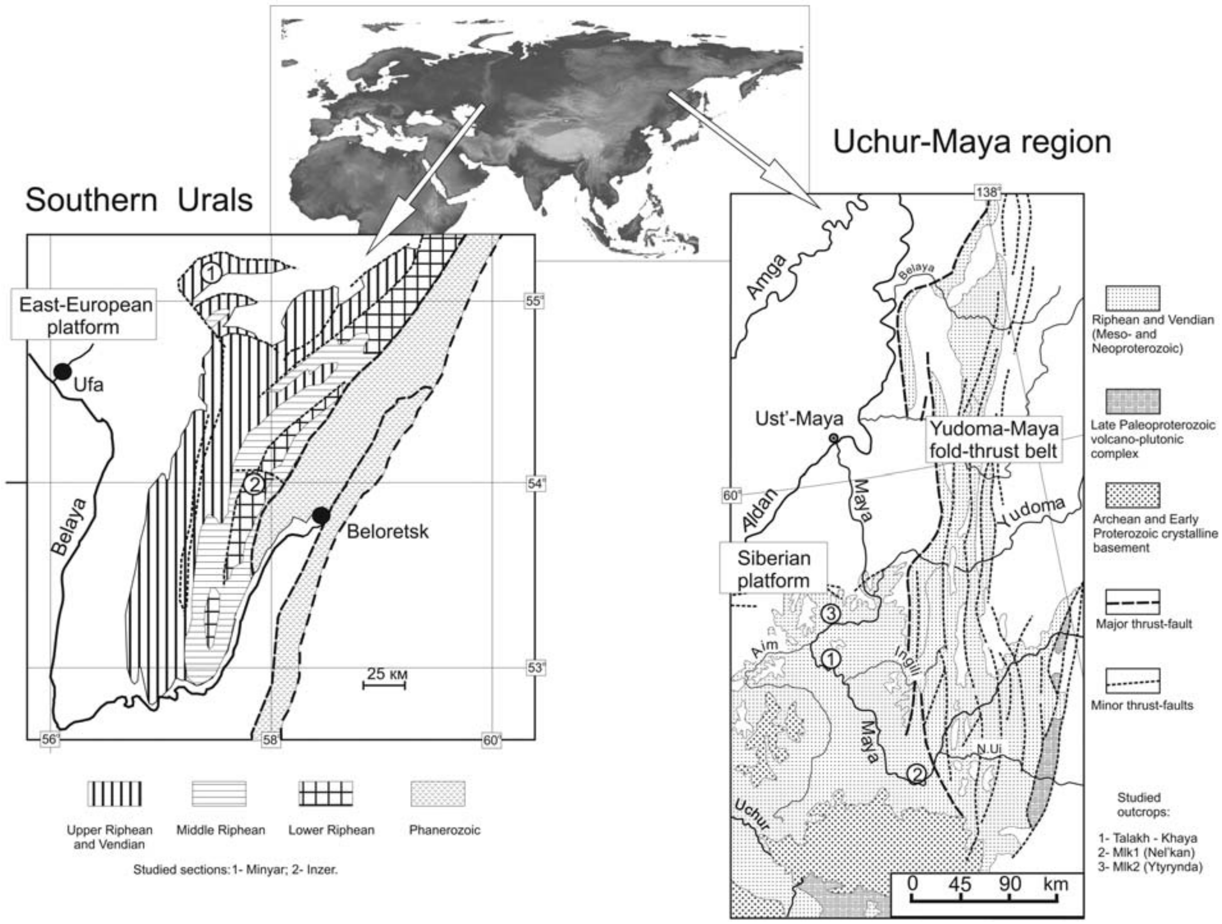


Figure 1. Locality and simplified geological maps of the Uchur-Maya (southeastern Siberia) and Bashkirian (southern Ural) regions [after *Semikhatov and Serebrjakov*, 1983; *Willner et al.*, 2001]. The numbers show the location of the main Talakh-Khaya and Minyar sections and of other outcrops investigated in the present study.

tens of kilometers along the middle course of the Maya river. The Malgina Formation is mainly constituted by red, green and pale argillaceous limestones which are gradually replaced by pale greenish, pinkish, yellowish and grayish dolostones of the Tsipanda Formation. In some sections, principally located to the western part of the region, the upper beds of the Malgina Formation are composed of dark, sometimes bituminous limestones with thicknesses reaching up to 30 m. Within the limits of the Uchur-Maya underformed zone, the total thickness of both the Malgina and Tsipanda formations is fairly uniform (~400–500 m). Considered separately, however, the individual thickness of these formations can vary significantly. The Malgina Formation, for instance, ranges from 35 to 120 m thick.

[6] We collected 680 oriented hand samples from the Talakh-Khaya section exposed along the right bank of the Maya river, some tens of kilometers below the mouth of the Ingili river (Figure 1). The choice of this section was guided by the excellent conditions of exposure, by the relative absence of any tectonic or metamorphic event in this area, by the small proportion of dark bituminous beds and by the thickness of the Malgina Formation (~110 m) in this location relative to elsewhere in the undeformed zone [*Semikhatov and Serebrjakov*, 1983]. The thickness of the Tsipanda Formation reaches ~290 m here. The entire Malgina Formation was sampled with a narrow spacing between samples of approximately 10–15 cm in the lower ~50 m and then with a spacing of ~1–1.5 m in the upper part of the section including the lower one third (~100 m) of the Tsipanda Formation. Note that this sampling was carried out across two subsections A and B ~300 m apart with a clear ~1 m thick stratigraphic overlap.

[7] Recent geochronological data indicate that the age of the Malgina and Tsipanda formations are younger than 1100 Ma, which is a U-Pb age obtained from detrital zircons collected from the

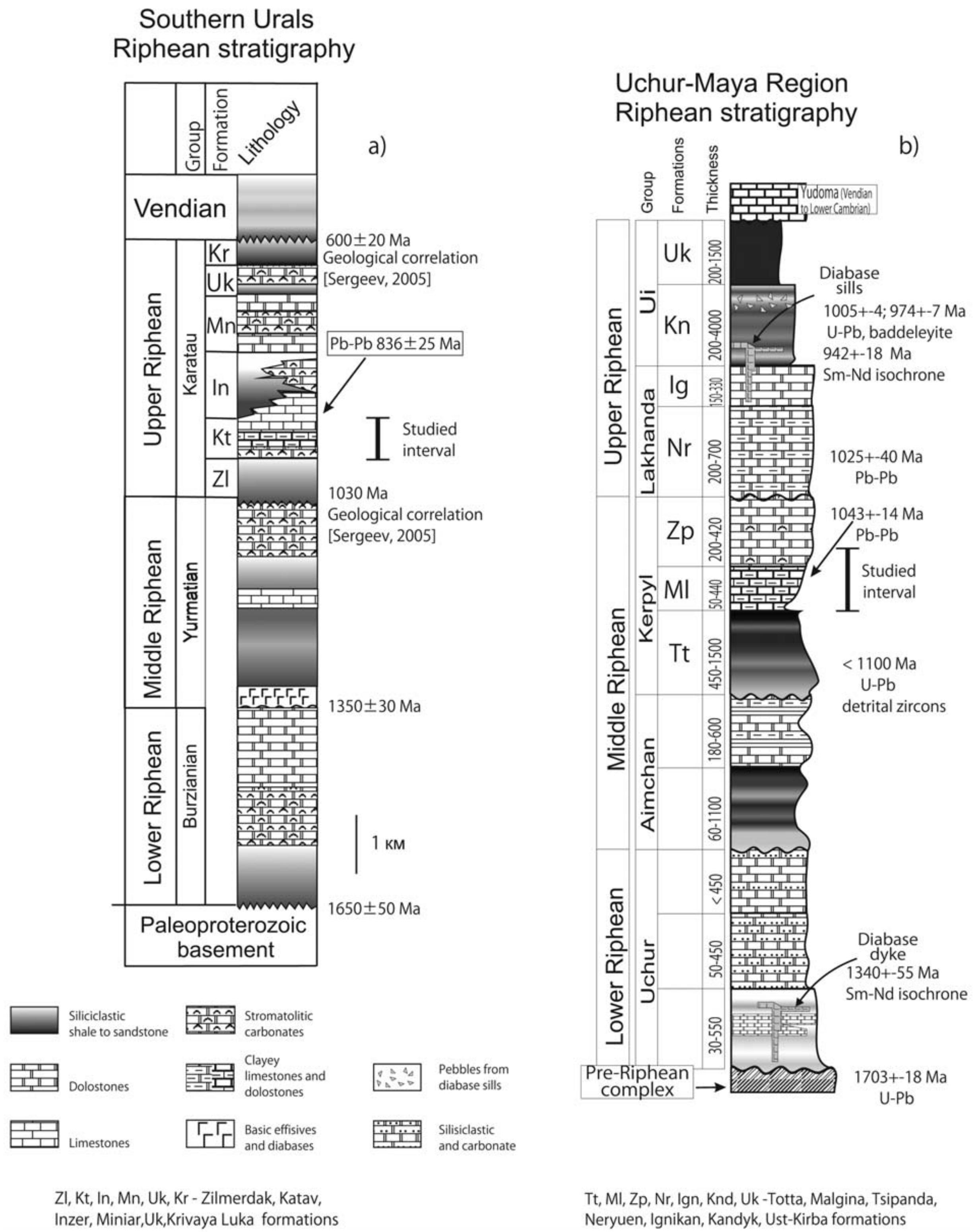


Figure 2. Simplified description of the Riphean successions in the (a) Bashkirian and (b) Uchur-Maya regions [after *Gallet et al.*, 2000; *Sergeev*, 2006]. Names of the geologic formations are indicated at the bottom.

underlying Totta Formation [*Khudoley et al.*, 2006], and older than 1005 ± 4 Ma, which is a U-Pb age on baddeleyite extracted from mafic sills intruding the overlying Upper Riphean Lakhanda group and the Kandyk Formation [*Rainbird et al.*, 1998]. Interestingly, pebbles from these sills have been found in rocks from the upper part of the Kandyk Formation, which is the lower member of the Uy group (Figure 2) [*Semikhatov and Serebrjakov*, 1983]. These sills were therefore emplaced during the deposition of the Kandyk Formation. Pb-Pb isochrons yielding two ages at 1043 ± 14 Ma and 1025 ± 40 Ma were also recently obtained on limestones from the upper and middle parts of the Malgina Formation and the lower part of the Lakhanda group (Milkon subformation–middle part of the Neryuen Formation), respectively [*Ovchinnikova et al.*, 2001; *Semikhatov et al.*, 2000]. These ages are considered to be closely related to the time of early diagenesis in the sediments. On the other hand, an age of 1035 ± 60 Ma was obtained for carbonates from the Sukhaya Tunguska Formation (Turukhansk region, northwestern Siberian platform) assumed to be coincident in time with the Tsipanda Formation [*Ovchinnikova et al.*, 1995]. At present, all the available geochronological data therefore indicate that the Malgina and the Tsipanda formations were emplaced between ~1060 Ma and ~1000 Ma.

2.2. Katav Formation From Southern Urals

[8] The section of the Katav Formation presented here is located on the territory of the Bashkirian anticlinorium (southern Urals; Figure 1), which represents a thrust and fold zone at the southeastern edge of the east European platform. The carbonate Katav Formation is the second oldest formation of the sedimentary carbonate terrigenous Karatau group of Upper Riphean age, lying above the Zilmerdak Formation and below the Inzer, Minyar, Uk and Krivaya Luka formations (Figure 2). These Riphean strata were deposited in a shallow water marine basin along the platform margin [*Maslov et al.*, 1997]. The main stages of tectonic deformations (folding and thrusting), which probably induced local rotations and relative displacements within the Bashkirian anticlinorium, have been dated to the Late Paleozoic [*Giese et al.*, 1999]. However, there is also strong evidence for older Vendian to Ordovician deformations, most probably related to the Cadomian or the Baikalian orogen [*Maslov et al.*, 1997].

[9] We sampled one of the best sections of the Katav Formation, located in the vicinity of the railway station of the town Minyar (Chelyabinsk region), in the western, relatively weakly deformed part of the Bashkirian anticlinorium. The Minyar section consists of ~200 m of unmetamorphosed reddish, greenish and grayish limestones. Reddish limestones predominate in the lower part of the section, while those with greenish and grayish colors prevail above. The strata are gently tilted by ~10° to ~20° toward the north/northeast. About 230 oriented blocks were collected within the section with a sampling interval of ~1–1.5 m. Only a few stratigraphic intervals were not sampled because of poor accessibility; the thickest gap reaches ~16 m, but in aggregate the sampling gaps do not exceed ~10% of the total thickness.

[10] The age of the Upper Riphean Katav Formation is constrained by several recent radiometric determinations, which were summarized by *Bartley et al.* [2007] and *Kuznetsov et al.* [2006]. Pb-Pb analyses of limestones from the lower part of the Inzer Formation yielded an age of 836 ± 25 Ma, most probably reflecting the time of the early diagenesis in these sediments [*Ovchinnikova et al.*, 1998]. This result is further supported by Rb-Sr data providing an age of ~835–805 Ma for the time of early burial diagenesis in the Inzer Formation [*Gorokhov et al.*, 1995]. A Pb-Pb isochron also yielded an age of 780 ± 85 Ma for the middle part of the Minyar Formation [*Ovchinnikova et al.*, 2000]. It is worth noting that K/Ar ages obtained on globular glauconites in the sixties to eighties provided rough determinations of ~900–800 Ma for the Inzer Formation and ~940 Ma for the Katav Formation [*Keller and Chumakov*, 1983]. These ages must be considered with some caution because most of them do not rely on modern analyses. Other age constraints have been derived from the correlation based on paleontological data (stromatolites and organic walled microfossils) between the Zilmerdak Formation, underlying the Katav Formation, and the Lakhanda group of the Uchur-Maya region. The age of the Lakhanda group has been established as roughly 1030 Ma [*Ovchinnikova et al.*, 2001]. The available data therefore indicate that the Katav Formation was deposited between ~1030 and ~800 Ma.

3. Paleomagnetic Analyses

[11] Most paleomagnetic experiments were carried out using a three-axis 2G cryogenic magnetometer housed in the magnetically shielded laboratory at the Institut de Physique du Globe de Paris. Samples were all thermally demagnetized in 12–18 steps. Several rock magnetic measurements were also performed in the Paleomagnetic laboratory of the Institute of Physics of the Earth in Moscow. Components of magnetization were identified using the PaleoMac [*Cogné*, 2003] or *Enkin*'s [1994] paleomagnetic software packages.

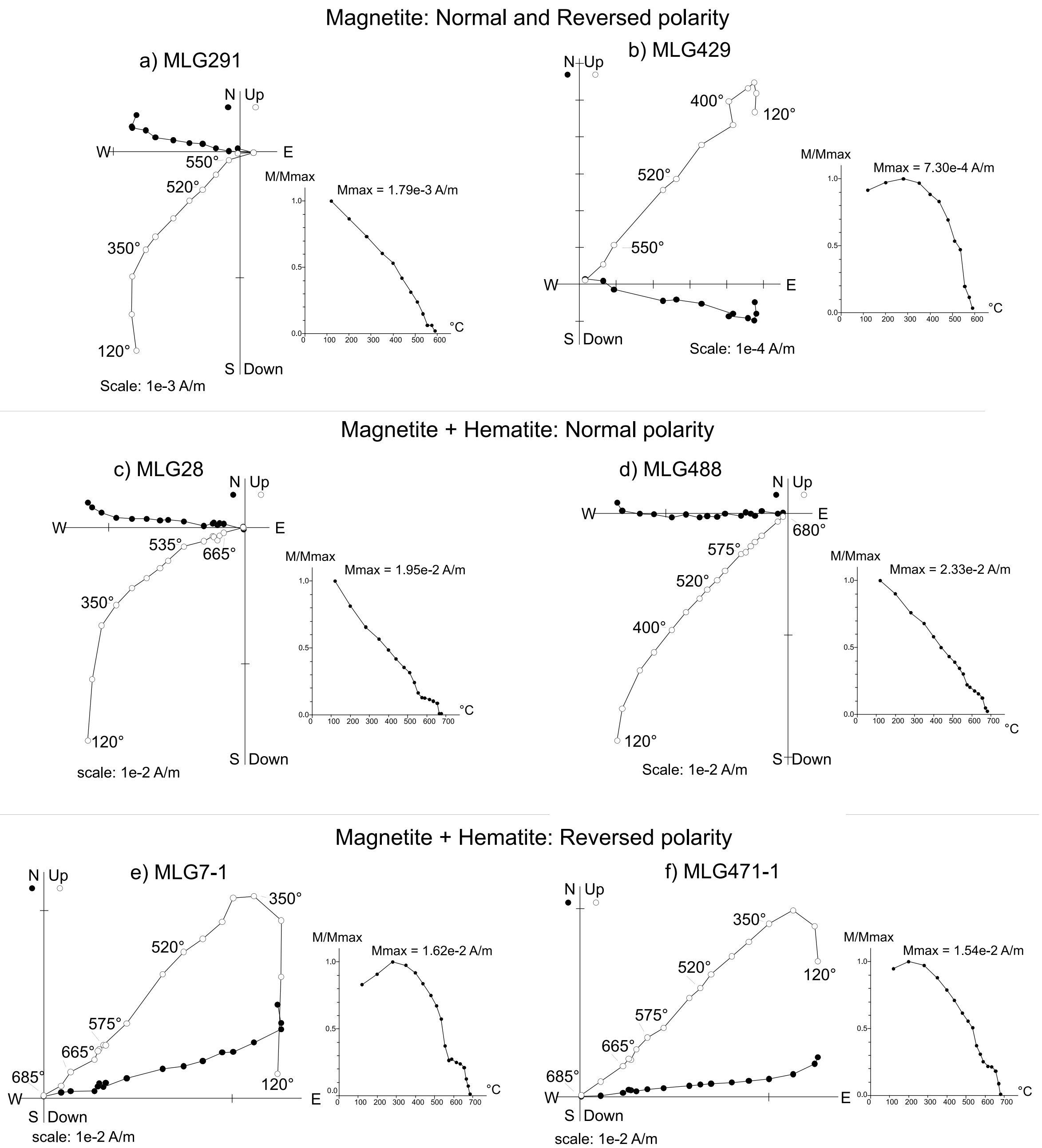


Figure 3. Orthogonal vector diagrams in stratigraphic coordinates of progressive thermal demagnetization of samples from the Talakh-Khaya section. The evolution of magnetization moments versus temperatures are also reported to the right of each vector diagram. Examples of two samples of (a) normal and (b) reversed magnetic polarity whose magnetization is principally carried by magnetite. (c and d) Examples of two samples of normal magnetic polarity whose magnetization is carried by a mixture of magnetite and hematite. (e and f) same as in Figures 3c and 3d but the magnetic polarity is reversed.

3.1. Paleomagnetic Data From the Malgina and Tsipanda Formations

[12] The magnetic properties of rocks from the Malgina Formation have already been studied by *Gallet et al.* [2000]. They sampled these deposits in four sections, the Selia, Haahar, Ingili and Emelekeen sections, which are a few tens of kilometers from the Talakh-Khaya section. We observe the same paleomagnetic behavior as described by *Gallet et al.* [2000]. Thermal demagnetization of the natural remanent magnetization (NRM) reveals the presence of two magnetization components

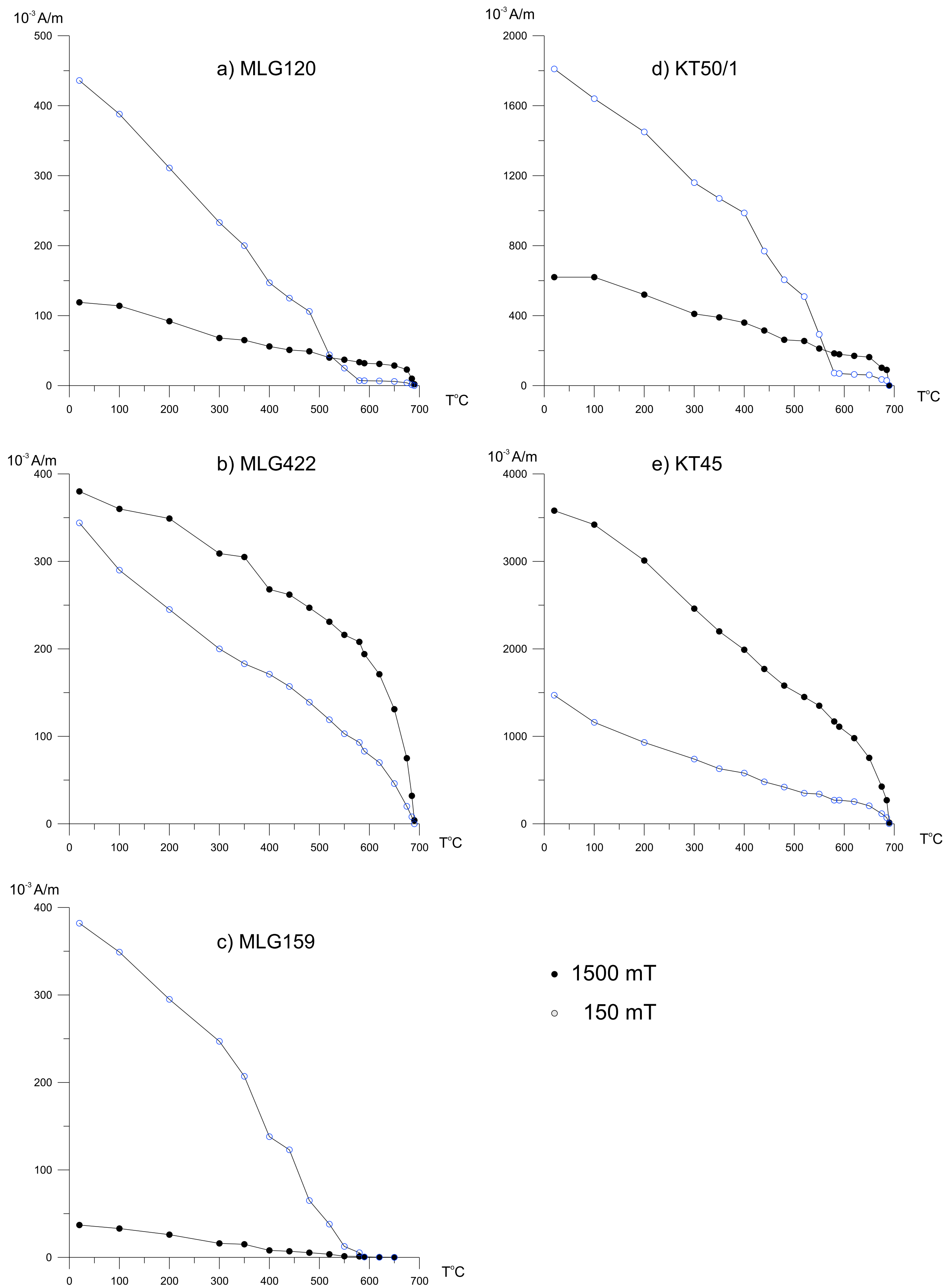


Figure 4. Examples of thermal demagnetization of a two-axis differential IRM (1.5 T and 0.15 T) for representative samples from the (a–c) Talakh-Khaya and (d and e) Minyar sections.

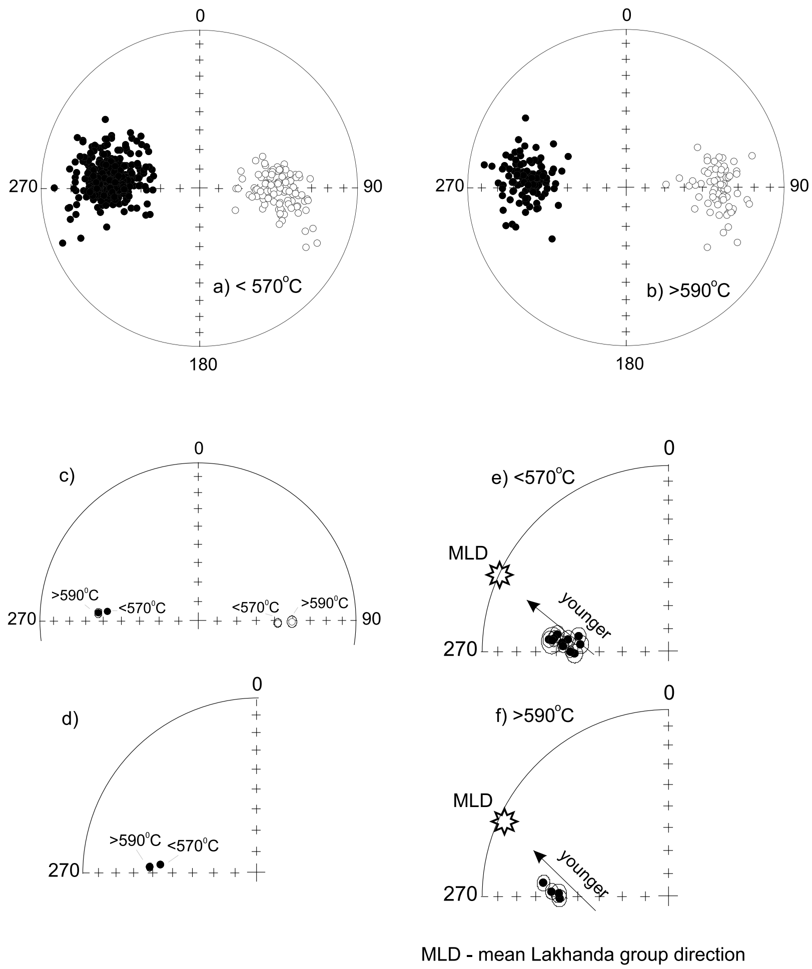


Figure 5. Equal area projection of paleomagnetic directions obtained from the Talakh-Khaya section. (a) Paleomagnetic directions isolated in the unblocking temperature range of magnetite (<570°C). (b) Hematite-related paleomagnetic directions isolated in the high-temperature range (>590°C). Averaged (c) normal and reversed and (d) mixed paleomagnetic directions obtained in the temperature range of magnetite and hematite. Evolution of the paleomagnetic directions averaged over sliding intervals of 40 samples obtained in the temperature range of (e) magnetite and (f) hematite. MLD indicates the mean paleomagnetic direction obtained from the younger Lakhanda Group.

(Figure 3). A first component, isolated up to ~300°C–450°C, has a steep inclination and likely has a recent origin. The second component, which exhibits the two magnetic polarities, is isolated up to ~570°C–590°C or ~680°C (Figure 3). These unblocking temperatures indicate that magnetite and/or hematite dominate the magnetic mineralogy in the studied samples. Such variety in magnetic mineralogy is further illustrated by several examples of thermal demagnetization of a differential (0.15 T and 1.5T) isothermal remanent magnetization (IRM) acquired in two perpendicular directions, showing complete or partial demagnetization of those IRM components below or above ~580°C (Figure 4). Nevertheless, the strong inflexion observed around 580°C in many demagnetization diagrams clearly shows the frequent coexistence of both magnetite and hematite in the same samples (see Figures 3c–3f). Magnetization components were easily isolated in most samples from the Talakh-Khaya section, in particular in the lowest ~75–80 m, where almost 100% of the samples yielded suitable paleomagnetic results. However, the success rate of analyses was much lower in the upper part of the section mostly because the samples are generally more weakly magnetized (<1–3.10^{-5} A/m above ~300°C). Among the 62 samples collected from the Tsipanda Formation, only 18 provided a high-temperature magnetization component (but with a maximum angle of deviation ≥15° for 4 samples).

[13] The west/east pointing paleomagnetic directions calculated for the high-temperature magneti-

Table 1. Paleomagnetic Directions Obtained From the Talakh-Khaya Section[a]

Formation and Outcrops	Polarity, Mineral, and Stratigraphic Level	N	In Situ D	In Situ I	In Situ K	In Situ α_{95} (deg)	Tilt Corrected D (deg)	Tilt Corrected I (deg)	Tilt Corrected K	Tilt Corrected α_{95} (deg)	Reversal Test, γ/γ_c (deg)	Paleomagnetic Poles Latitude (deg)	Paleomagnetic Poles Longitude (deg)	Paleomagnetic Poles dp (deg)/dm (deg)
	All Talakh-Khaya Section: Comparison Between Magnetization Carried by Magnetite or Hematite													
Malgina, Talakh-Khaya, latitude = 58.56°N, longitude = 134.39°E	hematite normal and reversed	175	272.9	38.3	40.7	1.7	272.9	38.4	40.1	1.7				
	magnetite normal and reversed	439	274.8	43.3	38.3	1.1	274.9	43.6	38.3	1.1		−24.0	234.4	0.9/1.4
	magnetite normal	330	275.8	41.8	39.8	1.2	276.0	42.1	39.8	1.2	6.9/2.5			
	magnetite reversed	109	91.4	−47.5	40.7	2.1	91.5	−48.2	43.0	2.1				
	hematite normal	105	274.4	37.1	42.5	2.1	274.4	37.1	41.6	2.2	4.5/3.4			
	hematite reversed	70	90.5	−40.0	40.2	2.7	90.5	−40.4	40.2	2.7				
	Reversal Tests													
	lower 24 m, normal	129					276.0	46.4	46.7	1.8	3.6/2.8			
	lower 24 m, reversed	110					91.5	−48.3	43.2	2.0				
	lower 24 m, MAD ≤ 8°, normal	126					275.7	46.2	47.2	1.8	3.6/2.8			
	lower 24 m, MAD ≤ 8°, reversed	100					91.6	−48.5	44.0	2.1				
	lower 24 m, MAD ≤ 3°, normal	74					273.4	46.2	58.0	2.1				
	lower 24 m, MAD ≤ 3°, reversed	67					93.1	−47.4	45.7	2.5	1.2/3.3			
	samples from interval MLG347v–MLG381v, ~2.6 m (387–651 cm), all, normal	10					283.7	43.9	27.9	8.4				
	samples from interval MLG347v–MLG381v, ~2.6 m (387–651 cm), all, reversed	17					86.7	−52.9	54.8	4.6	14.4/9.2			
	samples from interval MLG347v–MLG381v, ~2.6 m (387–651 cm), MAD ≤ 3°, normal	5					277.1	48.5	40.3	9.9				
	samples from interval MLG347v–MLG381v, ~2.6 m (387 cm – 651 cm), MAD ≤ 3°, reversed	10					87.0	−52.0	51.3	6.2	7.3/12.0			
	lower 24 m, without interval MLG347v –MLG381v, 21.4 m, normal	119					275.4	46.5	46.5	1.9				

Table 1. (continued)

Formation and Outcrops	Polarity, Mineral, and Stratigraphic Level	N	In Situ D	In Situ I	In Situ K	In Situ α_{95} (deg)	Tilt Corrected D (deg)	Tilt Corrected I (deg)	Tilt Corrected K	Tilt Corrected α_{95} (deg)	Reversal Test, γ/γ_c (deg)	Paleomagnetic Poles Latitude (deg)	Paleomagnetic Poles Longitude (deg)	Paleomagnetic Poles dp (deg)/dm (deg)
	lower 24 m, without interval MLG347v –MLG381v, 21.4 m, reversed	94					92.2	−47.5	43.2	2.2	2.4/2.9			
Tsipanda, Talakh-Khaya, latitude = 58.56°N, longitude = 134.39°E		14	282.5	35.5	17.7	9.7	283.2	35.3	17.4	9.8		−23.4	223.8	6.5/11.3
Other Nearby Sections														
Neryuen, Milkon subformation, Nel'kan, latitude = 57.60°N, longitude = 136.07°E		39	295.8	−18.3	23.8	4.8	295.8	−18.3	23.8	4.8		−5.3	199.2	2.6/5.0
Neryuen, Milkon subformation, Ytyrynda, latitude = 58.92°N, longitude = 134.57°E		27	295.2	−13.4	23.5	5.9	295.2	−13.4	23.5	5.9		−6.7	199.4	3.1/6.0

[a] Uchur-Maya region, southeastern Siberia. Reversal tests are performed on different data selections and a distinction is made between the magnetization components carried by magnetite and hematite. Mean paleomagnetic directions obtained from two small sections (Nelkan and Ytyrynka) encompassing the Neryuen Formation are also reported.

zation component are very similar to that previously obtained by *Gallet et al.* [2000] from the Malgina Formation (Figure 5 and Table 1). We remind the reader here that the primary origin of the west/east direction was supported by several lines of evidence, including a positive reversal test, a positive fold test and a positive conglomerate test. The more detailed sampling carried out in the present study provides additional information on the magnetization processes in the sediments from the Malgina and Tsipanda formations and on the evolution of the paleomagnetic directions through the Talakh-Khaya section. First, for taking into account the fact that the magnetization appears principally carried by a mixture of magnetite and hematite, we isolated the high-temperature magnetization component below and above 580°C in order to (roughly) distinguish the paleomagnetic directions mostly recorded by magnetite from those carried by hematite. The results clearly show that the two sets of directions do not statistically share the same mean direction (γ = 5.4°, γ_c = 2.0° at 95% of confidence) [*McFadden and McElhinny*, 1990]. The hematite-related directions exhibit shallower inclinations (Figures 5a–5c and Table 1). The difference between the magnetite and hematite-related mean directions, which amounts to 5–6°, may be due to a different response of the minerals to the compaction of sediments during their burial. Flat and elongated grains of hematite may have been more affected by compaction. On the other hand, the inclination shallowing could also be linked to the argillaceous content of the sediments. Hematite grains growing within relatively large flat clay particles would have been preferentially rotated under compaction. In any case, these two possibilities would strengthen the primary (precompaction) origin of the analyzed high-temperature magnetization component. A reversal test was performed on both the magnetite- and hematite-related magnetization components [*McFadden and McElhinny*, 1990]. Negative results are obtained (Table 1), which will be further discussed in section 5. Furthermore, instead to estimate only general "magnetite" and "hematite" mean directions for the entire section, we also computed submean directions considering sliding subsets, with no overlap, of 40 samples (Table 2). This simple procedure reveals a clear trend, whatever the magnetic carrier, magnetite or hematite (Figures 5e and 5f), toward shallower inclinations from bottom to top of the section. This trend progressively brings the paleomagnetic directions closer to the mean direction previously determined for the overlying Neoproterozoic Lakhanda group (Figure 2) [*Pavlov et al.*, 2002]. This feature does

Table 2. Evolution in the Paleomagnetic Directions Observed Across the Talakh-Khaya and Minyar Sections Using Sliding Windows of 40 and 20 Samples, Respectively

Ordinal Sample Numbers	Number of Samples	Declination (deg)	Inclination (deg)	K	α_{95} (deg)
Talakh-Khaya Section (Malgina and Tsipanda Formations)					
1–40	40	276.8	45.1	40.9	3.6
41–80	40	274.5	51.2	37.1	3.8
81–120	40	279.6	49.7	41.6	3.5
121–160	40	268.6	48.6	37.1	3.8
161–200	40	269.7	46.5	102.0	2.2
201–240	40	274.8	42.7	73.0	2.7
241–280	40	273.1	43.2	73.6	2.7
281–320	40	278.9	39.7	46.4	3.4
321–360	40	276.4	38.6	54.4	3.1
361–400	40	275.8	36.3	53.3	3.1
401–438	38	275.3	37.7	21.2	5.2
Minyar Section (Katav Formation)					
1–20	20	47.5	39.0	23.9	6.8
21–40	20	51.9	40.1	71.6	3.9
41–60	20	49.1	40.9	63.3	4.1
61–80	20	53.0	37.3	49.6	4.7
81–100	20	54.7	31.9	57.2	4.4
101–120	20	54.6	32.6	51.4	4.6
121–140	20	57.3	29.5	35.2	5.6
141–160	20	55.6	27.6	45.7	4.9
161–180	20	53.7	26.7	53.7	4.5
181–200	20	52.3	31.1	29.9	6.1

not appear related to any systematic evolution in anisotropy of magnetic susceptibility (AMS) measured on samples well distributed through the section (with AMS always less than 1% and Kmin roughly perpendicular to the bedding plane). The changes in paleomagnetic direction observed in Talakh-Khaya, therefore, most probably reflect the motion of Siberia during the sediment deposition.

3.2. Paleomagnetic Results From the Katav Formation

[14] The Katav Formation was the subject in the early sixties of one of the first paleomagnetic studies of Precambrian rocks in the former Soviet Union [*Komissarova*, 1970]. Further work was conducted in the seventies to early eighties [*Shipunov*, 1991] but these paleomagnetic data, obtained only using partial or single-point thermal demagnetization procedures, do not satisfy enough modern experimental requirements. The stepwise thermal demagnetization routine used in the present study allows detection of two magnetization components. A lower unblocking temperature component is first isolated up to ~300°C, but sometimes up to ~400°C (Figure 6). The directions obtained for this component are close to that of the present-day field at the site, and likely have a modern origin. At higher temperatures, most samples show a second magnetization component, which decays toward the origin of the demagnetization diagrams (Figure 6). This component possesses the two magnetic polarity states (Figure 7) and is generally destroyed around 680°C. From the evolution of the magnetic moments (NRM and IRM) during heating, there is clear evidence for a mixture of both magnetite and hematite (Figures 4d, 4e, and 6b–6d). The frequent coexistence of both moderate and high-coercivity minerals is confirmed by hysteresis loop meaurements exhibiting clear wasp-waisted shapes (Figures 8a and 8b). In contrast with the previous results, however, the directions obtained for the magnetite- and hematite-bearing magnetization components are identical, thus showing no differential inclination shallowing effect which may be related to the higher carbonate (lesser argillaceous) content in the Katav Formation.

[15] Several lines of evidence support a primary origin for the high-temperature magnetization component isolated in the Minyar section. The first was obtained from scanning electron microscope (SEM) observations made on several samples. These samples display titanomagnetite grains with exsolution textures, supporting their detrital origin. (Figure 8c). The second point is the presence of numerous magnetic polarity reversals within the section. Several samples collected at different transitions between intervals of opposite magnetic polarities yield unusual paleomagnetic directions (Figures 6e and 6f). The latter probably reflect either the "true" record of a transitional geomagnetic field or an artifact induced by the simultaneous lock-in of both normal and reversed polarity magnetizations in those strata (or perhaps a combination of these two possibilities). After their removal, the two groups of remaining directions with opposite polarities successfully pass the reversal test designed by *McFadden and McElhinny* [1990] (γ = 2.6°; γ_c = 3.3°; Table 3). Positive reversal tests are also obtained when the section is divided in two subsections (lower ~80 m and upper ~80 m; Table 2). Note that in this case, the two mean paleomagnetic directions (combining normal and reversed polarity data) are different at the 95% confidence level. Moreover, although only slight changes in dipping attitude are observed within the Minyar section, a positive fold test, according to the modified version of *Enkin*'s [2003] fold test, is obtained at 95% when using the high-temperature magnetic directions [see also *Shipunov*, 1991].

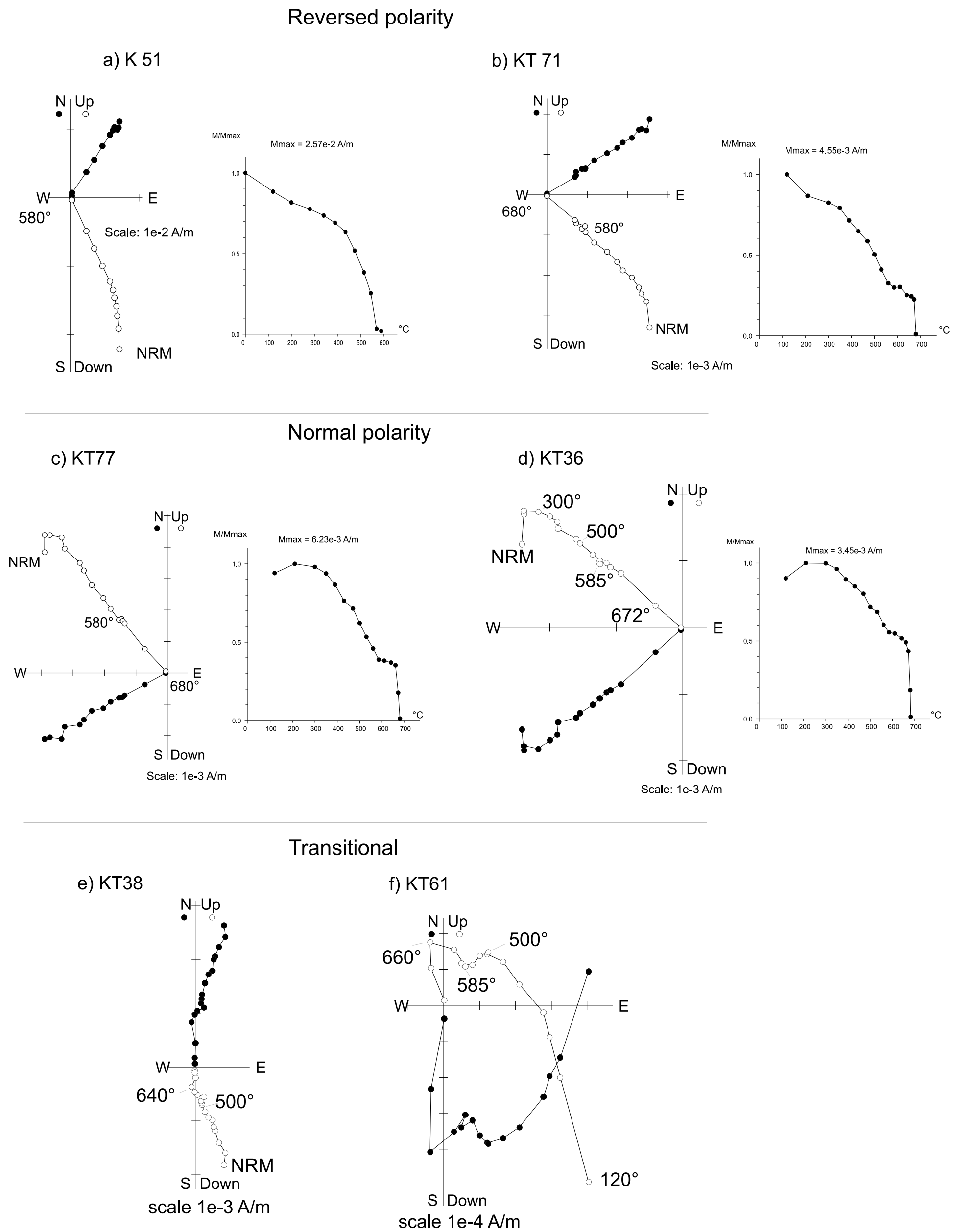


Figure 6. Orthogonal vector diagrams in stratigraphic coordinates of progressive thermal demagnetization of samples from the Minyar section. The evolutions of magnetization moments versus temperatures are also reported to the right of each vector diagram. (a and b) Two examples of samples with a reversed magnetic polarity. (c and d) Two examples of samples with a normal magnetic polarity. (e and f) Two examples of samples having recorded a transitional magnetic direction.

[16] We studied two additional outcrops of the Katav Formation, each yielding the possibility to perform a fold test. In those cases, the age of folding may be as old as Vendian to Ordovician [e.g., *Maslov et al.*, 1997]. The first outcrop is located in the vicinity of the village of Pervomaysky, some 1.5 km southwest from the Minyar section. It shows evidence of a meter-scale post-depositional rock deformation event. The Fisher parameter K computed from 23 samples increased by a factor of 5 after bedding correction, yielding a positive fold test (Figures 9a–9d). The second outcrop was sampled along the road Ufa-Beloretsk, ~90 km to the south of the Minyar section. It shows a two-limb fold exposed over a distance of ~40 m. One paleomagnetic site was collected from

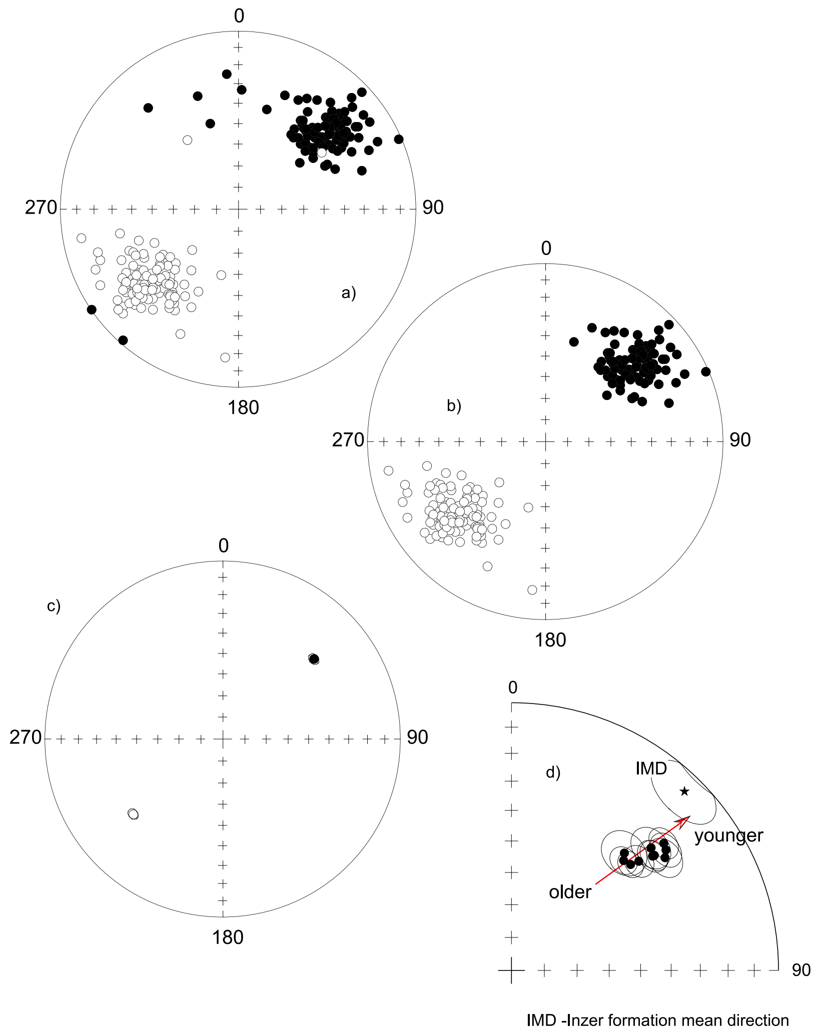


Figure 7. Equal area projection of paleomagnetic directions obtained from the Minyar section after bedding correction. Directions isolated for the high-temperature (>400°C) magnetic component: (a) all directions and (b) after removal of the "transitional" directions. (c) Mean normal and reversed paleomagnetic directions obtained from the section. (d) Evolution of paleomagnetic directions within the section averaged over sliding intervals of 20 samples. IMD indicates the mean paleomagnetic direction obtained from the younger Inzer Formation.

each limb. The two groups of samples reveal dual magnetic polarities (Figures 9e–9g). Their mean directions are clearly different in in situ coordinates, whereas they become identical at the 95% level after bedding correction. It is worth pointing out that the latter are close to that observed from the Minyar and Pervomaysky sections (Figure 9h and Table 3).

[17] Submean paleomagnetic directions were also computed for the Minyar section from a successive nonoverlapping series of 20 samples. As in the Talakh-Khaya section, a systematic trend toward lower inclinations (by ~10°) is observed, bringing the paleomagnetic directions obtained in the upper part of the Katav Formation closer to the mean directions we found from two near-located outcrops of the overlying Inzer Formation (Figure 7d and Table 3). This trend, which is not related to any evolution in AMS measurements carried out through the section (again with AMS of less than 1% and Kmin roughly perpendicular to the bedding plane), likely describes the plate motion during sediment deposition.

[18] At this step, it is worth recalling that widespread remagnetization was reported in rocks of different ages from the Ural-Mongolian fold belt [e.g., *Komissarova*, 1970; *Pechersky and Didenko*, 1995; *Grishin et al.*, 1997]. This remagnetizaton, consistently showing reversed polarity, was thought to be of Upper Paleozoic age based on

 10.1029/2009GC002583

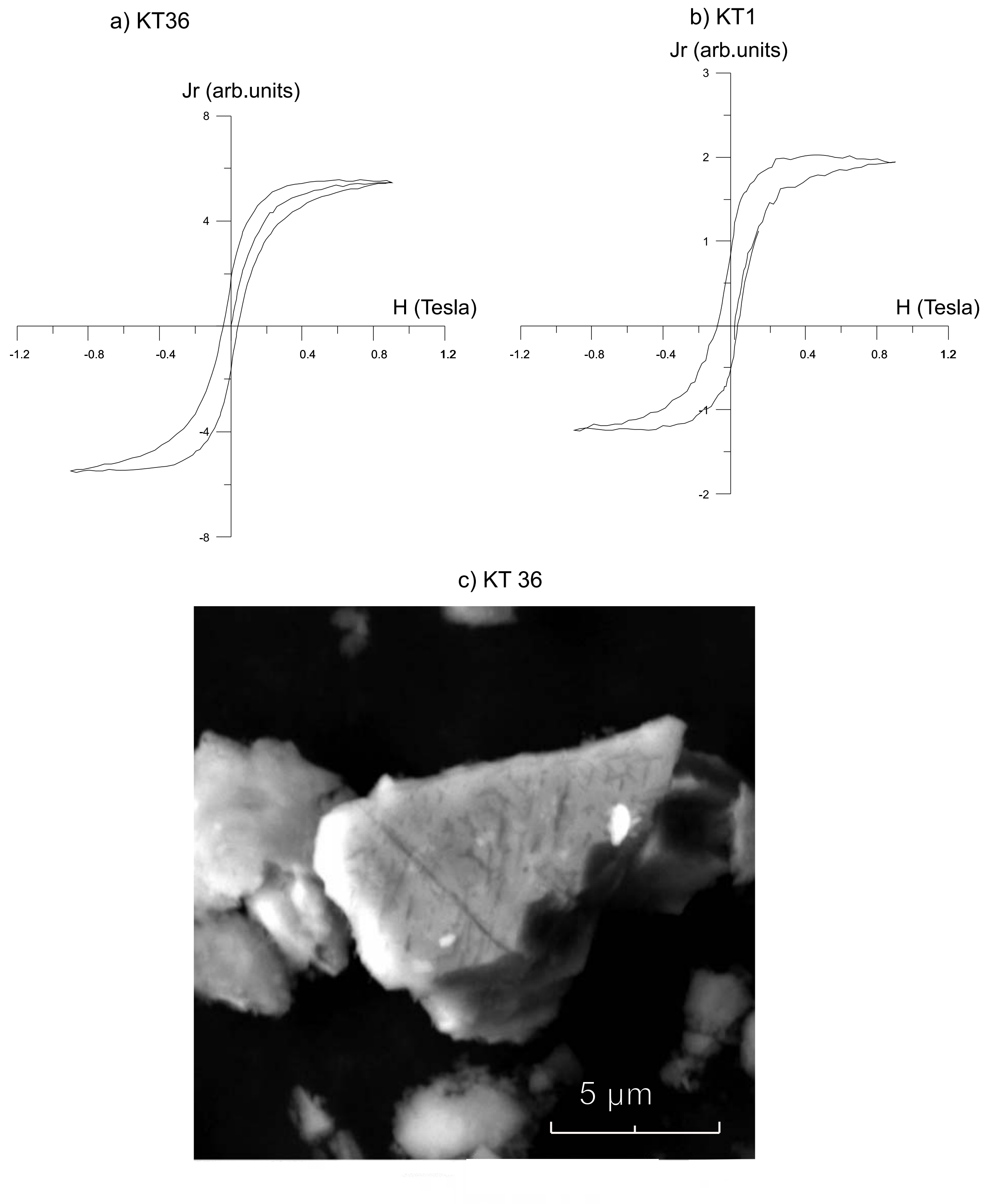


Figure 8. (a and b) Hysteresis loop measurements and (c) scanning electron microscope observation from different samples from the Minyar section (Katav Formation, southern Urals). The grain from sample KT36 seen in the center of Figure 8c is a low-titanium exsolved magnetite whose composition is Fe, 67.69%; 0, 26.04%; Ti, 2.50%; Al, 0.29%; Si, 1.55%; Ca, 0.92%; and V, 1.01%.

Table 3. Paleomagnetic Directions Obtained From the Katav Formation[a]

Outcrops	Polarity	N	In Situ D (deg)	In Situ I (deg)	In Situ K	In Situ α_{95}	Tilt Corrected D (deg)	Tilt Corrected I (deg)	Tilt Corrected K	Tilt Corrected α_{95} (deg)	Reversal Test, γ/γ_c (deg)	Paleomagnetic Poles Latitude (deg)	Paleomagnetic Poles Longitude (deg)	Paleomagnetic Poles dp (deg)/dm (deg)
Katav Formation														
Minyar, latitude = 55.06°N, longitude = 57.52°E	reversed	92	58.3	42.8	38.2	2.4	52.1	32.4	39.9	2.4				
	normal	110	242.0	−45.3	32.7	2.4	233.6	−34.7	34.3	2.3				
	general	202	60.3	44.2	34.6	1.7	52.9	33.7	36.5	1.7	2.6/3.3	35.9	168.4	1.5/1.9
Reversal Tests														
	lower 79.9 m (samples KT1–KT64), reversed	32					50.1	37.7	44.7	3.7				
	lower 79.9 m (samples KT1–KT64), normal	23					228.5	−42.4	42.6	4.5	4.9/5.9			
	upper 72.9 m (samples KT104–KT105), reversed	57					52.7	29.1	42.0	2.9				
	upper 72.9 m (samples KT104–KT105), normal	42					237.5	−29.0	43.4	3.3	4.2/4.5			
Pervomaysky, latitude = 55.05°N, longitude = 57.54°E		23	42.6	39.5	5.2	14.7	59.2	33.3	29.7	5.6	only three samples of reversed polarity	31.6	161.6	3.6/6.4
Road Ufa-Beloretsk, latitude, = 54.30°N, longitude = 57.20°E	reversed	9	36.5	28.4	12.6	15.1	38.4	31.4	27.2	10.1				
Road Ufa-Beloretsk, latitude = 54.30°N, longitude = 57.20°E	normal	9	226.0	−21.5	19.7	11.9	228.3	24.9	88.3	5.5				
Road Ufa-Beloretsk, latitude = 54.30°N, longitude = 57.20°E	general	18	41.5	25.0	15.2	9.2	43.6	28.2	36.7	5.8	10.8/10.9	38.2	179.2	3.5/6.4
Inzer Formation														
Site 1, latitude = 55.08°N, longitude = 57.56°E		14	50.8	5.7	45.8	5.9	50.8	6.2	45.6	5.9				
Site 2, latitude = 55.06°N, longitude = 57.59°E		11	40.6	45.3	10.9	14.5	34.1	26.1	14.3	12.5		27.7[b]	185.9[b]	4.6/9.2[b]
Zilmerdak Formation														
Latitude = 54.20°N, longitude = 57.62°E		73	39.7	54.3	4.8	8.5	3.6	11.6	6.0	7.4		41.6	232.8	7.5/5.4

[a] Minyar, Pervomaysky, and "Ufa-Beloretsk road" sections, southern Urals. Reversal tests are performed on different data selections. Mean paleomagnetic directions obtained from three sections encompassing two the Inzer Formation and the other the Zilmerdak Formation are also reported.
[b] Mean site 1 + site 2; N = 25.

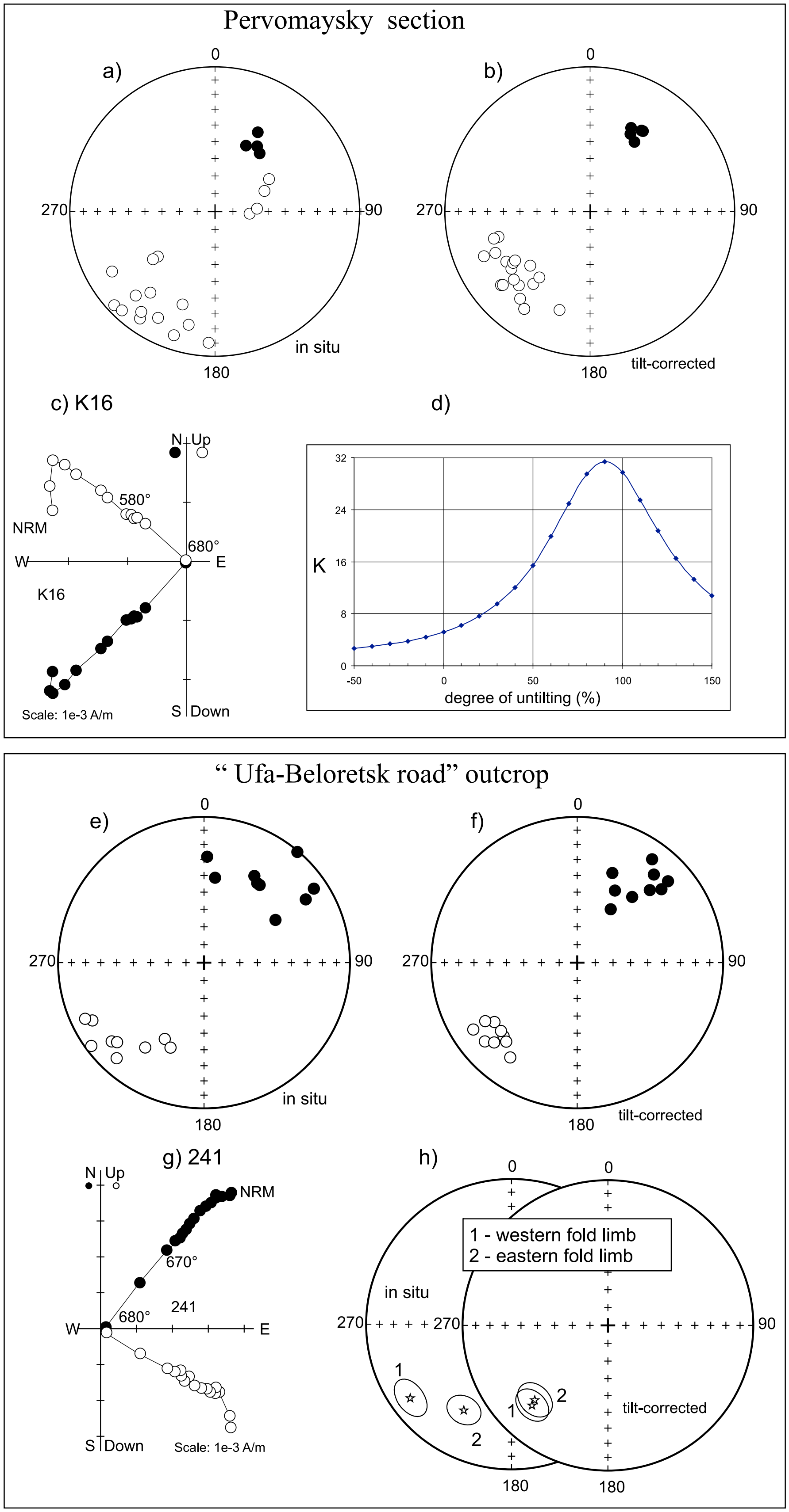

Pervomaysky section
a)
0
270
90
180
in situ
b)
tilt-corrected
c) K16
N Up
580°
680°
NRM
W
E
K16
Scale: 1e-3 A/m
S Down
d)
K
degree of untilting (%)
"Ufa-Beloretsk road" outcrop
e)
f)
g) 241
670°
680°
241
h)
1 - western fold limb
2 - eastern fold limb
1
2

Figure 9

the proximity of the obtained paleomagnetic poles with the Upper Paleozoic segment of the eastern European apparent polar wander path (this plate being located in the Northern Hemisphere at this time) [e.g., *Smethurst et al.*, 1998; *Cocks and Torsvik*, 2007]. Although the paleomagnetic pole derived from the Minyar section is also close to that segment, a remagnetization of the section appears very unlikely [see *Pavlov and Gallet*, 2009, Figure 6]. The preceding arguments coupled with the numerous magnetic polarity reversals observed from that section are clearly incompatible with the occurrence of the late Carboniferous-Permian Kiaman reversed polarity superchron. Moreover, the paleomagnetic poles obtained for the Katav and Inzer formations (Table 3) are rather similar to the ~700–800 Ma mean pole proposed by *Meert and Torsvik* [2003] and *Walderhaug et al.* [2007] for the eastern European platform, which was assumed to be located in the Southern Hemisphere. These arguments indicate a primary origin for the high-temperature magnetization component isolated in the Minyar section.

4. Magnetostratigraphy of the Talakh-Khaya and Minyar Sections and Supplementary Results

[19] As a preliminary remark, we acknowledge the problem of the polarity option for our two magnetostratigraphic data sets. In both cases, the choice between normal and reversed paleomagnetic directions is not trivial and is currently under discussion [e.g., *Gallet et al.*, 2000; *Pavlov et al.*, 2002; *Pisarevsky and Natapov*, 2003; *Cocks and Torsvik*, 2007; *Meert et al.*, 2007; *Walderhaug et al.*, 2007]. It is particularly critical for the results from the Minyar section as there is still ambiguity on the hemispheric position of Baltica during the Late Neoproterozoic and Vendian [*Meert et al.*, 2007; *Walderhaug et al.*, 2007]. The hemispheric solution for the Talakh-Khaya results strongly depends on the location of Vendian and Early Cambrian Siberian poles. Recent paleomagnetic data obtained by *Shatsillo et al.* [2006] from Vendian red beds of the southern Siberian platform favor an "Indian Ocean trend" of the Siberian apparent polar wander path (APWP) during the Neoproterozoic, rather than a "Pacific" trend. If correct, the north paleomagnetic pole of the Malgina and Tsipanda formations should be located in the eastern hemisphere and thus the west pointing paleomagnetic directions found in these formations should be considered of normal magnetic polarity. This option is different from that chosen by *Gallet et al.* [2000].

[20] A sequence of 33 magnetic polarity intervals is obtained from the Talakh-Khaya section. Each interval is represented by several samples (Figure 10; the paleomagnetic directions reported in Figure 10 are those determined in the magnetite-unblocking temperature range). All magnetic polarity reversals are found within the lower 24 m of the section (see enlargement in Figure 10), while the upper 174 m are a single normal polarity zone. Taking into account the change in polarity option, the new data appear to be in good agreement with the poorly resolved (because of insufficient sampling density) magnetostratigraphic sequences obtained by *Gallet et al.* [2000]. They also indicate the presence of a stratigraphically thick interval of normal magnetic polarity, encompassing the middle-upper parts of the Malgina Formation and the lower part of the Tsipanda Formation. This thick interval was not seen from the previous results and is a striking feature of the Talakh-Khaya magnetic record. Other paleomagnetic data yield some constraints on the location of its upper (younger) limit. Whereas the upper part of the Tsipanda Formation is not suitable for paleomagnetic investigation (this study), the upper lying formations from the Lakhanda and Ui groups are more favorable for this purpose [e.g., *Pavlov et al.*, 2000, 2002]. Thermal demagnetization analysis of samples collected from several sections of the Neryuen Formation yielded a high-temperature magnetization component of normal polarity (Figure 11) [*Pavlov et al.*, 2000]. The same polarity was observed in samples from the lower part of the Ignikan Formation [*Pavlov et al.*, 2000].

Figure 9. Paleomagnetic results obtained from two outcrops of the Katav Formation, the first located close to the village of Pervomaysky and the other located along the road Ufa-Beloretsk (southern Urals). Data from the Pervomaysky section: equal area projections of the high-temperature paleomagnetic directions obtained (a) before and (b) after bedding correction, (c) example of orthogonal vector diagram in stratigraphic coordinates of progressive thermal demagnetization, and (d) Fisher precision parameter as a function of stepwise unfolding. Data from the "Ufa-Beloretsk road" outcrop: equal area projections of the high-temperature paleomagnetic directions obtained from twofold limbs (e) before and (f) after bedding correction, (g) example of orthogonal vector diagram in stratigraphic coordinates of progressive thermal demagnetization, and (h) equal area projections of the mean paleomagnetic directions obtained from the twofold limbs before and after bedding correction.

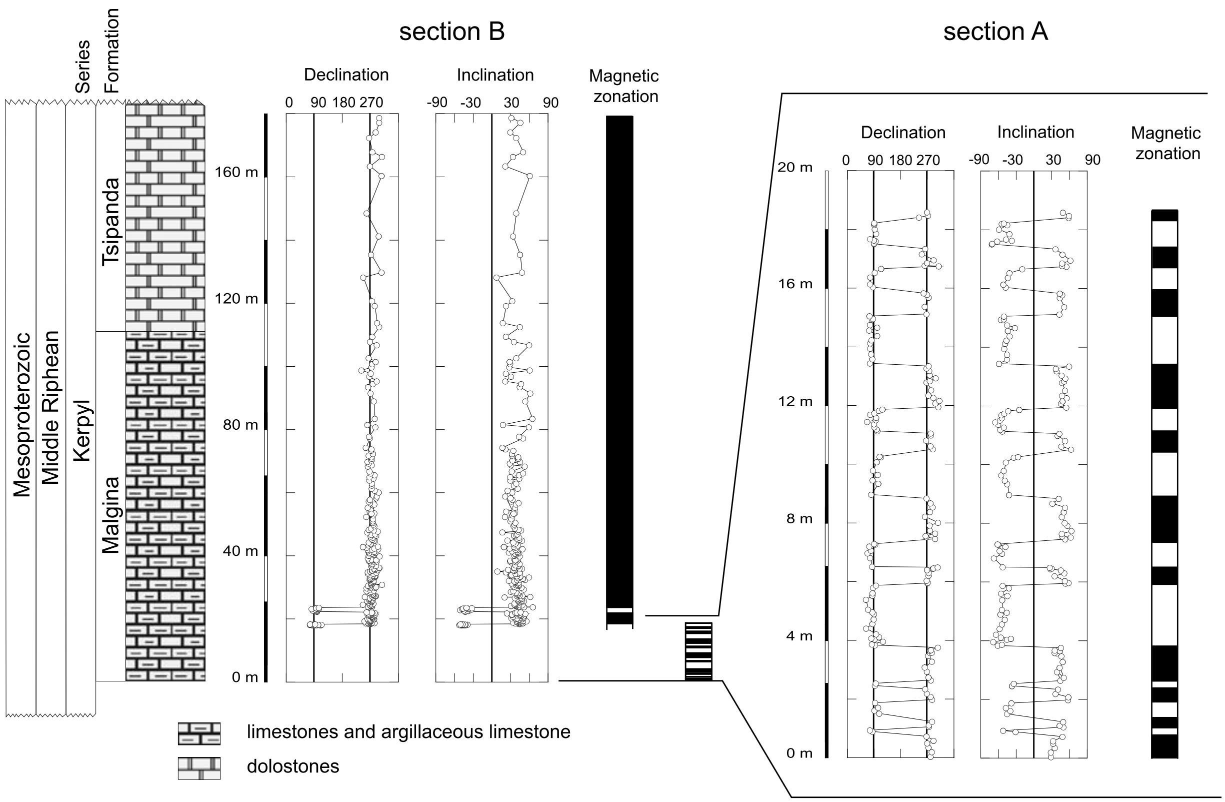


Figure 10. (left) Magnetostratigraphy of the Talakh-Khaya section (Uchur-Maya region). The magnetic polarity option is given assuming a Northern Hemisphere position for Siberia at this time (see section 4). (right) An enlargement of the lower part of the section.

The end of this magnetic interval may in fact occur somewhere between the upper part of the Ignikan Formation and the lower part of the Kandyk Formation, as samples with a reversed polarity magnetization were found by *Pavlov et al.* [2002] from the Kandyk and Ust-Kirba formations (Figure 12). All these data therefore suggest a long duration for the normal polarity interval (see below), which begins within the Malgina Formation and contains the Mesoproteroic-Neoproterozoic boundary traced in the Uchur-Maya region (Figure 2).

[21] Following *Meert et al.* [2007] and *Walderhaug et al.* [2007], we assumed a Southern Hemisphere position for the eastern European platform around 800 Ma (i.e., a normal polarity for the southwest pointing paleomagnetic directions obtained from the Minyar section). The Minyar section contains 43 magnetic polarities intervals, 8 of which are defined by one sample (Figure 13). 34 magnetic polarity intervals occur within the upper ~70 m, while a ~40 m thick interval immediately below this does not show any magnetic reversal. This new record encompassing the Katav Formation is much more detailed than the sequences previously determined by *Shipunov* [1991], *Komissarova* [1970], and *Komissarova et al.* [1997]. We also obtained preliminary magnetostratigraphic data from the underlying terrigeneous Zilmerdak Formation sampled near the village of Inzer, about 100 km to the south of the Minyar section. The directions of the high-temperature magnetization component are rather scattered, but a positive fold test attests to the primary origin of the magnetic signal, and at least 23 additional magnetic polarity intervals are observed (Figure 14 and Table 3). Considered together, the data reported in the present study thus show evidence for approximately one hundred magnetic polarity reversals around the Mesoproterozoic-Neoproterozoic boundary, although a contin-

Figure 11. Paleomagnetic and magnetostratigraphic data obtained from two small sections (Nelkan and Ytyrynda) from the Uchur-Maya region encompassing the Neryuen Formation (lowermost Upper Riphean). (a–c) Examples of orthogonal vector diagrams in stratigraphic coordinates of progressive thermal demagnetization. Equal area projections of the paleomagnetic directions obtained after bedding correction from the (d) Nelkan and (e) Ytyrynda sections. (f) Magnetostratigraphic results obtained from the Nelkan and Ytyrynda sections.

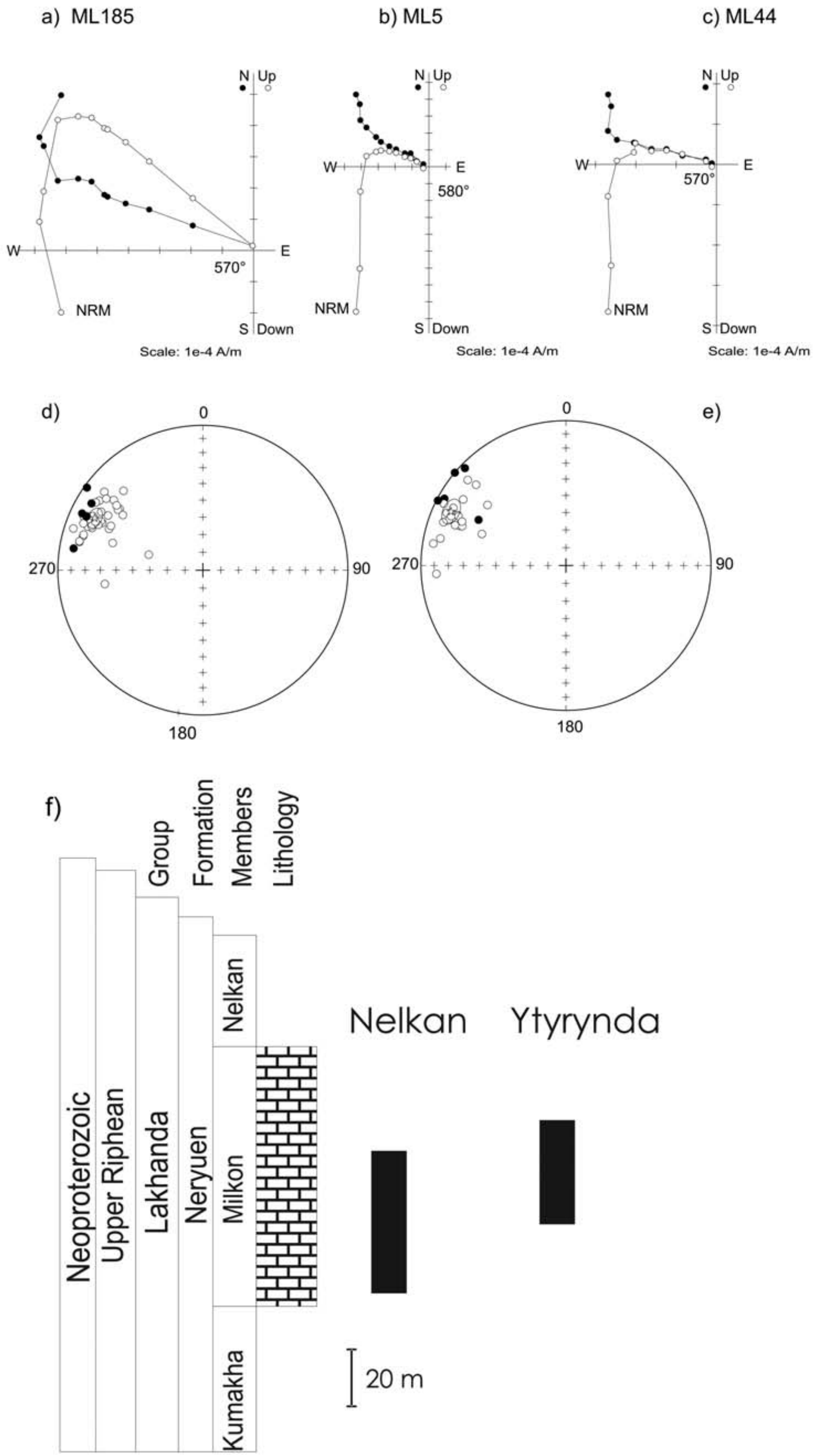
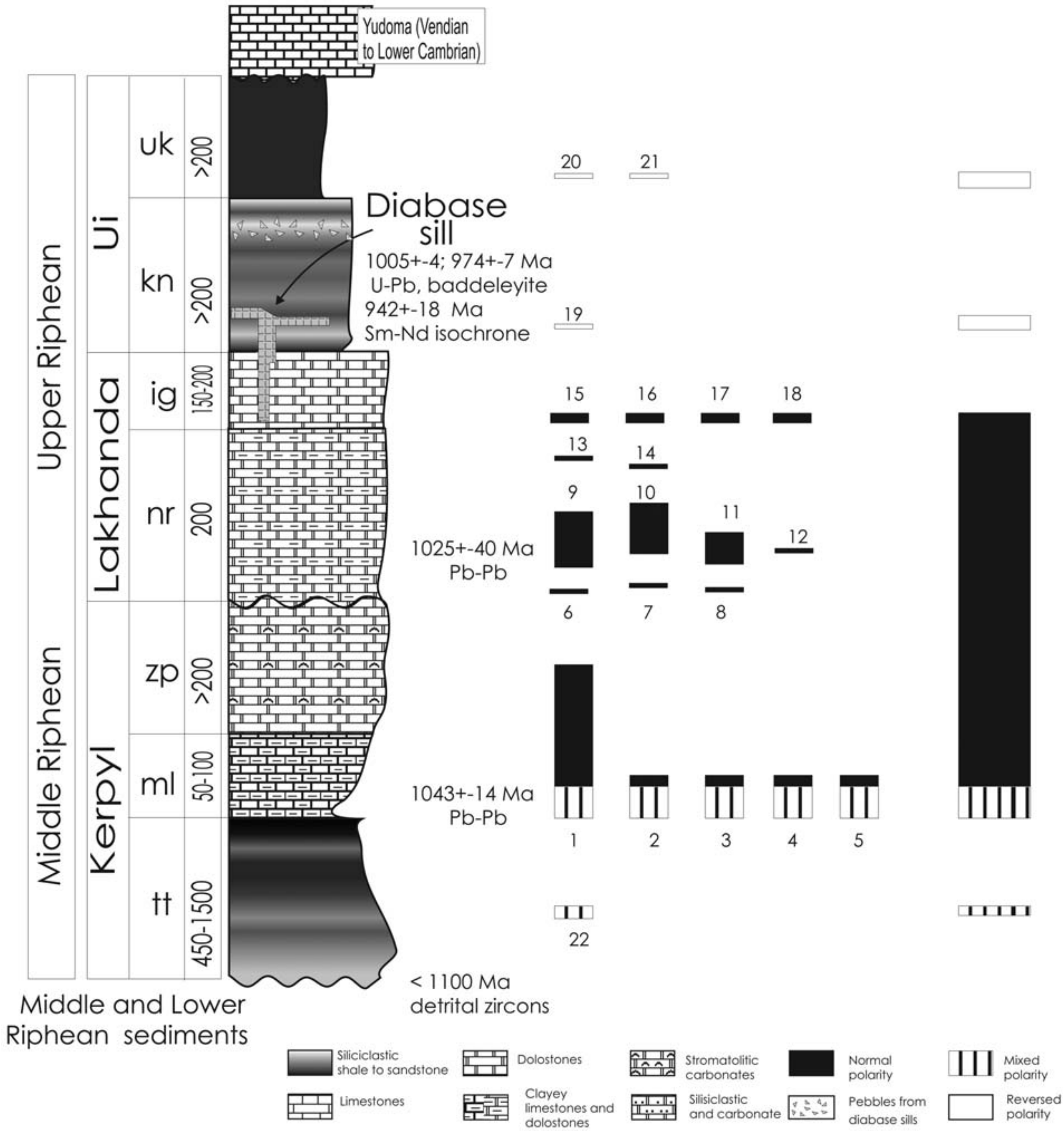

a) ML185
b) ML5
c) ML44
N Up
W
E
S Down
570°
580°
NRM
Scale: 1e-4 A/m
d)
e)
0
90
180
270
f)
Neoproterozoic
Upper Riphean
Group
Lakhanda
Formation
Neryuen
Members
Nelkan
Milkon
Kumakha
Lithology
Nelkan
Ytyrynda
20 m

Figure 11



Studied outcrops: Malgina formation: 1-Talakh Khaya (this work);
2-Selia; 3-Emelekeen;4- Khaakhar;5-Ingili - [*Gallet et al., 2000*]; Neryuen formation, Kumakha subformation: 6-Neryuen;
7-Khandy-Makit; 8- Ingili-2; Milkon subformation: 9-Ytyrynda (this work);10-Nelkan (this work); 11- Ingili-3;12- Tastakh ;
Neryuen formation, Nelkan subformation - 13-Lakhanda; 14-Nelkan-2;
Ignikan formation:15-Emelekeen; 16-Ingili-4; 17-Red Cliffs; 18-Lakes Chuiskie, - [*Pavlov et al.,2000*];
Sills -19- Sourdonnakh; Ust-Kirba formation - 20-Kyry-Ytyga; 21-Kavalkan - [*Pavlov et al., 2002*];
Totta formation - 22-Borya mountain - [*Pavlov, 1994*].
Formations: tt-Totta; ml- Malgina; zp-Tsipanda; nr-Neryuen; ig-Ignikan; kn-Kandyk; uk-Ust-Kirba: .

Figure 12. Synthesis of magnetic polarity data obtained from numerous outcrops investigated in the Uchur Maya region. The numbers (from 1 to 22) refer to different outcrops indicated at the bottom. A simplified composite magnetic polarity sequence is reported to the right.

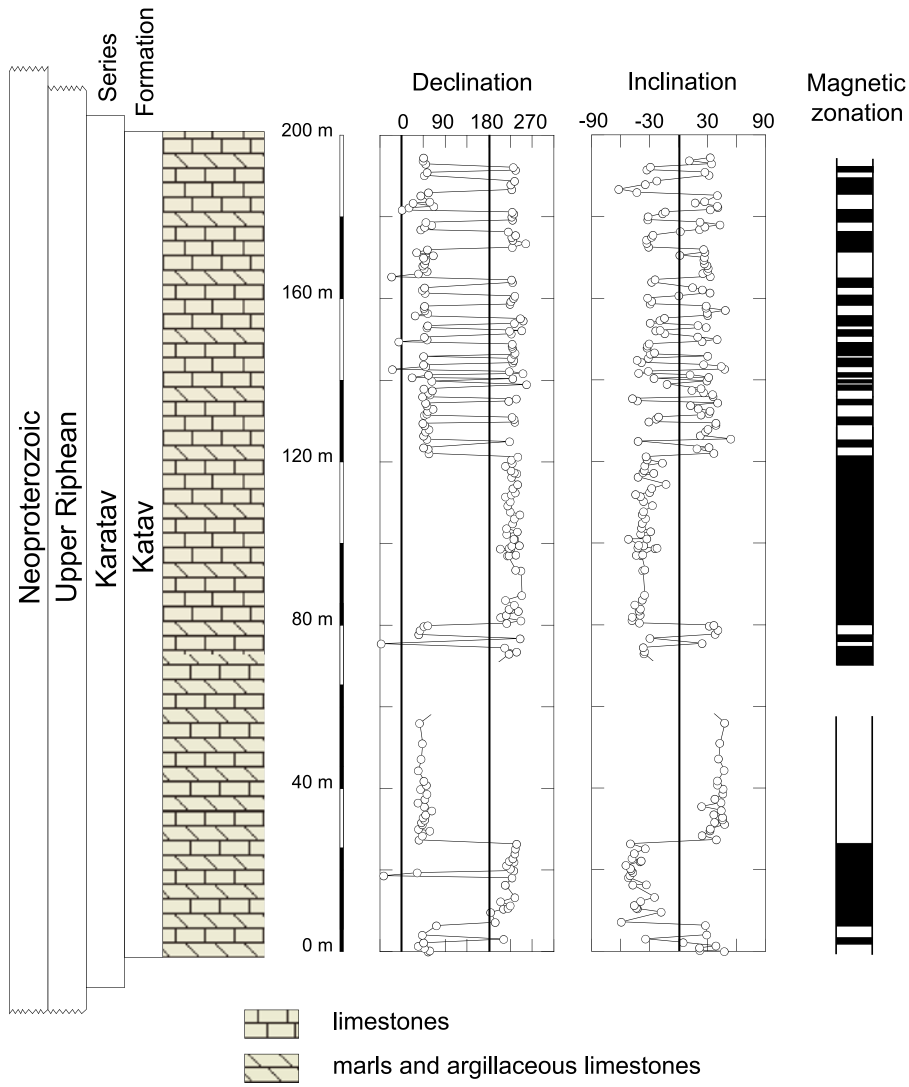


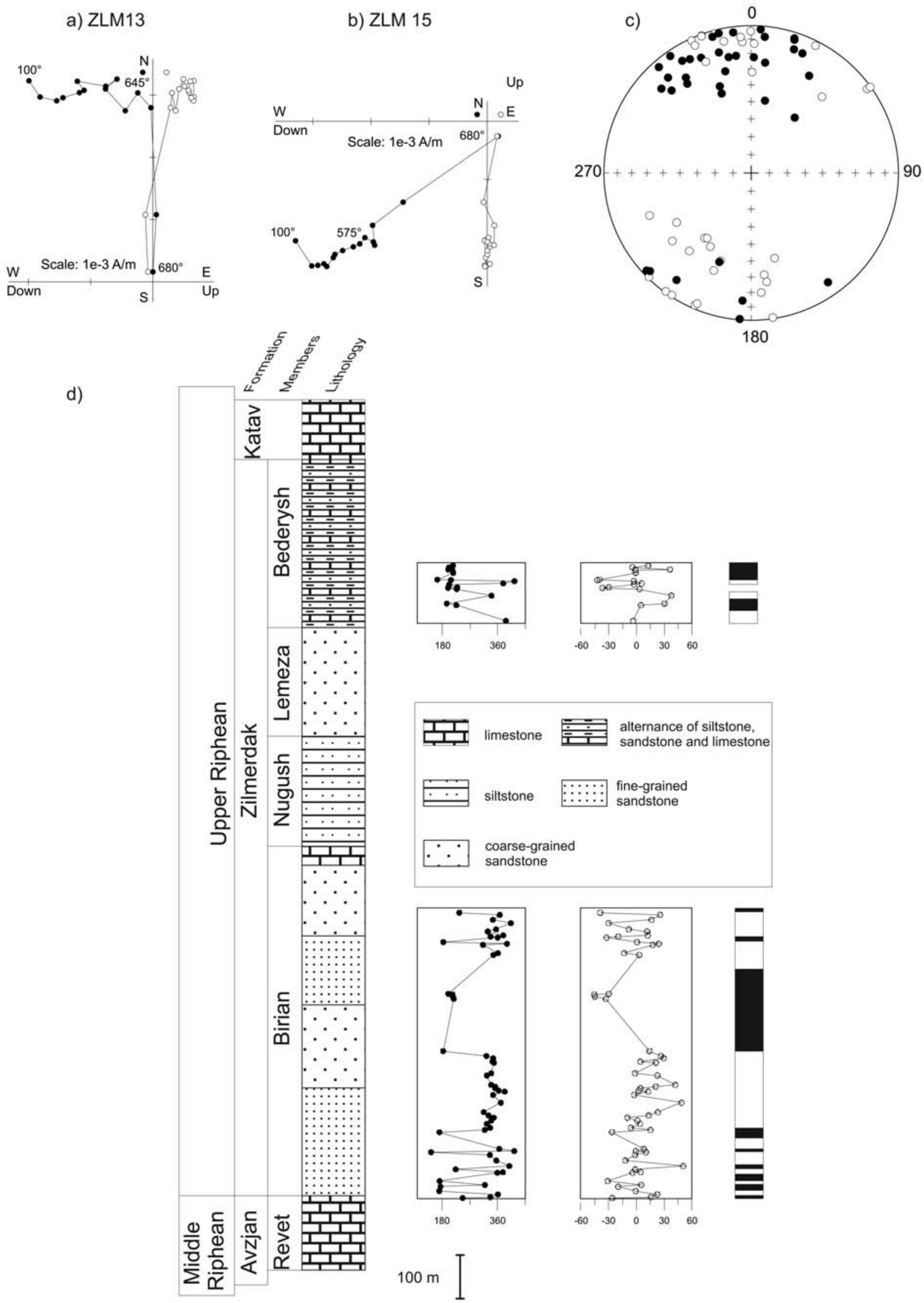
Figure 13. Magnetostratigraphy of the Minyar section (southern Ural). The magnetic polarity option is given assuming a Southern Hemisphere position for the eastern European platform at this time (see section 4).

uous magnetic polarity sequence cannot be established yet.

5. Discussion

[22] The numerous geomagnetic polarity reversals observed in the Talakh-Khaya and Minyar sections provide a rare opportunity to better constrain the behavior of the Earth's magnetic field at two distinct (but relatively close) time intervals of the Proterozoic. In particular, our new results shed further light on the possible occurrence of asymmetric polarity reversals during the Proterozoic that might indicate a greater contribution of nondipole sources during this period than during the Phanerozoic [e.g., *Pesonen and Nevanlinna*, 1981; *Nevanlinna and Pesonen*, 1983; *Kent and Smethurst*, 1998]. In addition, rough approximations can be made on the sedimentation rates across the studied sections to obtain important new information on the changes in magnetic reversal frequency during Precambrian time.

[23] The occurrence of asymmetrical polarity reversals during the Proterozoic has been suggested on the basis of a very limited data set, mainly obtained from the Keweenawan lavas in Canada dated at ~1.1 Ma (with differences in inclination as high as ~25° between normal and reversed polarity directions) [*Pesonen and Nevanlinna*, 1981; *Nevanlinna and Pesonen*, 1983]. This possibility was discussed and challenged by *Gallet et al.* [2000] from their magnetostratigraphic investigation of the two coeval late Mesoproterozoic Malgina and Linok



a) ZLM13
b) ZLM 15
c)
d)
Scale: 1e-3 A/m
Formation
Members
Lithology
Upper Riphean
Middle Riphean
Katav
Zilmerdak
Avzjan
Bederysh
Lemeza
Nugush
Birian
Revet
limestone
alternance of siltstone, sandstone and limestone
siltstone
fine-grained sandstone
coarse-grained sandstone
100 m

Figure 14

formations from the southeastern and northwestern Siberian platform, respectively. These authors did not confirm the persistence of such a property of the Precambrian geomagnetic field [see also *Gose et al.*, 2006; *Dunlop and Yu*, 2004]. Nevertheless, the new data reported in the present study, together with results from other sections not available in 2000, provide additional constraints on this issue.

[24] The paleomagnetic directions determined for the high-temperature magnetization component from the Minyar section yield a positive reversal test (Table 3). This result holds both for the entire data set and for successive subsets of ~60 samples isolated within the section. We thus find no evidence for an asymmetrical geomagnetic field during the time of deposition of the Katav Formation (i.e., during ~20 Myr between ~1030 Ma and ~800 Ma; see below). *Gallet et al.* [2000] previously obtained a positive reversal test in three sections from the Uchur-Maya region encompassing the lower part of the Malgina Formation. The data from the Talakh-Khaya section, which encompasses the entire Malgina Formation and the lower part of the Tsipanda Formation, are much more numerous but, considered as a whole (438 directions), they fail the reversal test (Table 1). The same negative result is observed when only the data obtained from the lower ~24 m of the section are taken into account, thus avoiding the data defining the long normal polarity interval within the upper part of the Malgina Formation and the Tsipanda Formation and limiting any potential effect due to the motion of Siberia. However, the interpretation of this characteristic in terms of geomagnetic field behavior appears unsatisfactory for two reasons. The first relies on the quality of the data. If only the best defined paleomagnetic directions with a maximum angle of deviation ≤3° are retained, the reversal test then becomes positive (with classification A according to *McFadden and McElhinny* [1990] (Table 1)). The second reason springs from the observation that the main source of the nonantipodality between the normal and reversed polarity directions in the Talakh-Khaya section arises from a restricted stratigraphic interval, between ~3.9 and ~6.5 m from the base, which only contains a pair of normal and reversed polarity intervals. If this zone is excluded from the computations, the reversal test is positive whatever the data selection (Table 1). Moreover, if only the directions with a maximum angle of deviation ≤3° are considered for this interval, they pass the reversal test. This means that evidence for an asymmetrical geomagnetic field from this section is tenuous, and most probably originates from very local lithological disturbances. This conclusion is further supported by the positive reversal test also obtained from the Linok Formation, in the Turukhansk region [*Gallet et al.*, 2000], considered as coeval with the Malgina Formation [e.g., *Semikhatov*, 1995].

[25] Recent paleomagnetic and magnetostratigraphic results dated to different time intervals of the Late Archean and of the Proterozoic also provided positive reversal tests, which again contradict the persistent or even the temporary occurrence of an asymmetrical geomagnetic field during this period. Among those studies, there are the data obtained from the ~2.7 Ga flood basalts in the Pilbara craton (Western Australia) [*Strik et al.*, 2003], from the ~2.0–1.6 Ga mafic dykes of the eastern Bushveld Complex (South Africa) [*Letts et al.*, 2005], from red beds in the ~1.8 Ga Shoksha Formation (Russia) [*Pisarevsky and Sokolov*, 2001], from the ~1.4 Ga Belt-Purcell Supergroup (North America) [*Elston et al.*, 2002], from the ~1.1 Ga Umkondo dolerites in the Kalahari craton (southern Africa) [*Gose et al.*, 2006] and from the ~0.8 Ga Aksu dyke swarm (Tarim basin) [*Chen et al.*, 2004]. We further note that positive reversal tests were also obtained from eastern Canadian formations and carbonatite complexes coeval with the ~1.1 Ga Keweenawan lava flows [e.g., *Costanzo-Alvarez et al.*, 1993; *Symons*, 1994], which argues against a regional consistency of the asymmetrical geomagnetic reversals found in the Keweenawan lavas. The latter observation was then interpreted as resulting either of nonaveraged secular variation [*Costanzo-Alvarez et al.*, 1993] or of unremoved secondary magnetization [*Dunlop and Yu*, 2004]. More recently, two additional paleomagnetic studies conducted on the Keweenawan volcanic rocks favor the view that the differences in inclination observed between the normal and reversed polarity lavas would be principally due to

Figure 14. Paleomagnetic and magnetostratigraphic data obtained for the Zilmerdak Formation (lowermost Upper Riphean) from a section located near the village of Inzer (southern Urals). (a and b) Two examples of orthogonal vector diagrams in stratigraphic coordinates of progressive thermal demagnetization. (c) Equal area projection of the paleomagnetic directions obtained after bedding correction. (d) Magnetostratigraphic results obtained from the section.

age progression and rapid continental motion of the North American plate between the two groups of lava flows [*Tauxe and Kodama*, 2009; *Swanson-Hysell et al.*, 2009]. We therefore consider that there is currently no convincing evidence for a long-standing asymmetric geomagnetic field during the Proterozoic that would make the Precambrian geomagnetic field markedly less dipolar than during the Phanerozoic [*Gallet et al.*, 2000; *Dunlop and Yu*, 2004].

[26] Computing magnetic reversal frequencies during the Proterozoic from our magnetostratigraphic data is clearly not an easy task as this requires the use of constraints on the duration of sediment deposition in the studied sections (where short-time-ranging biostratigraphic markers are virtually absent). And only very rough estimates of the mean sedimentation rates across the Talakh-Khaya and Minyar sections can be proposed considering the available isotopic, lithological and paleomagnetic data.

[27] The middle-upper Malgina and the middle Kandyk formations were dated at 1043 ± 14 Ma and 1005 ± 4 Ma, respectively [*Ovchinnikova et al.*, 2001; *Rainbird et al.*, 1998]. In the Uchur-Maya undeformed zone, this time interval of ~40 Myr is represented by ~700 m of sediment accumulation, which yields a mean sedimentation rate of ~1–2 cm/1000 years. To first order, such an estimate appears reasonable when compared with other lithologically similar sequences of Phanerozoic shallow water carbonates [e.g., *Bosscher and Schlager*, 1993; *Altermann and Nelson*, 1998; *Satolli et al.*, 2007]. In the case of the paleomagnetic directional trend observed within the ~180 m of the Talakh-Khaya section (with a difference of paleolatitude of ~7° between the top and the base of the section), if a "reasonable" velocity of ~3 cm/year (i.e., the rough mean value for the present plate network) is considered for the Siberian plate, the sampled section would have a rough duration of ~25 Myr. This would yield a sedimentation rate on the order of 1 cm/1000 years, consistent with the previous estimate. The same rough value is also obtained from the directional trend found from the Minyar section through the Katav Formation (duration of ~20 Myr for a thickness of ~200 m, again considering a plate motion of ~3 cm/year). For the computations below, we will therefore consider this conservative, rather low, mean sedimentation rate of ~1 cm/1000 years.

[28] In the Talakh-Khaya section, we find a sharp transition between a period of ~2 Myr, at the base of section, characterized by a magnetic reversal frequency of ~10 reversals per Myr (22 reversals within ~20 m) and a period above of ~16 Myr of constant magnetic polarity (Figure 10). Data obtained from the overlying formations [*Pavlov et al.*, 2000, 2002; this study] indicate that the duration of this interval of fixed polarity could have been on the order of 30 Myr or possibly longer (Figure 12). It is worth pointing out that even decreasing the sedimentation rate by a factor of 2 (which is on average not supported by the available isotopic ages) would maintain a very rapid transition between a period of high magnetic reversal frequency (~5 reversals/Myr) and a superchron. By contrast, if the sedimentation rate within the Talakh-Khaya section, in particular in its lower part, is higher than ~1 cm/1000 years, the magnetic reversal frequency would then reach a rate much higher than during the past, well-documented, ~150 Myr. Although less extreme, the magnetostratigraphic results from the Myniar section also indicate a relatively sharp contrast in magnetic reversal frequency between a rate of ~4.9 reversals/Myr during the upper third of the section (34 reversals during ~7 Myr) immediately after a ~4 Myr long interval with no reversal (Figure 13; for comparison, this duration is equivalent to that of chron C33r succeeding the Cretaceous Long Normal Superchron [*Cande and Kent*, 1995]).

[29] We acknowledge the crude nature of our computations. Nevertheless, they reveal the same feature as found in the detailed magnetostratigraphy of the ~1.4 Ga North American Belt–Purcell Supergroup [*Elston et al.*, 2002]. In the latter study, one long reversed polarity interval with a duration of ~30 Myr was found in the middle part of the section, followed first by a thin zone with frequent geomagnetic reversals, next by a ~5–10 Myr long normal polarity interval and finally again by a zone with many reversals. This sequence also suggests sharp transitions between periods of frequent reversals and superchron(s). This striking feature may well be an important property of the Precambrian geomagnetic field. However, from the analysis of the geomagnetic polarity time scale over the past 150 Myr, *Hulot and Gallet* [2003] also showed that no special behavior in reversal rate, such as a medium-term decreasing trend, could be confidently identified in the period of ~40 Myr immediately preceding the Cretaceous long normal superchron (with an average reversal frequency of ~2–3 reversals per Myr). This superchron lacked a clear precursor. As a result, *Hulot and Gallet* [2003] questioned the validity of linking the origination of superchrons to change in core-mantle

boundary conditions. On the contrary, the close juxtaposition or alternation of long periods without reversal and periods with frequent reversals may attest to the nonlinear nature of the fluid geodynamo processes, that could induce sudden transitions between reversing and nonreversing states of the geodynamo. Our results and those of *Elston et al.* [2002] tend to support such a view, at least for Precambrian time.

[30] From numerical simulations of the magnetohydrodynamical processes in Earth's core with a smaller inner core than today, *Coe and Glatzmaier* [2006] recently argued that the magnetic reversal frequency should have been lower on average during the Precambrian than during the Phanerozoic (see also *Roberts and Piper* [1989] and *Biggin et al.* [2008, 2009] for a discussion). Magnetostratigraphic data allowing a direct test of this hypothesis are obviously not numerous enough. For instance, *Dunlop and Yu* [2004] proposed that the period between ~1050 Ma and ~820 Ma (the "Greenville time"), which comprises the time interval of deposition of the Malgina and Katav formations, was principally characterized by four "dominant" polarity chrons. Although this oversimplified picture cannot be disregarded because a continuous magnetic polarity sequence spanning this entire period is not yet available, we note that the Malgina Formation contains 33 magnetic polarity intervals, the Katav Formation 43 intervals and the underlying (older) Zilmerdak Formation 23 additional intervals. Furthermore, simply considering the total number of the magnetic polarity intervals found in the Minyar and Talakh-Khaya sections (76) and their cumulated estimated duration (~45 Myr) yields an averaged reversal rate of ~1.7 reversals per Myr, a value very close to the long-term magnetic reversal frequency which has prevailed over the past 150 Myr (with the occurrence of a superchron in both cases). Taken as a whole, our data therefore do not indicate a particularly low magnetic reversal frequency around 1 Ga that might be considered as a consequence of a smaller inner core during the Proterozoic. Further research on the frequency of superchrons (rather than magnetic reversal frequency) during the Earth's middle age could provide crucial constraints on the results of 3-D geodynamo simulations such as those of *Coe and Glatzmaier* [2006].

6. Conclusions

[31] Our concluding remarks are twofold. The first point directly concerns the behavior of the geomagnetic field during the Precambrian. Our magnetostratigraphy of two Proterozoic sections from Siberia and the southern Urals dated between ~1100 Ma and ~800 Ma does not reveal a geomagnetic field markedly less dipolar than during more recent time [see also *Gallet et al.*, 2000; *Dunlop and Yu*, 2004]. We observe sharp transitions and alternations between long periods without reversal and periods with frequent reversals (with frequencies possibly higher than 5 to 10 reversals per Myr). However, this characteristic may not be restricted to the Precambrian geomagnetic field. Our study shows that conducting detailed magnetostratigraphic work in order to better constrain the geomagnetic field behavior during Precambrian time is an attainable and promising goal. In particular, the Siberian platform possesses many other sedimentary sections that may be suitable for investigating the frequency of superchrons during the Precambrian.

[32] The second point concerns the need for numerical geodynamo simulations in order to decipher the origin of superchrons and the cause of the sharp transitions observed between the reversing and nonreversing states of the geodynamo. Do they principally originate from the nonlinear nature of the geodynamo (as supported by *Hulot and Gallet* [2003]) or from medium-term changes at the core-mantle boundary? Our new magnetostratigraphic data clearly show that the first option, although rarely favored, should be considered with greater care. For this reason, there is a pressing need for additional numerical experiments of geodynamos with a variety of boundary conditions, different sizes of the inner core and, most importantly, long intervals of simulated years (>100 Myr). Such experiments could be crucial to improving our understanding of the past behavior of the geomagnetic field.

Acknowledgments

[33] We thank A. Shatsillo and V. Vodovozov for their help in collecting samples, N. Kuztetsov and V. Puchkov for constructive discussion on the field, and V. Tselmovich for his assistance with microscope investigation. We are grateful to D. Evans, A. Gogichaishvili, and S. Gilder for their comments on an early version of the manuscript. We also thank J. Tarduno, J. Feinberg, L. Tauxe, C. Mac Niocaill, and A. Maloof for their very constructive reviews. The manuscript benefited from the careful reading of B. Black. This study was supported by RFBR grants 07-05-00880 and 09-05-91056, CNRS PICS 4816, and IPGP. It was also partly financed by the INSU-CNRS program "SEDIT." This is IPGP contribution 2550.

References

Algeo, T. J. (1996), Geomagnetic polarity bias patterns through the Phanerozoic, *J. Geophys. Res.*, *101*, 2785–2814, doi:10.1029/95JB02814.

Altermann, W., and D. Nelson (1998), Sedimentation rates, basin analyses and regional correlations of three Neoarchaean and Paleoproterozoic sub-basin of the Kaapval craton as inferred from precise U-Pb zircon ages from volcanoclastic sediments, *Sediment. Geol.*, *120*, 225–256, doi:10.1016/S0037-0738(98)00034-7.

Bartley, J. K., M. A. Semikhatov, A. J. Kaufman, A. Knoll, M. C. Pope, and S. B. Jacobsen (2001), Global events across the Mesoproterozoic-Neoproterozoic boundary: C and Sr isotopic evidence from Siberia, *Precambrian Res.*, *111*, 165–202, doi:10.1016/S0301-9268(01)00160-7.

Bartley, J. K., L. Kah, J. McWilliams, and A. Stagner (2007), Carbon isotope chemostratigraphy of the Mesoprotereoic Avzyan Formation (southern Urals, Riisia): Signal recovery in a fold-and-thrust belt, *Chem. Geol.*, *237*, 211–232, doi:10.1016/j.chemgeo.2006.06.018.

Biggin, A. J., G. H. M. A. Strik, and C. G. Langereis (2008), Evidence for a very long term trend in geomagnetic secular variation, *Nat. Geosci.*, *1*(6), 395–398, doi:10.1038/ngeo181.

Biggin, A. J., G. H. M. A. Strik, and C. Langereis (2009), The intensity of the geomagnetic field in the late-Archaean: New measurements and an analysis of the updated IAGA palaeointensity database, *Earth Planets Space*, *61*, 9–22.

Bosscher, H., and W. Schlager (1993), Accumulation rates of carbonate platforms, *J. Geol.*, *101*, 345–355, doi:10.1086/648228.

Cande, S., and D. Kent (1995), Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, *100*, 6093–6095, doi:10.1029/94JB03098.

Chen, Y., B. Xu, S. Zhan, and Y. Li (2004), First mid-Neoproterozoic paleomagnetic results from the Tarim Basin (NW China) and their geodynamic implications, *Precambrian Res.*, *133*, 271–281, doi:10.1016/j.precamres.2004.05.002.

Cocks, L., and T. H. Torsvik (2007), Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic, *Earth Sci. Rev.*, *82*, 29–74, doi:10.1016/j.earscirev.2007.02.001.

Coe, R., and G. Glatzmaier (2006), Symmetry and stability of the geomagnetic field, *Geophys. Res. Lett.*, *33*, L21311, doi:10.1029/2006GL027903.

Cogné, J. P. (2003), PaleoMac: A Macintosh™ application for treating paleomagnetic data and making plate reconstructions, *Geochem. Geophys. Geosyst.*, *4*(1), 1007, doi:10.1029/2001GC000227.

Costanzo-Alvarez, V., D. Dunlop, and L. Pesonen (1993), Paleomagnetism of alkaline complexes and remagnetization in the Kapuskasing structural zone, Ontario, Canada, *J. Geophys. Res.*, *98*, 4063–4080, doi:10.1029/92JB02571.

Courtillot, V., and P. Olson (2007), Mantle plumes link magnetic superchrons to Phanerozoic mass depletion events, *Earth Planet. Sci. Lett.*, *260*, 495–504, doi:10.1016/j.epsl.2007.06.003.

Dunlop, D., and Y. Yu (2004), Intensity and polarity of the geomagnetic field during Precambrian time, in *Timescales of the Internal Geomagnetic Field*, *Geophys. Monogr. Ser.*, vol. 145, edited by J. Channell et al., pp. 85–100, AGU, Washington, D. C.

Elston, D., R. Enkin, J. Baker, and D. Kisilevsky (2002), Tightening the belt: Paleomagnetic-stratigraphic constraints on deposition, correlation, and deformation of the Middle Proterozoic (ca. 1.4 Ga) Belt-Purcell supergroup, United States and Canada, *Geol. Soc. Am. Bull.*, *114*, 619–638, doi:10.1130/0016-7606(2002)114<0619:TTBPSC>2.0.CO;2.

Enkin, R. (1994), A computer program package for analysis and presentation of paleomagnetic data, 16 pp., Pac. Geosci. Cent., Geol. Surv. of Can., Vancouver, B. C., Canada.

Enkin, R. (2003), The direction-correction tilt test: An all-purpose tilt/fold test for paleomagnetic studies, *Earth Planet. Sci. Lett.*, *212*, 151–166, doi:10.1016/S0012-821X(03)00238-3.

Gallet, Y., and V. Pavlov (1996), Magnetostratigraphy of the Moyero river section (north-western Siberia): Constraints on geomagnetic reversal frequency during the early Paleozoic, *Geophys. J. Int.*, *125*, 95–105, doi:10.1111/j.1365-246X.1996.tb06536.x.

Gallet, Y., V. Pavlov, M. Semikhatov, and P. Petrov (2000), Late Mesoproterozoic magnetostratigraphic results from Siberia: Paleogeographic implications and magnetic field behavior, *J. Geophys. Res.*, *105*, 16,481–16,499, doi:10.1029/1999JB900354.

Giese, U., U. Glasmacher, V. Kozlov, I. Matenaar, V. Puchkov, L. Stroink, W. Bauer, S. Ladage, and R. Walter (1999), Structural framework of the Bashkirian anticlinorium, SW Urals, *Geol. Rundsch.*, *87*, 526–544, doi:10.1007/s005310050229.

Glatzmaier, G., R. Coe, L. Hongre, and P. Roberts (1999), The role of the Earth's mantle in controlling the frequency of geomagnetic reversals, *Nature*, *401*, 885–890, doi:10.1038/44776.

Gorokhov, I., N. Melnikov, and T. Turchenko (1995), Two illite generations in the Upper Riphean shale: The Rb-Sr isotopic evidence, *Terra Nova*, *7*, 330–331.

Gose, W. A., R. E. Hanson, I. W. D. Dalziel, J. A. Pancake, and E. K. Seidel (2006), Paleomagnetism of the 1.1 Ga Umkondo large igneous province in southern Africa, *J. Geophys. Res.*, *111*, B09101, doi:10.1029/2005JB003897.

Grishin, D. V., D. M. Pechersky, and K. E. Degtyarev (1997), Paleomagnetism and reconstruction of Middle Paleozoic structures of central Kazakhstan, *Geotectonics, Engl. Transl.*, *31*, 71–81.

Hulot, G., and Y. Gallet (2003), Do superchrons occur without any paleomagnetic warning?, *Earth Planet. Sci. Lett.*, *210*, 191–201, doi:10.1016/S0012-821X(03)00130-4.

Keller, B., and N. Chumakov (1983), *Stratotype of Riphean: Stratigraphy and Geochronology* (in Russian), 184 pp. Nauka, Moscow.

Kent, D., and M. Smethurst (1998), Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian, *Earth Planet. Sci. Lett.*, *160*, 391–402, doi:10.1016/S0012-821X(98)00099-5.

Khudoley, A., R. Rainbird, R. Stern, A. Kropachev, L. Heaman, A. Zanin, V. Podkovyrov, V. Belova, and V. Sukhorukov (2001), Sedimentary evolution of the Riphean-Vendian basin of southeastern Siberia, *Precambrian Res.*, *111*, 129–163, doi:10.1016/S0301-9268(01)00159-0.

Khudoley, A., A. Kropachev, V. Tkachenko, A. Rublev, S. Sergeev, D. Matukov, and O. Lyahnitskaya (2006), Mesoproterozoic to Neoproterozoic evolution of the Siberian craton and adjacent microcontinents: An overview with constraints for a Laurentian connection, *Spec. Publ. SEPM Soc. Sediment. Geol.*, *86*, 209–226.

Komissarova, R. (1970), Study of the ancient magnetization of some sedimentary rocks of the southern Ural, in connection with the problem of metachronous remagnetization, doctoral dissertation, 140 pp., Inst. of Phys. of the Earth, Moscow.

Komissarova, R., A. Iosifidi, and A. Khramov (1997), Geomagnetic reversals recorded in the Late Riphean Katav formation, south Urals, *Izv. Russ. Acad. Sci. Phys. Solid Earth, Engl. Transl.*, *33*(2), 60–68.

Kuznetsov, A., M. Semikhatov, A. Maslov, I. Gorokhov, E. Prasolov, M. Krupenin, and I. Kislova (2006), New data on Sr- and C-isotopic chemostratigraphy of the upper Riphean type section (southern Urals), *Stratigr. Geol. Correl.*, *14*, 602–628, doi:10.1134/S0869593806060025.

Lay, T., J. Hernlund, and B. A. Buffett (2008), Core-mantle boundary heat flow, *Nat. Geosci.*, *1*, 25–32, doi:10.1038/ngeo.2007.44.

Letts, S., T. Torsvik, S. Webb, L. Ashwal, E. Eide, and G. Chunnett (2005), Palaeomagnetism and $^{40}Ar/^{39}Ar$ geochronology of mafic dykes from the eastern Bushveld Complex (South Africa), *Geophys. J. Int.*, *162*, 36–48, doi:10.1111/j.1365-246X.2005.02632.x.

Maslov, A., B. Erdtmann, K. Ivanov, S. Ivanov, and M. Krupenin (1997), The main tectonic events, depositional history, and the palaeogeography of the southern Urals during the Riphean-early Palaeozoic, *Tectonophysics*, *276*, 313–335, doi:10.1016/S0040-1951(97)00064-4.

McFadden, P., and M. McElhinny (1990), Classification of the reversal test in palaeomagnetism, *Geophys. J. Int.*, *103*, 725–729, doi:10.1111/j.1365-246X.1990.tb05683.x.

McFadden, P., and R. Merrill (1984), Lower mantle convection and geomagnetism, *J. Geophys. Res.*, *89*, 3354–3362, doi:10.1029/JB089iB05p03354.

McFadden, P., and R. Merrill (2000), Evolution of the geomagnetic reversal rate since 160 Ma: Is the process continuous?, *J. Geophys. Res.*, *105*, 28,455–28,460, doi:10.1029/2000JB900258.

Meert, J. G., and T. H. Torsvik (2003), The making and unmaking of a supercontinent: Rodinia revisited, *Tectonophysics*, *375*, 261–288.

Meert, J., H. Walderhaug, T. H. Torsvik, and B. Hendricks (2007), Age and paleomagnetic signature of the Alno Carbonatite complex (NE Sweden): Additional controversy for the Neoproterozoic position of Baltica, *Precambrian Res.*, *154*, 159–174, doi:10.1016/j.precamres.2006.12.008.

Nevanlinna, H., and L. Pesonen (1983), Late Precambrian Keweenawan asymmetric polarities as analyzed by axial offset dipole geomagnetic models, *J. Geophys. Res.*, *88*, 645–658, doi:10.1029/JB088iB01p00645.

Opdyke, N., and J. Channell (1996), *Magnetic Stratigraphy*, 364 pp., Academic, London.

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

Ovchinnikova, G., I. Vasil'eva, M. Semikhatov, A. Kuznetsov, I. Gorokhov, B. Gorokhovskii, and L. Levskii (1998), U–Pb systematics of Proterozoic carbonate rocks: The Inzer Formation of the Upper Riphean stratotype (southern Urals), *Stratigr. Geol. Correl.*, *6*, 336–347.

Ovchinnikova, G., I. Vasil'eva, M. Semikhatov, I. Gorokhov, A. Kuznetsov, B. Gorokhovskii, and L. Levskii (2000), The Pb-Pb trail dating of carbonates with open U-Pb systems: The Min'yar Formation of the Upper Riphean stratotype, southern Urals, *Stratigr. Geol. Correl.*, *8*, 529–543.

Ovchinnikova, G., M. Semikhatov, I. Vasil'eva, I. Gorokhov, O. Kaurova, V. Podkovyrov, and B. Gorokhovskii (2001), Pb–Pb age of carbonates from the middle Riphean Malga Formation, Uchur-Maya region of east Siberia, *Stratigr. Geol. Correl.*, *9*, 3–16.

Pavlov, V. (1994), Paleomagnetic poles of the Uchuro-Maya hypostratotype of Riphean and the Riphean drift of the Aldanian block of the Siberian Platform (in Russian), *Dokl. Acad. Sci.*, *336*, 533–537.

Pavlov, V., and Y. Gallet (1998), Upper Cambrian to Middle Ordovician magnetostratigraphy from the Kulumbe river section (northwestern Siberia), *Phys. Earth Planet. Inter.*, *108*, 49–59, doi:10.1016/S0031-9201(98)00087-9.

Pavlov, V., and Y. Gallet (2005), A third superchron during the Early Paleozoic, *Episodes*, *28*, 78–84.

Pavlov, V., and Y. Gallet (2009), Katav limestones: A unique example of remagnetization or an ideal recorder of the Neoproterozoic geomagnetic field?, *Izv. Russ. Acad. Sci. Phys. Solid Earth, Engl. Transl.*, *45*, 31–40.

Pavlov, V., Y. Gallet, and A. Shatsillo (2000), Palaeomagnetism of the upper Riphean Lakhanda Group of the Uchur-Maya area and the hypothesis of the late Proterozoic supercontinent, *Izv. Russ. Acad. Sci. Phys. Solid Earth, Engl. Transl.*, *36*, 638–648.

Pavlov, V., Y. Gallet, Y. Petrov, D. Zhuravlev, and A. Shatsillo (2002), Uy series and late Riphean sills of the Uchur-Maya area: Isotopic and palaeomagnetic data and the problem of the Rodinia supercontinent, *Geotectonics, Engl. Transl.*, *36*, 278–292.

Pechersky, D. M., and A. N. Didenko (1995), *The Paleoasian Ocean* (in Russian), 296 pp., OIFZ, Moscow.

Pesonen, L., and H. Nevanlinna (1981), Late Precambrian Keweenawan asymmetric reversals, *Nature*, *294*, 436–439, doi:10.1038/294436a0.

Pisarevsky, S., and L. Natapov (2003), Siberia and Rodinia, *Tectonophysics*, *375*, 221–245, doi:10.1016/j.tecto.2003.06.001.

Pisarevsky, S., and S. Sokolov (2001), The magnetostratigraphy and a 1780 Ma palaeomagnetic pole from the red sandstones of Vazhinka River section, Karelia, Russia, *Geophys. J. Int.*, *146*, 531–538, doi:10.1046/j.0956-540x.2001.01479.x.

Rainbird, R., R. Stern, A. Khudoley, A. Kropachev, L. Heaman, and V. Sukhorukov (1998), U-Pb geochronology of Riphean supracrustal rocks from southeast Siberia and its bearing on the Laurentia-Siberia connection, *Earth Planet. Sci. Lett.*, *164*, 409–420, doi:10.1016/S0012-821X(98)00222-2.

Roberts, N., and J. Piper (1989), A description of the behaviour of the Earth's magnetic field, in *Geomagnetism*, vol. 3, edited by J. Jacobs, pp. 163–260, Elsevier, New York.

Satolli, S., J. Besse, F. Speranza, and F. Calamita (2007), The 125–150 Ma high-resolution apparent polar wander path for Adria from magnetostratigraphic sections in Umbria–Marche (northern Apennines, Italy): Timing and duration of the global Jurassic–Cretaceous hairpin turn, *Earth Planet. Sci. Lett.*, *257*, 329–342, doi:10.1016/j.epsl.2007.03.009.

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

Semikhatov, M., and S. Serebrjakov (1983), The Siberian hypostratotype of the Riphean (in Russian), *Trans. Akad. Nauk SSSR Geol. Inst.*, *367*, 1–224.

Semikhatov, M., G. Ovchinnikova, I. Gorokhov, A. Kuznetsov, I. Vasilieva, B. Gorokhovskii, and V. Podkovyrov (2000), Isotopic age of boundary between middle and upper Riphean: Pb–Pb geochronology of carbonate rocks of the Lakhanda Group, east Siberia, *Dokl. Russ. Acad. Sci.*, *372*, 216–221.

Sergeev, V. (2006), Silicificated microfossils of Precambrian: Their nature, classification and biostratigraphical significance (in Russian), *Trans. Russ. Akad. Nauk Geol. Inst.*, *567*, 1–280.

Shatsillo, A., V. Pavlov, and A. Didenko (2006), Paleomagnetism of Vendian rocks in the southwest of the Siberian Platform, *Russ. J. Earth Sci.*, *8*, ES2003, doi:10.2205/2005ES000182.

Shipunov, S. (1991), Paleomagnetism of Katav suite of southern Ural, *Izv. Russ. Acad. Sci. Phys. Solid Earth, Engl. Transl.*, *3*, 97–109.

Smethurst, M. A., A. N. Khramov, and T. H. Torsvik (1998), The Neoproterozoic and Paleozoic paleomagnetic data for the Siberian platform: From Rodinia to Pangea, *Earth Sci. Rev.*, *43*, 1–24, doi:10.1016/S0012-8252(97)00019-6.

Smirnov, A. V., and J. A. Tarduno (2004), Secular variation of the Late Archaean Early Proterozoic geodynamo, *Geophys. Res. Lett.*, *31*, L16607, doi:10.1029/2004GL020333.

Strik, G., T. S. Blake, T. E. Zegers, S. H. White, and C. G. Langereis (2003), Palaeomagnetism of flood basalts in the Pilbara Craton, Western Australia: Late Archaean continental drift and the oldest known reversal of the geomagnetic field, *J. Geophys. Res.*, *108*(B12), 2551, doi:10.1029/2003JB002475.

Swanson-Hysell, N. L., A. C. Maloof, B. P. Weiss, and D. A. D. Evans (2009), No asymmetry in geomagnetic reversals recorded by 1.1-billion-year-old Keweenawan basalts, *Nat. Geosci.*, *2*, 713–717, doi:10.1038/NGEO622.

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

Tauxe, L., and K. P. Kodama (2009), Paleosecular variation models for ancient times: Clues from Keweenawan lava flows, *Phys. Earth Planet. Inter.*, *177*, 31–45, doi:10.1016/j.pepi.2009.07.006.

Walderhaug, H., T. Torsvik, and E. Halvorsen (2007), The Egersund dykes (SW Norway): A robust Early Ediacaran (Vendian) palaeomagnetic pole from Baltica, *Geophys. J. Int.*, *168*, 935–948, doi:10.1111/j.1365-246X.2006.03265.x.

Willner, A., T. Ermolaeva, L. Stroink, U. Glasmacher, U. Giese, V. Puchkov, V. Kozlov, and R. Walter (2001), Contrasting provenance signals in Riphean and Vendian sandstones in the SW Urals (Russia): Constraints for a change from passive to active continental margin conditions in the Neoproterozoic, *Precambrian Res.*, *110*, 215–239, doi:10.1016/S0301-9268(01)00190-5.