Paleomagnetism of Upper Vendian sediments from the Winter Coast, White Sea region, Russia: Implications for the paleogeography of Baltica during Neoproterozoic times

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[1]   Paleomagnetic results from an Upper Vendian sedimentary sequence exposed along the White Sea shoreline, NW Russia are described. These classical exposures have been the subject of intense paleontological investigations due to their well-preserved Ediacara fauna, but no paleomagnetic results have as yet been published. A total of 337 hand samples and 210 oriented drill cores (35 sites) along three profiles have been collected at the locality (65.5°, 40.0°E) where a 555 ± 3 Ma U–Pb age of comagmatic zircons from volcanic ash layers has been recently obtained. Standard paleomagnetic procedures yield two main natural remanent magnetization (NRM) components: an intermediate-temperature (150°–350°C), single-polarity component (D = 121°, I = 72°, n = 232 samples, k = 46.0, α_{95} = 1.3°, pole position at 40.0°N, 79.0°E, dp = 2.0°, dm = 2.3°) and a high-temperature (550°–680°C) dual-polarity component (normal polarity: D = 278°, I = 43°, n = 54 samples, k = 25.2, α_{95} = 3.9°, reversed polarity: D = 101°, I = −39° n = 40, K = 23.3, α_{95} = 4.8°, south pole position at 24°S, 132°E, dp = 2.3°, dm = 3.8°). This latter component, termed Z, passes reversal, stratigraphic, and consistency tests and is interpreted to reflect the direction of the Earth's magnetic field during Late Vendian times. These results put Baltica into low northern latitudes (between 10° and 35°) and the resulting pole position requires modification of the most recent Apparent Polar Wander Paths (APWP) for Baltica.   INDEX TERMS: 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 8157 Tectonophysics: Evolution of the Earth: Plate motions—past (3040); 9335 Information Related to Geographic Region: Europe; 9619 Information Related to Geologic Time: Precambrian; KEYWORDS: palaeomagnetism, Vendian, Baltica

1. Introduction

[2]   The existence of a supercontinent, Rodinia, during Neoproterozoic times and its breakup which started some 750–720 Ma [Dalziel et al., 1994; Powell et al., 1993] is now widely accepted. However, details of the paleogeographic relations between the various continental fragments and their drift history after breakup of the supercontinent are still sparse. This is especially true for latest Proterozoic (Vendian) times, where two conflicting paleomagnetic data sets exist, putting the former Rodinia continents either into relatively high (>60°S) [McKerrow et al., 1992; Smethurst et al., 1998] or rather low (<30°S) [Torsvik et al., 1992] latitudes. The global distribution of continents during Neoproterozoic times, however, is of great importance with

respect to various climatic models for "Snowball Earth" hypotheses and the driving force behind low-latitude glaciations [Hoffman et al., 1998]. For Vendian times some considerable progress has been made recently as far as the paleogeography of Siberia [Pisarevsky et al., 2000] and Laurentia [Meert et al., 1994; Williams et al., 1995] are concerned, the database for Baltica is still rather sparse and internally inconsistent.

[3]   Recent discussions of the Vendian Apparent Polar Wander Path (APWP) have concentrated on controversies regarding the paleomagnetic data from the Fen Complex [Meert et al., 1998; Piper, 1988; Poorter, 1975; Smethurst et al., 1998] and the paleogeography of Baltica prior to the well-established early Ordovician paleopoles [Smethurst et al., 1998]. The underlying problems of these controversies are the lack of paleomagnetic data for Late Riphean to early Ordovician times.
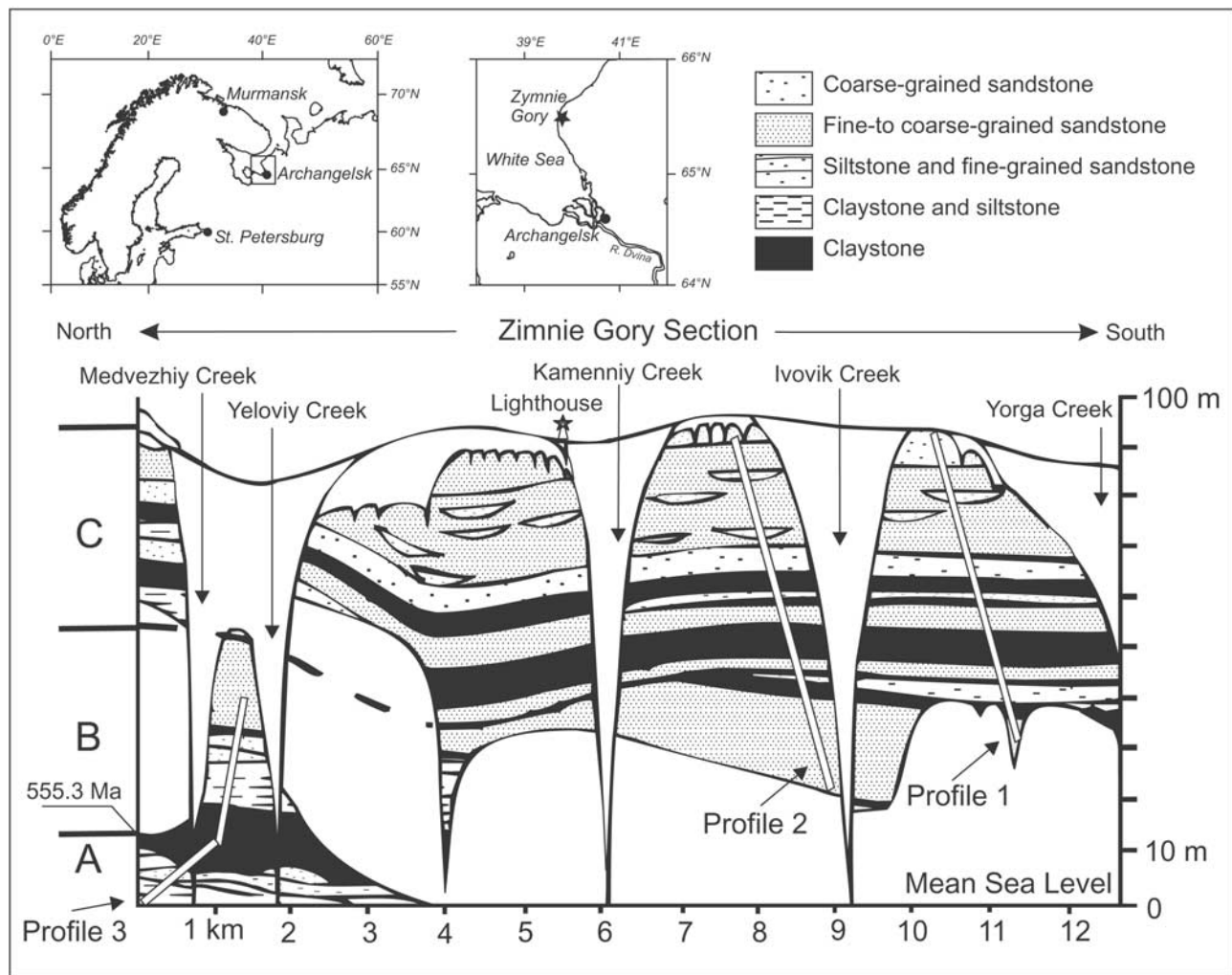
Figure 1. Stratigraphy section and geographic location (insets) of profiles sampled at Zimnie Gory (modified after the work of *Martin et al.* [2000]). A, B, and C refer to the three coarsening upward sequences identified by *Martin et al.* [2000]. The base of sequence B has been dated radiometrically as 555.3 Ma [*Martin et al.*, 2000].

[4] In order to provide paleomagnetic data of high quality for the intervening time period, a detailed study of radiometrically dated (555 ± 3 Ma) [*Martin et al.*, 2000] sediments of late Vendian age has been undertaken. These rocks are exposed along the Russian White Sea (Winter Coast) and contain a well-documented Ediacara fauna which has been studied in detail since the early 1970s [e.g., *Fedonkin*, 1981].

2. Geological Setting and Sampling

[5] Roughly 2 million km^2 of the East European platform are covered with Vendian (650–544 Ma) rocks, reaching a maximum thickness of 2500 m in the Ukraine [*Sokolov and Fedonkin*, 1985]. Traditionally this succession is divided into a lower part, where effusive and pyroclastic rocks dominate and an upper part, dominated by sediments and marked by the occurrence of classical Ediacara faunal communities [*Fedonkin*, 1981]. In the Russian literature, the upper Vendian is subdivided into the Redkinsky and Kotlinsky series [*Fedonkin*, 1981]. One of the classic type areas for the Upper Vendian in Russia is along the shoreline cliffs at Zimnie Gory on the White Sea Coast (Figure 1)

[*Fedonkin*, 1981]. These unmetamorphosed and undeformed siliciclastic rocks were deposited on the pre-Cambrian Fennoscandian Shield and form the uppermost part of the Ust-Pinega Formation, which in turn represents the upper part of the Redkinsky biostratigraphic horizon [*Grazhdankin and Bronnikov*, 1997].

[6] The section exposed at Zimnie Gory (Figure 1) consists of three upward-coarsening sequences, labeled A, B, and C [*Martin et al.*, 2000]. Sequence A reaches a thickness of 10 m and consists of interbedded siltstones and clay stones with fine to medium grained sandstones, showing well developed cross bedding features. Sequence B, 55 m in thickness and disconformably overlaying sequence A, consists of variegated clay stones, coarsening upward to siltstones and sandstones. Within the lowest part of sequence B, volcanic ash layers of up to 10 cm in thickness have been observed. The transition between B and C is clearly marked by a very low angle erosional disconfirmity. At its base, sequence C, reaching maximum thicknesses of up to 55 m, is marked by a basal conglomerate which is overlain by interbedded sandstones and siltstones. Recently, the volcanic ash layers of sequence B have been dated and

yield a mean U–Pb single grain zircon age of 555 ± 3 Ma [*Martin et al.*, 2000] clearly placing them in the terminal Neoproterozoic (Neoproterozoic III) [*Knoll*, 2000].

[7] Paleomagnetic sampling was carried out along three profiles (labeled 1, 2, and 3) covering the stratigraphic sequences A, B, and C (Figure 1). Correlation between the profiles is possible in the field using well-defined lithological marker horizons. In total, a composite section covering 76 m of stratigraphic thickness was sampled.

[8] Profile 1 is located near the abandoned settlement of Yorga, 2 km to the north of Yorga Creek (65°24.2′N, 39°42.3′E), profile 2 is directly at the Zimnie Gory lighthouse (65°25.9′N, 39°42.3′E), and profile 3 at the Yelovy and Medvezhiy creeks 9 km to the north of profiles 1 and 2 (Figure 1). A total of 337 hand samples and 210 (35 sites) drill cores, using a portable, petrol driven drill were taken and oriented using magnetic and Sun compasses. Profiles 1 and 2 overlap stratigraphically (Figure 1) and a total of 267 hand samples and 210 cores were collected. For profile 3 a total of 70 hand samples were collected with an average spacing of 10–20 cm between the samples. Unfortunately, it was not possible to carry out parallel sample of the lower section of profile 3. Due to the rather soft character of the material, drilling was only possible in parts of the section which are dominated by siltstones and sandstones. The lithologies sampled comprise gray, green, brown, and variegated clay stones, siltstones, and sandstones.

3. Laboratory Procedures

[9] Hand samples and drill cores were either cut into cubic specimens of 2 × 2 × 2 cm or cylinders of 2.54 cm in diameter and 2.5 cm height. Each hand sample is represented by up to 10 cubic specimens, each drill core by one specimen. A total of 550 cubic specimens from 270 hand samples and 210 specimens from drill cores have been subjected to stepwise thermal and alternating field (AF) demagnetization experiments. Samples were measured in St. Petersburg and in Munich using JR-4 spinner (St. Petersburg) and 2G cryogenic magnetometers (Munich), the latter being housed in a magnetically shielded room. After each heating step, the magnetic susceptibility was measured using a KLY 2 kappabridge in order to monitor mineralogical changes during heating.

[10] The demagnetization results were analyzed using orthogonal plots [*Zijderveld*, 1967] and stereographic projection of the data. Linear demagnetization trajectories defined by at least three successive demagnetization steps were identified by eye and subjected to principle component analysis (PCA) according to the method of *Kirschvink* [1980]. Mean directions were calculated according to *Fisher* [1953]. Since the field procedures for taking oriented hand samples were similar to the ones used for magnetostratigraphic studies, the mean remanence directions and associated statistics for this portion of the collection are all calculated at the sample level. Results for specimens from oriented drill cores were averaged on site level.

[11] Representative specimens were subjected to detailed rock magnetic studies, such as thermomagnetic analysis of the Curie temperatures and determination of the hysteresis properties in order to identify the carriers of magnetization as well as the grain size spectrum. All these experiments were carried out in Munich using a Variable Field Translation Balance (VFTB).

4. Rock Magnetic Properties

[12] Although the initial intensities of the natural remanent magnetization (NRM) are rather variable, they nevertheless form three distinctive groups. Red, reddish-gray, and maroon colored specimens yield intensities from 1 to 12 mA/m (group 1), whereas gray and greenish-gray rocks are more weakly magnetized ranging from 0.1 to 1.5 mA/m (groups 2 and 3). This bimodal distribution in NRM intensities is also reflected during experimental determination of their Curie temperature spectra and the coercivity characteristics of the samples. Specimens of group 1 show steady decay of the intensity up to temperatures of 450–500°C, followed by a minor increase in intensity between 500°C and 600°C (Figure 2, specimens 176 and 003). The thermomagnetic behavior of group 2 specimens is dominated by a dramatic increase in intensity by a factor of up to 30 at temperatures of 520°–550°C (Figure 2c). This increase in intensity is typical only for the heating cycle and was not reproducible during cooling and might reflect formation and destruction of a high-temperature magnetic phase. Group 3 specimens demonstrate reproducible heating–cooling behavior without any peaks (Figure 2d) rather similar to group 1 samples, but group 2 and 3 samples are all magnetically softer reaching saturation in external fields of 100 mT and display coercivities of 30 mT.

[13] The rock magnetic properties, together with the results of the thermal and AF demagnetization experiments manifest the complex and occasionally unstable magnetic composition of these rocks, and are interpreted to reflect the dominance of very small (single-domain and pseudo-single-domain) particles of titanomagnetite and magnetite in combination with maghemite and hematite. The concentration of the magnetic particles is generally very low and dominated by paramagnetic material.

5. Component Analysis and Field Tests

[14] During stepwise thermal demagnetization experiments, three components of the NRM were isolated in the majority of the specimens (Figure 3). These components, labeled A, B, and Z, have been identified according to their unblocking temperatures and their directional behavior. The directional distribution of these components is distinct and clearly Fisherian when plotted on stereographic diagrams (Figure 4).

[15] Component A, is steeply dipping and yields a mean northeasterly direction (Figure 4a and Table 1), and is present in almost all specimens. It is rather similar to the local present-day geomagnetic field directions, and may relate to an overprint direction of recent origin.

[16] Component B, pointing to the SE with steep positive inclinations in situ (Figure 4b), is isolated in the interval 300°–500°C (Figures 3a–3c). Upon unfolding the precision parameter k [*Fisher*, 1953] decreases slightly, suggesting component B is postfolding in origin. Both components A and B were observed in specimens derived from hand samples and drill cores. Above 550°C a third, dual-polarity component Z can be identified,
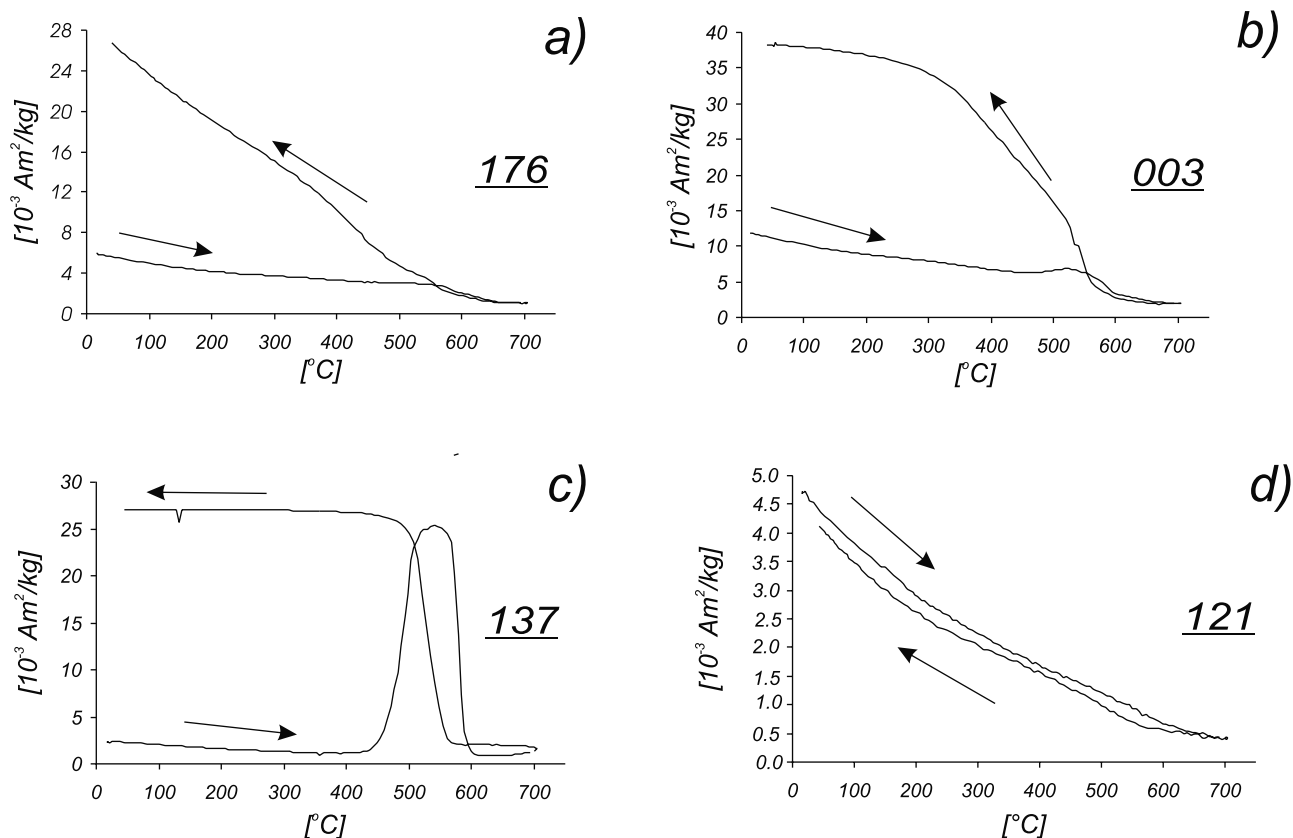
Figure 2. Thermomagnetic properties of red (a and b) and grayish colored (c and d) sediment samples from Zimnie Gory.

predominantly in red-colored specimens obtained from hand samples taken in the lower parts of the section (profile 3), where drilling was not possible due to the rather soft nature of these lithologies. Component Z points either to the NW with positive intermediate inclinations (Figure 3b) or to the SE with negative intermediate inclinations (Figures 3a and 3c and 4c). Maximum

unblocking temperatures of 680°C are in accord with the red color of the specimens and point to hematite as the carrier of this component. The mean direction for component Z (Table 1) is based on results obtained from 94 stratigraphic levels (70 hand samples) from profile 3, covering a stratigraphic thickness of some 23 m with each sample direction being an average of the subsamples
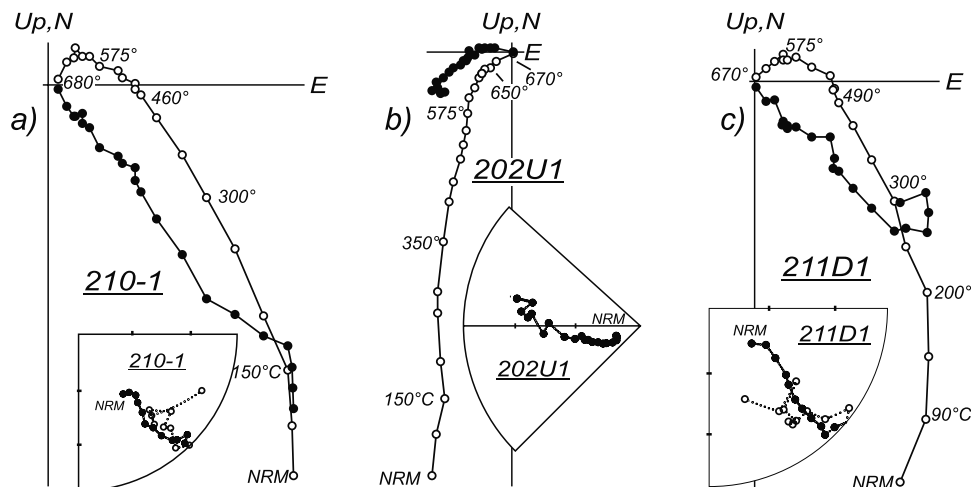

Figure 3. Results of thermal demagnetization of red-colored sediments plotted in orthogonal [*Zijderveld*, 1967] and stereographic projection. In orthogonal projection, full (open) circles represent projections onto the horizontal (vertical) plane. Full (open) circles in stereographic plots represent projections onto the lower (upper) hemisphere. The data are shown in stratigraphic coordinates.
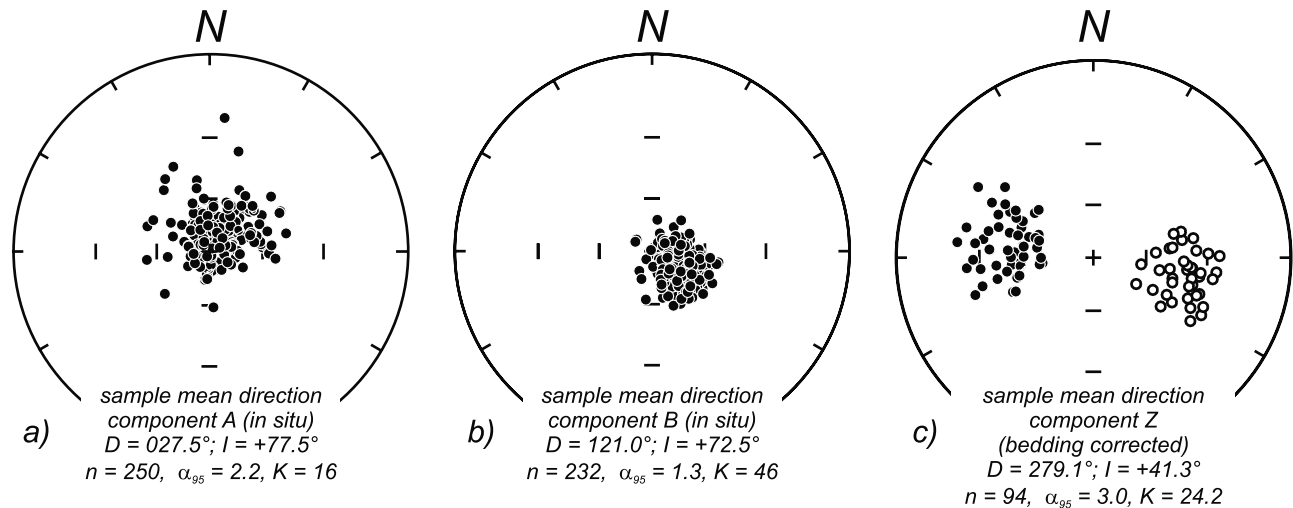
Figure 4. Sample directions in stereographic projection for components A (a), B (b), and Z (c) in geographic (a and b) and stratigraphic (c) coordinates. D and I stand for declination and inclination, n is the number of samples used to calculate the mean, and α_{95} and k are the *Fisher* [1953] precision parameters. Other conventions as in Figure 3.

measured for that horizon. The directions are antipodal (Figure 4c), with a clearly stratigraphically related reversal pattern (Figure 5), and the directions pass the reversal test [*McFadden and McElhinny*, 1990] with classification B. The dispersal parameters improve slightly upon unfolding, the fold test however is not statistically significant due to only minor variations in structural attitude.

[17] In addition to these well defined directions, forming clearly distinct and Fisherian directional clusters, a fourth type of directional behavior during thermal demagnetization was observed in some samples. These magnetizations are generally identified within a very narrow unblocking temperature spectrum and plot as linear segments in orthogonal projection. However, when the sample directions are plotted in stereographic projection, they plot along three distinct great circles, which intersect close to B. This strongly suggests that these directions are the result of overlapping unblocking temperature spectra. At this stage, however, further interpretation of this behavior is not possible.

6. Possible Age of the NRM Components

[18] Component Z is carried predominantly by hematite and is identified with dual polarity and the polarity changes are clearly stratigraphically controlled (Figure 5). Based on the positive reversal test described above, component Z is interpreted to be of primary origin, or acquired at latest during very early diagenetic processes, and is thus considered to reflect the direction of the Earth's magnetic field during latest Vendian times. In addition, the paleopole position for component Z does not bear any similarity to poles of younger age. Comparison with the Van der Voo reliability criteria for paleomagnetic data [*Van der Voo*, 1990] this component fulfills six out of the seven criteria. Component A, however, is very similar to the local present-day geomagnetic field direction, and so probably represents a very young overprint.

[19] Assignment of a magnetization age for component B is less clear. The resulting paleopole position for this component plots very close to the Early Ordovician segment of the APWP for Baltica [*Smethurst et al.*, 1998]. We, therefore, tentatively assign an Early Ordovician (Tremadoc) age to component B (Figure 6) which fulfills three of the Van der Voo reliability criteria. The mechanisms and geological evidence, however, for a remagnetization event at this time remain obscure.

7. Redefinition of the Neoproterozoic/Early Paleozoic APWP and Implications for the Paleogeography of Baltica

[20] The new data presented here provide an important paleopole position with which to constrain the Late Pre-

Table 1. Characteristic Sample Mean Directions of Magnetization Identified in Samples From the Winter Coast

Component	n	Geographic coordinates				Stratigraphic coordinates			
		Dec	Inc	k	α_{95}	Dec	Inc	k	α_{95}
A	250	27.5	77.5	16.0	2.2	27.3	79.9	16.0	2.2
B	232	121.0	72.5	46.0	1.3	129.2	71.8	43.0	1.4
Z(N)	54	279.8	43.5	23.1	4.1	277.9	43.1	25.2	3.9
Z(R)	40	101.3	−41.3	23.8	4.7	100.6	−39.0	23.3	4.8
Z = Z(N) + Z(R)	94	280.4	42.6	23.5	3.1	279.1	41.3	24.2	3.0

n, number of samples. Dec and Inc are declination and inclination. Also given is the precision parameter k and the radius of the cone of 95% confidence [*Fisher*, 1953]. Z(N) and Z(R) identify normal and reversed polarity for component Z.
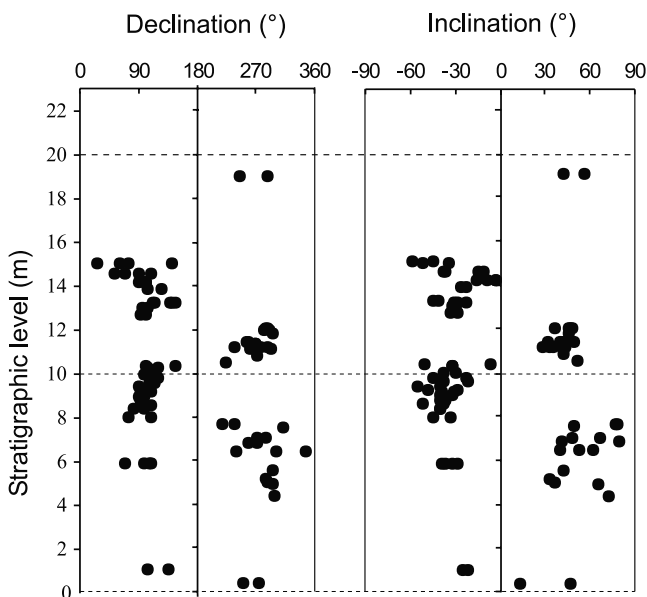
Figure 5. Declination and inclination of component Z versus stratigraphic level at profile 3 (Medvezhiy Creek) showing the stratigraphically controlled nature of the reversal pattern.

cambrian sector of the APWP for Baltica. When the new data are compared with the most recently published APWP for Baltica [*Smethurst et al.*, 1998 for Vendian to Permian times; *Torsvik et al.*, 1996 for the Upper Riphean to Vendian segment], it is immediately clear that the new data do not plot on the Neoproterozoic or younger parts of the path. However, as discussed by the original authors, the pre-Ordovician section of the computed APWP is based on sparse data, some of which are of questionable reliability [see also *Meert et al.*, 1998] and some do not meet the first three reliability criteria of *Van der Voo* [1990]. While these seven reliability criteria were not intended by the original author to be used in a hierarchical sense, it is the current authors opinion that paleopoles should meet at least the first three criteria, i.e., have a well-determined rock age, sufficient number of samples, and adequate demagnetization, before they can be considered reliable and used as key poles in the construction of an APWP. Exceptions to this are when the paleopole is constrained by positive field tests, but the pole should, in the current authors' opinions, still satisfy two of the first three criteria. Another important point is that radiometric ages indicate a 583 ± 15 Ma age for the Fen complex [*Meert et al.*, 1998], in agreement with previous data [see *Piper*, 1988], but in contrast to the 565 Ma age quoted in the work of *Torsvik et al.* [1996]. Obviously, this raises questions for the APWP presented by Torsvik et al. as the five poles used by them (the Sredny, Komagnes, and Fen paleopoles, poles 40–44 in Table 1 of *Torsvik et al.* [1995]) to constrain the Vendian and which show two distinct groupings, spanning 75° of longitude, are apparently coeval. It has been suggested by *Meert et al.* [1998], however, who also present new paleomagnetic data for the Fen Complex which are in agreement with earlier data, that the Fen Complex has in fact been remagnetized. If inverted, the paleopole positions from the Fen complex [*Meert et al.*,

1998; *Piper*, 1988] show strong similarities to the Permian–Triassic segment of the APWP for Baltica [*Meert et al.*, 1998; *Smethurst et al.*, 1998], thus a Permian–Triassic remagnetization age for the Fen complex cannot be ruled out [*Meert et al.*, 1998; *Smethurst et al.*, 1998]. The same line of argumentation could also be applied to the results from the Sredny Dykes (pole 43 in Table 1 of *Torsvik et al.* [1996]). The inverted Sredny pole position plots on the Jurassic segment of the APWP for Baltica, and there are apparent discrepancies concerning the age of the Sredny dykes, with values ranging from ca. 360 Ma, 525 ± 20 Ma, to 580 ± 20 Ma and a minimum intrusion age of 546 ± 4 Ma as quoted in the work of *Torsvik et al.* [1995].

[21] The new data presented here have a well-constrained age of 555 ± 3 Ma, and thus provide an important pole position for a time period which until now has been at best poorly constrained paleomagnetically, and bring into question the validity of the Riphean to Early Ordovician segment of the APWP of *Torsvik et al.* [1995] as outline below.

[22] After a critical assessment of the available paleomagnetic data there are only three fully published paleopoles available which satisfy the first three *Van der Voo* [1990] criteria for Late Riphean to Early Ordovician times. These poles comprise two results from the Fen complex which gives radiometric ages of 583 ± 15 Ma, and 584 ± 19 Ma [*Meert et al.*, 1998; *Piper*, 1988], and the 553 ± 6 Ma Alnø Complex paleopole [*Piper*, 1981], although this latter pole would appear to be slightly older in age (∼590 Ma) from as yet unpublished radiometric data (T. H. Torsvik, personal communication, 2002), thus further complicating the matter. This is in contrast to the model of *Torsvik et al.*
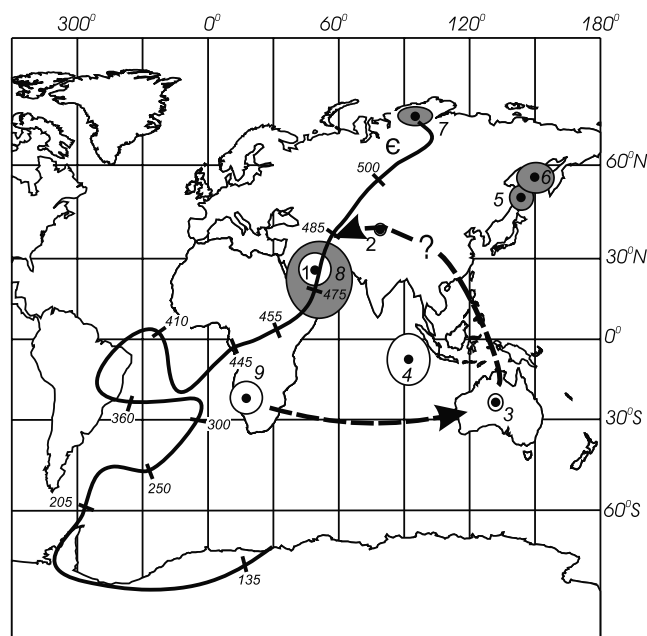

Figure 6. Proposed APWP for Baltica (stippled line) for Late Proterozoic to Early Ordovician times and the path of *Smethurst et al.* [1998] for Neoproterozoic and Paleozoic times (solid line). Ages are in My, pole numbers refer to "code" in Table 2, dp and dm (or α95) are shown as ovals, shaded ovals indicate poles that may be remagnetized as discussed in text.

Table 2. Selected Pole Position for Late Riphean to Early Paleozoic Times for Baltica

Code	Rock unit	Age, My	B	N	Pole position Lat, °N	Pole position Long, °E	dp, °	dm, °	Reference
1	Early Paleozoic mean pole	475	4[a]		283	513	10.5[b]		*Smethurst et al.* [1998]
2	Winter Coast, component B	Tremadoc[c]		232	400	790	20	23	this study
3	Winter Coast, component Z	555 ± 3		94	−253	1322	23	37	this study
4	Alnø Complex	553 ± 6[d]	21	103	−76	920	47	93	*Piper* [1981]
5	Fen tinguates	583 ± 15	20	144	501	1439	49	79	*Piper* [1988]
6	Fen Central Complex	583 ± 15	6	55	560	1500	70	100	*Meert et al.* [1998]
7	Sredny Dyke	580 ± 20	1	24	729	947	2.3[b]		*Torsvik et al.* [1995]
8	Egersund Dyke	616[e], 650[f]	4	35	220	510	14.0[b]		*Poorter* [1972]
9	Late Proterozoic Mean Pole	750	3[a]		−281	173	7.6[b]		*Torsvik et al.* [1996]

B is number of sites, N is number samples, Lat and Long are latitude and longitude of the pole position, and dp and dm are the errors associated with the pole.

[a]Number of studies used to compute the mean pole.
[b]α_{95} [*Fisher*, 1953].
[c]Probable remagnetization age.
[d]Alternative age of 590 Ma, unpublished data (T. H. Torsvik, personal communication, 2002).
[e]New age of 616 Ma after the work of *Bingen et al.* [1998].
[f]Age as quoted in the work of *Torsvik et al.* [1996].

[1996], where the Alnø pole was not considered, and where the Early Vendian segment of the path is constrained by the 616 Ma Egersund [*Poorter*, 1972; *Storetvedt*, 1966; new age date provided by *Bingen et al.*, 1998] pole position (Figure 6, and Table 1 of *Torsvik et al.* [1996]). However, the Egersund pole position lies directly on the Early Ordovician segment of the APWP, thus bringing the reliability of this pole, at face value, into question. This pole position is derived from 616 Ma mafic dykes, which have been intruded into Late Proterozoic age anorthosite rocks. Available paleomagnetic data from the country rocks yield significantly different results [*Hargraves and Fish*, 1972], thus implying rather selective remagnetization processes if the Egersund pole really is an Ordovician remagnetization. On the other hand, the study of Hargraves and Fish was carried out some time ago and does not meet modern reliability requirements, thus making qualitative judgment of the data difficult and highlighting the need for modern paleomagnetic studies.

[23] If the directions published for the Fen complex are considered to reflect remagnetization events, as suggested in the literature, the remaining reliable data implies a rather simple APWP (Table 2 and Figure 6), which connects the mean pole for the Riphean with the late Vendian poles for the Winter Coast (this study) and the data for the Alnø complex [*Piper*, 1981], although as mentioned, there are questions concerning the age of this complex. This path indicates continued low paleolatitudes for Baltica from the Latest Riphean to the Late Vendian. The Late Vendian to Ordovician segment of the APWP remains unconstrained. Alternatively, if the results for the Fen Complex and/or the Sredny Dykes are interpreted to be of primary (approx. 585 Ma) age, the proposed path gains complexity. It has to connect the Riphean pole position (positioned at 25°S) with the poles for the Fen Complex (positioned at 60°N), swing back to the pole for the Winter Coast (and the Alnø Complex) which is at a latitude of 25°S, and subsequently back to the NW to connect with the well-constrained Ordovician segment of the path [*Smethurst et al.*, 1998]. Given the age constraints for the individual pole positions (Table 2) this implies rather high drift velocities in the order of up to 30 cm/y.

[24] In summary, the late Riphean and late Vendian paleopoles (poles 3 and 9 in Table 2) indicate low paleolatitudes for Baltica. If these two data points can be directly connected, this would indicate low paleolatitudes for Baltica throughout this time period, thus lending support to "Snowball Earth" paleoclimatic models which require low paleolatitudes for all major continents. However, this interpretation of the paleomagnetic data remains speculative and highlights the need for more reliable pole positions for the Riphean to late Vendian time interval. Other implications of these data include that there was no relationship between Laurentia and Baltica in the Neoproterozoic/Vendian. This has important implications for most of the current models on the opening of the Iapetus Ocean.

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