THE GEOLOGICAL SOCIETY
OF AMERICA®

Ediacaran–Cambrian paleogeography of Baltica: A paleomagnetic view from a diamond pit on the White Sea east coast

Natalia M. Fedorova[1,*], Mikhail L. Bazhenov[1,†], Joseph G. Meert[2,*,§], and Nikolay B. Kuznetsov[1,3,4,*]
[1]GEOLOGICAL INSTITUTE, RUSSIAN ACADEMY OF SCIENCES, PYZHEVSKY LANE 7, MOSCOW 109017, RUSSIA
[2]DEPARTMENT OF GEOLOGICAL SCIENCES, 355 WILLIAMSON HALL, UNIVERSITY OF FLORIDA, GAINESVILLE, FLORIDA 32611-2120, USA
[3]INSTITUTE OF PHYSICS OF THE EARTH, RUSSIAN ACADEMY OF SCIENCES, BOL'SHAYA GRUZNISKAYA UL. 10, MOSCOW 123995, RUSSIA
[4]GUBKIN RUSSIAN STATE OIL AND GAS UNIVERSITY, LENINSKY AVENUE 65, MOSCOW 119991, RUSSIA

ABSTRACT

The controversial late Ediacaran to Cambrian paleogeography is largely due to the paucity and low reliability of available paleomagnetic poles. Baltica is a prime example of these issues. Previously published paleomagnetic results from a thick clastic sedimentary pile in the White Sea region (northern Russia) provided valuable Ediacaran paleontological and paleomagnetic data. Until recently, Cambrian-age rocks in northern Russia were known mostly from boreholes or a few small outcrops. A recent mining operation in the Winter Coast region exposed >60 m of red sandstone and siltstone of the Cambrian Brusov Formation from the walls of a diamond pit. Paleomagnetic data from these rocks yield two major components. (1) A single-polarity A component is isolated in ~90% of samples between 200 and 650 °C. The corresponding pole (Pole Latitutde, P_{lat} = 20°S; Pole Longitude, P_{long} = 227°E, α_{95} = 7°) agrees with the Early Ordovician reference pole for Baltica. (2) A dual-polarity B component is identified in ~33% of samples, mostly via remagnetization circles, isolated from samples above 650 °C. The corresponding pole (P_{lat} = 12°S; P_{long} = 108°E, α_{95} = 5°) is close to other late Ediacaran data but far from all younger reference poles for Baltica.

We argue for a primary magnetization for the B component and the secondary origin of the other Cambrian poles from Baltica. This in turn requires a major reshuffling of all continents and blocks around the North Atlantic. The early stages of Eurasia amalgamation and models for the evolution of the Central Asian Orogenic Belt require revision.

INTRODUCTION

A general rule is that the older the rocks, the more difficult, on average, it is to extract a reliable paleomagnetic signal due to a more protracted history over which different processes can lead to heating and alteration. This unofficial opinion is supported by the distribution of paleomagnetic data that are used for construction of global apparent polar wander paths (APWPs). This distribution is clearly not uniform; there are distinct minima, for example at the Devonian-Carboniferous boundary (see Torsvik et al., 2012, fig. 3 therein). The end of the Ediacaran Period and the beginning of the early Cambrian is another problematic interval that can be illustrated by Siberian paleomagnetic data. In Siberia, many good middle Cambrian and younger data are available, while numerous studies of late Ediacaran–early Cambrian rocks resulted in either an uncontestable polarity scale or unambiguous poles (Kirschvink and Rozanov, 1984; Pisarevsky et al., 1997; Torsvik et al., 1998; Khramov, 2000; Gallet et al., 2003; Pavlov et al., 2004; Shatsillo, 2006; Shatsillo et al., 2015).

Moreover, this confusing pattern is not a Siberian peculiarity; similarly contradictory data are found for the late Ediacaran–Cambrian of Baltica (Meert, 2014; Meert et al., 2007) and Laurentia (Abrajevitch and Van der Voo, 2010). The fact that Cambrian-age rocks on Baltica are rare aggravates the situation and no Cambrian poles are available for this craton (based on the most recent time scale). In 2001, the first Cambrian poles from northern and southern Sweden (Torsvik and Rehnström, 2001) extended the APWP and placed Baltica at high southern latitudes in the late Ediacaran and Cambrian (Şengör et al., 1993; Kheraskova et al., 2003; Meert and Lieberman, 2004). This simple explanation was soon contested by late Ediacaran poles that positioned Baltica close to the equator (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005; Levashova et al., 2013; Fedorova et al., 2014).

It was known from boreholes that upper horizons of the predominantly late Ediacaran sequence in the White Sea region (northern Russia) may be as young as early Cambrian (Grazhdankin, 2003; Alekseev et al., 2005, and references therein). After the discovery of Devonian diamondiferous kimberlite pipes in this region, mining operations started and penetrated several tens of meters into the previously unexposed upper horizons of the sequence. We gained access into one of the diamond pits (with permission from the SeverAlmaz Company), and collected a limited number of samples from the Brusov Formation. This paper is based on paleomagnetic data from this section and their implications.

*Emails: Fedorova: namife90@gmail.com; Meert: jmeert@ufl.edu; Kuznetsov: kouznikbor@mail.ru
†Deceased.
§Corresponding author.

GEOLOGICAL SETTING AND SAMPLING

The study area is on the northern rim of the East European Platform (Baltica) to the east of the White Sea (Fig. 1) and ~300 km away from the Timanian margin of Baltica, where deformation is generally thought to have occurred in the late Ediacaran (Kuznetsov at el., 2007, 2010). The most recent studies, however, indicate that the provenance signal from the Timanian orogen appeared in these sediments by the middle Cambrian, suggesting that the deformation may be a bit older than late Ediacaran (Kuznetsov et al., 2014; Slama and Pedersen, 2015; Zhang et al., 2015). The lack of observed deformation in the study area for the late Ediacaran and Cambrian indicates that there was no relative motion between the White Sea area and the rest of Baltica.

According to geologic and geophysical data, the nonexposed basement comprises mostly Paleoproterozoic complexes (Mintz et al., 2015); this is further substantiated by 1.9–1.7 Ga xenocrystic zircons that dominate in the Devonian kimberlites (Griban' et al., 2012). Borehole and geophysical data indicate that the basement is unconformably overlain by sediments that are correlated with Mesoproterozoic and early Neoproterozoic rocks of the southern Urals (Maslov, 2004). This section is covered without angular unconformity, but most likely with stratigraphic disconformity by the ~1000-m-thick late Ediacaran–early Cambrian sequence that comprises the Ust'-Pinega, Mezen and Padun Groups, which are further subdivided into a number of formations (Fig. 2; Alekseev et al., 2005; Grazhdankin, 2003, 2014; Kuznetsov et al., 2014). This sequence can be generally characterized as follows.

1. The entire sequence is composed of clastic rocks and clays, many of which are red.

2. There are numerous tuff horizons in the upper Ust'-Pinega and Mezen Groups that can be used as markers (e.g., Aksenov and Volkova, 1969), but no marker horizons of other types are present.

3. Various Ediacaran fossils and microfossils are found at many levels in the upper Ust'-Pinega and Mezen Groups, whereas the fauna in the Padun Series is impoverished (Fedonkin et al., 2007; Ivantsov et al., 2004; Grazhdankin, 2014).

4. Magmatic zircons in tuff beds from the middle Ust'-Pinega Series yielded an U-Pb age of 558 ± 1 Ma (the age is in Grazhdankin, 2014).

5. A U-Pb age of 555.3 ± 0.3 Ma was obtained from the basal Zimnegory (Martin et al., 2000; note that this age was recently recalculated to 552.85 ± 0.77 Ma using new decay constants by Schmitz, 2012; however, we retain the original age for uniformity in this paper as not all ages have been recalculated).

6. Magmatic zircons in tuff beds from the lowermost Mezen Group yielded a U-Pb age of 550.2 ± 4.6 Ma (Iglesia-Llanos et al., 2005).

The late Ediacaran–early Cambrian sequence was intruded by numerous kimberlite pipes in the Middle–Late Devonian (Golubkova et al., 2013). A thin sedimentary veneer, mostly of poorly indurated sandstones, was formed in this area in the late Carboniferous–early Permian. The entire Ediacaran–Permian sedimentary section dips gently to the east-southeast and is commonly regarded as the western limb of the Mezen syncline.

The studied section encompasses the upper part of the ~200-m-thick Brusov Formation, which is the uppermost unit in the Padun Group. The youngest isotopic age of 550.2 ± 4.6 Ma is from magmatic zircons within a tuff bed at the base of the Mezen Group (Fig. 2; Iglesia-Llanos et al., 2005). The geochronological sample is located ~400–500 m below the sampled Brusov beds. Additional paleontological age constraints include the occurrence (~250–350 m below our samples) of *Sabellidites cambriensis* tubes (Alekseev et al., 2005). This fossil is very common in upper Ediacaran and lowermost Cambrian strata of Baltica (Kirsanov, 1968; Sokolov, 1968; Orlowski, 1985, 1989; Ivantsov, 1990), especially in the lower Cambrian Lontova Formation in the vicinity of Saint Petersburg (Yanishevsky, 1926). The *Sabellidites cambriensis* zone straddles the Precambrian-Cambrian boundary in the GSSP (Global Boundary Stratotype Section and Point), succession of Newfoundland (Landing et al., 1989). Somewhat upsection, but still ~200 m below our samples, vertical tubes of *Skolithos* or *Rosselia* types as much as 10 mm in diameter and 150 mm in depth were found with
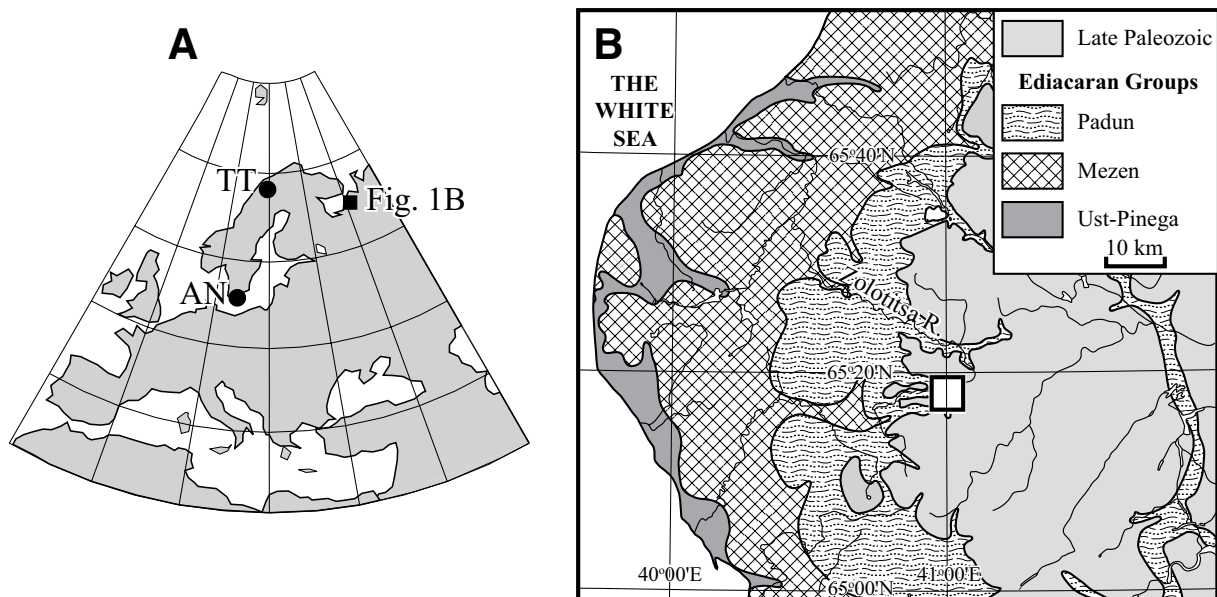

Figure 1. (A) Location of Cambrian study areas where paleomagnetic data are available: TT—early Cambrian Tornetrask Formation; AN—Late Cambrian Andrarum Formation, both from Torsvik and Rehnström (2001). (B) Simplified geologic map of the eastern White Sea area (simplified after Astafiev et al., 2012). Rectangle denotes our study area.
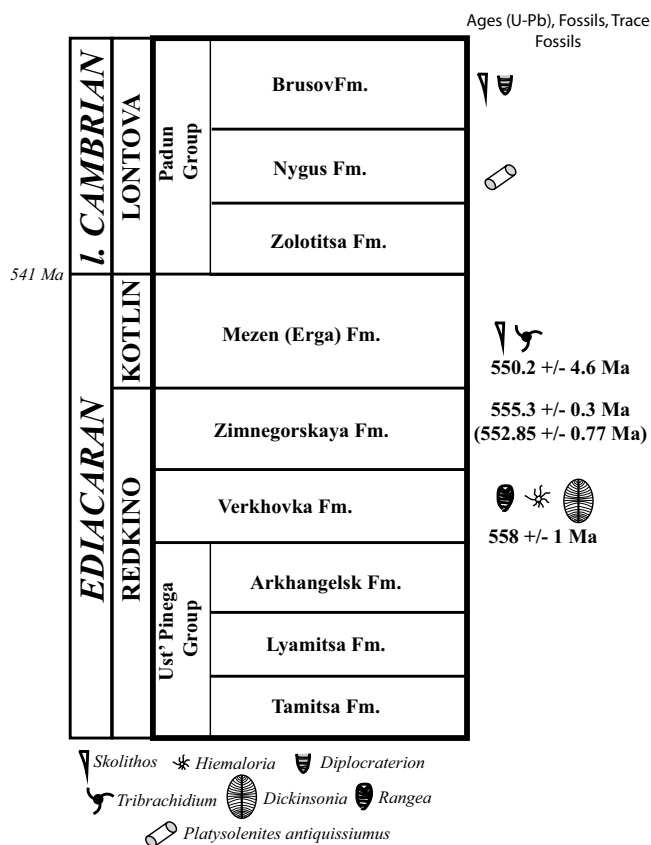
Figure 2. Generalized stratigraphy, ages, and key fossils from the White Sea region adapted from Kuznetsov et al. (2014) and Grazhdankin (2014). Ages are discussed in the text. Fm.—formation; L.—lower.

some *Diplocraterion* traces (Grazhdankin and Krayushkin, 2007). The problematic tubular fossil, *Platysolenites antiquissimus* Eichwald 1860 is thought to be an agglutinated foraminifer (Lipps and Rozanov, 1996; Streng et al., 2005; McIlroy et al., 2001) and occurs in the middle part of the Padun Series (Alekseev et al., 2005). This fossil is confined to the lower Cambrian (Lontova Horizon) in Baltica (Rozanov, 1983). No identifiable fossils were found in the Brusov Formation; the data here strongly indicate that it is early Cambrian in age or younger (see following discussion).

During diamond prospecting in this region, many kimberlite bodies were penetrated by boreholes, in which were found numerous carbonate debris and blocks to several meters in size that were trapped in the kimberlite pipes during emplacement. Conodonts from different carbonate blocks vary in age from the late Tremadocian (Early Ordovician) to the Rhuddanian (early Silurian) (Tolmacheva et al., 2013); Popov and Gorjansky (1994) reported upper Cambrian brachiopods from other pipes.

In northern Russia, the entire Ediacaran–Cambrian terrigenous sequence and its members thicken to the east and northeast (Maslov et al., 2008). Detrital zircon studies of the Brusov Formation show a typical Baltic provenance without an input from the Timan orogen, which is northeast of our study area (Kuznetsov et al., 2014, 2015). In contrast, the younger deposits, from the middle Cambrian on, show thickening to the west, and the provenance signal in the Sablino Formation from an area south of Ladoga Lake (at ~60°N, 32°E) shows a considerable input of Timanian origin (Kuznetsov et al., 2011). These observations indicate that our study area belonged to the northeastern (Timanian) passive margin of

Baltica, where the disintegrated cratonic rocks were delivered from south to west. During the early-middle Cambrian, the Timanian orogeny took place as a result of the collision of Baltica and the Arctida continent (Kuznetsov et al., 2014). Combining all available data, for example, the lack of carbonates and the Timanian provenance signal in the Brusov rocks indicate that they are most probably of the early–early-middle Cambrian age.

The diamond pit of the SeverAlmaz Company (red rectangle in Fig. 1B) penetrates ~60 m into the Brusov Formation rocks surrounding the pipe. (All stratigraphic positions herein are in meters above sea level). These sandstones and siltstones, mostly red, are flat-lying. The sediments form an eruptive breccia with a few meters to few tens of meters wide contact zone with sharp external boundaries. The brecciated sediments show no evidence of hydrothermal or metasomatic alteration; in particular, no veins of any composition were found in either the kimberlite or host sediments. The Brusov rocks are poorly lithified and commonly water saturated; as a result, the pit is ~100 m in depth and 2 km in diameter. We limited our collection of paleomagnetic samples to well away from the contact with the kimberlite pipe.

Outside of the inner brecciated zone, small volumes of deformed sediments that are considered soft-sediment slumps are found among flat-lying beds at different stratigraphic levels. The only sampled slump (5 samples) is a small 1.0 × 0.5 m section where the sandstone beds generally dip to southwest.

Due to the mechanical weakness of the Brusov red sediments, we had to sample wherever we could, often just one or two samples at a point. The samples were oriented with a magnetic compass, and global positioning system readings of each sampling point were recorded as well as the stratigraphic thickness between the adjacent samples. Then (with the aid of mine servicemen) all sampling data were transformed into elevation above sea level with an accuracy of ±0.2 m and a sampling log was constructed. In total, 115 samples are unevenly spread over a 60 m interval; the uppermost ~10 m of the section proved to be too weathered for sampling. For convenience and statistical comparisons, the set of 115 stratigraphically ordered samples was divided into 6 nonoverlapping subsets of ~20 samples that were treated as sites (from bottom to top, D1–D6; Table 1).

PALEOMAGNETIC METHODS AND RESULTS

Two 20 mm cubic sister specimens were cut from the samples when possible. Individual specimens from each sample were subjected to stepwise thermal demagnetization up to 700 °C in a homemade oven with a residual field of ~10 nT. Magnetization intensities were measured with Czech spinner magnetometers JR-4 and JR-6 within Helmholtz coils to reduce the ambient field at the paleomagnetic laboratory (Moscow, Russia). After examining demagnetization data, the remaining 75% of the collection was repeatedly demagnetized with the aid of a standard ASC-TD-48 oven and measured on a 2G Enterprises 755R cryogenic magnetometer placed in a magnetically shielded room in the Paleomagnetic Laboratory of the University of Florida (Gainesville, Florida, USA). Demagnetization data were analyzed using orthogonal vector plots (Zijderveld, 1967) via principal component analysis (Kirschvink, 1980). Component directions and remagnetization circles were combined as suggested by McFadden and McElhinny (1988). For statistical analysis, the best defined component and/or remagnetization circle from each pair of sister specimens was used. Paleomagnetic analysis and calculations were carried out with the PaleoMac software (Cogné, 2003).

A weak scattered component is removed from many samples after heating to between 200 and 250 °C. That low-temperature component is most probably of viscous origin and will not be considered further in our discussion. Most of the natural remanent magnetization (NRM) in the redbeds

TABLE 1. PALEOMAGNETIC RESULTS ON THE EARLY CAMBRIAN
BRUSOV FORMATION

Identification	M	N1	N2	D° (°)	I (°)	k	α_{95} (°)
Component A							
D1	FM	20	15	165.1	60.2	29	7.2
D2	FM	20	19	175.2	58.4	25	6.9
D3	FM	20	16	165.1	64.1	63	4.7
D4	FM	20	20	173.1	63.3	67	4.0
D5	FM	20	18	166.4	63.3	34	6.0
D6*	FM	15	13	183.7	61.6	34	7.2
Slump-IS	FM	6	5	20.0	87.9	64	9.6
Slump-TC	FM	6	5	254.0	53.4	51	10.8
A samples*	FM	115	101	171.7	61.6	36	2.4
A sites	FM	(6)	(6)	171.6	62.0	388	3.4
		Pole: lat 18.7°S, long 227.5°E, α_{95} = 4.7°					
Component B							
D1	AGC	20	3c	195.5	−13.1		11.7
D2	MM	20	1d3c	130.0	−19.1	52	11.6
D3	AGC	20	7c	203.9	−26.4		11.7
D4	AGC	20	4c	180.1	−31.7		11.7
D5	AGC	20	8c	201.2	−22.9		4.7
D6	MM	15	4d2c	108.9	−20.3	22	15.0
B samples	MM	115	5d29c	108.7	−15.4	9	8.6
B sites	MM	(6)	(2d4c)	106.7	−14.2	19	17.4
		Pole: lat 13.5°S, long 118.7°E, α_{95} = 12.7°					

Note: Sites are numbered from bottom to top as described in the text. All data are in situ except for Slump-TC. M—method used for calculation a result; FM—Fisher statistics (Fisher, 1953); MM—combined paleomagnetic directions and remagnetization circles (McFadden and McElhinny, 1988); AGC—average remagnetization circles (shown in italics for visibility). Slump-IS—in situ; Slump-TC—tilt corrected. As no direct counterpart for concentration parameter is available for the latter type of data, the corresponding cells are left empty, and the confidence circles are computed with the aid of PaleoMac software (Cogné, 2003). N1—number of samples (sites) studied; N2—number of samples (sites) used for calculation of a result and the type of data used: d—directions (shown for MM results only); c—remagnetization circles. D—declination; I—inclination; k—concentration parameter; α_{95}—confidence circle (Fisher, 1953).
   *Samples from the slump are not included.

is represented by a well-defined component (A) that persists from 200 to 650 °C. This component was identified in 112 of 116 samples. In many samples, the corresponding linear segments on orthogonal plots decay toward the origin without any clear great-circle trajectories (Figs. 3A–3C). In other samples, remagnetization circles are clearly visible, with most of angular shift occurring above 600 °C (Fig. 3D). Component A has the same polarity everywhere and forms a distinct cluster. When component A directions are transformed to virtual geomagnetic poles, and the standard 45° cutoff is applied, 10 outliers are removed. The six site means are statistically identical, very tightly clustered, and show no systematic shift through the section; two overall means on the sample and site level differ by <1° (Table 1).

We sampled a limited slump, and both sample and site directions of component A in this structure and flat-lying beds are better grouped in situ than after tilt correction (Figs. 4A, 4B; Table 1); the concentration parameter ratios are 1.17 and 1.87 for samples and sites, respectively. Thus the tilt test (McElhinny, 1964) is inconclusive. Neither component B directions nor remagnetization circles could be recovered from the slump.

After removal of component A above 620–630 °C, a component B with very different direction can be reliably isolated from seven samples only (Figs. 3C, 3E). Its wider presence, however, is indicated by remagnetization circles that are determined in an additional 33 samples. All directly isolated component B directions have easterly declination and shallow inclination, thus indicating a single (eastern) polarity for all these

few samples. During demagnetization (Figs. 3D, 3F), vector end points move eastward to the isolated B directions along most remagnetization circles, and therefore indicate an eastern polarity of this remanence. In a few cases, sample directions trend toward the end point in an opposite direction (Fig. 3H) that we ascribe to component B being of western polarity in these samples. When directly determined and inferred polarities of component B are compiled into a stratigraphic log, their distribution proves to be rather regular, with the eastern polarity zone in the 30–40 m interval, western polarity zone in the 40–50 m interval, and eastern polarity zone in the uppermost 50–67 m interval (Fig. 5C). There are two out-of-order samples that appear to disturb the simple pattern (question marks in Fig. 5C). As these samples are stratigraphically separated by <0.5 m but are from remote parts of the pit, this change of polarity may be due to an imprecise correlation across the field area. The presence of 3 polarity zones within the 35-m-thick section may indicate a fairly high reversal rate, but more definite correlations with Ediacaran–early Cambrian magnetostratigraphy from in the Urals and Siberia (Meert et al., 2016; Bazhenov et al., 2016; Shatsillo et al., 2015) are premature.

For two sites (Table 1; Fig. 5A), we calculated the component B site-mean direction by combining vectors and planes (McFadden and McElhinny, 1988). For the remaining sites, where remagnetization circles only are recognized, their intersections agreed with the corresponding site mean for component A. This is not surprising, as remagnetization circles tend to intersect closer to the least-dispersed paleomagnetic components (Halls, 1976). Thus the only way to extract any information on the possible direction of component B in such sites is to compute the average great circles and utilize them at the next level of statistical treatment. The overall mean of component B was thus computed for 2 site means and 4 average great circles at the site level, and for 5 B components and 29 unit remagnetization circles at the sample level. Both mean directions are very similar, but the confidence circle for the former is much larger (Table 1).

Demagnetization data unambiguously indicate that both A and B components reside in hematite, which may account for their imperfect separation. Another reason for the low success rate for B component is that many samples acquire spurious remanence above 620 °C, often terminating demagnetization in both laboratories. The lack of rock-magnetic data in our study may seem uncommon, but a recent study of chemical remanent magnetization (CRM) of artificial and natural samples provided a wealth of new data but were unable to outline any robust criteria to discriminate between CRM and detrital remanent magnetization (DRM) in redbeds (Jiang et al., 2015). Jiang et al. (2015) noted that blocking temperature spectra may be used to discriminate between remanence mechanisms in redbeds because CRM samples tend to have a gradual intensity decay starting around 200 °C, whereas DRM samples tend to have a more discrete unblocking spectra at temperatures above 600 °C. Jiang et al. (2015) argued that this behavior could potentially prove useful in determining the type of remanence preserved in redbeds. Unfortunately, our experience shows that the above rule cannot be universally applied, as we can demonstrate both patterns in completely remagnetized redbed collections. In particular, both CRM- and DRM-type plots of NRM intensity versus temperature (not illustrated) are present among the Brusov redbeds with predominating well-defined component A. We note the unique opportunity afforded to us during this study allowed us only limited sampling before the mining operations took place.

INTERPRETATION AND DISCUSSION

The paleomagnetic pole (Pole Latitude, Plat = 19°S; Pole Longitude, Plong = 227°E, α_{95} = 4.7°) for component A is very close to the Early Ordovician (480–470 Ma) reference poles (Fig. 6), implying a similar age
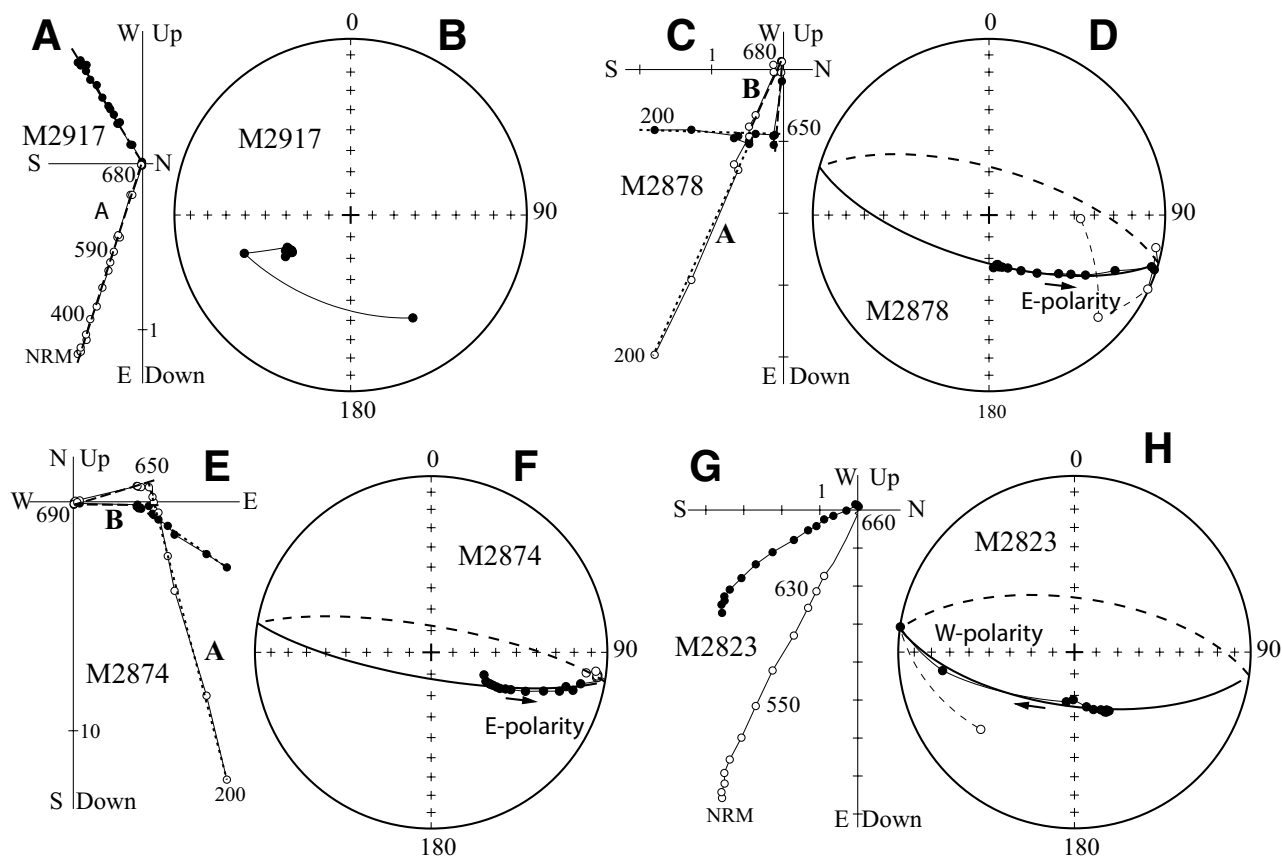
Figure 3. Thermal demagnetization data of representative red fine-grained sandstones and siltstones of the early Cambrian Brusov Formation in geographic coordinates. A, C, E, and G are orthogonal plots. Black circles are vector end points projected onto horizontal plane; white circles are vector end points projected onto vertical plane. Isolated high-temperature components are denoted by thick dashed lines. A—Component A; B—Component B; W-polarity—western polarity option; E-polarity—eastern polarity option. Temperature steps are in degrees Celsius. Magnetization intensities are in mA/m.
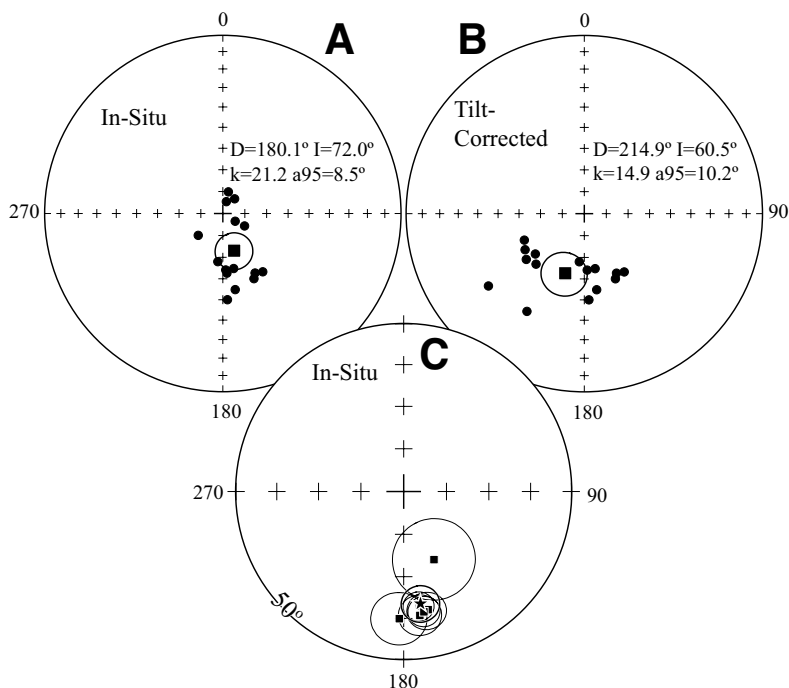
Figure 4. Directions of component A (circles) in the site where a slump was sampled. (A) In geographic coordinates. (B) In stratigraphic coordinates. Star is the site-mean direction with associated confidence circle. (C) Site means (squares) and the overall mean (star) with associated confidence circles in geographic coordinates. All symbols and lines are projected onto the lower hemisphere. Note that plot C is zoomed. D—declination; I—inclination; k—kappa precision; α_{95}—cone of 95% confidence about the mean direction (Fisher, 1953).
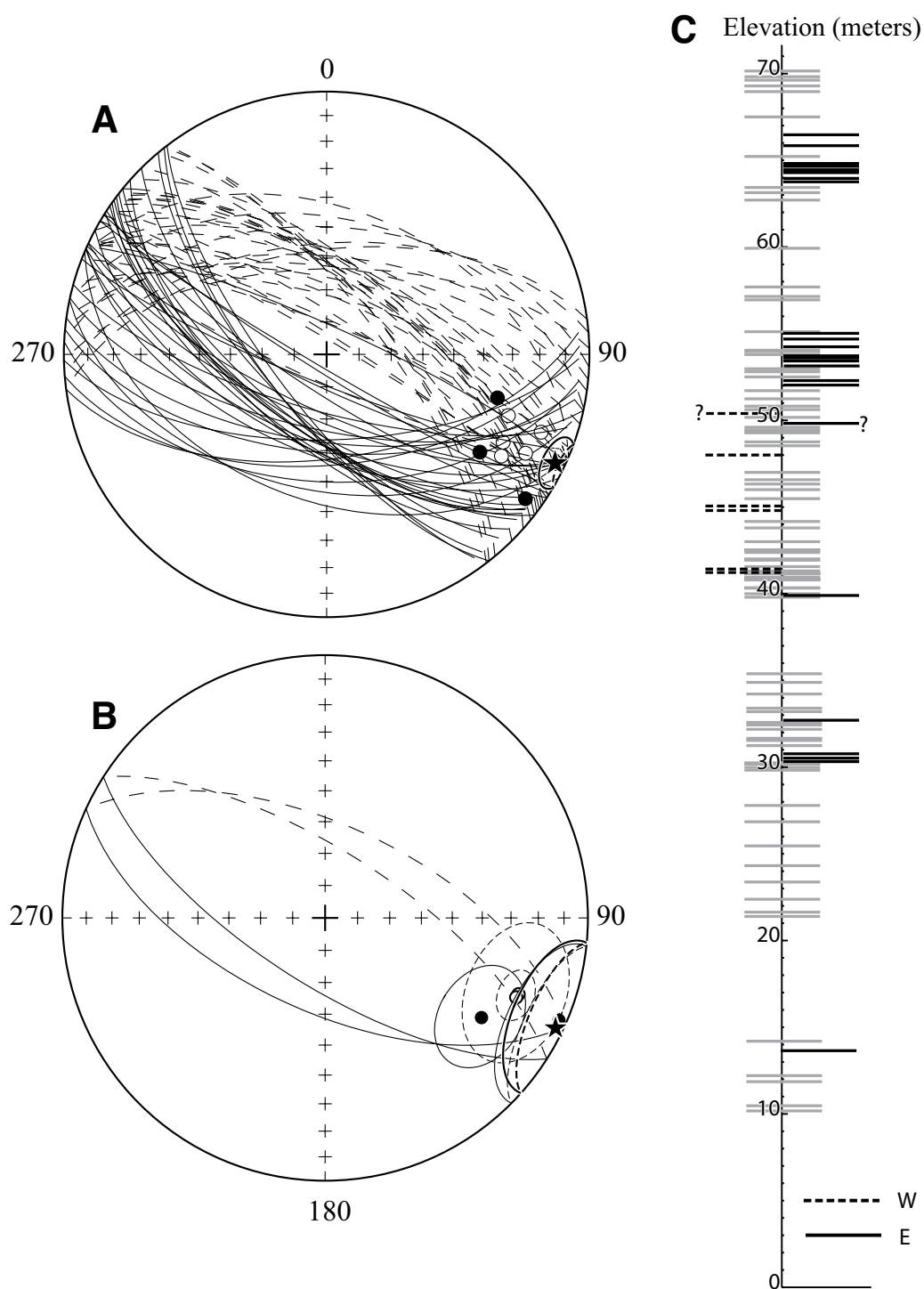
Figure 5. Stereoplots of component B directions (dots) and remagnetization circles and its mean directions (stars). (A) On the sample levels. (B) On the site levels. Black symbols and solid lines are projected onto lower hemisphere; white symbols and dashed lines are projected onto upper hemisphere. (C) Polarity zonation for the studied section: thick solid black lines denote eastern polarity, thick dashed black lines denote western polarity; light grey denotes levels where component B was not isolated. Value axis is in meters above sea level.

of this remanence, in accord with the conclusion by Popov et al. (2002, 2005) for older members of the same sequence. Based on the details of the remagnetization process and the results of the tilt test, we provisionally conclude that component A postdates deformation.

The paleomagnetic pole (Plat = 12°S, Plong = 108°E, α_{95} = 4.4 °; Fig. 6) for component B differs considerably from all Phanerozoic reference data for Baltica. The B pole on the global projection, however, may look suspiciously close to the tip of the Devonian spur (400–380 Ma) on the Baltic APWP (Fig. 5), but the angular difference is significant. No traces of synemplacement alteration related to kimberlite intrusions were reported from the study area and so there is no evidence to support a mid-Paleozoic overprinting in the area. In contrast, the B pole is close to the latest Ediacaran poles from the White Sea area (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005) and the Uralian eastern margin of Baltica (Levashova et al., 2013; Fedorova et al., 2014).

Although not compelling, this evidence favors a large time span between the acquisition of components A and B. We provisionally conclude that the Brusov Formation accumulated mostly during the Terreneuvian Epoch (ca. 541–521 Ma).

A dual-polarity magnetization is often regarded as a sign of primary magnetization, despite several cases of dual-polarity overprinting (Johnson and Van der Voo, 1986, 1989). In addition, the stratigraphic restriction of polarity zones through the section also points to the primary origin of component B. The paleomagnetic poles of components A and B are in good agreement with the Ordovician reference and late Ediacaran poles for Baltica. This allows us to suggest that component B is primary and component A is of secondary origin.

There is a dearth of Cambrian age poles from Baltica and the data give conflicting results. Results from the Andrarum Shale and Tornetrask Formation (500 and 535 Ma) suggest a high-latitude position for our study

area in Baltica (~54°; Torsvik and Rehnström, 2001). A pole from the early Cambrian Nexø Sandstone in Denmark (ca. 540 Ma; Lewandowski and Abrahamsen, 2003) yields a lower latitude position (~20°) for Baltica, albeit higher than our results. Our new datum places the study location near the equator (2° ± 3°, S or N). These results highlight the issues related to the APWP for Baltica (see Meert, 2014) in that seemingly reliable poles indicate either very fast plate motion or unusual configurations of the geomagnetic field.

In the case of our new data, one may suspect very strong inclination shallowing. The corresponding pole, however, is close to the late Ediacaran poles from the west Urals, where Levashova et al. (2013) argued for negligible to minor inclination shallowing. Thus, inclination shallowing cannot account for the paleolatitudinal differences between our study and previous Cambrian-age studies from Baltica.

The ca. 500 Ma Andrarum pole from southern Sweden (Torsvik and Rehnström, 2001) is based on 10 samples from a limited stratigraphic interval and is not confirmed by a field test. The older ca. 535 Ma Tornetrask pole from northern Sweden (Torsvik and Rehnström, 2001) seems more reliable and is based on a dual-polarity remanence isolated from six sites. The pole from the early Cambrian Nexø Sandstone resembles Permian poles from Baltica, but Lewandowksi and Abrahamsen (2003) argued that a pervasive remagnetization of the Nexø is unlikely because there was no remagnetization of other rock units in the same region. Our new result also suffers from a lack of field tests for primary remanence. In summary, none of the Cambrian-age paleomagnetic poles seems overly reliable. The strongest support for a primary magnetization in the Brusov samples is based on the fact that this pole does not match any younger reference poles for Baltica (Fig. 6).

We provide yet another rationale in support of a primary magnetization in the Brusov rocks. A paleomagnetic study of Middle–Late Devonian
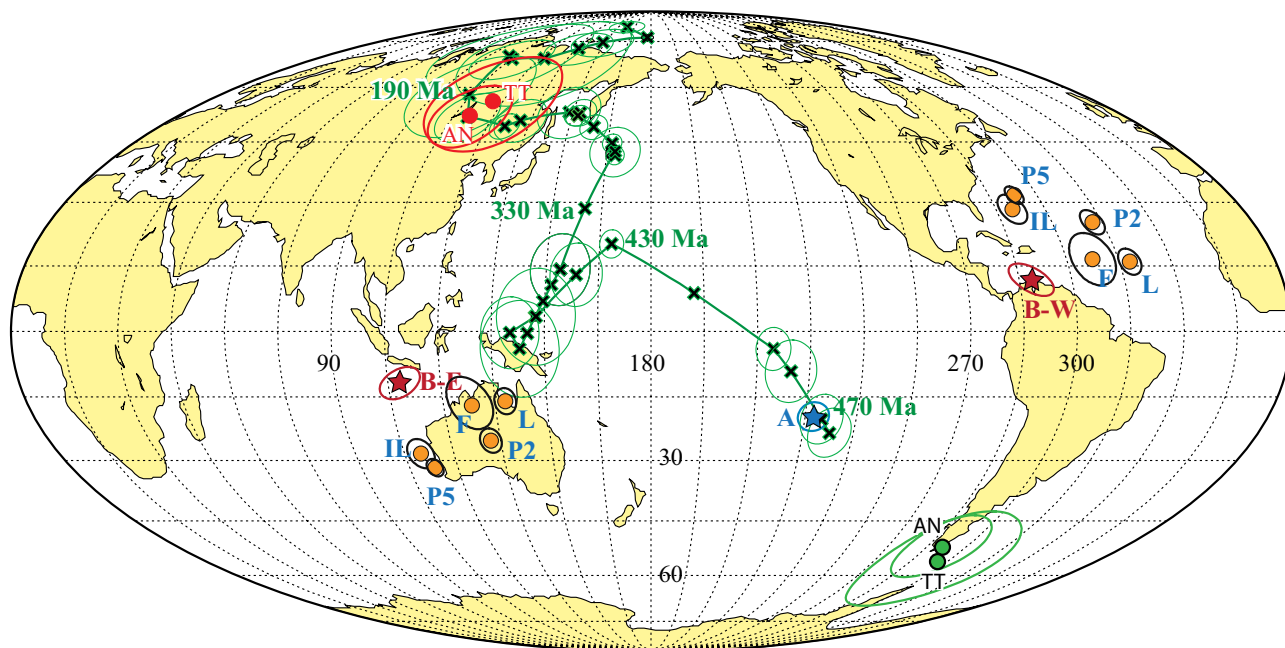

Figure 6. The Phanerozoic apparent polar wander path of Baltica (black oblique crosses and green connecting line) with ages in Ma (Torsvik et al., 2012). Red stars denote the early Cambrian Brusov poles for component B (E and W are eastern and western polarity, respectively); blue star (A), same for component A. Orange circles—late Ediacaran poles for Baltica [Popov et al., 2002, 2005 (P2, P5); Iglesia-Llanos et al., 2005 (IL); Levashova et al., 2013 (L); Fedorova et al., 2014 (F)] presented in both polarity options. Green filled circles—the Cambrian Andrarum (AN) and Tornetrask (TT) poles with associated confidence circles (Torsvik and Rehnström, 2001) in commonly used polarity option. Red filled circles—the same after polarity switch.

dikes from the northern Kola Peninsula showed that most of the dikes are remagnetized, and the overall mean of that overprint agrees well with the ca. 190 Ma reference pole for Baltica (Veselovskiy et al., 2016). Moreover, multiple manifestations of this remagnetization are found throughout Fennoscandia on different age rocks, including the Andrarum and Tornetrask poles (Fig. 6; for more detail, see Veselovskiy et al., 2016). Thus, the Andrarum, Tornetrask, and Nexø poles are all somewhere along the younger APWP for Baltica (see Fig. 6), whereas the Brusov pole is unique.

If the assumption of the secondary origin of the Cambrian Andrarum and Tornetrask and Nexø results (Torsvik and Rehnström, 2001; Lewandowski and Abrahamsen, 2003) is accepted, the Ediacaran–Cambrian paleogeographic evolution of the circum–North Atlantic region needs to be substantially revised. The high-latitude position of Baltica in the early Ediacaran (616 Ma) is based on a single pole from the Egersund dikes (Walderhaug et al., 2007). The Ediacaran pole from northern Finland (Hailuto pole; Klein et al., 2015) places northern Baltica (common point at 65.3°N, 41.0°E) in subtropical latitudes, presumably in the Southern Hemisphere (~25°). The 600–570 Ma age of this pole, as noted by Klein et al. (2015), is inferred rather than geochronologically dated. The periequatorial latitudes in the late Ediacaran (555–545 Ma) are the most robust results from Baltica. Our new results from the Brusov Formation extend this low-latitude paleogeography into the early Cambrian. Baltica moved to higher latitudes by the Early Ordovician. More detailed paleogeography of the North Atlantic bordering landmasses (Laurentia, Siberia) is beyond the scope of this paper.

Baltica is a key element in the amalgamation of northern Eurasia, as are the elements of the Uralian and Central Asian orogenic belts. A number of conflicting tectonic models for the formation of Eurasia have been published. Models proposed by Şengör et al. (1993, 2014) and Şengör and Natal'in (1996; herein the SN model) are common starting points in the discussion. The major feature of the SN model is the presence of the Kipchak arc, which is presumed to have rifted from Baltica and Siberia in the Ediacaran (ca. 600 Ma). Multiple episodes of complex deformation of this arc in the Paleozoic eventually led to the present-day structure of Central Asia. The SN model includes a multitude of tectonic elements with different kinematics and evolutionary histories, eventually coalescing into Eurasia. Testing this model with paleomagnetic data is a daunting task, requiring scores of high-resolution paleomagnetic data. Even the robust Permian data set cannot be used for a rigorous test of the SN model yet, but is generally compatible with the final stages of tectonic evolution of Central Asia predicted by this model (Levashova et al., 2003). For older epochs, the available paleomagnetic data are too few and scattered to allow for such testing.

Fortunately, the SN model contains crucial starting assumptions, as emphasized by Şengör and Natal'in (1996). The most important initial constraint for the evolution of the Altaids is the assumption that the Siberian and Baltic cratons were united as a single mass along their present-day northern margins during the earliest Ediacaran and, according to the SN model, essentially retained the same relative positions until the Early Ordovician. In that model, rifting of the Kipchak arc commenced during the early Ediacaran (ca. 600 Ma). This hypothesis was tested by Windley et al. (2007), who compared the then-available reconstructions of northern continents and concluded that all are incompatible with the SN model. Although these reconstructions are incompatible with the SN model, they are also incompatible with each other. Hence the conclusion by Windley et al. (2007) simply highlights the controversial paleogeographies of the Ediacaran–Ordovician interval.

Since 2007, new Ediacaran and early Cambrian paleomagnetic data have allowed for further testing of the SN model. According to Walderhaug et al. (2007), Baltica was at high latitudes in the early Ediacaran, but its orientation differs considerably from that predicted by the SN model; still, the difference is not prohibitive (Fig. 7A). More problematic for the SN
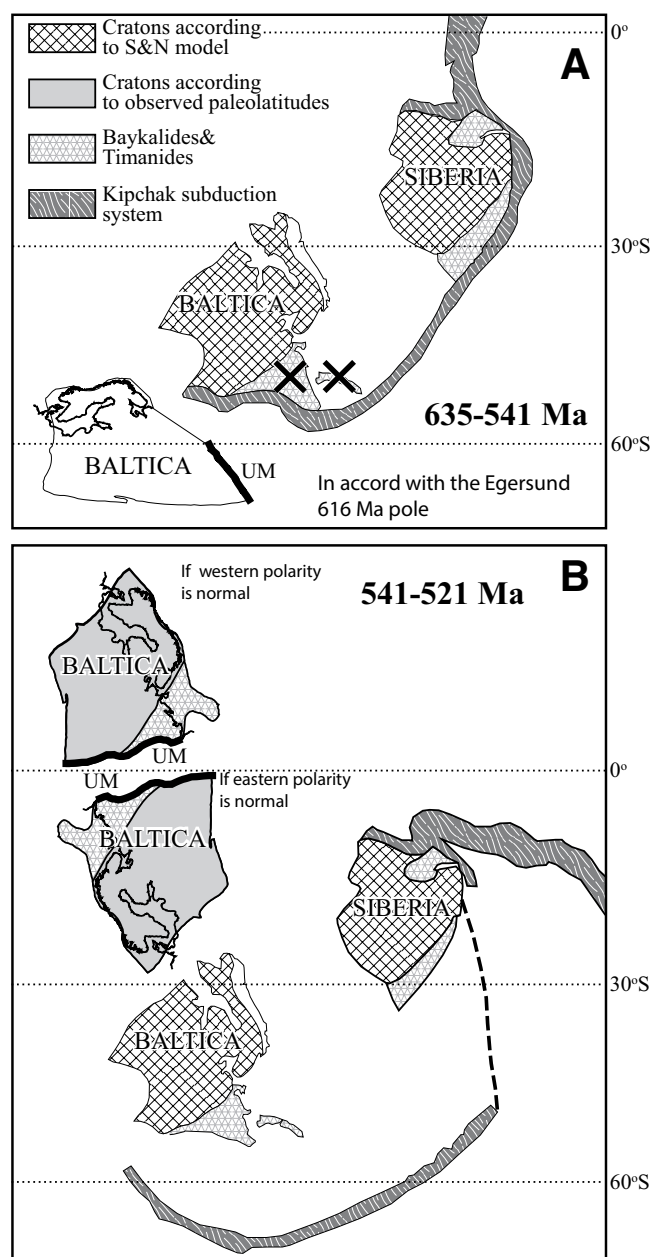

Figure 7. Comparison of the observed locations of Baltica with those predicted by the SN model (Şengör et al., 1993, 2014). (A) Ediacaran time. (B) Early Cambrian time. All units are similarly patterned in both A and B. Two options for Baltica in B correspond to different polarity options for the early Cambrian pole. Thick dashed line is a transform boundary from Şengör et al. (2014). UM—Uralian margin (thick line). X's denote the parts of the Baikalides that docked to Baltica in post-Ediacaran time (Kuznetsov et al., 2014) (see text).

model is that both geological data and the results of detrital zircon studies from different formations from northern and northeastern Baltica indicate that the Baikalides in the SN model could not be the craton margin, from which the Kipchak arc was rifted. In particular, there is no provenance signal from the Timanides in the rocks as young as the earliest Cambrian Brusov Formation (Kuznetsov et al., 2014); such a signal first appears in middle Cambrian sediments (ca. 520 ± 5 Ma; Kuznetsov et al., 2011;

Miller et al., 2011; Slama and Pedersen, 2015). Consequently, the part of Baltica margin from which the Kipchak arc originated becomes so small that any connection between this arc and the Baltica craton is problematic.

The Ediacaran pole from northern Finland (Klein et al., 2015) and especially the late Ediacaran and early Cambrian data from northern and eastern Russia place Baltica at low latitudes to the north and west of Siberia (assuming one polarity option). All these locations are incompatible with the SN model (Fig. 7B). Although Baltica moved to higher latitudes by the Early Ordovician, its return to exactly the same position as in the early Ediacaran appears unlikely. So, instead of simple and elegant paleogeography predicted by the SN model, the current paleomagnetic data from Baltica require a more complicated scenario. Any new tectonic model must include space for the Arctida landmass to collide with Baltica during the latest Neoproterozoic or Cambrian during the Timanian orogeny (Kuznetsov et al., 2007, 2014; Filatova and Khain, 2010). With these additional constraints, such a complicated early history of the Altaids deprives the SN model of its simple appeal and begs the question, what are the Ediacaran–Cambrian relationships between Baltica and Siberia?

REFERENCES CITED
Abrajevitch, A., and Van der Voo, R., 2010, Incompatible Ediacaran paleomagnetic directions suggest an equatorial geomagnetic dipole hypothesis: Earth and Planetary Science Letters, v. 293, p. 164–170, doi:10.1016/j.epsl.2010.02.038.

Aksenov, E.M., and Volkova, S.A., 1969, Volcano-sedimentary horizons of the Redkino Formation of the Valday Series: Doklady Academy of Sciences USSR, v. 188, p. 635–638.

Alekseev, A.S., Grazhdankin, D.V., Reimers, A.N., Minchenko, G.V., Krayushkin, A.V., Larchenko, V.A., Ushakov, V.N., and Stepanov, V.P., 2005, New data on the upper age limit of the ore-bearing sequence of the Arkhangelsk diamond province, in Zinchuk, N.N., ed., Geology of diamonds—Present and future: Voronezh, Russia, Voronezh University, p. 235–241 (in Russian).

Astafiev, B.Y., et al., 2012, Description of the State Geological Map of Russian Federation (third edition): Saint Petersburg, VSEGEI (A.P. Karpinsky Russian Geological Research Institute), Baltic Series, Sheet Q-37, scale 1:1,000,000, 302 p. (in Russian)

Bazhenov, M.L., Levashova, N.M., Meert, J.G., Golovanova, I.V., Danukalov, K.N., and Fedorova, N.M., 2016, Late Ediacaran magnetostratigraphy of Baltica: Evidence for magnetic field hyperactivity?: Earth and Planetary Science Letters, v. 435, p. 124–135, doi:10.1016/j.epsl.2015.12.015.

Cogné, J.-P., 2003, PaleoMac: A Macintosh™ application for treating paleomagnetic data and making plate reconstructions: Geochemistry, Geophysics, Geosystems, v. 4, 1007, doi:10.1029/2001GC000227.

Fedonkin, M.A., Simonetta, A., and Ivantsov, A.I., 2007, New data on Kimberella, the Vendian mollusc-like organism (White Sea region, Russia): Palaeoecological and evolutionary implications, in Vickers-Rich, P., and Komarower, P., eds., Rise and fall of the Vendian biota: Geological Society, London, Special Publication 286, p. 157–179, doi:10.1144/SP286.12.

Fedorova, N.M., Levashova, N.M., Meert, J.G., Maslov, A.V., and Krupenin, M.T., 2014, New paleomagnetic data on Baltica based on upper Ediacaran deposits on the western slope of the Middle Urals: Doklady Earth Sciences, v. 456, p. 512–516, doi:10.1134/S1028334X14050134.

Filatova, N.I., and Khain, V.E., 2010, The Arctida craton and Neoproterozoic–Mesozoic orogenic belts of the Circum-Polar region: Geotectonics, v. 44, p. 203–227, doi:10.1134/S0016852110030015.

Fisher, R.A., 1953, Dispersion on a sphere: Royal Society of London Proceedings, ser. A, v. 217, p. 295–305, doi:10.1098/rspa.1953.0064.

Gallet, Y., Pavlov, V., and Courtillot, V., 2003, Magnetic reversal frequency and apparent polar wander of the Siberian platform in the earliest Palaeozoic, inferred from the Khorbusuonka river section (northeastern Siberia): Geophysical Journal International, v. 154, p. 829–840, doi:10.1046/j.1365-246X.2003.01996.x.

Golubkova, A.B., Nosova, A.A., and Larionov, Y.O., 2013, MG-ilmenite megacrysts from the Arkhangelsk kimberlites, Russia: Genesis and interaction with kimberlite melt and postkimberlite fluid: Geochemistry International, v. 51, p. 353–381, doi:10.1134/S0016702913030038.

Grazhdankin, D.V., 2003, Structure and depositional environment of the Vendian complex in the southeastern White Sea area: Stratigraphy and Geological Correlation, v. 11, p. 313–331.

Grazhdankin, D.V., 2014, Patterns of evolution of the Ediacaran soft-bodied biota: Journal of Paleontology, v. 88, p. 269–283, doi:10.1666/13-072.

Grazhdankin, D.V., and Krayushkin, A.V., 2007, Trace fossils and the upper Vendian boundary in the southeastern White Sea region: Doklady Earth Sciences, v. 416, p. 1027–1031, doi:10.1134/S1028334X07070100.

Griban', Y.G., Samsonov, A.V., and Lepekhina, E.N., 2012, Zircon xenocrystals from kimberlite of the Grib pipe: Evidence on the early Precambrian basement of the Arkhangelsk diamond province, in Petrov, V.A., ed., News about ore formation processes: IGEM RAS (Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of the Russian Academy of Sciences), p. 65–68 (in Russian).

Halls, H.C., 1976, A least-square method to find a remanence direction from converging remagnetization circles: Royal Astronomical Society Geophysical Journal, v. 45, p. 297–304, doi:10.1111/j.1365-246X.1976.tb00327.x.

Iglesia Llanos, M.P., Tait, J.A., Popov, V., and Abalmassova, A., 2005, Palaeomagnetic data from Ediacaran (Vendian) sediments of the Arkhangelsk region, NW Russia: An alternative apparent polar wander path of Baltica for the Late Proterozoic–early Palaeozoic: Earth and Planetary Science Letters, v. 240, p. 732–747, doi:10.1016/j.epsl.2005.09.063.

Ivantsov, A.Y., 1990, New data on ultrastructure of sabelliditids (Pogonophora): Paleontological Journal, v. 4, p. 125–128.

Ivantsov, A.Y., Malakhovskaya, Y.E., and Serezhnikova, E.A., 2004, Some problematic fossils from the Vendian of the southeastern White Sea region: Paleontological Journal, v. 38, p. 1–9.

Jiang, Z., Liu, Q., Dekkers, M.J., Tauxe, L., Qin, H., Barryn, V., and Torrent, J., 2015, Acquisition of chemical remanent magnetization during experimental ferrihydrite-hematite conversion in Earth-like magnetic field—Implications for paleomagnetic studies of red beds: Earth and Planetary Science Letters, v. 428, p. 1–10, doi:10.1016/j.epsl.2015.07.024.

Johnson, R.J.E., and Van der Voo, R., 1986, Paleomagnetism of the late Precambrian Fourchu Group, Cape Breton Island, Nova Scotia: Canadian Journal of Earth Sciences, v. 23, p. 1673–1685, doi:10.1139/e86-155.

Johnson, R.J.E., and Van der Voo, R., 1989, Dual-polarity early Carboniferous remagnetization of the Fisset Brook Formation, Cape Breton Island, Nova Scotia: Geophysical Journal, v. 97, p. 259–273, doi:10.1111/j.1365-246X.1989.tb00500.x.

Kheraskova, T.N., Didenko, A.N., Bush, V.A., and Volozh, Y.A., 2003, The Vendian–early Paleozoic history of the continental margin of eastern Paleogondwana, Paleoasian Ocean, and Central Asian foldbelt: Russian Journal of Earth Sciences, v. 5, p. 165–184, doi:10.2205/2003ES000123.

Khramov, A.N., 2000, The general magnetostratigraphic scale of the Phanerozoic, in Zhamoida, A.I., ed., Supplements to the Stratigraphic Code of Russia: Transactions of VSEGEI (A.P. Karpinsky Russian Geological Research Institute), p. 24–45 (in Russian).

Kirsanov, V.V., 1968, New data on Precambrian stratigraphy of the central part of the Russian Platform: Izvestiya Akademii Nauk SSSR, Seriya Geologicheskaya, 4, p. 98–113 (in Russian).

Kirschvink, J.L., 1980, The least-square line and plane and the analysis of palaeomagnetic data: Royal Astronomical Society Geophysical Journal, v. 62, p. 699–718, doi:10.1111/j.1365-246X.1980.tb02601.x.

Kirschvink, J.L., and Rozanov, A.Y., 1984, Magnetostratigraphy of Lower Cambrian strata from the Siberian Platform: Palaeomagnetic pole and preliminary polarity time-scale: Geological Magazine, v. 121, p. 189–203, doi:10.1017/S0016756800028259.

Klein, R., Salminena, J., and Mertanen, S., 2015, Baltica during the Ediacaran and Cambrian: A paleomagnetic study of Hailuoto sediments in Finland: Precambrian Research, v. 267, p. 94–105, doi:10.1016/j.precamres.2015.06.005.

Kuznetsov, N.B., Soboleva, A.A., Udoratina, O.V., Hertseva, M.V., and Andreichev, V.L., 2007, Pre-Ordovician tectonic evolution and volcano-plutonic associations of the Timanides and northern pre-Uralides, northeast part of the East European craton: Gondwana Research, v. 12, p. 305–323, doi:10.1016/j.gr.2006.10.021.

Kuznetsov, N.B., Natapov, L.M., Belousova, E.A., and O'Reilly, S.Y., and Griffin, W.L., 2010, Geochronological, geochemical and isotopic study of detrital zircon suites from late Neoproterozoic clastic strata along the NE margin of the East European Craton: Implications for plate tectonic models: Gondwana Research, v. 17, p. 583–601, doi:10.1016/j.gr.2009.08.005.

Kuznetsov, N.B., Orlov, S.Y., Miller, E.L., Shazillo, A.V., Dronov, A.V., Soboleva, A.A., Udoratina, O.V., and Gehrels, G., 2011, First results of U/Pb dating of detrital zircons from early Paleozoic and Devonian sandstones of the Baltic-Ladoga region (south Ladoga area): Doklady Earth Sciences, v. 438, p. 759–765, doi:10.1134/S1028334X11060316.

Kuznetsov, N.B., Belousova, E.A., Alekseev, A.S., and Romanyuk, T.V., 2014, New data on detrital zircons from the sandstones of the lower Cambrian Brusov Formation (White Sea region, east-European craton): Unraveling the timing of the onset of the Arctida-Baltica collision: International Geology Review, v. 56, p. 1945–1963, doi:10.1080/00206814.2014.977968.

Kuznetsov, N.B., Alekseev, A.S., Belousova, E.A., Romanyuk, T.V., and Reimers, A.N., 2015, First results of U/Pb isotope dating (LA–ICP–MS) of detrital zircons from sandstones of the Lower Cambrian Brusov Formation of the southeastern White Sea region: A constraint on the lower age limit of the beginning of the Arctida-Baltica collision: Doklady Earth Sciences, v. 460, p. 28–32, doi:10.1134/S1028334X15010195.

Landing, E., Myrow, P., Benus, A.P., and Narbonne, G.M., 1989, The Placentian Series: Appearance of the oldest skeletized faunas in southeastern Newfoundland: Journal of Paleontology, v. 63, p .739–769.

Lewandowski, M., and Abrahamsen, N., 2003, Paleomagnetic results from the Cambrian and Ordovician sediments of Bornholm (Denmark) and southern Sweden and paleogeographical implications for Baltica: Journal of Geophysical Research, v. 108, 2516, doi:10.1029/2002JB002281.

Levashova, N.M., Degtyarev, K.E., Bazhenov, M.L., Collins, A.Q., and Van der Voo, R., 2003, Middle Paleozoic paleomagnetism of east Kazakhstan: Post-Middle Devonian rotations in

a large-scale orocline in the central Ural-Mongol belt: Tectonophysics, v. 377, p. 249–268, doi:10.1016/j.tecto.2003.09.013.

Levashova, N.M., Bazhenov, M.L., Meert, J.G., Kuznetsov, N.B., Golovanova, I.V., Danukalov, K.N., and Fedorova, N.M., 2013, Paleogeography of Baltica in the Ediacaran: Paleomagnetic and geochronological data from the clastic Zigan Formation, south Urals: Precambrian Research, v. 236, p. 16–30, doi:10.1016/j.precamres.2013.06.006.

Lipps, J.H., and Rozanov, A.Y., 1996, The late Precambrian–Cambrian agglutinated fossil Platysolenites: Paleontological Journal, v. 30, p. 679–687.

Martin, M.W., Grazhdankin, D.V., Bowring, S.A., Evans, D.A.D., Fedonkin, M.A., and Kirschvink, J.L., 2000, Age of Neoproterozoic bilaterian body and trace fossils, White Sea, Russia: Implications for metazoan evolution: Science, v. 288, p. 841–845, doi:10.1126/science.288.5467.841.

Maslov, A.V., 2004, Riphean and Vendian sedimentary sequences of the Timanides and Uralides, the eastern periphery of the East European Craton: Geological Society, London, Memoirs 30, p. 19–35.

Maslov, A.V., Grazhdankin, D.V., Podkovyrov, V.N., Ronkin, Y.L., and Lepikhina, O.P., 2008, Composition of sediment provenances and patterns in geological history of the late Vendian Mezen basin: Lithology and Mineral Resources, v. 43, p. 260–280, doi:10.1134/S002449020803005X.

McElhinny, M.W., 1964, Statistical significance of the fold test in palaeomagnetism: Royal Astronomical Society Geophysical Journal, v. 8, p. 338–340, doi:10.1111/j.1365-246X.1964.tb06300.x.

McFadden, P.L., and McElhinny, M.W., 1988, The combined analysis of remagnetization circles and direct observations in palaeomagnetism: Earth and Planetary Science Letters, v. 87, p. 161–172, doi:10.1016/0012-821X(88)90072-6.

McIlroy, D., Green, O.R., and Brasier, M.D., 2001, Paleobiology and evolution of the earliest agglutinated foraminifera: Platysolenites, Spirosolenites and related forms: Lethaia, v. 34, p. 13–29, doi:10.1080/002411601300068170.

Meert, J.G., 2014, Ediacaran–Early Ordovician paleomagnetism of Baltica: A review: Gondwana Research, v. 25, p. 159–169, doi:10.1016/j.gr.2013.02.003.

Meert, J.G., Bazhenov, M.L., Levashova, N.M., and Landing, E., 2016, Rapid changes of magnetic field polarity in the Late Ediacaran: Linking the CER and increased UV-B radiation: Gondwana Research, v. 34, p. 149–157, doi:10.1016/j.gr.2016.01.001.

Meert, J.G., and Lieberman, B.S., 2004, A palaeomagnetic and palaeobiogeographic perspective on latest Neoproterozoic and early Cambrian tectonic events: Journal of the Geological Society [London], v. 161, p. 477–487, doi:10.1144/0016-764903-107.

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

Miller, E.L., Kuznetsov, N., Soboleva, A., Udoratina, O., Grove, M.J., and Gehrels, G., 2011, Baltica in the Cordillera?: Geology, v. 39, p. 791–794, doi:10.1130/G31910.1.

Mints, M.V., et al., 2015, East European Craton: Early Precambrian history and 3D models of deep crustal structure: Geological Society of America Special Paper 510, 433 p., doi:10.1130/9780813725109.

Orlowski, S., 1985, Lower Cambrian and its trilobites in the Holy Cross Mts (Poland): Acta Geologica Polonica, v. 35, p. 231–250.

Orlowski, S., 1989, Trace fossils in the Lower Cambrian sequence in the Swiqtokrzyskie Mountains, central Poland: Acta Palaeontologica Polonica, v. 34, p. 211–231.

Pavlov, V., Gallet, Y., Shatsillo, A., and Vodovozov, V., 2004, Paleomagnetism of the Lower Cambrian from the lower Lena River Valley: Constraints on the apparent polar wander path from the Siberian platform and the anomalous behavior of the geomagnetic field at the beginning of the Phanerozoic: Izvestiya Physics of the Solid Earth, v. 40, p. 114–133.

Pisarevsky, S.A., Gurevich, E.L., and Khramov, A.N., 1997, Paleomagnetism of Lower Cambrian sediments from the Olenek river section (northern Siberia): Paleopoles and the problem of magnetic polarity in the Early Cambrian: Geophysical Journal International, v. 130, p. 746–756, doi:10.1111/j.1365-246X.1997.tb01869.x.

Popov, L., and Gorjansky, V., 1994, First record of Upper Cambrian from the eastern White Sea coast: New evidence from obolids (Brachiopoda): GFF, v. 116, p. 31–35, doi:10.1080/11035899409546139.

Popov, V., Iosifidi, A., Khramov, A., Tait, J., and Bachtadse, V., 2002, Paleomagnetism of upper Vendian sediments from the Winter Coast, White Sea region, Russia: Implications for the paleogeography of Baltica during Neoproterozoic times: Journal of Geophysical Research, v. 107, 2315, doi:10.1029/2001JB001607.

Popov, V.V., Khramov, A.N., and Bachtadse, V., 2005, Palaeomagnetism, magnetic stratigraphy, and petromagnetism of the upper Vendian sedimentary rocks in the sections of the Zolotitsa River and in the Verkhotina Hole, Winter Coast of the White Sea, Russia: Russian Journal of Earth Sciences, v. 7, no. 2, p. 1–29.

Rozanov, A.Y., 1983, Platysolenites, in Urbanek, A., and Rozanov, A.Y., eds., Upper Precambrian and Cambrian palaeontology of the East European Platform: Warsaw, Wydawnictwa Geologiczne, p. 94–100.

Schmitz, M.D., 2012, Appendix 2—Radiometric ages used in GTS2012, in Gradstein, F., et al., compilers, A geologic time scale 2012: Boston, Elsevier, p. 1045–1082.

Şengör, A.M.C., and Natal'in, B.A., 1996, Paleotectonics of Asia: Fragments of a synthesis, in Yin, A., and Harrison, M., eds., The tectonic evolution of Asia: New York, Cambridge University Press, p. 486–640.

Şengör, A.M.C., Natal'in, B.A., and Burtman, V.S., 1993, Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia: Nature, v. 364, p. 299–307, doi:10.1038/364299a0.

Şengör, A.M.C., Natal'in, B.A., Van der Voo, R., and Sunal, G., 2014, A new look at the Altaids: A superorogenic complex in northern and central Asia as a factory of continental crust. Part II: Palaeomagnetic data, reconstructions, crustal growth and global sea-level: Australian Journal of Earth Sciences, v. 107, p. 131–181.

Shatsillo, A.V., 2006, Vendian paleomagnetism of the southern Siberian platform and some aspects of late Precambrian geodynamics [Ph.D. thesis]: Moscow, Institute of Physics of the Earth, Russian Academy of Sciences, 238 p. (in Russian).

Shatsillo, A.V., Kuznetsov, N.B., Pavlov, V.E., Fedonkin, M.A., Priyatkina, N.S., Serov, S.G., and Rudko, S.V., 2015, First magnetostratigraphic data for the stratotype of the upper Neoproterozoic Lopata Formation (north-east of the Yenisei ridge): Problems of its age and paleogeography of the Siberian platform at the boundary of the Phanerozoic and Proterozoic: Doklady Earth Sciences, v. 465, p. 1211–1214, doi:10.1134/S1028334X15120065.

Slama, J., and Pedersen, R.B., 2015, Zircon provenance of SW Caledonian phyllites reveals a distant Timanian sediment source: Journal of the Geological Society [London], v. 172, p. 465–478, doi:10.1144/jgs2014-143.

Sokolov, B.S., 1968, Vendian and early Cambrian Sabelliditida (Pogonophora) of the USSR: Problems of paleontology, in International Geological Congress, XXIII Session, Reports of Soviet Geologists for the Meeting of the International Palaeontological Union: Moscow, Nauka, p. 73–79 (in Russian).

Streng, M., Babcock, L.E., and Hollingsworth, J.S., 2005, Agglutinated protists from the Lower Cambrian of Nevada: Journal of Paleontology, v. 79, p. 1214–1218, doi:10.1666/0022-3360(2005)079[1214:APFTLC]2.0.CO;2.

Tolmacheva, T.Y., Alekseev, A.S., and Reimers, A.N., 2013, Conodonts in xenoliths from kimberlite pipes of the southwestern White Sea region (Arkhangel'sk Oblast): Key to Ordovician stratigraphic and paleogeographic reconstructions of the East European platform: Doklady Earth Sciences, v. 451, p. 687–691, doi:10.1134/S1028334X13070088.

Torsvik, T.H., and Rehnström, E.F., 2001, Cambrian palaeomagnetic data from Baltica: Implications for true polar wander and Cambrian palaeogeography: Journal of the Geological Society [London], v. 158, p. 321–329, doi:10.1144/jgs.158.2.321.

Torsvik, T.H., Meert, J.G., and Smethurst, M.A., 1998, Polar wander and the Cambrian: Science, v. 279, p. 9a–10a, doi:10.1126/science.279.5347.9a.

Torsvik, T.H., et al., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, v. 114, p. 325–368, doi:10.1016/j.earscirev.2012.06.007.

Veselovskiy, R.V., Bazhenov, M.L., and Arzamastsev, A.A., 2016, Paleomagnetism of Devonian dykes in the northern Kola Peninsula and its bearing on the apparent polar wander path of Baltica in the Precambrian: Tectonophysics, v. 675, p. 91–102, doi:10.1016/j.tecto.2016.03.014.

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

Windley, B.P., Alexeiev, D.V., Xiao, W., Kroner, A., and Badarch, G., 2007, Tectonic models for accretion of the Central Asian Orogenic Belt: Journal of the Geological Society [London], v. 164, p. 31–47, doi:10.1144/0016-76492006-022.

Yanishevsky, M.E., 1926, On the remains of tubular worms from Cambrian blue clays: Ezhegodnik Russkogo Paleontologicheskogo Obchestva, v. 4, p. 99–112 (in Russian).

Zhang, W., Roberts, D., and Pease, V., 2015, Provenance characteristics and regional implications of Neoproterozoic Timanian-margin successions and a basal Caledonian nappe in northern Norway: Precambrian Research, v. 268, p. 153–167, doi:10.1016/j.precamres.2015.07.006.

Zijderveld, J.D.A., 1967, AC demagnetization of rocks: Analysis of results, in Collinson, D.W., and Creer, K.M., eds., Methods in paleomagnetism: Amsterdam, Elsevier, p. 254–286.